Real-ESSI Simulator

Domain Specific Language

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http://real-essi.us

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Contents

Chapter 1

Input, Domain Specific Language (DSL)

1991-2005-2010-2011-2012-2015-2016-2017-2020-2021-

1.1 Chapter Summary and Highlights

1.2 Introduction

This chapter presents the domain specific language developed for the Real-ESSI. The language was designed with a primary goal of developing FEA models and interfacing them with various Real-ESSI functionalities. In addition to that, syntax is used to self-document models, provide physical-unit safety, provide common flow control structures, provide modularity to scripting via user functions and "include" files, and provide an interactive environment within which models can be created, validated and verified.

The development of Real-ESSI Domain specific language (DSL) (the Finite Element Interpreter, FEI) is based on LEX (Lesk and Schmidt, 1975) and YACC (Johnson, 1975).

Self-documenting ensures that the resulting model script is readable and understandable with little or no reference to the users manual. This is accomplished by providing a command grammar structure and wording similar to what would be used in a natural language description of the problem.

FEA analysis is unitless, that is, all calculations are carried out without referencing a particular unit system. This leaves the task of unit correctness up to the user of FEA analysis. This represents a recurring source of error in FEA analysis. Physical unit safety is enforced in Real-ESSI by implementing all base variables as physical quantities, that is, all variables have a unit associated with it. The adimensional unit is the base unit for those variables which have no relevant unit (like node numbers). Command calls are sensitive to units. For example, the node creation command call expects the node coordinates to be input with the corresponding units (length in this case). Additionally, the programming/command language naturally supports operation with units like arithmetic operations (quantities with different unit types will not add or subtract but may be multiplied). This approach to FEA with unit awareness provides an additional layer of security to FEA calculations, and forces the user to carefully think about units. This can help catch some common mistakes.

The Real-ESSI language provides modularity through the `include` directive/command, and user functions. This allows complex analysis cases to be parameterized into modules and functions which can be reused in other models.

Finally, an emphasis is placed on model verification and validation. To this end, Real-ESSI provides an interactive programming environment with all the ESSI syntax available. By using this environment. the user can develop tests to detect errors in the model that are not programming errors. For example, the user can query nodes and elements to see if they are set to appropriate states. Also, several standard tools are provided to check element validity (Jacobian, etc.).

The ESSI language provides reduced model development time by providing the aforementioned features along with meaningful error reporting (of syntax and grammatical errors), a help system, command completion and highlighting for several open source and commercial text editors.

Some additional ideas are given by Dmitriev (2004), Stroustrup (2005), Niebler (2005), Mernik et al. (2005), Ward (2003), etc.

1.3 Domain Specific Language (DSL), English Language Binding

Overview of the language syntax.

- Each command line has to end with a semicolon ";"
- Comment on a line begins with either "//" or "!" and last until the end of current line.
- Units are required (see more below) for all quantities and variables.
- Include statements allow splitting source into several files
- All variables are double precision (i.e. floats) with a unit attached.
- All standard arithmetic operations are implemented, and are unit sensitive.
- Internally, all units are represented in the base SI units (m - s - kg).
- The syntax ignores extra white spaces, tabulations and newlines. Wherever they appear, they are there for code readability only. (This is why all commands need to end with a semicolon).
- The user should be familiar with the list of the reserved keywords from Section 1.7 on page 347.

1.3.1 Running Real-ESSI

At the command line type "essi", to get to the ESSI prompt and start Real-ESSI in interactive mode.

Command line output

```


  The Finite Element Interpreter Endeavor

  The Real-ESSI Simulator
  Modeling and Simulation of Earthquakes, and Soils, and Structures ↩
   and their Interaction

  Sequential processing mode.

Version Name      : Real-ESSI Global Release, June2018. Release date: ↩
   Jun 13 2018 at 11:02:19. Tag: adc085ae70
Version Branch    : GLOBAL_RELEASE
Compile Date      : Jun 13 2018 at 14:36:56
Compile User      : jeremic
Compile Sysinfo   : sokocalo 4.13.0-43-generic x86_64 GNU/Linux
```

```
Runtime User      : jeremic
Runtime Sysinfo   : sokocalo 4.13.0-43-generic x86_64 GNU/Linux
Time Now          : Jun 13 2018 at 15:32:52
Days From Release : 0
PostProcessing Compatible Version: ParaView 5.1.2
PostProcessing Compatible Version: ESSI-pvESSI Date: Feb 15 2018 at ↩
   11:00:28. Tag: 58fe430a19

Static startup tips:
 * Remember: Every command ends with a semicolon ';'.
 * Type 'quit;' or 'exit;' to finish.
 * Run 'essi -h' to see available command line options.

ESSI>
```

A number of useful information about Real-ESSI is printed on the screen. From here, commands can be input manually or a file may be included via the `include` command which is as follows.

```
include "foobar.fei";
```

to include the file `foobar.fei`.

A more efficient way to start Real-ESSI and analyze an example is to pass input file name to the command line. Real-ESSI command to execute an input file immediately is done by issuing the following command: `essi -f foobar.fei`. This will execute essi directly on input file `foobar.fei`. After executing the file, the essi interpreter will continue in interactive mode unless the command line flag `-n` or `--no-interactive` is set. A list of command line options is available by calling essi from the command line as `essi -h`.

Command line output

```


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Version Branch    : GLOBAL_RELEASE
Compile Date      : Jun 13 2018 at 14:36:56
Compile User      : jeremic
Compile Sysinfo   : sokocalo 4.13.0-43-generic x86_64 GNU/Linux
Runtime User      : jeremic
Runtime Sysinfo   : sokocalo 4.13.0-43-generic x86_64 GNU/Linux
Time Now          : Jun 13 2018 at 16:22:08
Days From Release : 0
PostProcessing Compatible Version: ParaView 5.1.2
PostProcessing Compatible Version: ESSI-pvESSI Date: Feb 15 2018 at ↩
   11:00:28. Tag: 58fe430a19

Static startup tips:
 * Remember: Every command ends with a semicolon ';'.
 * Type 'quit;' or 'exit;' to finish.
 * Run 'essi -h' to see available command line options.

The Real-ESSI Simulator
Modeling and Simulation of Earthquakes, and Soils, and Structures and ↩
   their Interaction

Usage: essi [-cfhnsmbe FILENAME]
  -c --cpp-output                : Output cpp version of the model.
  -f --filename [FILENAME]       : run ESSI on a FILENAME.
  -h --help                      : Print this message.
  -n --no-interactive            : Disable interactive mode.
  -s --set-variable              : Set a variable from the command line.
  -d --dry-run                   : Do not execute ESSI API calls. ↩
   Just parse.
  -m --model-name [NAME]         : Set the model name from the ↩
   command line.
  -p --profile-report [FILENAME] : Set the filename for the profiler ↩
   report (and activate lightweight profiling)


Example to set a variable name from command line:
    essi -s a=10,b=20,c=30
Runs ESSI with variables a, b, and c set to 10, 20 and 30 respectively.
At this time, only ESSIunits::unitless variables can be set.
```

1.3.2 Finishing Real-ESSI Program Run

To properly finish Real-ESSI program run, and save and close all the output files, user has to use final, closure command:

```
bye;
```

Command `bye;` has to be included at the end of input file script, or at the end of each interactive/interpretative session. Command `bye;` ensures that Real-ESSI program gracefully exits simulation, and that all the output files are properly saved and closed. Proper finishing of simulation using Real-ESSI Simulator is very much necessary, while the choice of command `bye;` is done as an homage to Professor Knuth and his Literate Programming endeavor (Knuth, 1984), that is driving much of the Real-ESSI DSL development.

There are a number of alternative final commands, for example:

```
exit;
quit;
zdravo;
```

```
vozdra;
dvojka;
voljno;
zaijian;
tschuess;
geia-sou;
tchau;
sair;
khoda-hafez;
doei;
nasvidenje;
ajde-bok;
izhod;
konec;
czesc;
ciao;
hoscakal;
```

These additional, alternative final commands can all be written using original scripts:

zdravo ↔ здраво

vozdra ↔ воздра

dvojka ↔ двојка

voljno ↔ вољно

zaijian ↔ 再见

tschuess ↔ tschüss

geia-sou ↔ γεια σου

khoda-hafez ↔ خداحافظ

hoscakal ↔ hoşçakal

1.3.3 Real-ESSI Variables, Basic Units and Flow Control

Variables are defined using the assignment (=) operator. For example,

```
var_x   =  7;      //Results in the variable x be set to 7 (unitless)
var_y = 3.972e+2;  //Scientific notation is available.
```

The language contains a list of reserved keywords. Throughout this documentation, reserved keywords are highlighted in blue or red.

All standard arithmetic operations are available between variables. These operations can be combined arbitrarily and grouped together with parentheses.

```
var_a = var_x + var_y;       // Addition
var_b = var_x - var_y;       // Subtraction
var_c = var_x * var_y;         // Product
var_d = var_x / var_y;         // Quotient
var_e = var_y % var_x;         // Modulus (how many times x fits in y)
```

The 'print' command can be used to display the current value of a variable.

```
print var_x;
print var_y;
print var_a;
print var_b;
print var_c;
print var_d;
print var_e;
```

Command line output

```
var_x = 7 []
var_y = 397.2 []
var_a = 404.2 []
var_b = -390.2 []
var_c = 2780.4 []
var_d = 0.0176234 []
var_e = 5.2 []
```

Here the "unit" (sign) [] means that the quantities are unitless.

The command 'whos' is used to see all the currently defined variables and their values. After a fresh start of essi, needed to clear up all the previously defined variables, command whos;' produces a list of predefined variables:

Command line output

```
ESSI> whos;

Declared variables:
  *       Day =           86400 [s]
  *       GPa =               1 [GPa]
  *      Hour =            3600 [s]
  *        Hz =               1 [Hz]
  *       MPa =               1 [MPa]
  *    Minute =              60 [s]
  *         N =               1 [N]
  *        Pa =               1 [Pa]
  *      Week =          604800 [s]
  *        cm =               1 [cm]
  *      feet =          0.3048 [m]
  *        ft =          0.3048 [m]
  *         g =             9.81  [m*s^-2]
  *      inch =           0.0254  [m]
  *        kN =                1  [kN]
  *       kPa =                1  [kPa]
  *        kg =                1  [kg]
  *       kip =          4448.22  [N]
  *        km =                1  [km]
  *       ksi =      6.89476e+06  [Pa]
  *       lbf =          4.44822  [N]
  *       lbm =         0.453592  [kg]
  *         m =                1  [m]
  *      mile =          1609.35  [m]
  *        mm =                1  [mm]
  *        pi =          3.14159  []
  *       psi =          6894.76  [Pa]
  *         s =                1  [s]
  *      yard =           0.9144  [m]

    * = locked variable
ESSI>
```

Predefined variables shown above have a preceding asterisk to show they are locked variables which cannot be modified. The purpose of these locked variables are to provide names for units. Imperial units are also supported as shown above.

The units for variable are shown between the brackets. Note that unit variables have the same name as their unit, which is not the case for user defined variables. Variables preceded by a star (*) are locked variables which can't be modified.

For example, the variable 'm' defines 'meter'. So to define a new variable L1 which has meter units we do:

```
L1 = 1*m;      //  Defines L1 to 1 m.
L2 = 40*mm;    //  Defines L2 to be 40 millimeters.
```

Even though L2 was created with millimeter units, it is stored in base units.

`print L2;` displays

Command line output

```
 L2 = 0.04 [m]
```

As additional examples, let us define few forces:

```
F1 = 10*kN;
F2 = 300*N;
F3 = 4*kg*g;
```

Here g is the predefined acceleration due to gravity.

Arithmetic operations do check (and enforce) for unit consistency. For example, `foo = L1 + F1;` produces an error because units are not compatible. However, `bar = L1 + L2;` is acceptable. On the other hand, multiplication, division and modulus, always work because the result produces a quantity with new units (except when the adimensional quantity is involved).

```
A = L1*L2;
Stress_n = F1 / A;
```

Units for all variables are internally converted to SI units ($kg - m - s$) and stored in that unit system. Variables can be *displayed* using different units by using the [] operator. This does not change the variable, it just displays the value of variable with required unit. For example,

```
print Stress_n;            //Print in base SI units.
print Stress_n in Pa;        //Print in Pascal
print Stress_n in kPa;       //Print in kilo Pascal
```

Command line output

```
Stress_n = 250000 [kg*m^-1*s^-2]

Stress_n = 250000 [Pa]

Stress_n = 250 [kPa]
```

The DSL provides functions to test the physical units of variables. For example,

`print isForce(F1);`

Will print an adimensional, Boolean `1` because `F1` has units of force. While,

`print isPressure(F);`

will print an adimensional, Boolean `0`. The language also provides comparison of quantities with same units (remember all values are compared in SI Units).

`print F1 > F2;`

will print an adimensional, Boolean `1` since `F1` is greater than `F2`.

The program flow can be controlled with `if` and `while` statements, i.e.:

```
if (isForce(F1))
{
 print F1;    // This will be executed
};

if (isForce(L1))
{
 print L1;    // This will not.
};
```

Note the necessary semicolon (;) at the closing brace. Unlike C/C++, the braces are always necessary. Closing colon is also always necessary.

The "else" statement is also available:

```
if (isForce(L1))
{
 print L1;     // This will not execute
}
else
{
 print L2;     // This will execute instead
};
```

While loops are also available:

```
i = 0;
while( i < 10)
{
 print i;
 i = i +1;
};
```

1.3.4 Modeling

This section details ESSI modeling commands. Angle brackets <> are used for quantity or variable placeholder, that is, they indicate where user input goes. Within the angle brackets, the expected unit type is given as well, i.e.. <L> means the command expects an input with a value and a length unit. The symbol <.> represents the adimensional quantity.

In addition to that, the vertical bar | ("OR" sign)) is used to separate two or more keyword options, i.e. [a|b|c] is used indicate keyword options a or b or c. The symbol |...| is used to denote where several long options exist and are explained elsewhere (an example of this is available below in a material model definitions).

All commands require unit consistency. Base units, SI or other can be used as indicated below:

- length, symbol L, units [m, inch, ft]
- mass, symbol M, units [kg, lbm],
- time, symbol T, units [s]

Derived units can also be used:

- angle, symbol rad (radian), unit $[dimensionless, L/L]$
- force, symbol N (Newton), units $[N, kN, MN, M * L/T^2]$,
- stress, symbol Pa (Pascal), units $[Pa, kPa, MPa, N/L^2, M/L/T^2]$

- strain, symbol (no symbol), units $[L/L]$
- mass density, symbol (no symbol), units $[M/L^3]$
- force density, symbol (no symbol), units $[M/L^2/T^2]$

All models have to be named: `model name "model_name_string";` This is important as output files are named based on model name.

Each loading stage has to be named as well. A new loading stage[1] is defined like this:

`new loading stage "loading stage name string";`

In addition to model name, loading stage name is used for output file name for given loading stage.

[1]See more in section 101.4.5 on page 73 in Jeremić et al. (1989-2025).

Modeling, Material Model: Adding a Material Model to the Finite Element Model

Adding constitutive material model to the finite element model/domain is done using command:

```
add material  # <.> type |...|
                  mass_density = <M/L^3>
                  (more model dependent parameters) ;
```

- Material number # (or alternatively No) is a distinct integer number used to uniquely identify this material.
- Mass density should be defined for each material (even if only static analysis is performed, for example if self weight is to be used as a loading stage).
- Depending on material model, there will be additional material parameters that are defined for each material model/type below:

Starting with version 03-NOV-2015 all elastic-plastic material models require explicit specification of the constitutive integration algorithm. More information on this can be found in 1.3.5. Only the material linear_elastic_isotropic_3d_LT ignores this option.

Choices for material_type are listed below.

Modeling, Material Model: Linear Elastic Isotropic Material Model

The command is:

```
add material # <.> type linear_elastic_isotropic_3d
     mass_density = <M/L^3>
     elastic_modulus = <F/L^2>
     poisson_ratio = <.>;
```

where:

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is an isotropic modulus of elasticity of a material (units: stress)
- poisson_ratio is a Poisson's ratio [dimensionless]

More on this material model can be found in Section 104.6.1 on Page 181 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Cross Anisotropic Linear Elastic Material Model

The command is:

```
add material  # <.> <material_number>
                type linear_elastic_crossanisotropic
                mass_density = <M/L^3>
                elastic_modulus_horizontal = <F/L^2>
                elastic_modulus_vertical = <F/L^2>
                poisson_ratio_h_v  = <.>
                poisson_ratio_h_h  = <.>
                shear_modulus_h_v = <F/L^2>;
```

where:

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus_horizontal` is an anisotropic modulus of elasticity for horizontal plane of a material $[F/L^2]$
- `elastic_modulus_vertical` is an anisotropic modulus of elasticity for vertical direction of a material $[F/L^2]$
- `poisson_ratio_h_v` is a Poisson's ratio for horizontal-vertical directions [dimensionless]
- `poisson_ratio_h_h` is a Poisson's ratio for horizontal-horizontal directions [dimensionless]
- `shear_modulus_h_v` is a shear modulus for horizontal-vertical directions $[F/L^2]$

It is assumed that vertical axes is global Z axes.

More on this material model can be found in Section 104.6.1 on Page 181 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: von Mises Associated Material Model with Linear Isotropic and/or Kinematic Hardening

Implements von Mises family of constitutive models, with linear kinematic and/or isotropic hardening.

The command is:

```
add material # <.> type vonMises
  mass_density = <M/L^3>
  elastic_modulus = <F/L^2>
  poisson_ratio = <.>
  von_mises_radius = <F/L^2>
  kinematic_hardening_rate = <F/L^2>
  isotropic_hardening_rate = <F/L^2> ;
```

where:

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of material $[F/L^2]$
- `poisson_ratio` is the Poisson's ratio material [ ]
- `von_mises_radius` is the radius of the deviatoric section of the von Mises yield surface $[F/L^2]$
- `kinematic_hardening_rate` is the rate of the kinematic hardening $[F/L^2]$
- `isotropic_hardening_rate` is the rate of the kinematic hardening $[F/L^2]$

More on this material model can be found in Section 104.6.6 on Page 186 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: von Mises Associated Material Model with Isotropic Hardening and/or Armstrong-Frederic Nonlinear Kinematic Hardening

This command is for von Mises family of constitutive models, with Armstrong-Frederick kinematic and/or isotropic hardening.

The command is:

```
add material # <.> type vonMisesArmstrongFrederick
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    von_mises_radius = <.>
    armstrong_frederick_ha = <F/L^2>
    armstrong_frederick_cr =  <.>
    isotropic_hardening_rate = <F/L^2> ;
```

where:

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of material $[F/L^2]$
- poisson_ratio is the Poisson's ratio material [ ]
- von_mises_radius is the radius of the deviatoric section of the von Mises yield surface $[F/L^2]$
- armstrong_frederick_ha controls rate of the kinematic hardening $[F/L^2]$
- armstrong_frederick_cr controls the saturation limit for kinematic hardening [Dimensionless]
- isotropic_hardening_rate is the rate of the kinematic hardening $[F/L^2]$

More on this material model can be found in Section 104.6.6 on Page 186 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Drucker-Prager Associated Material Model with Linear Isotropic and/or Kinematic Hardening

This command is for Drucker-Prager family of constitutive models, with linear kinematic and/or isotropic hardening. This material uses associate plastic flow rule.

The command is:

```
add material # <.> type DruckerPrager
  mass_density = <M/L^3>
  elastic_modulus = <F/L^2>
  poisson_ratio = <.>
  druckerprager_k = <.>
  kinematic_hardening_rate = <F/L^2>
  isotropic_hardening_rate = <F/L^2>
  initial_confining_stress = <F/L^2> ;
```

where:

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of material $[F/L^2]$
- poisson_ratio is the Poisson's ratio material [ ]
- druckerprager_k slope of the Drucker-Prager yield surface in p-qm space (equivalent to M parameter) [dimensionless]
- kinematic_hardening_rate is the rate of the kinematic hardening $[F/L^2]$
- isotropic_hardening_rate is the rate of the isotropic hardening $[F/L^2]$

More on this material model can be found in Section 104.6.7 on Page 192 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Drucker-Prager Associated Material Model with Isotropic Hardening and/or Armstrong-Frederick Nonlinear Kinematic Hardening

A Drucker-Prager constitutive model with associative plastic-flow rule, Armstrong-Frederick kinematic hardening, and linear isotropic hardening and linear elastic isotropic elasticity law.

The command is:

```
add material # <.> type DruckerPragerArmstrongFrederickLE
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    druckerprager_k = <.>
    armstrong_frederick_ha = <F/L^2>
    armstrong_frederick_cr = <.>
    isotropic_hardening_rate = <F/L^2>
    initial_confining_stress = <F/L^2>;
```

where:

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of material $[F/L^2]$
- `poisson_ratio` is the Poisson's ratio material [ ]
- `druckerprager_k` slope of the Drucker-Prager yield surface in p-qm space (equivalent to M parameter) [Dimensionless]
- `armstrong_frederick_ha` controls rate of the kinematic hardening $[F/L^2]$
- `armstrong_frederick_cr` controls the saturation limit for kinematic hardening [Dimensionless]
- `isotropic_hardening_rate` is the rate of the isotropic hardening $[F/L^2]$
- `initial_confining_stress` initial confining (mean) pressure $[F/L^2]$

More on this material model can be found in Section 104.6.7 on Page 192 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Drucker-Prager Associated Material Model with Isotropic Hardening and/or Armstrong-Frederick Nonlinear Kinematic Hardening and Nonlinear Duncan-Chang Elasticity

A Drucker-Prager constitutive model with associative plastic-flow rule, Armstrong-Frederick kinematic hardening, and Duncan-Chang non-linear isotropic elasticity law.

The command is:

```
add material # <.> type DruckerPragerArmstrongFrederickNE
  mass_density = <M/L^3>
  DuncanChang_K = <.>
  DuncanChang_pa = <F/L^2>
  DuncanChang_n = <.>
  DuncanChang_sigma3_max = <F/L^2>
  DuncanChang_nu = <.>
  druckerprager_k = <.>
  armstrong_frederick_ha = <F/L^2>
  armstrong_frederick_cr = <.>
  isotropic_hardening_rate = <F/L^2>
  initial_confining_stress = <F/L^2>;
```

where:

- `mass_density` is the mass density of material $[M/L^3]$
- `DuncanChang_K` parameter controlling Young's modulus $[< . >]$
- `DuncanChang_pa` reference pressure $[F/L^2]$
- `DuncanChang_n` exponent $[< . >]$
- `DuncanChang_sigma3_max` maximum value for σ_3 $(\sigma_3 < 0)$ elastic properties are constant for greater values of σ_3 $[F/L^2]$
- `DuncanChang_nu` Poisson's ratio $[F/L^2]$
- `druckerprager_k` slope of the Drucker-Prager yield surface in p-qm space (equivalent to M parameter) [Dimensionless]
- `armstrong_frederick_ha` controls rate of the kinematic hardening $[F/L^2]$
- `armstrong_frederick_cr` controls the saturation limit for kinematic hardening [Dimensionless]
- `isotropic_hardening_rate` is the rate of the isotropic hardening $[F/L^2]$
- `initial_confining_stress` initial confining (mean) pressure $[F/L^2]$

More on this material model can be found in Section 104.6.7 on Page 192 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Drucker-Prager Nonassociated Material Model with Linear Isotropic and/or Kinematic Hardening

This command defines Drucker-Prager family of constitutive models, with linear kinematic and/or isotropic hardening. This material uses non-associate plastic flow rule.

The command is:

```
add material # <.> type DruckerPragerNonAssociateLinearHardening
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    druckerprager_k = <.>
    kinematic_hardening_rate = <F/L^2>
    isotropic_hardening_rate = <F/L^2>
    initial_confining_stress = <F/L^2>
    plastic_flow_xi = <.>
    plastic_flow_kd = <.>;
```

where:

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of material $[F/L^2]$
- poisson_ratio is the Poisson's ratio material [ ]
- druckerprager_k slope of the Drucker-Prager yield surface in p-qm space (equivalent to M parameter) [Dimensionless]
- kinematic_hardening_rate is the linear rate of the kinematic hardening $[F/L^2]$
- isotropic_hardening_rate is the linear rate of the isotropic hardening $[F/L^2]$
- initial_confining_stress initial confining (mean) pressure $[F/L^2]$
- plastic_flow_xi governs the amplitude of plastic volume changes. The higher ξ, the higher the dilatancy. If $\xi = 0$, the material model will only produce deviatoric plastic strains. [.]
- plastic_flow_kd governs the size of the dilatancy surface, a cone in the stress space on which no plastic volume changes occur. k_d governs the size of this cone: if k_d is equal to zero, the dilatancy surface shrinks to a line (the hydrostatic axis), so that only dilative soil deformation is possible. [.]

More on this material model can be found in Section 104.6.7 on Page 192 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Drucker-Prager Nonassociated Material Model with Linear Isotropic and/or Armstrong-Frederick Nonlinear Kinematic Hardening

This command defines Drucker-Prager family of constitutive models, with nonlinear kinematic and/or linear isotropic hardening. This material uses non-associated plastic flow rule.

The command is:

```
add material # <.> type DruckerPragerNonAssociateArmstrongFrederick
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    druckerprager_k = <.>
    armstrong_frederick_ha = <F/L^2>
    armstrong_frederick_cr = <.>
    isotropic_hardening_rate = <F/L^2>
    initial_confining_stress = <F/L^2>
    plastic_flow_xi = <.>
    plastic_flow_kd = <.>;
```

where:

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of material $[F/L^2]$
- poisson_ratio is the Poisson's ratio material [ ]
- druckerprager_k slope of the Drucker-Prager yield surface in p-qm space (equivalent to M parameter) [Dimensionless]
- armstrong_frederick_ha a kinematic hardening parameter, which governs the initial stiffness after the yield $[F/L^2]$
- armstrong_frederick_cr a kinematic hardening parameter. $\frac{h_a}{c_r}$ governs the limit of the back-stress [Dimensionless]
- isotropic_hardening_rate is the rate of the kinematic hardening $[F/L^2]$
- initial_confining_stress initial confining (mean) pressure $[F/L^2]$
- plastic_flow_xi governs the amplitude of plastic volume changes - the higher ξ, the higher the dilatancy. If $\xi = 0$, the material model will only produce deviatoric plastic strains. [.]
- plastic_flow_kd governs the size of the dilatancy surface, a cone in the stress space on which no plastic volume changes occur. k_d governs the size of this cone: if k_d is equal to zero, the dilatancy surface shrinks to a line (the hydrostatic axis), so that only dilative soil deformation is possible. [.]

More on this material model can be found in Section 104.6.7 on Page 192 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

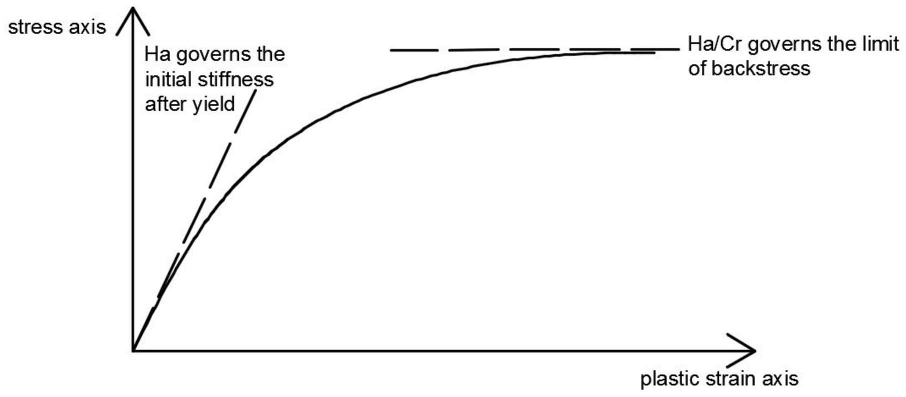

stress axis
Ha governs the initial stiffness after yield
Ha/Cr governs the limit of backstress
plastic strain axis

Figure 1.1: The physical meanings of h_a and c_r

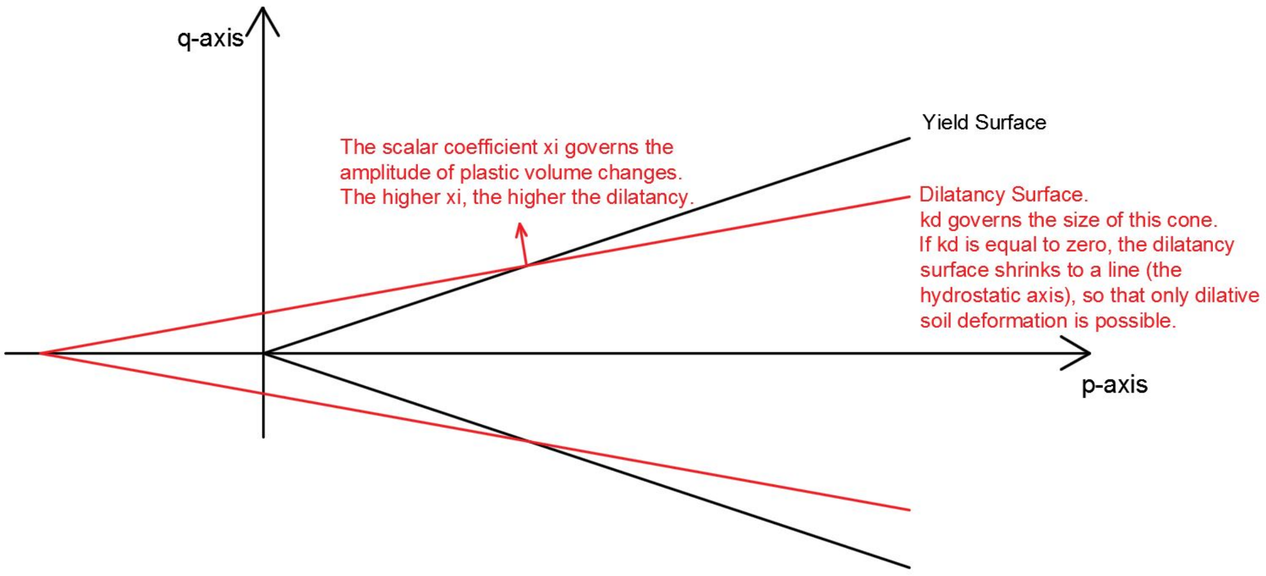

q-axis
Yield Surface
The scalar coefficient xi governs the amplitude of plastic volume changes. The higher xi, the higher the dilatancy.
Dilatancy Surface. kd governs the size of this cone. If kd is equal to zero, the dilatancy surface shrinks to a line (the hydrostatic axis), so that only dilative soil deformation is possible.
p-axis

Figure 1.2: The physical meanings of ξ and k_d

The physical meanings of h_a, c_r, ξ, and k_d are shown in Figure (1.1) and Figure (1.2).

Modeling, Material Model: Hyperbolic Drucker-Prager Nonassociated Material Model with Linear Isotropic and/or Armstrong-Frederick Nonlinear Kinematic Hardening

This command defines a hyperbolic Drucker-Prager constitutive model, with nonlinear kinematic and/or linear isotropic hardening. This material uses non-associated plastic flow rule.

The command is:

```
add material # <.> type ↩
 HyperbolicDruckerPragerNonAssociateArmstrongFrederick
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    friction_angle = <.>
    cohesion = <F/L^2>
    rounded_distance = <F/L^2>
    armstrong_frederick_ha = <F/L^2>
    armstrong_frederick_cr = <.>
    isotropic_hardening_rate = <F/L^2>
    initial_confining_stress = <F/L^2>
    plastic_flow_xi = <.>
    plastic_flow_kd = <.>;
```

where:

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of material $[F/L^2]$
- `poisson_ratio` is the Poisson's ratio for material [ ]
- `friction_angle` is the initial friction angle of the material. If isotropic hardening is present, friction angle will evolve. [rad]
- `cohesion` is a material constant that defines the cohesion of the material $[F/L^2]$
- `rounded_distance` is the parameter that controls the shape of the rounded apex of yield surface $[F/L^2]$
- `armstrong_frederick_ha` a kinematic hardening parameter, that governs the initial stiffness after the yield $[F/L^2]$
- `armstrong_frederick_cr` a kinematic hardening parameter. It is noted that ratio $\frac{h_a}{c_r}$ controls the asymptote the back-stress, that can be related to the ultimate shear strength [.]
- `isotropic_hardening_rate` is the rate of the isotropic hardening $[F/L^2]$
- `initial_confining_stress` initial confining (mean) pressure, a small value just get initial stress out of cone zone $[F/L^2]$

- `plastic_flow_xi` governs the amplitude of plastic volume changes - the higher ξ, the higher the dilatancy. If $\xi = 0$, the material model will only produce deviatoric plastic strains. [.]

- `plastic_flow_kd` governs the size of the dilatancy surface, a cone in the stress space on which no plastic volume changes occur. k_d governs the size of this cone: if k_d is equal to zero, the dilatancy surface shrinks to a line (the hydrostatic axis), so that only dilative soil deformation is possible. [.]

More on this material model can be found in Section 104.6.8.5 on Page 205 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Rounded Mohr-Coulomb Associated Linear Isotropic Hardening Material Model

The command is:

```
add material # <.> type roundedMohrCoulomb
    mass_density = <M/L^3>
    elastic_modulus = <F/L^2>
    poisson_ratio = <.>
    RMC_m = <.>
    RMC_qa = <F/L^2>
    RMC_pc = <F/L^2>
    RMC_e = <.>
    RMC_eta0 = <.>
    RMC_Heta = <F/L^2>
    initial_confining_stress = <F/L^2>

```

where

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of material $[F/L^2]$
- poisson_ratio is the Poisson's ratio material [ ]
- RMC_m $0 < m < 1$ parameter of the RMC yield function. Controls roundness of apex in p-q space. [ ]
- RMC_qa q_a parameter of the RMC yield function. Controls roundness of apex in p-q space. $[F/L^2]$
- RMC_pc p pressure offset $[F/L^2]$
- RMC_e e parameter controls roundness of the deviatoric cross-section of the yield surface. $0.5 < e <= 1$, $e = 0.5$ results in a triangular deviatoric section while $e = 1$ is round. [ ]
- RMC_eta0 controls the opening of the yield surface [ ]
- RMC_Heta isotropic (linear) hardening of the yield surface $[F/L^2]$
- initial_confining_stress initial confining (mean) pressure $[F/L^2]$

More on this material model can be found in Section 104.6.9 on Page 208 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Cam Clay Material Model

The command is:

```
add material # <.> type CamClay
  mass_density = <M/L^3>
  M = <.>
  lambda = <.>
  kappa = <.>
  e0 = <.>
  p0 = <F/L^2>
  poisson_ratio = <.>
  initial_confining_stress = <F/L^2>
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `e0` void ratio (e_0) at the reference pressure, [dimensionless]
- `M` Cam-Clay slope of the critical state line in stress space, [dimensionless]
- `lambda` Cam-Clay normal consolidation line slope, (unit: dimensionless)
- `kappa` Cam-Clay unload-reload line slope, (unit: dimensionless)
- `poisson_ratio` Constant Poisson-ratio
- `p0` Cam-Clay parameter (p_0). Tip of the yield surface in q-p space. $[F/L^2]$
- `initial_confining_stress` initial confining (mean) pressure $[F/L^2]$

More on this material model can be found in Section 104.6.10 on Page 209 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: von Mises Associated Multiple Yield Surface Material Model

The command is:

```
    add material # <.> type vonMisesMultipleYieldSurface
      mass_density = <M/L^3>
      elastic_modulus = <F/L^2>
      poisson_ratio = <.>
      total_number_of_yield_surface = <.>
      radiuses_of_yield_surface = <string>
      radiuses_scale_unit = <F/L^2>
      hardening_parameters_of_yield_surfaces = <string>
      hardening_parameters_scale_unit = <F/L^2> ;

```

where

- mass_density is the mass density of material $[M/L^3]$
- elastic_modulus is the elastic modulus of the material $[F/L^2]$
- poisson_ratio is the constant Poisson-ratio [dimensionless]
- total_number_of_yield_surface is the total number of yield surfaces. [dimensionless]
- radiuses_of_yield_surface is the radius list of multiple yield surfaces. This parameter gives the radiuses of each yield surface from the smallest to the biggest. This parameter should be a string which contains the dimensionless radiuses. The radiuses should be separated by a blank space or a comma. [string]
- radiuses_scale_unit is the unit of the each yield surface. This parameter also provides a method to scale up or scale down the radiuses of each yield surfaces. $[F/L^2]$
- hardening_parameters_of_yield_surfaces is the hardening parameters corresponding to each yield surface. This parameter should be a string which contains the dimensionless hardening parameters. The hardening parameters should be separated by a blank space or a comma. [string]
- hardening_parameters_scale_unit The unit of the each hardening parameter. This parameter also provides a method to scale up or scale down the hardening parameter of each yield surfaces. $[F/L^2]$

Modeling, Material Model: von Mises Associated Multiple Yield Surface Material Model that Matches G/G_{max} Curves

The command is:

```
add material # <.> type vonMisesMultipleYieldSurfaceGoverGmax
  mass_density = <M/L^3>
  initial_shear_modulus = <F/L^2>
  poisson_ratio = <.>
  total_number_of_shear_modulus = <.>
  GoverGmax = <string>
  ShearStrainGamma = <string> ;
```

Command Example is

```
add material # 1 type vonMisesMultipleYieldSurfaceGoverGmax
   mass_density = 0.0*kg/m^3
   initial_shear_modulus = 3E8 * Pa
   poisson_ratio = 0.0
   total_number_of_shear_modulus = 9
   GoverGmax =
   "1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063"
   ShearStrainGamma =
   "0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01";
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `initial_shear_modulus` is the initial maximum shear modulus, namely, the Gmax. $[F/L^2]$
- `poisson_ratio` is the constant Poisson-ratio. [dimensionless]
- `total_number_of_shear_modulus` is the total number of shear modulus, including the initial maximum shear modulus. The total number of yield surface is one less than the total number of shear modulus. Namely, (N+1) areas are divided by N surfaces. [dimensionless]
- `GoverGmax` is the G/Gmax from experiments, including the initial shear modulus. Namely, the first element should be 1.0. Each element is dimensionless. The input should be separated by a blank space or a comma. [string]
- `ShearStrainGamma` is the shear strain γ corresponding to the GoverGmax. Note that $\gamma = 2\varepsilon$ when the input is prepared. The first element should be 0.0 corresponding to the initial shear modulus. Each element is dimensionless. The input should be separated by a blank space or a comma. [string]

Modeling, Material Model: Drucker-Prager Nonassociated Multi-Yield Surface Material Model

The command is:

```
add material # <.> type DruckerPragerMultipleYieldSurface
  mass_density = <M/L^3>
  elastic_modulus = <F/L^2>
  poisson_ratio = <.>
  initial_confining_stress = <F/L^2>
  reference_pressure = <F/L^2>
  pressure_exponential_n = <.>
  cohesion = <F/L^2>
  dilation_angle_eta = <.>
  dilation_scale = <.>
  total_number_of_yield_surface = <.>
  sizes_of_yield_surfaces = <string>
  yield_surface_scale_unit = <F/L^2>
  hardening_parameters_of_yield_surfaces = <string>
  hardening_parameters_scale_unit = <F/L^2>;
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of the material $[F/L^2]$
- `poisson_ratio` is the constant Poisson-ratio [dimensionless]
- `initial_confining_stress` is the initial confining (mean) pressure $[F/L^2]$
- `reference_pressure` is the reference pressure for the initial modulus. This parameter is usually 101kPa. $[F/L^2]$
- `pressure_exponential_n` is the exponential number of the pressure dependent modulus. [dimensionless]
- `cohesion` is the attraction force is the soil. $[F/L^2]$
- `dilation_angle_eta` controls the dilation and compaction of the material. When the stress ratio is smaller than this parameter, plastic compaction takes place. When the stress ratio is greater than this parameter, the plastic dilation takes place. [dimensionless]
- `dilation_scale` controls the rate of the dilation or compaction in the plastic flow. [dimensionless]
- `total_number_of_yield_surface` is the total number of yield surfaces. [dimensionless]

- `radiuses_of_yield_surface` is the radius list of multiple yield surfaces. This parameter gives the radiuses of each yield surface from the smallest to the biggest. This parameter should be a string which contains the dimensionless radiuses. The radiuses should be separated by a blank space or a comma. [string]
- `radiuses_scale_unit` is the unit of the each yield surface. This parameter also provides a method to scale up or scale down the radiuses of each yield surfaces. $[F/L^2]$
- `hardening_parameters_of_yield_surfaces` is the hardening parameters corresponding to each yield surface. This parameter should be a string which contains the dimensionless hardening parameters. The hardening parameters should be separated by a blank space or a comma. [string]
- `hardening_parameters_scale_unit` The unit of the each hardening parameter. This parameter also provides a method to scale up or scale down the hardening parameter of each yield surfaces. $[F/L^2]$

Modeling, Material Model: Drucker-Prager Nonassociated Material Model that Matches G/G_{max} Curves

The command is:

```
add material # <.> type DruckerPragerMultipleYieldSurfaceGoverGmax
  mass_density = <M/L^3>
  initial_shear_modulus = <F/L^2>
  poisson_ratio = <.>
  initial_confining_stress = <F/L^2>
  reference_pressure = <F/L^2>
  pressure_exponential_n = <.>
  cohesion = <F/L^2>
  dilation_angle_eta = <.>
  dilation_scale = <.>
  total_number_of_shear_modulus = <.>
  GoverGmax = <string>
  ShearStrainGamma = <string>
```

Command Example is

```
add material # 1 type DruckerPragerMultipleYieldSurfaceGoverGmax
  mass_density = 0.0*kg/m^3
  initial_shear_modulus = 3E8 * Pa
  poisson_ratio = 0.0
  initial_confining_stress = 1E5 * Pa
  reference_pressure = 1E5 * Pa
  pressure_exponential_n = 0.5
  cohesion = 0. * Pa
  dilation_angle_eta =1.0
  dilation_scale = 0.0
  total_number_of_shear_modulus = 9
  GoverGmax =
  "1,0.995,0.966,0.873,0.787,0.467,0.320,0.109,0.063"
  ShearStrainGamma =
  "0,1E-6,1E-5,5E-5,1E-4, 0.0005, 0.001, 0.005, 0.01";
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of the material $[F/L^2]$
- `poisson_ratio` is the constant Poisson-ratio [dimensionless]
- `initial_confining_stress` is the initial confining (mean) pressure $[F/L^2]$
- `reference_pressure` is the reference pressure for the initial modulus. This parameter is usually 101kPa. $[F/L^2]$

- `pressure_exponential_n` is the exponential number of the pressure dependent modulus. [dimensionless]
- `cohesion` is the attraction force is the soil. $[F/L^2]$
- `dilation_angle_eta` controls the dilation and compaction of the material. When the stress ratio is smaller than this parameter, plastic compaction takes place. When the stress ratio is greater than this parameter, the plastic dilation takes place. [dimensionless]
- `dilation_scale` controls the rate of the dilation or compaction in the plastic flow. For this automatic G/Gmax match, the dilation scale has to be zero, which means only deviatoric plastic flow is allowed. If the users want to have volumetric dilation, they can match the G/Gmax manually with the other DruckerPragerMultipleYieldSurface command. [dimensionless]
- `total_number_of_shear_modulus` is the total number of shear modulus, including the initial maximum shear modulus. The total number of yield surface is one less than the total number of shear modulus. Namely, (N+1) areas are divided by N surfaces. [dimensionless]
- `GoverGmax` is the G/Gmax from experiments, including the initial shear modulus. Namely, the first element should be 1.0. Each element is dimensionless. The input should be separated by a blank space or a comma. [string]
- `ShearStrainGamma` is the shear strain γ corresponding to the GoverGmax. Note that $\gamma = 2\varepsilon$ when the input is prepared. The first element should be 0.0 corresponding to the initial shear modulus. Each element is dimensionless. The input should be separated by a blank space or a comma. [string]

Modeling, Material Model: Rounder Mohr-Coulomb Nonassociated Multi-Yield Surface Material Model

The command is:

```
add material # <.> type RoundedMohrCoulombMultipleYieldSurface
  mass_density = <M/L^3>
  elastic_modulus = <F/L^2>
  poisson_ratio = <.>
  initial_confining_stress = <F/L^2>
  reference_pressure = <F/L^2>
  pressure_exponential_n = <.>
  cohesion = <F/L^2>
  RMC_shape_k =<.>
  dilation_angle_eta = <.>
  dilation_scale = <.>
  total_number_of_yield_surface = <.>
  sizes_of_yield_surfaces = <string>
  yield_surface_scale_unit = <F/L^2>
  hardening_parameters_of_yield_surfaces = <string>
  hardening_parameters_scale_unit = <F/L^2>;
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `elastic_modulus` is the elastic modulus of the material $[F/L^2]$
- `poisson_ratio` is the constant Poisson-ratio [dimensionless]
- `initial_confining_stress` is the initial confining (mean) pressure $[F/L^2]$
- `reference_pressure` is the reference pressure for the initial modulus. This parameter is usually 101kPa. $[F/L^2]$
- `pressure_exponential_n` is the exponential number of the pressure dependent modulus. [dimensionless]
- `cohesion` is the attraction force is the soil. $[F/L^2]$
- `RMC_shape_k` controls the shape of the rounded Mohr-Coulomb yield surface. [dimensionless]
- `dilation_angle_eta` controls the dilation and compaction of the material. When the stress ratio is smaller than this parameter, plastic compaction takes place. When the stress ratio is greater than this parameter, the plastic dilation takes place. [dimensionless]
- `dilation_scale` controls the rate of the dilation or compaction in the plastic flow. [dimensionless]

- `total_number_of_yield_surface` is the total number of yield surfaces. [dimensionless]
- `radiuses_of_yield_surface` is the radius list of multiple yield surfaces. This parameter gives the radiuses of each yield surface from the smallest to the biggest. This parameter should be a string which contains the dimensionless radiuses. The radiuses should be separated by a blank space or a comma. [string]
- `radiuses_scale_unit` is the unit of the each yield surface. This parameter also provides a method to scale up or scale down the radiuses of each yield surfaces. $[F/L^2]$
- `hardening_parameters_of_yield_surfaces` is the hardening parameters corresponding to each yield surface. This parameter should be a string which contains the dimensionless hardening parameters. The hardening parameters should be separated by a blank space or a comma. [string]
- `hardening_parameters_scale_unit` The unit of the each hardening parameter. This parameter also provides a method to scale up or scale down the hardening parameter of each yield surfaces. $[F/L^2]$

Modeling, Material Model: Tsinghhua Liquefaction Material Model

The command is:

```
add material # <.> type TsinghuaLiquefactionModel
  mass_density = <M/L^3>
  poisson_ratio = <.>
  initial_confining_stress = <F/L^2>
  liquefaction_G0  = <.>
  liquefaction_EXPN  = <.>
  liquefaction_c_h0  = <.>
  liquefaction_mfc  = <.>
  liquefaction_mdc  = <.>
  liquefaction_dre1  = <.>
  liquefaction_Dre2  = <.>
  liquefaction_Dir  = <.>
  liquefaction_Alpha  = <.>
  liquefaction_gamar  = <.>
  liquefaction_pa  = <.>
  liquefaction_pmin  = <.>
```

Command Example is

```
add material # 1 type TsinghuaLiquefactionModel
  mass_density = 0.0*kg/m^3
  poisson_ratio = 0.1
  initial_confining_stress = 1E5 *Pa
  liquefaction_G0 = 800
  liquefaction_EXPN  = 0.5
  liquefaction_c_h0  = 1.0
  liquefaction_mfc   = 1.2
  liquefaction_mdc  =  0.4
  liquefaction_dre1  =  0.5
  liquefaction_Dre2  =  1500
  liquefaction_Dir  =  0.1
  liquefaction_Alpha  =  0.01
  liquefaction_gamar  =  0.01
  liquefaction_pa  =  1E5
  liquefaction_pmin  =  100 ;
```

where

- `mass_density` is the mass density of material $[M/L^3]$
- `poisson_ratio` is the constant Poisson ratio [dimensionless]
- `initial_confining_stress` is the initial confining (mean) pressure $[F/L^2]$
- `liquefaction_G0` is initial modulus scale at the reference pressure. For medium dense soil, G0 is 800. [dimensionless]

- `liquefaction_EXPN` is the exponential number of the pressure dependent modulus. [dimensionless]
- `liquefaction_c_h0` is the plastic modulus coefficient. This parameter should be determined by the G/Gmax curve. When the G/Gmax curve is hyperbolic, h is 1.2. The range of h is 0.7-1.2 [dimensionless].
- `liquefaction_mfc` is the slope of the failure surface in p-q plane. The range of $M_{f,c}$ is 1.4-1.8 [dimensionless].
- `liquefaction_mdc` is the slope of the phase transition surface in p-q plane. The range of $M_{d,c}$ is 0.3-1.0 [dimensionless].
- `liquefaction_dre1` is the accumulation coefficient of the reversible dilatancy. This parameter is usually 0.4 [dimensionless].
- `liquefaction_Dre2` is the release coefficient of the reversible dilatancy. This range of $d_{re,2}$ is 1000-1500 [dimensionless].
- `liquefaction_Dir` is the coefficient of irreversible dilatancy. The parameter d_{ir} controls the initial slope of the irreversible strain development with respect to the number of reversible loadings. Intuitively, when d_{ir} is bigger, the soil becomes liquefaction faster. The parameter d_{ir} can be around 0.2 [dimensionless].
- `liquefaction_Alpha` is the limit of the irreversible strain. Intuitively, α controls the maximum strain after the liquefaction. The parameter α can be around 0.03 [dimensionless].
- `liquefaction_gamar` is the maximum shear strain length in one liquefaction loading. Intuitively, this parameter controls the maximum strain size of one loop. This parameter can be around 0.05 [dimensionless].
- `liquefaction_pa` is the reference pressure. Usually, this parameter is 10000 [dimensionless].
- `liquefaction_pmin` is the minimum pressure in the calculation. If the pressure is smaller than p_{min} during the calculation, the pressure will be set to p_{min}. This parameter can be 1. Increasing this parameter can avoid the potential numerical errors on small numbers [dimensionless].

Modeling, Material Model: SANISand Material Model, version 2004

The command is:

```
add material # <.> type sanisand2004
   mass_density = <M/L^3>
   e0 = <.>
   sanisand2004_G0 = <.>
   poisson_ratio = <.>
   sanisand2004_Pat = <.>
   sanisand2004_p_cut = <.>
   sanisand2004_Mc = <.>
   sanisand2004_c = <.>
   sanisand2004_lambda_c = <.>
   sanisand2004_xi = <.>
   sanisand2004_ec_ref = <.>
   sanisand2004_m = <.>
   sanisand2004_h0 = <.>
   sanisand2004_ch = <.>
   sanisand2004_nb = <.>
   sanisand2004_A0 = <.>
   sanisand2004_nd = <.>
   sanisand2004_z_max = <.>
   sanisand2004_cz = <.>
   initial_confining_stress = <F/L^2>;
```

where

- `MaterialNumber`: Material tag
- `mass_density` is the mass density of material $[M/L^3]$
- `sanisand2004_e0` initial void ratio [ ]
- `sanisand2004_G0` normalized elastic shear modulus [ ]
- `poisson_ratio` Poisson's ratio [ ]
- `sanisand2004_Pat` atmospheric pressure $[F/L^2]$
- `sanisand2004_p_cut` pressure cut-off ratio $[F/L^2]$
- `sanisand2004_Mc` Critical stress ratio at triaxial compression [ ]
- `sanisand2004_c` tension-compression strength ratio $c = M_e/M_c$ [ ]
- `sanisand2004_lambda_c` parameter for critical state line [ ]
- `sanisand2004_xi` parameter for critical state line [ ]

- `sanisand2004_ec_ref` reference void for critical state line [ ]
- `sanisand2004_m` opening of the yield surface [ ]
- `sanisand2004_h0` bounding surface parameter [ ]
- `sanisand2004_ch` bounding surface parameter [ ]
- `sanisand2004_nb` bounding surface parameter [ ]
- `sanisand2004_A0` dilatancy parameter [ ]
- `sanisand2004_nd` dilatancy parameter [ ]
- `sanisand2004_z_max` maximum z fabric parameter [ ]
- `sanisand2004_cz` fabric hardening parameter [
- `initial_confining_stress` is the initial confining stress $p = -1/3\sigma_{ii}$ and it is positive in compressions (since there is that $-$ (minus) sign in front of sum of normal stresses (σ_{ii} indicial notation summation convention applies) that are positive in tension [stress].

More on this material model can be found in section 104.6.11 on Page 213 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Important note: This material model should be used together with explicit constitutive algorithms, e.g. `Forward_Euler` or `Forward_Euler_Subincrement`. For better result, it is suggested to apply strain increments, or sub-increments, smaller than 1e-4.

Modeling, Material Model: SANISand Material Model, version 2008

The command is:

```
add material # <.> type sanisand2008
    mass_density = <M/L^3>
    e0 = <.>
    sanisand2008_G0 = <.>
    sanisand2008_K0 = <.>
    sanisand2008_Pat = <.>
    sanisand2008_k_c = <.>
    sanisand2008_alpha_cc = <.>
    sanisand2008_c = <.>
    sanisand2008_lambda = <.>
    sanisand2008_ec_ref = <.>
    sanisand2008_m = <.>
    sanisand2008_h0 = <.>
    sanisand2008_ch = <.>
    sanisand2008_nb = <.>
    sanisand2008_A0 = <.>
    sanisand2008_nd = <.>
    sanisand2008_p_r = <.>
    sanisand2008_rho_c = <.>
    sanisand2008_theta_c = <.>
    sanisand2008_X = <.>
    sanisand2008_z_max = <.>
    sanisand2008_cz = <.>
    sanisand2008_p0 = <F/L^3>
    sanisand2008_p_in = <F/L^3>
    algorithm = explicit (or) implicit
    number_of_subincrements = <.>
    maximum_number_of_iterations = <.>
    tolerance_1 = <.>
    tolerance_2 = <.>;
```

where

- `MaterialNumber`: Number of the ND material to be used ;
- `Algorithm`: Explicit (=0) or Implicit (=1) ;
- `rho`: density ;
- `e0`: initial void ratio at zero strain ;
- `G0`: Reference elastic shear modulus [stress];
- `K0`: Reference elastic bulk modulus [stress];
- `sanisand2008_Pat`: atmospheric pressure for critical state line ;

- `sanisand2008_k_c`: cut-off factor; for $p < k_c P_{at}$, use $p = k_c P_{at}$ for calculation of G; (a default value of $k_c = 0.01$ should work fine) ;
- `sanisand2008_alpha_cc`: critical state stress ratio ;
- `sanisand2008_c`: tension-compression strength ratio ;
- `sanisand2008_lambda`: parameter for critical state line ;
- `sanisand2008_xi`: parameter for critical state line ;
- `sanisand2008_ec_ref`: reference void for critical state line, ; $e_c = e_r lambda (p_c/P_{at})^x i$;
- `sanisand2008_m`: opening of the yield surface ;
- `sanisand2008_h0`: bounding surface parameter ;
- `sanisand2008_ch`: bounding surface parameter ;
- `sanisand2008_nb`: bounding surface parameter ;
- `sanisand2008_A0`: dilatancy parameter ;
- `sanisand2008_nd`: dilatancy parameter ;
- `sanisand2008_p_r`: LCC parameter ;
- `sanisand2008_rho_c`: LCC parameter ;
- `sanisand2008_theta_c`: LCC parameter ;
- `sanisand2008_X`: LCC parameter ;
- `sanisand2008_z_max`: fabric parameter ;
- `sanisand2008_cz`: fabric parameter ;
- `sanisand2008_p0`: yield surface size ;
- `sanisand2008_p_in` ;
- `number_of_subincrements` number of subincrements in constitutive simulation
- `maximum_number_of_iterations` maximum number of iterations
- `tolerance_1` Explicit: tolerance for intersection point (distance between two consecutive points) Implicit: yield function tolerance

- `tolerance_2` Implicit: residual tolerance

More on this material model can be found in Section 104.6.12 on Page 219 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Cosserat Linear Elastic Material Model

The command is:

```
add material # <.> type Cosserat_linear_elastic_isotropic_3d
    mass_density = <M/L^3>
    lambda = <F/L^2>
    mu = <F/L^2>
    chi = <F/L^2>
    pi1 = <F>
    pi2 = <F>
    pi3 = <F>
    ;
```

- `MaterialNumber` unique material Number.
- `mass_density` the density of the material.
- `lambda`, `mu`, `chi`, `pi1`, `pi2`, `pi3` are the 6 Cosserat elastic constants (Eringen, 2012).

The relations between elastic constants is as follows Eringen (2012). Note the Young's modulus and the Poisson's ratio are different from the classical elasticity:

- Young's modulus $E = (2\mu + \chi)(3\lambda + 2\mu + \chi)$.
- Shear modulus $G = \mu + 1/2\chi$.
- Poisson's ratio $\nu = \lambda/(2\lambda + 2\mu + \chi)$.
- Characteristic length for torsion $l_t = ((\pi_2 + \pi_3)/(2\mu + \chi))^{1/2}$.
- Characteristic length for bending $l_b = (\pi_3/2(2\mu + \chi))^{1/2}$.
- Coupling number $N = (\chi/2(\mu + \chi))$
- Polar ratio $\Phi = (\pi_2 + \pi_3)/(\pi_1 + \pi_2 + \pi_3)$

According to Eringen Eringen (2012), the 6 elastic constants should satisfy the following conditions

$$\begin{array}{ccc} 3\lambda + 2\mu + \chi \geq 0 \ , & 2\mu + \chi \geq 0 \ , & \chi \geq 0 \ , \\ 3\pi_1 + \pi_2 + \pi_3 \geq 0 \ , & \pi_3 + \pi_2 \geq 0 \ , & \pi_3 - \pi_2 \geq 0 \ . \end{array} \tag{1.1}$$

Modeling, Material Model: von Mises Cosserat Material Model

The command is:

```
add material # <.> type Cosserat_von_Mises
    mass_density = <M/L^3>
    lambda = <F/L^2>
    mu = <F/L^2>
    chi = <F/L^2>
    pi1 = <F>
    pi2 = <F>
    pi3 = <F>
    plastic_internal_length = <L>
    von_mises_radius = <F/L^2>
    isotropic_hardening_rate = <F/L^2>
    ;
```

- `MaterialNumber` unique material Number.
- `mass_density` the density of the material.
- `lambda`, `mu`, `chi`, `pi1`, `pi2`, `pi3` are the 6 Cosserat elastic constantsEringen (2012).
- `plastic_internal_length` is the characteristic length in the plasticity.
- `von_mises_radius` is radius of the unified yield surface of force-stress and couple-stress.
- `isotropic_hardening_rate` is the rate of isotropic hardening.

Modeling, Material Model: Uniaxial Linear Elastic, Fiber Material Model

The command is:

```
add material # <.> type uniaxial_elastic
    elastic_modulus = <F/L^2>
    viscoelastic_modulus = <mass / length / time> ;
```

where

- `MaterialNumber` unique material Number.
- `elastic_modulus` elastic modulus of the material.
- `viscoelastic_modulus` damping tangent.

More on this material model can be found in Section **??** on Page **??** in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

As the name implies, `uniaxiale_elastic` material model works with uniaxial element only. For 3D elements, for example solid brick elements, please use 3D material models, for example, `linear_elastic_isotropic_3d`.

Modeling, Material Model: Stochastic Uniaxial Linear Elastic Model

The command is:

```
add material # <.> type stochastic_uniaxial_elastic ↩
   uncertain_elastic_modulus = random variable # <.> ↩
   elastic_modulus_scale_unit = <F/L^2>;
```

where

- uncertain_elastic_modulus specify uncertain elastic modulus of the material through a defined random variable.
- elastic_modulus_scale_unit specify the unit scale factor that would be multiplied with the polynomial chaos coefficients of the random variable.

As the name implies, stochastic_uniaxial_elastic material model works with stochastic uniaxial element only.

For example:

```
add material # 1 type stochastic_uniaxial_elastic ↩
   uncertain_elastic_modulus = random variable # 1 ↩
   elastic_modulus_scale_unit = 1*Pa;
```

Add material #1 as stochastic_uniaxial_elastic material with uncertain elastic modulus characterized by the polynomial chaos coefficients of random variable 1 and scale factor $1 * Pa$.

Modeling, Material Model: Stochastic Uniaxial Nonlinear Armstrong Frederick Model

The command is:

```
add material # <.> type stochastic_uniaxial_Armstrong_Frederick
constitutive triple product # <.>
armstrong_frederick_ha = random variable # <.>
armstrong_frederick_ha_scale_unit = <F/L^2>
armstrong_frederick_cr = random variable # <.>
```

or

```
add material # <.> type stochastic_uniaxial_Armstrong_Frederick
constitutive triple product # <.>
armstrong_frederick_ha = random variable # <.>
armstrong_frederick_ha_scale_unit = <F/L^2>
armstrong_frederick_cr = random variable # <.>
polynomial_chaos_terms_ha = <.>
polynomial_chaos_terms_cr = <.>
polynomial_chaos_terms_incremental_strain = <.>;
```

Note that the difference between these two commands is that the first command would by default use the full polynomial chaos (PC) bases defined in the provided `constitutive triple product` for probabilistic constitutive modeling. The second command would support user-specified number of polynomial chaos terms for uncertain `armstrong_frederick_ha`, `armstrong_frederick_cr` and `incremental_strain`. This enables users to perform truncation of PC bases for probabilistic constitutive modeling.

The command input parameters are:

- `constitutive triple product #` specifies the ID of the triple product, that would be used in probabilistic constitutive updating. In stochastic finite element method (FEM), the first and second PC basis for this triple product should come from the joint PC representation of uncertain parameters `armstrong_frederick_ha` and `armstrong_frederick_cr`. The third PC basis for this triple product should come from the PC representation of uncertain FEM system response, e.g., uncertain structural displacement.
- `armstrong_frederick_ha = random variable #` specifies the uncertain Armstrong Frederick parameter ha through a defined random variable.
- `armstrong_frederick_ha_scale_unit` specifies the unit scale factor that would be multiplied with the polynomial chaos coefficients of the random variable of uncertain Armstrong Frederick parameter ha.
- `armstrong_frederick_cr = random variable #` specifies the uncertain Armstrong Frederick parameter cr through a defined random variable.

- polynomial_chaos_terms_ha specifies the number of polynomial chaos basis of uncertain ha involved in the probabilistic constitutive updating.

- polynomial_chaos_terms_cr specifies the number of polynomial chaos basis of uncertain cr involved in the probabilistic constitutive updating.

- polynomial_chaos_terms_incremental_strain specifies the number of polynomial chaos basis of uncertain incremental strain $d\epsilon$ involved in the probabilistic constitutive updating.

As the name implies, stochastic_uniaxial_Armstrong_Frederick material model works with stochastic uniaxial element only.

For example:

```
add material # 1 type stochastic_uniaxial_Armstrong_Frederick
constitutive triple product # 1
armstrong_frederick_ha = random variable # 1
armstrong_frederick_ha_scale_unit = 1*Pa
armstrong_frederick_cr = random variable # 2
polynomial_chaos_terms_ha = 10
polynomial_chaos_terms_cr = 10
polynomial_chaos_terms_incremental_strain = 30;
```

Add material # 1 as stochastic_uniaxial_Armstrong_Frederick material with triple product # 1 for probabilistic constitutive updating.

Uncertain parameter ha is characterized by random variable # 1 using scale unit $1{*}$Pa.

Uncertain parameter cr is characterized by random variable # 2. The number of polynomial chaos basis for uncertain parameters ha, cr and incremental strain in probabilistic constitutive updating are 10, 10 and 30, respectively.

Modeling, Material Model: Uniaxial Nonlinear Concrete, Fiber Material Model, version 02

The command is:

```
add material # <.> type uniaxial_concrete02
    compressive_strength = <F/L^2>
    strain_at_compressive_strength = <.>
    crushing_strength = <F/L^2>
    strain_at_crushing_strength = <.>
    lambda = <.>
    tensile_strength = <F/L^2>
    tension_softening_stiffness = <F/L^2>;
```

- `compressive_strength` compressive strength.
- `strain_at_compressive_strength` strain at compressive strength.
- `crushing_strength` crushing strength.
- `strain_at_crushing_strength` strain at crushing strength.
- `lambda` ratio between unloading slope at epscu and initial slope.
- `tensile_strength` tensile strength.
- `tension_softening_stiffness` tension softening stiffness (absolute value) (slope of the tension softening branch).

More on this material model can be found in Section **??** on Page **??** in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Faria-Oliver-Cervera Concrete Material

The command is:

```
add material No (or #) <material_number>
    type FariaOliverCerveraConcrete
    elastic_modulus            = <F/L^2>
    poisson_ratio              = <.>
    tensile_yield_strength     = <F/L^2>
    compressive_yield_strength = <F/L^2>
    plastic_deformation_rate   = <.>
    damage_parameter_Ap        = <.>
    damage_parameter_An        = <.>
    damage_parameter_Bn        = <.>
```

where

- `No (or #) <material_number>` is a unique material integer number (does not have to be sequential, any unique positive integer number can be used).
- `type FariaOliverCerveraConcrete` is the material type.
- `elastic_modulus` is the elastic modulus of material $[F/L^2]$
- `poisson_ratio` is the Poisson's ratio material.
- `tensile_yield_strength` is the tensile yield strength $[F/L^2]$
- `compressive_yield_strength` is the compressive yield strength $[F/L^2]$

Modeling, Material Model: Plane Stress Layered Material

The command is:

```
add material No (or #) <element_number>
    type PlaneStressLayeredMaterial
    number_of_layers = <.>
    thickness_array = <string>
    thickness_scale_unit = <L>
    with material # <string>
    ;
```

where

- `No (or #) <material_number>` is a unique material integer number (does not have to be sequential, any unique positive integer number can be used).
- `type PlaneStressLayeredMaterial` is the material type.
- `number_of_layers` is the number of layers in this layered material. For reinforced concrete wall element, this will be just 3 layers, inside/confined concrete, reinforcement, and outside/unconfined concrete.
- `thickness_array` is the thickness ratio of each individual material.
- `thickness_scale_unit` set the length unit and the scale factor for the thickness of the layered material.
- `material # <string>` is the string of predefined individual material tags.

Modeling, Material Model: Uniaxial Nonlinear Steel, Fiber Material Model, version 01

The command is:

```
add material # <.> type uniaxial_steel01
    yield_strength = <F/L^2>
    elastic_modulus = <F/L^2>
    strain_hardening_ratio = <.>
    a1 = <.>
    a2 = <.>
    a3 = <>
    a4 = <.> ;
```

- `yield_strength` yield strength.
- `elastic_modulus` initial elastic tangent.
- `strain_hardening_ratio` strain-hardening ratio (ratio between post-yield tangent and initial elastic tangent).
- `a1, a2, a3, a4` isotropic hardening parameters
  - a1: isotropic hardening parameter, increase of compression yield envelope as proportion of yield strength after a plastic strain of a2*(fy/Ep). ;
  - a2: isotropic hardening parameter (see explanation under a1) ;
  - a3: isotropic hardening parameter, increase of tension yield envelope as proportion of yield strength after a plastic strain of a4*(fy/Ep) ;
  - a4: isotropic hardening parameter (see explanation under a3) ;

More on this material model can be found in Section **??** on Page **??** in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Uniaxial Nonlinear Steel, Fiber Material Model, version 02

The command is:

```
add material # <.> type uniaxial_steel02
    yield_strength = <F/L^2>
    elastic_modulus = <F/L^2>
    strain_hardening_ratio = <.>
    R0 = <.>
    cR1 = <.>
    cR2 = <.>
    a1 = <.>
    a2 = <.>
    a3 = <>
    a4 = <.> ;
```

- `yield_strength`: yield strength ;
- `elastic_modulus`: initial elastic tangent ;
- `strain_hardening_ratio`: strain-hardening ratio (ratio between post-yield tangent and initial elastic tangent) ;
- `R0, cR1, cR2`: control the transition from elastic to plastic branches. Recommended values: R0=between 10 and 20, cR1=0.925, cR2=0.15 ;
- `a1, a2, a3, a4`: isotropic hardening parameters ;
  - a1: isotropic hardening parameter, increase of compression yield envelope as proportion of yield strength after a plastic strain of a2*(Fy/E). ;
  - a2: isotropic hardening parameter (see explanation under a1) ;
  - a3: isotropic hardening parameter, increase of tension yield envelope as proportion of yield strength after a plastic strain of a4*(Fy/E) ;
  - a4: isotropic hardening parameter (see explanation under a3) ;

More on this material model can be found in Section **??** on Page **??** in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Material Model: Plane Stress Plastic Damage Concrete Material

This is a plane stress version of the plastic damage concrete model developed by Faria et al. (1998). This material was implemented as part of the endeavor to model reinforced concrete shells, plates and shear walls. It should only be used together with Inelastic Layered Shell Section and 4 Node Shell NLDKGQ/Xin-Zheng-Lu, see page 100.

The command is:

```
add material No (or #) <material_number> type ↩
   PlasticDamageConcretePlaneStress
    elastic_modulus             = <F/L^2>
    poisson_ratio               = <.>
    tensile_yield_strength      = <F/L^2>
    compressive_yield_strength  = <F/L^2>
    plastic_deformation_rate    = <.>
    damage_parameter_Ap         = <.>
    damage_parameter_An         = <.>
    damage_parameter_Bn         = <.>
```

where

- `No (or #) <material_number>` is a unique material integer number (does not have to be sequential, any unique positive integer number can be used).
- `elastic_modulus` is the elastic modulus of material $[F/L^2]$
- `poisson_ratio` is the Poisson's ratio material.
- `tensile_yield_strength` is the tensile yield strength $[F/L^2]$
- `compressive_yield_strength` is the compressive yield strength $[F/L^2]$
- `plastic_deformation_rate` governs the post-yield hardening modulus in the effective (undamaged) space and the plastic strain rate
- `damage_parameter_Ap` governs the tensile fracture energy and affects the ductility of the tensile response
- `damage_parameter_An` governs the softening behavior of concrete in compression, it changes the ductility but does not alter the peak strength
- `damage_parameter_Bn` governs the softening behavior of concrete in compression, it changes both the ductility and the peak strength

Modeling, Material Model: Plane Stress Rebar Material

This is a plane stress version of the Uniaxial Nonlinear Steel material. This material was implemented as part of the endeavor to model reinforced concrete shells, plates and shear walls. This model should be used together with Inelastic Layered Shell Section and 4 Node Shell NLDKGQ/Xin-Zheng-Lu, see page 100.

The command is:

```
add material No (or #) <material_number> type PlaneStressRebarMaterial
    with uniaxial_material # <.>
    angle = <degree> ;
```

where

- `No (or #) <material_number>` is a unique material integer number (does not have to be sequential, any unique positive integer number can be used).
- `with uniaxial_material #` is the material tag of predefined uniaxial steel material
- `angle` is the angle of uniaxial steel rebars. The angle is 0 along the direction formed by the first two nodes of a 4 Node Shell element.

Modeling, Nodes: Adding Nodes

Nodes can be added to the finite element model.

The command is:

```
 add node # <.> at (<L>,<L>,<L>)  with <.> dofs;
```

For example:

```
add node No 1 at (1.0*m, 2.5*m, 3.33*m) with 3 dofs;
```

adds a node number 1 at coordinates $x = 1.0m$, $y = 2.5m$ and $z = 3.33m$ with 3 dofs. The nodes can be of 3dofs $[u_x, u_y, u_z]$, 4dofs $[]u_x, u_y, u_z, p]$ (u-p elements) , 6dofs $[u_x, u_y, u_z, r_x, r_y, r_z]$ (beams and shells) and 7 dofs $[u_x, u_y, u_z, p, U_x, U_y, U_z]$ (upU element) types. Description of output for nodes of different dof types can be found in section 206.6

Modeling, Nodes: Adding Stochastic Nodes

Nodes can be added to the stochastic finite element model. Different from deterministic finite element analysis, nodes in stochastic FEM should specify the number of polynomial chaos (PC) terms for each physical nodal degree of freedom (dof).

The command is:

```
add node # <.> at (<L>,<L>,<L>)  with <.> dofs polynomial_chaos_terms ↩
   = <.>;
```

Where:

- polynomial_chaos_terms specifies the number of polynomial chaos terms for each physical nodal dof.

The stochastic nodes can also be added as:

```
add node # <.> at (<L>,<L>,<L>)  with <.> dofs polynomial_chaos_terms ↩
   as random field # <.>;
```

Which specifies the number of polynomial chaos terms for each physical nodal dof using the number of Hermite PC basis of a defined random field.

For example:

```
add node # 1 at (1.0*m, 0.0*m, 0.0*m) with 3 dofs ↩
   polynomial_chaos_terms = 10;
```

Add a node # 1 at coordinates $x = 1.0m$, $y = 0.0m$ and $z = 0.0m$ with 3 physical dofs. For each physical dof, the number of terms for polynomial chaos expansion is 10.

```
add node # 1 at (1.0*m, 0.0*m, 0.0*m) with 3 dofs ↩
   polynomial_chaos_terms as random field # 2;
```

Add a node # 1 at coordinates $x = 1.0m$, $y = 0.0m$ and $z = 0.0m$ with 3 physical dofs. For each physical dof, the number of terms for polynomial chaos expansion is equal to the number of PC basis of random field # 2.

Modeling, Nodes: Define Nodal Physical Group

Physical Group for nodes can be defined as well.

The command is:

```
define physical_node_group "string";
```

For example:

```
define physical_node_group "my_new_node_group";
```

this would create a new physical_node_group with name "my_new_node_group".

Description of output for physical groups can be found in section 206.5.5

Modeling, Nodes: Adding Nodes to Nodal Physical Group

Already created nodes can be added to the (any) physical_node_group.

The command is:

```
add nodes (<.>,<.>,...) to physical_node_group "string";
```

For example:

```
add nodes (1,2,3) to physical_node_group "my_new_node_group";
```

this would add node tag (1,2 and 3) to already created physical_node_group "my_new_node_group". Please note that the nodes (1,2 and 3) must be added to the model before they are added to the physical_node_group.

Description of output for physical groups can be found in section 206.5.5

Modeling, Nodes: Removing Nodal Physical Group

Already defined node physical group physical_node_group can be removed.

The command is

```
remove physical_node_group "string";
```

For example:

```
remove physical_node_group "my_new_node_group";
```

this would delete the physical_node_group "my_new_node_group".

Modeling, Nodes: Print Nodal Physical Group

Printing already defined nodal physical grouop physical_node_group is possible too.

The command is:

```
 print physical_node_group "string";
```

For example:

```
 print physical_node_group "my_new_node_group";
```

this would print the information about physical_node_group "my_new_node_group".

```
PHYSICAL_NODE_GROUP my_new_node_group
[1 2 3]
```

Modeling, Nodes: Removing Nodes

Nodes can be removed from the finite element model, for example during excavation, removal of finite elements.

The command is:

```
remove node No (or #) <.>;
```

For example:

```
remove node # 1;
```

Modeling, Nodes: Adding Nodal Mass, for 3DOFs and/or 6DOFs

Nodal mass can be added to nodes with 3 DOFs and/or 6DOFs. This is in addition to nodal mass that is obtained from finite elements.

The command for 3DOFs nodes (truss, solids, wall) is:

```
add mass to node # <.>
mx = <M>
my = <M>
mz = <M>;
```

Simularly, the command for 6DOFs nodes (beams and shells) is:

```
add mass to node # <.>
mx = <M>
my = <M>
mz = <M>
Imx = <M*L^2>
Imy = <M*L^2>
Imz = <M*L^2>;
```

Modeling, Finite Element: Adding Finite Elements

The basic structure for adding any finite element is:

```
add element No (or #)
   type <finite_element_type>
   with nodes (<.>, ..., <.>)|
   {element dependent parameters};
```

Choices for `finite_element_type` are listed below

Modeling, Finite Element: Define Finite Element Physical Group

Physical group for finite elements can be defined.

The command is:

```
define physical_element_group "string";
```

For example:

```
define physical_element_group "my_new_element_group";
```

this would create a new physical_element_group with name "my_new_element_group".

Description of output for physical groups can be found in Section 206.5.5.

Modeling, Finite Element: Adding Elements to Physical Element Group

Finite elements, that already exist in the finite element domain, can be added to the physical_element_group.

The command is:

```
add elements (<.>,<.>,...) to physical_node_group "string";
```

For example:

```
add elements (1,2,3) to physical_node_group "my_new_node_group";
```

this would add elements with tags/numbers (1,2 and 3) to already created physical_element_group "my_new_element_g
Please note that the elements (1,2 and 3) must be added to the model before they are added to the physical_element_group.

Description of output for physical groups can be found in Section 206.5.5.

Modeling, Finite Element: Remove Physical Finite Element Group

Finite elements can also be removed from the physical_element_group.

The command is:

```
remove physical_element_group "string";
```

For example:

```
remove physical_element_group "my_new_element_group";
```

this would delete the physical_element_group "my_new_element_group".

Modeling, Finite Element: Print Physical Finite Element Group

Details of the physical_element_group can be printed.

The commands is:

```
 print physical_element_group "string";
```

For example:

```
 print physical_element_group "my_new_element_group";
```

this would print the information about physical_element_group "my_new_element_group".

```
PHYSICAL_ELEMENT_GROUP my_new_element_group
[1 2 3]
```

Modeling, Finite Element: Remove Finite Element

Finite elements can be removed, for example if modeling requires excavation, removal of finite elements and nodes.

The command is:

```
remove element # <.>;
```

For example,

```
remove element # 1;
```

Modeling, Finite Element: Truss Element

The command is:

```
add element No (or #) <element_number>  type truss
            with nodes (n1, n2)
            use material No (or #) <material_number>
            section_area <section_area> [unit];
            mass_density <mass_density> [unit];
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type truss` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `use material No (or #)` is the material number which makes up the element. Material has to be a uniaxial material, and it can be either elastic or one of the elastic-plastic materials defined for uniaxial behavior.
- `section_area` is the cross section area $[L^2]$

Description of output by this element can be found in Section 206.8.1. more on this finite element can be found in Section 102.6 on Page 98 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Kelvin-Voigt Element

The command is:

```
add element # <.> type Kelvin_Voigt
    with nodes (<.>, <.>)
    axial_stiffness = <F/L>
    axial_viscous_damping = <F/L*T>;
```

where

- `No  (or  #) <element_number>` is a unique element integer number, that does not have to be sequential, any unique positive integer number can be used
- `type Kelvin_Voigt` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `axial_stiffness` represents the stiffness in the axial direction, $[F/L]$
- `axial_viscous_damping` represents the viscosity, or viscous damping coefficient, in the axial direction, $[F/L*T]$

Note: Nodes defining this element cannot be at the same location, that is, this is a two node element and direction of this element is calculated from two distinct locations/coordinates of nodes.

Modeling, Finite Element: Inerter Element

The command is:

```
add element # <.> type Inerter
    with nodes (<.>, <.>)
    inertance = <M>;
```

where

- `No (or #) <element_number>` is a unique element integer number, that does not have to be sequential, any unique positive integer number can be used
- `type Inerter` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `inertance` represents the inertance in the axial direction, $[M]$

Note: Nodes defining this element cannot be at the same location, that is, this is a two node element and direction of this element is calculated from two distinct locations/coordinates of nodes.

Modeling, Finite Element: Shear Beam Element

The command is:

```
add element # <.> type ShearBeam
  with nodes (<.>, <.>)
  cross_section = <l^2>
  use material # <.>;
```

where

- No (or #) <element_number> is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- with nodes (n1, n2) are the 2 nodes (node numbers) defining this element. NOTE: element is supposed to be alligned along vertical, Z direction !!
- use material No (or #) is the material (LT-based material) number which makes up the element.
- section_area is the cross section area $[L^2]$

Description of output by this element can be found in Section 206.8.3. more on this finite element can be found in Section 102.9 on page 108 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Stochastic Shear Beam Element

Add stochastic shear beam element for stochastic finite element analysis.

```
add element # <.> type stochastic_shear_beam with nodes (<.>, <.>)
  use material # <.>
  triple product # <.>
  cross_section = <L^2>
  mass_density = <M/L^3>;
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used).
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element.
- `use material No (or #)` is the stochastic uniaxial material number that makes up the element.
- `triple product #` specifies the ID of the triple product, that would be used in the formation of elemental stochastic stiffness matrix. In stochastic finite element method (FEM), the first PC basis for this triple product should come from the PC representation of uncertain element stiffness. The second and third PC basis for this triple product should come from the PC representation of uncertain FEM system response, e.g., uncertain structural displacement.
- `section_area` is the cross section area $[L^2]$.
- `mass_density` is the density $[M/L^3]$.

For example:

```
add element # 1 type stochastic_shear_beam with nodes (1, 2) use ↩
   material # 1 triple product # 1 cross_section = 1*m^2 mass_density ↩
   = 2000*kg/m^3;
```

Add a stochastic shear beam element # 1 with stochastic nodes 1 and 2 using stochastic uniaxial material # 1.

The cross section of the element is 1 m^2 and mass density is 2000 kg/m^3.

Modeling, Finite Element: Elastic Beam–Column Element

The command is:

```
add element # <.> type beam_elastic with nodes (<.>, <.>)
    cross_section = <L^2>
    elastic_modulus = <F/L^2>
    shear_modulus = <F/L^2>
    torsion_Jx = <length^4>
    bending_Iy = <length^4>
    bending_Iz = <length^4>
    mass_density = <M/L^3>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

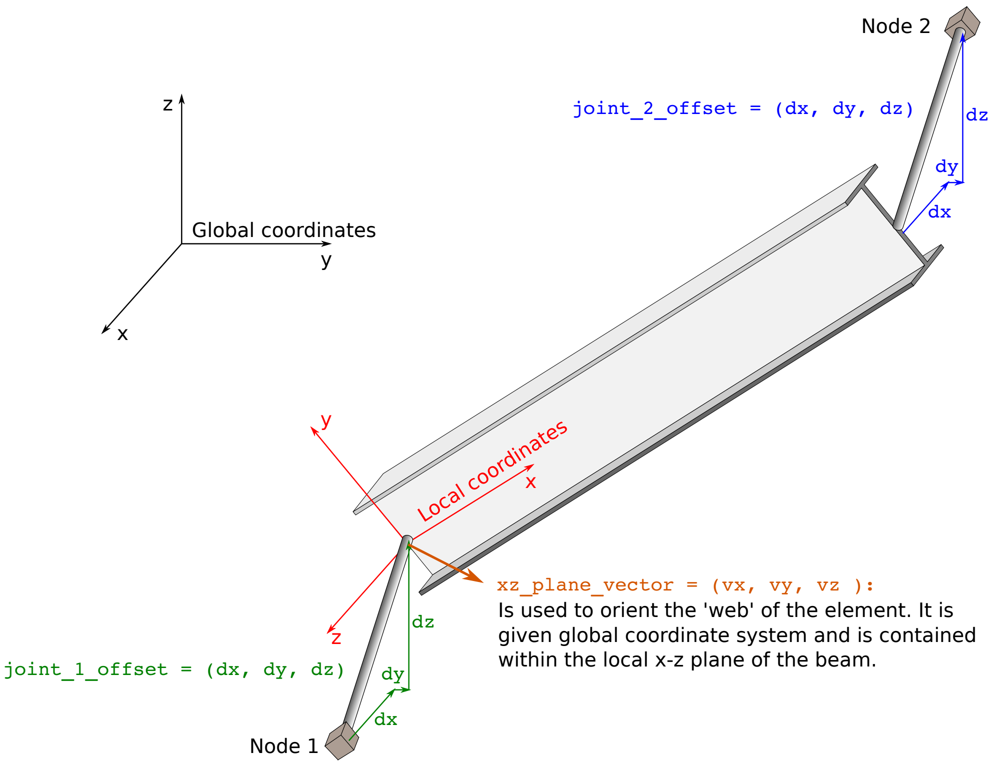

Node 2
joint_2_offset = (dx, dy, dz)
dz
dy
dx
z
Global coordinates
y
x
y
Local coordinates
x
xz_plane_vector = (vx, vy, vz):
Is used to orient the 'web' of the element. It is given global coordinate system and is contained within the local x-z plane of the beam.
dz
z
joint_1_offset = (dx, dy, dz)
dy
dx
Node 1

Figure 1.3: Beam Element, sketch of main geometric components.

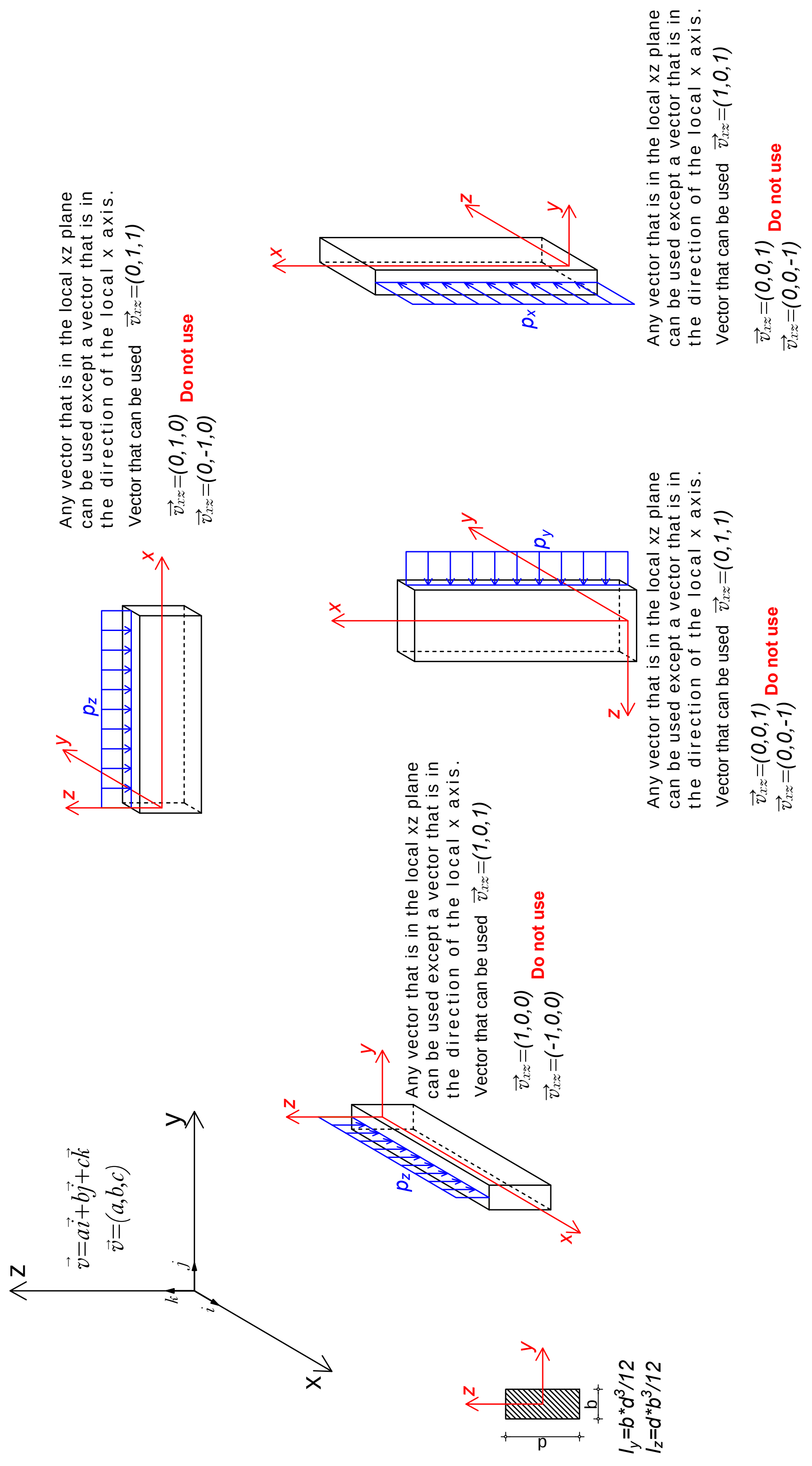
where

- No (or #) <element_number> is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- type beam_elastic is the element type
- with nodes (n1, n2) are the 2 nodes (node numbers) defining this element

- `cross_section` is the cross section area, $[L^2]$
- `elastic_modulus` elastic modulus of the material which makes up the beam, $[F/L^2]$
- `shear_modulus` shear modulus of the material which makes up the beam, $[F/L^2]$
- `torsion_Jx` cross section polar (torsional) moment of inertia, $[L^4]$
- `bending_Iy` cross section moment of inertia about local y axis, $[L^4]$
- `bending_Iz` cross section moment of inertia about local z axis, $[L^4]$
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `xz_plane_vector` a vector which defines the orientation of the local (beam coordinate system) xz plane in global coordinates. **NOTE:** Please make sure that your `xz_plane_vector` is a bit away from the actuall local x axes, the axes that runs along the beam elelent, in order to prevent numerical problems that might appear when vector cross products are performed inside the program... It is suggested that your `xz_plane_vector` be closer to local z axes... See Figure 1.4 on Page 86 for more in depth explanation of `xz_plane_vector`.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Description of output by this element can be found in Section 206.8.4

more on this finite element can be found in Section 102.7 on Page 99 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).



$I_y=b*d^3/12$
$I_z=d*b^3/12$
$\vec{v}=a\vec{i}+b\vec{j}+c\vec{k}$
$\vec{v}=(a,b,c)$
X
Y
Z
i
j
k
b
d
x
y
z
p_z
p_y
p_x
Any vector that is in the local xz plane can be used except a vector that is in the direction of the local x axis.
Vector that can be used $\vec{v}_{xz}$=(1,0,1)
$\vec{v}_{xz}$=(1,0,0)
$\vec{v}_{xz}$=(-1,0,0)
Do not use
Any vector that is in the local xz plane can be used except a vector that is in the direction of the local x axis.
Vector that can be used $\vec{v}_{xz}$=(0,1,1)
$\vec{v}_{xz}$=(0,1,0)
$\vec{v}_{xz}$=(0,-1,0)
Do not use
Any vector that is in the local xz plane can be used except a vector that is in the direction of the local x axis.
Vector that can be used $\vec{v}_{xz}$=(0,1,1)
$\vec{v}_{xz}$=(0,0,1)
$\vec{v}_{xz}$=(0,0,-1)
Do not use
Any vector that is in the local xz plane can be used except a vector that is in the direction of the local x axis.
Vector that can be used $\vec{v}_{xz}$=(1,0,1)
$\vec{v}_{xz}$=(0,0,1)
$\vec{v}_{xz}$=(0,0,-1)
Do not use

Figure 1.4: Beam Element, details of vector in X-Z plane.

Modeling, Finite Element: Large Displacement Elastic Beam–Column Element, with Corotational Transformation

The command is:

```
add element # <.> type beam_elastic_corotational with nodes (<.>, <.>)
    cross_section = <L^2>
    elastic_modulus = <F/L^2>
    shear_modulus = <F/L^2>
    torsion_Jx = <length^4>
    bending_Iy = <length^4>
    bending_Iz = <length^4>
    mass_density = <M/L^3>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type beam_elastic` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `cross_section` is the cross section area, $[L^2]$
- `elastic_modulus` elastic modulus of the material which makes up the beam, $[F/L^2]$
- `shear_modulus` shear modulus of the material which makes up the beam, $[F/L^2]$
- `torsion_Jx` cross section polar (torsional) moment of inertia, $[L^4]$
- `bending_Iy` cross section moment of inertia about local y axis, $[L^4]$
- `bending_Iz` cross section moment of inertia about local z axis, $[L^4]$
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `xz_plane_vector` a vector which defines the orientation of the local (beam coordinate system) xz plane in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Modeling, Finite Element: Timoshenko Elastic Beam–Column Element

The command is:

```
add element # <.> type beam_elastic_Timoshenko with nodes (<.>, <.>)
    cross_section = <L^2>
    elastic_modulus = <F/L^2>
    shear_modulus = <F/L^2>
    torsion_Jx = <length^4>
    bending_Iy = <length^4>
    bending_Iz = <length^4>
    mass_density = <M/L^3>
    shear_correction_coefficient = <.>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type beam_elastic` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `cross_section` is the cross section area, $[L^2]$
- `elastic_modulus` elastic modulus of the material which makes up the beam, $[F/L^2]$
- `shear_modulus` shear modulus of the material which makes up the beam, $[F/L^2]$
- `torsion_Jx` cross section polar (torsional) moment of inertia, $[L^4]$
- `bending_Iy` cross section moment of inertia about local y axis, $[L^4]$
- `bending_Iz` cross section moment of inertia about local z axis, $[L^4]$
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `shear_correction_coefficient` a parameter for shear correction. When this parameter becomes very large, the Timoshenko beam element becomes Euler-Bernoulli beam. If not specifically calibrated, can use 1.0 for this parameter.
- `xz_plane_vector` a vector which defines the orientation of the local (beam coordinate system) xz plane in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$

- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Description of output by this element can be found in Section 206.8.4. more on this finite element can be found in Section 102.7 on Page 99 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Timoshenko Elastic Beam–Column Element with Directional Shear Correction Coefficients

The command is:

```
add element # <.> type beam_elastic_Timoshenko_directional with nodes ↩
   (<.>, <.>)
    cross_section = <L^2>
    elastic_modulus = <F/L^2>
    shear_modulus = <F/L^2>
    torsion_Jx = <length^4>
    bending_Iy = <length^4>
    bending_Iz = <length^4>
    mass_density = <M/L^3>
    shear_correction_coefficient_y = <.>
    shear_correction_coefficient_z = <.>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type beam_elastic` is the element type
- `with nodes (n1, n2)` are the 2 nodes (node numbers) defining this element
- `cross_section` is the cross section area, $[L^2]$
- `elastic_modulus` elastic modulus of the material which makes up the beam, $[F/L^2]$
- `shear_modulus` shear modulus of the material which makes up the beam, $[F/L^2]$
- `torsion_Jx` cross section polar (torsional) moment of inertia, $[L^4]$
- `bending_Iy` cross section moment of inertia about local y axis, $[L^4]$
- `bending_Iz` cross section moment of inertia about local z axis, $[L^4]$
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `shear_correction_coefficient_y` parameter for shear correction about local y axis. When this parameter becomes very large, the Timoshenko beam element becomes Euler-Bernoulli beam. If not specifically calibrated, can use 1.0 for this parameter.

- `shear_correction_coefficient_z` parameter for shear correction about local z axis. When this parameter becomes very large, the Timoshenko beam element becomes Euler-Bernoulli beam. If not specifically calibrated, can use 1.0 for this parameter.
- `xz_plane_vector` a vector which defines the orientation of the local (beam coordinate system) xz plane in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Description of output by this element can be found in Section 206.8.4. more on this finite element can be found in Section 102.7 on Page 99 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Adding 1D Fiber to a Beam Cross Section

Fibers can be added to the fiber beam cross section.

The command is:

```
add fiber # <.> using material # <.> to section # <.> ↩
 fiber_cross_section = <area> fiber_location = (<L>,<L>);
```

For example:

```
add fiber # 1 using material # 1 to section # 1 ↩
 fiber_cross_section = 5*cm^2 fiber_location = (10*cm,10*cm);
```

adds a fiber number 1 to section number 1 at coordinates $y = 10$cm, $z = 10$cm with cross section area of 5cm^2 using material number 1.

The material for fiber must be a uniaxial material, for example uniaxial_concrete02, uniaxial_elastic, uniaxial_steel01, and uniaxial_steel02.

Modeling, Finite Element: Adding Fiber Section to the Finite Element Model

Fiber section can be added to the finite element model.

The command is:

```
 add section # <.> type FiberSection
     TorsionConstant_GJ = <F*L^2);
```

where

- `TorsionConstant_GJ` provides a linear torsional stiffness to the element.

Fibers can be added to the section as described in section 1.3.4 on page 92.

The command is:

```
add fiber # <.> using material # <.> to section # <.>  ↩
   fiber_cross_section = <area>
 fiber_location = (<L>,<L>);
```

where

- `fiber_cross_section` is the area of the fiber element. (Total cross section are is the sum of all fiber areas) $[L^2]$
- `fiber_location` location of the fiber in the beam local Y-Z plane.

Modeling, Finite Element: 3D Displacement Based Fiber Beam-Column Element

```
add element # <.> type BeamColumnDispFiber3d with nodes (<.>, <.>)
    number_of_integration_points = <.>
    section_number = <.>
    mass_density = <M/L^3>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type BeamColumnDispFiber3d` is the element type
- `with nodes (n1, n2)` are the 2 nodes defining this element
- `number_of_integration_points` is number of integration points to be used along the beam element
- `section_number` is the number of predefined section
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `xz_plane_vector` unit vector which defines the orientation of the web of the beam in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Description of output by this element can be found in Section 206.8.6,

Modeling, Finite Element: 3D Displacement Based Fiber Beam-Column Element with Corotational Coordinate Transformation

```
add element # <.> type BeamColumnDispFiber3d_Corotational with nodes ↩
   (<.>, <.>)
    number_of_integration_points = <.>
    section_number = <.>
    mass_density = <M/L^3>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type BeamColumnDispFiber3d_Corotational` is the element type
- `with nodes (n1, n2)` are the 2 nodes defining this element
- `number_of_integration_points` is number of integration points to be used along the beam element
- `section_number` is the number of predefined section
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `xz_plane_vector` unit vector which defines the orientation of the web of the beam in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

Description of output by this element can be found in section 206.8.6.

The co-rotational formulation used in this element is based on Crisfield (1990).

Modeling, Finite Element: 3DOF+6DOF=9DOF Beam-Column Element

```
add element # <.> type beam_9dof_elastic
    with nodes (<.>, <.>)
    cross_section = <L^2>
    elastic_modulus = <F/L^2>
    shear_modulus = <F/L^2>
    torsion_Jx = <length^4>
    bending_Iy = <length^4>
    bending_Iz = <length^4>
    mass_density = <M/L^3>
    xz_plane_vector = (<.>, <.>, <.> )
    joint_1_offset = (<L>, <L>, <L> )
    joint_2_offset = (<L>, <L>, <L> );
```

where

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type beam_9dof_elastic` is the element type
- `with nodes (n1, n2)` are the 2 nodes defining this element, where the first node (n1) is the one with 3 DOFs and the second (n2) is the one with 6 DOFs
- `cross_section` is the cross section area, $[L^2]$
- `elastic_modulus` elastic modulus of the material which makes up the beam, $[F/L^2]$
- `shear_modulus` shear modulus of the material which makes up the beam, $[F/L^2]$
- `torsion_Jx` cross section polar (torsional) moment of inertia, $[L^4]$
- `bending_Iy` cross section moment of inertia about local y axis, $[L^4]$
- `bending_Iz` cross section moment of inertia about local z axis, $[L^4]$
- `mass_density` mass per unit volume of the material, $[M/L^3]$
- `xz_plane_vector` unit vector which defines the orientation of the web of the beam in global coordinates.
- `joint_1_offset` vector defining the rigid offset between end of beam and connection node 1, $[L]$
- `joint_2_offset` vector defining the rigid offset between end of beam and connection node 2, $[L]$

This finite element has only 3DOFs (translations) at the first node, and full 6DOFs at the other, second node. Due to missing rotational stiffness on first, 3DOF node, this beam has zero torsional stiffness.

This element is useful for connection of solid (3DOFs per node) and structural (6DOFs per node) elements It his beam element is used on its own, DOF that corresponds to torsion of the second node (DOF number 7), should be fixed as this beam does not provide that stiffness.

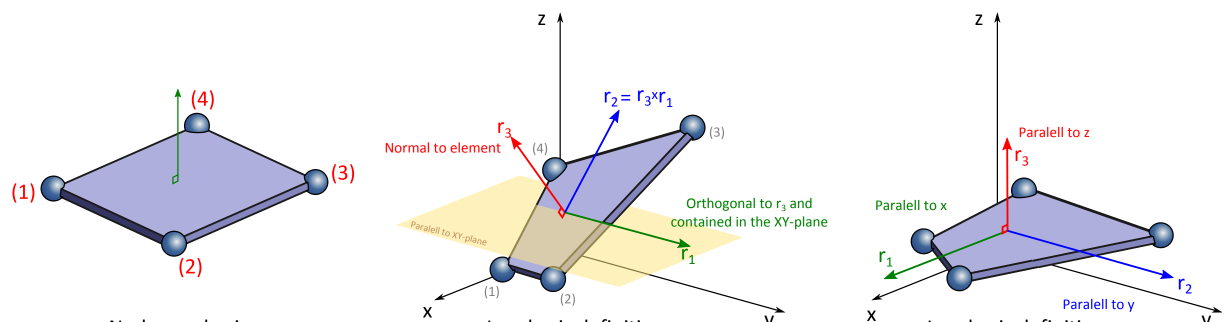
More on this finite element can be found in Section 102.8 on Page 102 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 4 Node ANDES Shell with Drilling DOFs

ANDES based 3D shell element including drilling degrees of freedom. Made up by patching together 4 ANDES shell triangle elements (and then averaging two and two squares made up two and two triangles).

The command is:

```
add element # <.> type 4NodeShell_ANDES
    with nodes (<.>, <.>, <.>)
    use material # <.>
    thickness = <L> ;
```



Node numbering is counter-clockwise

Local axis definition in general

Local axis definition if r_3 is nearly vertical

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `material # <.>` number of a previously defined material. (see `add material ...`)
- `thickness` shell thickness, $[L]$

Description of output by this element can be found in Section 206.8.5.

More on this finite element can be found in Section 102.10 on page 108 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 3 Node ANDES Shell with Drilling DOFs

```
add element # <.> type 3NodeShell_ANDES
    with nodes (<.>, <.>, <.>)
    use material # <.>
    thickness = <L> ;
```

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)

Modeling, Finite Element: 4 Node Shell NLDKGQ, or 4 Node Shell Xin-Zheng-Lu

This is a 3D quadrilateral shell element with membrane and drill DOFs based on the theory of generalized conforming element. This element accounts for the geometric nonlinearity of large deformation using a simplified version of updated Lagrangian formulation, where nodal coordinates are updated in each step, however strains and stresses are still calculated with reference to the original, undeformed system. It can be used together with elastic or inelastic sections. This element was originally developed by Professor Xin-Zheng Lu (Tsinghua University) and his students.

The command is:

```
add element # <.> type 4NodeShell_NLDKGQ
    with nodes (<.>, <.>, <.>, <.>)
    section_number = <.>;
```

It can also be called using the alternative command:

```
add element # <.> type 4NodeShell_XinZhengLu_Tsinghua
    with nodes (<.>, <.>, <.>, <.>)
    section_number = <.>;
```

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `with nodes (n1, n2, n3, n4)` are the 4 nodes defining this element
- `section_number` is the number of predefined shell cross section, described on page 101.

Modeling, Finite Element: Inelastic Layered Shell Section

This command is used to add a layered shell section. The section is made up of a number of layers with different thicknesses and different material properties (i.e., concrete layers or rebar layers). This type of section is used together with plane stress materials and shell elements.

The command is:

```
add section # <.> type LayeredShellFiber
    number_of_layers = <.>
    thickness_array = "<.>,<.>..."
    with material # "<.>,<.>..."
    thickness_scale_unit = <L>
    outofplane_shear_modulus = <F/L^2>;
```

where

- `number_of_layers` is the number of layers that the section has
- `thickness_array` is the relative thickness of each layer
- `with material #` is the material tag of each layer, only plane stress materials can be used here, see pages 63 and 64.
- `thickness_scale_unit` is the total thickness of the section
- `outofplane_shear_modulus` is the out-of-plane shear modulus of the section

Modeling, Finite Element: ElasticMembranePlaneStress Element (to be removed!)

NOTE: this element is being removed, and will not be available after Real ESSI version 19.07 (current). This is a 2D finite element, and we only maintain 3D finite elements. This element is replaced by a 3D 27 node elastic and/or elastic-plastic wall/plate/shell brick element.

The command is:

```
add element No (or #) <element_number>
    type ElasticMembranePlaneStress
    with nodes (n1, n2, n3, n4)
    use material No (or #) <material_number>
    thickness = <L> ;
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used).
- `type ElasticMembranePlaneStress` is the element type.
- `with nodes (n1, n2, n3, n4)` are the 4 nodes (node numbers) defining this element.
- `use material No (or #)` is the material number for linear elastic material that makes up the element.
- `thickness` is the thickness of the membrane.

Modeling, Finite Element: InelasticMembranePlaneStress Element (to be removed!)

NOTE: this element is being removed, and will not be available after Real ESSI version 19.07 (current). This is a 2D finite element, and we only maintain 3D finite elements. This element is replaced by a 3D 27 node elastic or elastic-plastic wall/plate/shell brick element or elastic-plastic shell element.

The command is:

```
add element No (or #) <element_number>
    type InelasticMembranePlaneStress
    with nodes (n1, n2, n3, n4)
    use material No (or #) <material_number>
    ;
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used).
- `type InelasticMembranePlaneStress` is the element type.
- `with nodes (n1, n2, n3, n4)` are the 4 nodes (node numbers) defining this element.
- `use material No (or #)` is the material number for inelastic material that makes up the element. Since this is a plane stress element, material needs to have plane stress constitutive integration algorithm available. In addition, this material should specify thickness of the element. Different layers and their thicknesses for different materials (for example concrete and steel) will be defined within material definition. `PlaneStressLayeredMaterial` is a material of this type.

Modeling, Finite Element: SuperElementLinearElasticImport

The command is:

```
add element No (or #) <element_number>
    type SuperElementLinearElasticImport
    with hdf5_file = <string>
    ;
```

where

- `No (or #) <element_number>` is a unique element integer number (does not have to be sequential, any unique positive integer number can be used).
- `type SuperElementLinearElasticImport` is the element type.
- `hdf5_file` specifies the HDF5 filename of the SuperElement with SuperElement data. The HDF5 file should contain the following datasets:
  - `Node` dataset within HDF5 file is organized in a column (a 1D dataset), and it specifies the node tags/numbers of nodes that make up the SuperElement.
  - `DofList` dataset within HDF5 file is a organized in a column, and it specifies the number of DOFs per each `Node`. For example if nodes are representing structural elements, they usually have 6 DOFs per node, while solids will have 3 DOFs per node. `DofList` dataset has to have the same number of entries as `Node` dataset, as each entry in `DofList` corresponds to one node from `Node` dataset.
  - `MassMatrix` is a matrix, that sets masses/numbers for a mass matrix of the SuperElement.
  - `StiffnessMatrix` is a matrix, that sets stiffness/numbers for a stiffness matrix of the SuperElement.
  - `ConnectNode` dataset within HDF5 file is organized in a column (a 1D dataset), and it specifies the node tags/numbers of nodes that are going to be connected to Real-ESSI mesh.
  - `ConnectNodeCoordinate` dataset within HDF5 file is organized in a matrix (a 2D dataset), and it specifies the nodal coordinates for nodes that are going to be connected to Real-ESSI mesh. Since each node has 3 coordinates, the length of `ConnectNodeCoordinate` is the same as the length of `ConnectNode` and each line has three entries, for X, Y and Z coordinates of given node.

  In addition to the minimum dataset requirements above, users can get more output from Real-ESSI:

  - Results for individual finite elements (internal forces, etc.), can be obtained if node, DofList, mass matrix and stiffness matrix for each finite element within the super element are provided.

– Graphical post-processing can be obtained if coordinates for all nodes and their connectivity into finite elements are provided (a mesh data).

Modeling, Finite Element: 8 Node Brick Element

The command is:

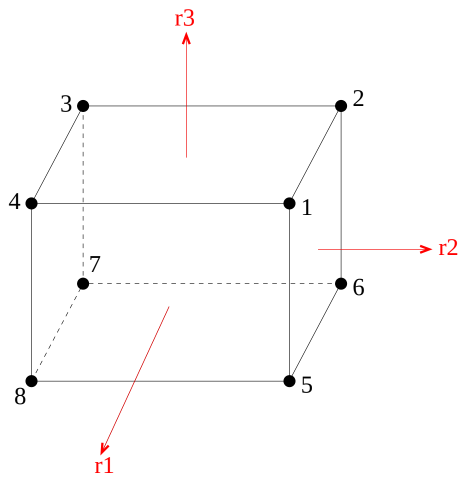
```
add element # <element_number> type 8NodeBrick
    using <.> Gauss points each direction
    with nodes (n1, n2, n3, n4, n5, n6, n7, n8)
    use material No (or #) <material_number>;
```

and/or;

```
add element # <element_number> type 8NodeBrick
    with nodes (n1, n2, n3, n4, n5, n6, n7, n8)
    use material No (or #) <material_number>;
```

where:

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type 8NodeBrick` is the element type.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8)` are the 8 nodes for this element, in the order as per figure below



- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$),

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.

Description of output by this element can be found in section 206.8.2.

More on this finite element can be found in Section 102.4.1 on page 87 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 20 Node Brick Element

The command is:

```
add element No (or #) <element_number> type 20NodeBrick
    using <.> Gauss points each direction
    with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                n9, n10, n11, n12, n13, n14, n15, n16,
                n17, n18, n19, n20 )
    use material No (or #) <material_number>;
```

and/or

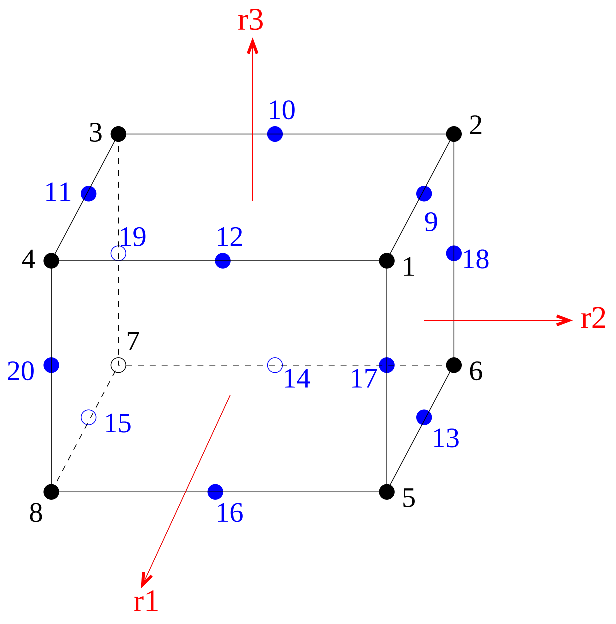
```
add element No (or #) <element_number> type 20NodeBrick
    with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                n9, n10, n11, n12, n13, n14, n15, n16,
                n17, n18, n19, n20 )
    use material No (or #) <material_number>;
```

where:

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type 20NodeBrick` is the element type. `20NodeBrick_elastic` can be used if elastic material is used. It this case, the stiffness and mass matrices will not be updated at each step.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, n17, n18, n19, n20)` are the 20 nodes for this element, written in the order defined as per figure below
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$),
- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms)

Description of output by this element can be found in Section 206.8.2.

More on this finite element can be found in Section 102.4.3 on page 89 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).


r3
10
3
2
11
9
19
12
4
1
18
r2
7
20
14
17
6
15
13
8
16
5
r1

Modeling, Finite Element: 27 Node Brick Element

The command is:

```
add element # <element_number>
            type 27NodeBrick
            using <.> Gauss points each direction
            with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                        n9, n10, n11, n12, n13, n14, n15, n16,
                        n17, n18, n19, n20, n21, n22, n23,
                        n124, n25, n26, n27  )
            use material # <material_number>;
```

and/or

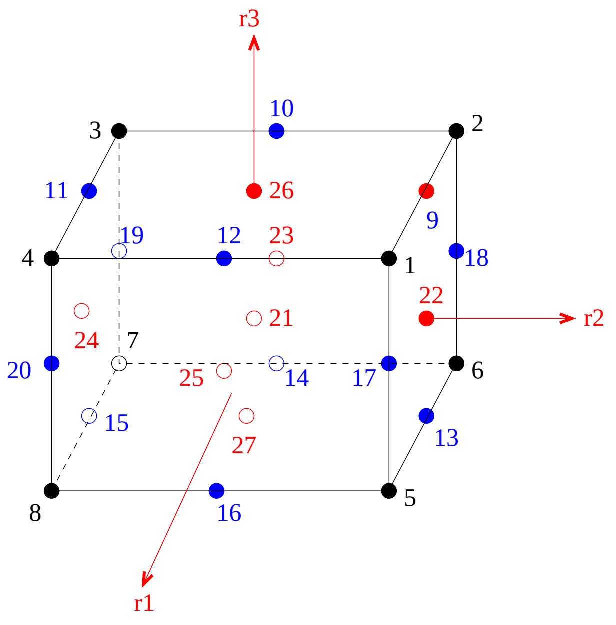
```
add element # <element_number>
            type 27NodeBrick
            with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                        n9, n10, n11, n12, n13, n14, n15, n16,
                        n17, n18, n19, n20, n21, n22, n23,
                        n124, n25, n26, n27  )
            use material # <material_number>;
```

where:

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type 27NodeBrick` is the element type.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, n17, n18, n19, n20) n21, n22, n23, n24, n25, n26, n27)` are the 27 nodes for this element, written in the order defined as per this figure
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$),
- `use material No (or #)` is the material number which makes up the element (nonlinear elastic and/or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms).

Description of output by this element can be found in Section 206.8.2.

More on this finite element can be found in Section 102.4.4 on page 91 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).



Modeling, Finite Element: Variable 8-27 Node Brick Element

The command is:

```
add element No (or #) <element_number> type variable_node_brick_8_to_27
            using <.> Gauss points each direction
            with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                        n9, n10, n11, n12, n13, n14, n15, n16,
                        n17, n18, n19, n20, n21, n22, n23, n24, n25, ↩
   n26, n27)
            use material No (or #) <material_number>;
```

and/or

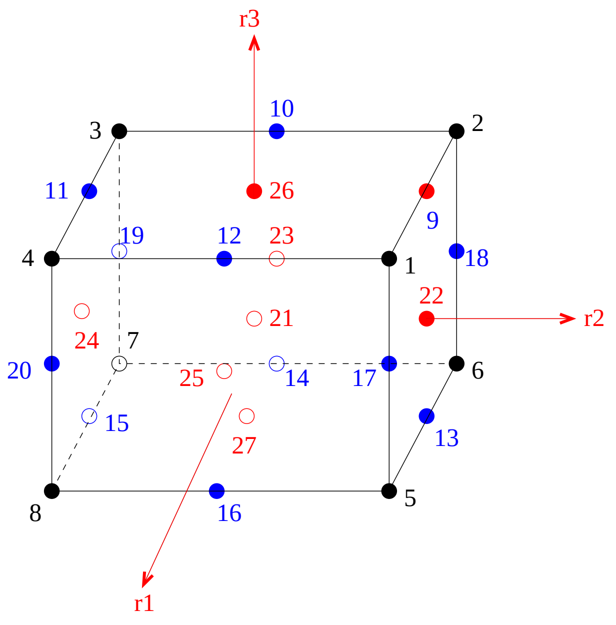
```
add element No (or #) <element_number> type variable_node_brick_8_to_27
            using <.> Gauss points each direction
            with nodes (n1, n2, n3, n4, n5, n6, n7, n8,
                        n9, n10, n11, n12, n13, n14, n15, n16,
                        n17, n18, n19, n20, n21, n22, n23, n24, n25, ↩
   n26, n27)
            use material No (or #) <material_number>;
```

where:

- `No (or #) <element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type variable_node_brick_8_to_27` is the element type
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8,`
  `n9, n10, n11, n12, n13, n14, n15, n16, n17, n18, n19, n20,`
  `n21, n22, n23, n24, n25, n26, n27)`
  are the 8 to 27 nodes for this element, written in the order defined as per this figure. Nodes 1-8 are obligatory, while any other nodes can be used but do not have to, the element will automatically pick proper shape functions. This element is good for transitions in meshing.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$),
- `material No (or #)` is the material number which makes up the element (nonlinear elastic and/or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the

element deforms)

Description of output by this element can be found in Section 206.8.2.



Modeling, Finite Element: 8 Node Brick u-p Element

The command is:

```
add element # <.> type 8NodeBrick_up
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 8NodeBrick_up
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8)` are the 8 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8

node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \leq \alpha \leq 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note: the permeability k_x, k_y, k_z is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$. Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

More on theory for this finite element can be found in Section 102.12.3.3 on page 126 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Description of output by this element can be found in Section 206.8.2 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 20 Node Brick u-p Element

The command is:

```
add element # <.> type 20NodeBrick_up
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 20NodeBrick_up
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, ↩ n17, n18, n19, n20)` are the 20 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick

finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \le \alpha \le 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note: the permeability k_x, k_y, k_z is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$. Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

More on theory for this finite element can be found in section 102.12.3.3 on page 126 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 27 Node Brick u-p Element

The command is:

```
add element # <.> type 27NodeBrick_up
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
  <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, ↩
  <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 27NodeBrick_up
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
  <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, ↩
  <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, ↩ n17, n18, n19, n20, n21, n22, n23, n24, n25, n26, n27)` are the 27 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each

direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \leq \alpha \leq 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note that, the permeability $\mathbf{k}$ is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$.

Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

More on theory for this finite element can be found in Section 102.12.3.3 on page 126 of the main document. Description of output by this element can be found in Section 206.8.2.

Modeling, Finite Element: 8 Node Brick u-p-U Element

The command is:

```
add element # <.> type 8NodeBrick_upU
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 8NodeBrick_upU
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8)` are the 8 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8

node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \leq \alpha \leq 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note that, the permeability $\mathbf{k}$ is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$. Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

Please note that the $u-p-U$ element, and the $u-p-U$ formulation is a dynamic formulation and is meant to be used with dynamic analysis, and not static analysis, so that all the element matrices, as described in theory section, noted below, are developed and used.

More on theory for this finite element can be found in Section 102.12.1.7 on page 120 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL). Description of output by this element can be found in Section 206.8.2 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: 20 Node Brick u-p-U Element

The command is:

```
add element # <.> type 20NodeBrick_upU
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
  <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 20NodeBrick_upU
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
  <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, ↩ n17, n18, n19, n20)` are the 20 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick

finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \leq \alpha \leq 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note that, the permeability $\mathbf{k}$ is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$. Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

Please note that the $u-p-U$ element, and the $u-p-U$ formulation is a dynamic formulation and is meant to be used with dynamic analysis, and not static analysis, so that all the element matrices, as described in theory section, noted below, are developed and used.

More on theory for this finite element can be found in section 102.12.1.8 on page 120 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL). Description of output by this element can be found in Section 206.8.2.

Modeling, Finite Element: 27 Node Brick u-p-U Element

The command is:

```
add element # <.> type 27NodeBrick_upU
    using <.> Gauss points each direction
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, ↩
   <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

and/or

```
add element # <.> type 27NodeBrick_upU
    with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>,<.>, <.>, <.>, <.>, <.>, <.>, <.>,<.>, ↩
   <.>, <.>, <.>)
    use material # <.>
    porosity = <.>
    alpha = <.>
    rho_s = <M/L^3>
    rho_f = <M/L^3>
    k_x = <L^3*T/M>
    k_y = <L^3*T/M>
    k_z = <L^3*T/M>
    K_s = <F/L^2>
    K_f = <F/L^2>;
```

where:

- `No (or #) <element_number>` is the unique element integer number that does not have to be sequential, any unique positive integer number can be used.
- `type 8NodeBrick_up` is the element type/name.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8, n9, n10, n11, n12, n13, n14, n15, n16, ↩ n17, n18, n19, n20, n21, n22, n23, n24, n25, n26, n27)` are the 27 nodes for this element, is specified order.
- `using <.> Gauss points each direction` is the number of Gauss points to be used in each

direction (r1, r2, and r3) for integration of finite element matrices (mass and stiffness). There can be from 1 to 6 Gauss points used (uniformly) in each direction (r1, r2, and r3). Command for the brick finite element (above) without number of Gauss points control is kept for back compatibility. For 8 node bricks 2 Gauss points are used in each direction ($2 \times 3 \times 3$), while for 20 nodes, 8-20 node and 8-27 node bricks 3 Gauss points are used in each direction ($3 \times 3 \times 3$).

- `use material No (or #)` is the material number which makes up the element (nonlinear elastic or elastic-plastic material properties for each integration (Gauss) point will evolve independently as the element deforms). Use LT version with LT materials.
- `porosity` is the porosity ($n = V_{voids}/V_{total}$) of material in this element.
- `alpha` is the parameter controlling level of effective stress analysis. For soils, usually $\alpha = 1$ is used, while for other materials (saturated concrete, bone material, etc.) lower values are used ($0 \leq \alpha \leq 1$).
- `rho_s` is the density of particles of the solid phase. It is important to note that this is a density of the actual mineral that makes up solid particles!.
- `rho_f` is the density of pore fluid. It is usually density of water, however, for unsaturated and partially saturated materials, this density will be different, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).
- `k_x` is the permeability in the x direction (global x) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_y` is the permeability in the y direction (global y) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `k_z` is the permeability in the z direction (global z) of the element. It is also important to note about the units used for permeability, as noted below. With isotropic permeability, usually the case, $k_x = k_y = k_z$.
- `K_s` is the bulk modulus of the soil phase particles. It is important to note that this is a bulk modulus of the actual mineral that makes up solid particles!
- `K_f` is the bulk modulus of the fluid phase that is found in porous material pores. It is usually bulk modulus of the fluid (physical value of the bulk modulus of fluid, for example water), however, for unsaturated and partially saturated materials, this density is a density of a mixture, as described in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Note that, the permeability $\mathbf{k}$ is used with dimensions of $[length]^3[time]/[mass]$, which is different from the usual soil mechanics convention, where the permeability has the dimension of velocity, i.e. $[length]/[time]$.

Their values are related by $k = K/\rho_f g$, where g is the gravitational acceleration at which the permeability is measured.

Please note that the $u - p - U$ element, and the $u - p - U$ formulation is a dynamic formulation and is meant to be used with dynamic analysis, and not static analysis, so that all the element matrices, as described in theory section, noted below, are developed and used.

More on theory for this finite element can be found in Section 102.12.1.9 on page 120 of the main document. Description of output by this element can be found in Section 206.8.2.

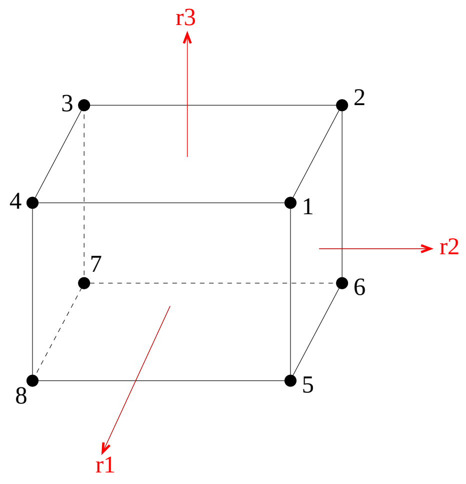
Modeling, Finite Element: 8 Node Cosserat Brick Element

The command is:

```
add element # <element_number> type Cosserat8NodeBrick
  with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)
  use material # <.>;
```

where:

- `<element_number>` is the unique element integer number (does not have to be sequential, any unique positive integer number can be used)
- `type Cosserat8NodeBrick` is the element type.
- `with nodes (n1, n2, n3, n4, n5, n6, n7, n8)` are the 8 nodes for this element. Each node should have 6 DOFs for this element. The element should be in the order as per figure below



- `use material No (or #)` is the material number which makes up the element. The element can use materials `Cosserat_linear_elastic_isotropic_3d` and `Cosserat_von_Mises`.

Modeling, Finite Element: Bonded Contact/Interface/Joint Element

The command is:

```
add element # <.> type BondedContact
    with nodes (<.>, <.>)
    penalty_stiffness = <F/L>
```

where

- `penalty_stiffness` represents the penalty stiffness in the three orthogonal x, y and z directions, that connects two nodes of this element.

Modeling, Finite Element: Coupled Bonded Contact/Interface/Joint Element

The command is:

```
add element # <.> type CoupledBondedContact
    with nodes (<.>, <.>)
    penalty_stiffness = <F/L>
    axial_viscous_damping = <F/L>
    shear_viscous_damping = <F/L>
    contact_plane_vector = (<.>, <.>, <.> );
```

where

- `penalty_stiffness` represents the penalty stiffness in the three orthogonal x, y and z directions, that connects two nodes of this element. The penalty stiffness is used for both solid and fluid DOFs.
- `axial_viscous_damping` is the viscous damping in axial.
- `shear_viscous_damping` is the viscous damping in shear.
- `contact_plane_vector` defines the normal to the contact/interface/joint plane.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Modeling, Finite Element: Force Based Dry Hard Contact/Interface/Joint Element

The command is:

```
add element # <.> type ForceBasedHardContact
    with nodes (<.>, <.>)
    axial_stiffness = <F/L>
    shear_stiffness = <F/L>
    axial_viscous_damping = <F/L>
    shear_viscous_damping = <F/L>
    friction_ratio = <.>
    contact_plane_vector = (<.>, <.>, <.> );
```

The axial force F_a and axial stiffness E_a in defined as

$$F_a = E_a * \delta_a \tag{1.2}$$

where

δ_a refers to the axial relative displacement in axial contact/interface/joint direction,

E_a refers to the axial stiffness in axial contact direction, and

- `axial_stiffness (b)` represents the stiffness in the axial/axial direction (local x axis).
- `shear_stiffness` Is the stiffness in the tangential (shear, local y or z axis) directions.
- `axial_viscous_damping` Is the viscous damping in axial/axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `friction_ratio` Coulomb friction ratio.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Force Based Dry Soft Contact/Interface/Joint Element

The command is:

```
add element # <.> type ForceBasedSoftContact
    with nodes (<.>, <.>)
    initial_axial_stiffness = <F/L>
    stiffening_rate = <1/m>
    max_axial_stiffness = <F/L>
    shear_stiffness = <F/L>
    axial_viscous_damping = <F/L>
    shear_viscous_damping = <F/L>
    friction_ratio = <.>
    contact_plane_vector = (<.>, <.>, <.> );
```

The axial force F_a and axial stiffness E_a in defined as

$$\begin{aligned} F_a &= b * exp(a * \delta_a) * \delta_a \\ E_a &= max(b * exp(a * \delta_a) * (1 + a * \delta_a), E_{max}) \end{aligned} \tag{1.3}$$

where

δ_a refers to the axial relative displacement in axial contact/interface/joint direction,

b refers to the axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact/interface/joint direction,

E_{max} refers to the maximum axial stiffness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).
- `stiffening_rate (a)` Represents exponential stiffening rate $exp(a * \delta_a)$ in axial direction.
- `max_axial_stiffness` (E_{max}) Defines the maximum stiffness in the axial direction (local x axis).
- `shear_stiffness` Is the stiffness in the tangential (shear, local y or z axis) directions.
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `friction_ratio` Coulomb friction ratio.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Force Based Coupled Hard Contact/Interface/Joint Element

The command is:

```
add element # <.> type ForceBasedCoupledHardContact
    with nodes (<.>, <.>)
    axial_stiffness = <F/L>
    axial_penalty_stiffness = <F/L>
    shear_stiffness = <F/L>
    axial_viscous_damping = <F/L>
    shear_viscous_damping = <F/L>
    friction_ratio = <.>
    contact_plane_vector = (<.>, <.>, <.> );
```

The axial force F_a and axial stiffness E_a in defined as

$$\begin{aligned} F_a &= b * \delta_a \\ E_a &= b \end{aligned} \tag{1.4}$$

where

δ_a refers to the axial relative displacement in axial contact/interface/joint direction,

b refers to the axial stiffness in axial contact/interface/joint direction, and

- `axial_stiffness (b)` represents the axial stiffness in the axial direction (local x axis).
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `shear_stiffness` Is the stiffness in the tangential (shear, local y or z axis) directions.
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `friction_ratio` Coulomb friction ratio.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Force Based Coupled Soft Contact/Interface/Joint Element

The command is:

```
add element # <.> type ForceBasedCoupledSoftContact
    with nodes (<.>, <.>)
    initial_axial_stiffness = <F/L>
    stiffening_rate = <1/m>
    max_axial_stiffness = <F/L>
    axial_penalty_stiffness = <F/L>
    shear_stiffness = <F/L>
    axial_viscous_damping = <F/L>
    shear_viscous_damping = <F/L>
    friction_ratio = <.>
    contact_plane_vector = (<.>, <.>, <.> );
```

The axial force F_a and axial stiffness E_a in defined as

$$\begin{aligned} F_a &= b * exp(a * \delta_a) * \delta_a \\ E_a &= max(b * exp(a * \delta_a) * (1 + a * \delta_a), E_{max}) \end{aligned} \tag{1.5}$$

where

δ_a refers to the axial relative displacement in axial contact/interface/joint direction,

b refers to the axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact/interface/joint direction,

E_{max} refers to the maximum axial stiffness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).
- `stiffening_rate (a)` Represents exponential stiffening rate $exp(a * \delta_a)$ in axial direction.
- `max_axial_stiffness` (E_{max}) Defines the maximum stiffness in the axial direction (local x axis).
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `shear_stiffness` Is the stiffness in the tangential (shear, local y or z axis) directions.
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `friction_ratio` Coulomb friction ratio.

- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Hard Contact/Interface/Joint Element with Elastic Perfectly Plastic Shear Behavior

The command is:

```
add element # <.> type StressBasedHardContact_ElPPlShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedHardContact_ElPPlShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * \epsilon_a \\ E_a &= b \end{aligned} \tag{1.6}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.2
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.

- `residual_friction_coefficient` (μ_r) Is the residual friction coefficient described in Section 104.7.3.2.
- `shear_zone_thickness` h Is the shear zone thickness.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Hard Contact/Interface/Joint Element with Nonlinear Hardening Shear Behavior

The command is:

```
add element # <.> type StressBasedHardContact_NonLinHardShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedHardContact_NonLinHardShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * \epsilon_a \\ E_a &= b \end{aligned} \tag{1.7}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact/interface/joint axial direction,

h is the shear zone thickness, and

- `axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress, described in Section 104.7.3.4
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.

- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.3
- `shear_zone_thickness` h Is the shear zone thickness.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Hard Contact/Interface/Joint Element with Nonlinear Hardening and Softening Shear Behavior

The command is:

```
add element # <.> type StressBasedHardContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedHardContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * \epsilon_a \\ E_a &= b \end{aligned} \tag{1.8}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact direction $\epsilon_a = \delta_a / h$,

δ_a is the relative axial penetration in contact/interface/joint axial direction,

h is the shear zone thickness, and

- `axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).

- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress, described in Section 104.7.3.4

- `rate_of_softening` (R_s) Is the parameter to control the rate of frictional softening described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as

$$\Delta\mu = -\frac{n * R_s(\mu_p - \mu_r)}{(\pi/2)^n \theta^{1/n-1}} * cos^2\theta\Delta\gamma^p \tag{1.9}$$

$$\theta = \frac{\mu_p - \mu}{\mu_p - \mu_r}(\pi/2)^n \tag{1.10}$$

  where, R_s is the frictional softening rate parameter, $\Delta\gamma^p$ is the plastic shear strain and n represents the size of the peak plateau.

$$\Delta\gamma^p = \sqrt{\Delta\epsilon_{ij}^p \Delta\epsilon_{ij}^p} \tag{1.11}$$

- `size_of_peak_plateau` (n) Is the frictional softening parameter to control the size of plateau as described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as shown in Equation 1.17.

- `axial_viscous_damping` Is the viscous damping in axial.

- `shear_viscous_damping` Is the viscous damping in shear.

- `peak_friction_coefficient_limit` (μ_{p0}) Is the limit to the peak frictional hardening parameter μ_p.

- `peak_friction_coefficient_rate_of_decrease` (k) Is the rate of decrease of peak frictional hardening parameter μ_p with axial stress, described in Section 104.7.3.4

$$\mu_p = max(\mu_{p0}, \mu_{p0} - k * log(\sigma_a/P_0)) \tag{1.12}$$

  where μ_{p0} is the peak frictional hardening limit, k is the peak frictional parameter rate of decrease and P_0 is the reference stress of $P_0 = 101kPa$.

- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.4

- `shear_zone_thickness` h Is the shear zone thickness.

- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.

- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Soft Contact/Interface/Joint Element with Elastic Perfectly Plastic Shear Behavior

The command is:

```
add element # <.> type StressBasedSoftContact_ElPPlShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedSoftContact_ElPPlShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned}
&\sigma_a = b * exp(a * \epsilon_a) * \epsilon_a \\
&E_a = max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max})
\end{aligned} \tag{1.13}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).

- `stiffening_rate (a)` Represents exponential stiffening rate $exp(a * \epsilon_a)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.2
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual friction coefficient described in Section 104.7.3.2
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Soft Contact/Interface/Joint Element with Nonlinear Hardening Shear Behavior

The command is:

```
add element # <.> type StressBasedSoftContact_NonLinHardShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedSoftContact_NonLinHardShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * exp(a * \epsilon_a) * \epsilon_a \\ E_a &= max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max}) \end{aligned} \tag{1.14}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis) for 1m penetration.

- `stiffening_rate` (a) Represents exponential stiffening rate $exp(sr * \epsilon_a)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.3
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.3
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Dry Soft Contact/Interface/Joint Element with Nonlinear Hardening and Softening Shear Behavior

The command is:

```
add element # <.> type StressBasedSoftContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedSoftContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * exp(a * \epsilon_a) * \epsilon_a \\ E_a &= max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max}) \end{aligned} \tag{1.15}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness` (b) represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `stiffening_rate` (a) Represents exponential stiffening rate $exp(sr * \epsilon_n)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress, described in Section 104.7.3.4
- `rate_of_softening` (R_s) Is the parameter to control the rate of frictional softening described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as

$$\Delta\mu = -\frac{n * R_s(\mu_p - \mu_r)}{(\pi/2)^n \theta^{1/n-1}} * cos^2\theta \Delta\gamma^p \tag{1.16}$$

$$\theta = \frac{\mu_p - \mu}{\mu_p - \mu_r}(\pi/2)^n \tag{1.17}$$

  where, R_s is the frictional softening rate parameter, $\Delta\gamma^p$ is the plastic shear strain and n represents the size of the peak plateau.

$$\Delta\gamma^p = \sqrt{\Delta\epsilon^p_{ij}\Delta\epsilon^p_{ij}} \tag{1.18}$$

- `size_of_peak_plateau` (n) Is the frictional softening parameter to control the size of plateau as described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as shown in Equation 1.17.
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `peak_friction_coefficient_limit` (μ_{p0}) Is the limit to the peak frictional hardening parameter μ_p.
- `peak_friction_coefficient_rate_of_decrease` (k) Is the rate of decrease of peak frictional hardening parameter μ_p with axial stress, described in Section 104.7.3.4

$$\mu_p = max(\mu_{p0}, \mu_{p0} - k * log(\sigma_a/P_0)) \tag{1.19}$$

where μ_{p0} is the peak frictional hardening limit, k is the peak frictional parameter rate of decrease and P_0 is the reference stress of $P_0 = 101kPa$.

- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.4
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Coupled Hard Contact/Interface/Joint Element with Elastic Perfectly Plastic Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledHardContact_ElPPlShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledHardContact_ElPPlShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * \epsilon_a \\ E_a &= b \end{aligned} \tag{1.20}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact/interface/joint axial direction,

h is the shear zone thickness, and

- `axial_stiffness (b)` represents the stiffness in the axial direction (local x axis).

- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.

- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.2
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual friction coefficient described in Section 104.7.3.2
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Coupled Hard Contact/Interface/Joint Element with Nonlinear Hardening Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledHardContact_NonLinHardShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledHardContact_NonLinHardShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * \epsilon_a \\ E_a &= b \end{aligned} \tag{1.21}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact direction $\epsilon_a = \delta_a / h$,

δ_a is the relative axial penetration in contact/interface/joint axial direction,

h is the shear zone thickness, and

- `axial_stiffness (b)` represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping

action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.

- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.3
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.3
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Coupled Hard Contact/Interface/Joint Element with Non-linear Hardening and Softening Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledHardContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness =<Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledHardContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    axial_stiffness = <Pa>
    axial_penalty_stiffness =<Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned}\sigma_a &= b * \epsilon_a \\ E_a &= b\end{aligned} \tag{1.22}$$

where

$E_a = b$ refers to the axial stiffness in axial contact/interface/joint direction,

ϵ_a refers to the axial strain in axial contact direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact/interface/joint axial direction,

h is the shear zone thickness, and

- `axial_stiffness` (b) represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress, described in Section 104.7.3.4
- `rate_of_softening` (R_s) Is the parameter to control the rate of frictional softening described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as

$$\Delta\mu = -\frac{n * R_s(\mu_p - \mu_r)}{(\pi/2)^n \theta^{1/n-1}} * cos^2\theta\Delta\gamma^p \tag{1.23}$$

$$\theta = \frac{\mu_p - \mu}{\mu_p - \mu_r}(\pi/2)^n \tag{1.24}$$

where, R_s is the frictional softening rate parameter, $\Delta\gamma^p$ is the plastic shear strain and n represents the size of the peak plateau.

$$\Delta\gamma^p = \sqrt{\Delta\epsilon_{ij}^p \Delta\epsilon_{ij}^p} \tag{1.25}$$

- `size_of_peak_plateau` (n) Is the frictional softening parameter to control the size of plateau as described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as shown in Equation 1.24.
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `peak_friction_coefficient_limit` (μ_{p0}) Is the limit to the peak frictional hardening parameter μ_p.
- `peak_friction_coefficient_rate_of_decrease` (k) Is the rate of decrease of peak frictional hardening parameter μ_p with axial stress, described in Section 104.7.3.4

$$\mu_p = max(\mu_{p0}, \mu_{p0} - k * log(\sigma_a/P_0)) \tag{1.26}$$

where μ_{p0} is the peak frictional hardening limit, k is the peak frictional parameter rate of decrease and P_0 is the reference stress of $P_0 = 101kPa$.

- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.4
- `shear_zone_thickness` h Is the shear zone thickness.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Coupled Soft Contact/Interface/Joint Element with Elastic Perfectly Plastic Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledSoftContact_ElPPlShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledSoftContact_ElPPlShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned}\sigma_a &= b * exp(a * \epsilon_a) * \epsilon_a \\ E_a &= max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max})\end{aligned} \tag{1.27}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `stiffening_rate (a)` Represents exponential stiffening rate $exp(sr * \epsilon_n)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.2
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual friction coefficient described in Section 104.7.3.2
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section **??**.

Modeling, Finite Element: Stress Based Coupled Soft Contact/Interface/Joint Element with Nonlinear Hardening Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledSoftContact_NonLinHardShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledSoftContact_NonLinHardShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness = <Pa>
    initial_shear_stiffness = <Pa>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * exp(a * \epsilon_a) * \epsilon_a \\ E_a &= max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max}) \end{aligned} \tag{1.28}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `stiffening_rate (a)` Represents exponential stiffening rate $exp(sr * \epsilon_n)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress described in Section 104.7.3.3
- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.3
- `shear_zone_thickness` h Is the shear zone thickness
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Stress Based Coupled Soft Contact/Interface/Joint Element with Nonlinear Hardening and Softening Shear Behavior

The command is:

```
add element # <.> type StressBasedCoupledSoftContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness =<Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    contact_plane_vector = (<.>, <.>, <.> );
```

and/or;

```
add element # <.> type StressBasedCoupledSoftContact_NonLinHardSoftShear
    with nodes (<.>, <.>)
    initial_axial_stiffness = <Pa>
    stiffening_rate = <>
    max_axial_stiffness = <Pa>
    axial_penalty_stiffness =<Pa>
    initial_shear_stiffness = <Pa>
    rate_of_softening = <>
    size_of_peak_plateau = <>
    axial_viscous_damping = <Pa*s>
    shear_viscous_damping = <Pa*s>
    peak_friction_coefficient_limit = <>
    peak_friction_coefficient_rate_of_decrease  = <.>
    residual_friction_coefficient = <.>
    shear_zone_thickness = <m>
    surface_vector_relative_tolerance = <.>;
```

The axial stress σ_a and axial stiffness E_a in defined as

$$\begin{aligned} \sigma_a &= b * exp(a * \epsilon_a) * \epsilon_a \\ E_a &= max(b * exp(a * \epsilon_a) * (1 + a * \epsilon_a), E_{max}) \end{aligned} \tag{1.29}$$

where

b refers to the initial axial stiffness in axial contact/interface/joint direction,

a refers to the stiffening rate in axial contact direction,

E_{max} refers to the maximum axial stiffness,

E_a refers to the axial stiffness,

ϵ_a refers to the axial strain in axial contact/interface/joint direction $\epsilon_a = \delta_a/h$,

δ_a is the relative axial penetration in contact axial direction,

h is the shear zone thickness, and

- `initial_axial_stiffness (b)` represents the stiffness in the axial direction (local x axis) for 1m penetration.
- `stiffening_rate (a)` Represents exponential stiffening rate $exp(sr * \epsilon_n)$ in axial direction.
- `max_axial_stiffness`(E_{max}) Defines the maximum stiffness in the axial direction (local x axis) for the contact/interface/joint element.
- `axial_penalty_stiffness` (E_p) defines the penalty stiffness between U_i degree of freedom (DoF) (saturated, coupled u-p-U element) and u_i DoF (dry u element) to enforce movement of fluid in u-p-U element with solid in u element in contact/interface/joint axial direction. This is useful for pumping action, gap opens and draws the fluid from u-p-U element and then gap closes and pumps, pushes fluid into u-p-U element.
- `initial_shear_stiffness` (E_s) Is the stiffness in the tangential (shear, local y or z axis) directions at $101kPa$ axial stress, described in Section 104.7.3.4
- `rate_of_softening` (R_s) Is the parameter to control the rate of frictional softening described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as

$$\Delta\mu = -\frac{n * R_s(\mu_p - \mu_r)}{(\pi/2)^n \theta^{1/n-1}} * cos^2\theta\Delta\gamma^p \tag{1.30}$$

$$\theta = \frac{\mu_p - \mu}{\mu_p - \mu_r}(\pi/2)^n \tag{1.31}$$

  where, R_s is the frictional softening rate parameter, $\Delta\gamma^p$ is the plastic shear strain and n represents the size of the peak plateau.

$$\Delta\gamma^p = \sqrt{\Delta\epsilon^p_{ij}\Delta\epsilon^p_{ij}} \tag{1.32}$$

- `size_of_peak_plateau` (n) Is the frictional softening parameter to control the size of plateau as described in Section 104.7.3.4. The frictional softening function is an inverse tangent function raised to power n with incremental form as shown in Equation 1.31.

- `axial_viscous_damping` Is the viscous damping in axial.
- `shear_viscous_damping` Is the viscous damping in shear.
- `peak_friction_coefficient_limit` (μ_{p0}) Is the limit to the peak frictional hardening parameter μ_p.
- `peak_friction_coefficient_rate_of_decrease` (k) Is the rate of decrease of peak frictional hardening parameter μ_p with axial stress, described in Section 104.7.3.4

$$\mu_p = max(\mu_{p0}, \mu_{p0} - k * log(\sigma_a/P_0)) \tag{1.33}$$

  where μ_{p0} is the peak frictional hardening limit, k is the peak frictional parameter rate of decrease and P_0 is the reference stress of $P_0 = 101kPa$.
- `residual_friction_coefficient` (μ_r) Is the residual frictional parameter as described in Section 104.7.3.4
- `shear_zone_thickness` h Is the shear zone thickness.
- `contact_plane_vector` Vector defining the normal to the contact/interface/joint plane.
- `surface_vector_relative_tolerance` defines the relative tolerance to find all the contact/interface/joint normals and create multiple contact elements for a given contact node pairs for a conforming surface-to-surface mesh.

IMPORTANT NOTE No. 1: `contact_plane_vector` defines a direction from Node I to Node J, that is, **from the first to the second node**. If this normal vector is reversed, the contact/interface/joint element behaves as a hook and is likely to create convergence issues.

IMPORTANT NOTE No. 2: Two nodes that form the Contact/Interface/Joint Element, need to be placed at the same physical location, coordinates in order to prevent convergence issues when nodes are separated and element tries to close the gap in the very first step.

Description of output by this element can be found in Section 206.8.8.

Modeling, Finite Element: Neoprene Isolator Finite Element

(command syntax is in development),

. . .

more on this finite element can be found in Section 102.11 on Page 109 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Lead Core Rubber Isolator/Dissipator Element

(command syntax is in development),

. . .

more on this finite element can be found in Section 102.11 on Page 109 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Frictional Pendulum Isolator/Dissipator Finite Element version01

(command syntax is in development),

. . .

more on this finite element can be found in Section 102.11 on Page 109 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Finite Element: Frictional Pendulum Isolator/Dissipator Finite Element version03

(command syntax is in development),

. . .

more on this finite element can be found in Section 102.11 on Page 109 in Lecture Notes by Jeremić et al. (1989-2025) (Lecture Notes URL).

Modeling, Damping: Adding Rayleigh Damping

First, define the Rayleigh damping.

```
add damping # <.> type Rayleigh with a0 = <1/T> a1 = <T> ↩
  stiffness_to_use = ↩
  <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
```

then apply it to element or node.

```
add damping # <.> to element # <.>;
```

```
add damping # <.> to node # <.>;
```

NOTE:

- If the simulation model is a distributed mass system (e.g. using solid brick elements with nonzero density), users should add damping to elements. In other words, if no additional mass were added to nodes, the command add damping to nodes won't have any effect in ESSI.
- If the simulation model is a lumped mass model (e.g. using the massless beam/truss with lumped mass at nodes), users should add damping to nodes.

Modeling, Damping: Adding 3rd Order Caughey Damping

First, define the 3rd-order Caughey damping

```
add damping # <.> type Caughey3rd
with a0 = <T> a1 = <1/T> a2 = <T^3> stiffness_to_use = ↩
   <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
```

then apply it to element or node.

```
add damping # <.> to element # <.>;
```

```
add damping # <.> to node # <.>;
```

NOTE:

- If the simulation model is a distributed mass system (e.g. using solid brick elements with nonzero density), users should add damping to elements. In other words, if no additional mass were added to nodes, the command add damping to nodes won't have any effect in ESSI.
- If the simulation model is a lumped mass model (e.g. using the massless beam/truss with lumped mass at nodes), users should add damping to nodes.

Modeling, Damping: Adding 4th Caughey Damping

First, define the 4th-order Caughey damping

```
add damping # <.> type Caughey4th
with a0 = <1/T> a1 = <T> a2 = <T^3> a3 = <T^5> stiffness_to_use = ↩
   <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
```

then apply it to element or node.

```
 add damping # <.> to element # <.>;
```

```
 add damping # <.> to node # <.>;
```

NOTE:

- If the simulation model is a distributed mass system (e.g. using solid brick elements with nonzero density), users should add damping to elements. In other words, if no additional mass were added to nodes, the command add damping to nodes won't have any effect in ESSI.
- If the simulation model is a lumped mass system (e.g. using the massless beam/truss with lumped mass at nodes), users should add damping to nodes.

Modeling, Constraints and Supports: Adding Constraints or Supports

```
fix node # <.> dofs [ux uy uz p Ux Uy Uz rx ry rz all];
```

where at least one of the DOF fixity codes (`ux uy uz p Ux Uy Uz rx ry rz all`) has to be invoked. These codes are

- `ux`, translation in x direction, for structures and solids (solid phase only in $u-p-U$ and $u-p$ elements)
- `uy`, translation in y direction, for structures and solids (solid phase only in $u-p-U$ and $u-p$ elements)
- `uz`, translation in z direction, for structures and solids (solid phase only in $u-p-U$ and $u-p$ elements)
- `p`, pore fluid pressure (for fluid phase in $u-p-U$ and $u-p$ elements))
- `Ux`, translation of pore fluid phase in x direction (for $u-p-U$ elements)
- `Uy`, translation of pore fluid phase in y direction (for $u-p-U$ elements)
- `Uz`, translation of pore fluid phase in z direction (for $u-p-U$ elements)
- `rx`, rotation around x axes (for structural elements)
- `ry`, rotation around y axes (for structural elements)
- `rz`, rotation around z axes (for structural elements)
- `all`, all applicable DOFs for a given node

Example fix translation x and y for node #3 `fix node # 3 dofs ux uy;`

Example fix all appropriate DOFs for node #7. `fix node # 7 dofs all;`

Modeling, Constraints and Supports: Adding Stochastic Constraints or Supports

Define fixities, boundary conditions for a stochastic node. The command would fix all the polynomial chaos expanded dofs associated with the specified physical dof.

```
fix node # <.> stochastic dofs [ux uy uz all];
```

where at least one of the DOF fixity codes (`ux uy uz all`) has to be invoked. These codes are

- `ux`, translation in x direction, including all the associated polynomial chaos expanded dofs.
- `uy`, translation in y direction, including all the associated polynomial chaos expanded dofs.
- `uz`, translation in z direction, including all the associated polynomial chaos expanded dofs.
- `all`, all applicable DOFs for a given node, including all the associated polynomial chaos expanded dofs.

For example,

```
fix node # 3 stochastic dofs ux uy;
```

Fix translation dofs ux and uy, including all the associated polynomial chaos expanded dofs, for stochastic node $\#$ 3.

Modeling, Constraints and Supports: Free Constraint or Support

Free the specified DOFs on a designated node.

```
free node # <.> dofs [ux uy ux p Ux Uy Uz rx ry rz];
```

Modeling, Constraints and Supports: Add Tied/Connected Main-Fillower Nodes for the Same DOFs

Add the equal dof for tied/connected nodes for the same degree of freedom.

```
add constraint equal_dof with
master node # <.> and
slave node # <.>
dof to constrain <.>;
```

Modeling, Constraints and Supports: Adding Tied/Connected, Main-Follower Nodes for Different DOFs

Add the equal dof for tied/connected nodes for different degree of freedom.

```
add constraint equal_dof with node # <.> dof <.> master and node # ↩
   <.> dof <.> slave;
```

Modeling, Constraints and Supports: Remove Tied/Connected Main-Follower equal DOFs

Remove the tied/connected nodes equal_dofs.

```
remove constraint equal_dof node # <.>
```

Modeling, Constraints and Supports: Adding Single Point Constraint to Nodes

Define the single point constraint to nodes on a particular degree of freedom for a specified value.

```
add single point constraint to node # <.>
dof to constrain <dof_type>
constraint value of <.>
```

Modeling, Acceleration Field: Adding Acceleration/Inertia Field

```
add acceleration field # <.>
    ax =  <acceleration in x direction>*[L/T^2]
    ay =  <acceleration in y direction>*[L/T^2]
    az =  <acceleration in z direction>*[L/T^2];
```

Example adding acceleration induced loading field for (some) elements

```
add acceleration field # 1
ax =     0*m/s^2
ay =     0*m/s^2
az = -9.81*m/s^2;
```

NOTE: see note on page 189 for command

```
add load # <.> to element # <.> type self_weight use acceleration ↩
   field # <.>;
```

Modeling, Loads: Nodal Loads

The general signature to add loads is

```
add load # <.> to node # <.>
    type <load type> <direction> = <force_amplitude>
    {more parameters};
```

The load # is a unique number assigned to each load. The node # is the number of a node which has already been defined. The load type refers to the functional form in time or pseudo-time (for static analysis) and can be any of the list

- `linear` Constant rate time dependence.
- `path` Use an arbitrary function defined in an external file.

Each force type except linear have additional parameters which will be explained later.

The force direction refers to the degree of freedom the force will be added to. These force directions are the conjugate in energy of the DOFs defined earlier. These are,

- `Fx`, force in x direction [1]
- `Fy`, force in y direction [1]
- `Fz`, force in z direction [1]
- `F_fluid_x`, force to the pore fluid phase in x direction [2]
- `F_fluid_y`, force to the pore fluid phase in y direction [2]
- `F_fluid_z`, force to the pore fluid phase in z direction [2]
- `Mx`, moment about x axes [3]
- `My`, moment about y axes [3]
- `Mz`, moment about z axes [3]

Example command for adding three linear forces $(fx = -10 * kN, fy = -10 * kN, fz = -10 * kN)$ to node # 1:

[1] Applies to solid phase only when connected to coupled elements

[1] Applies to fluid phase when connected to coupled elements. HOWEVER, please note that these are NOT pore fluid pressures, see section 102.12.1.5 on page 119, in Lecture Notes (Jeremić et al., 1989-2025) (Lecture Notes URL).

[1] For elements with rotational DOFs, i.e. beams, shells

```
add load # 1 to node #1 type linear Fx = -10*kN;
add load # 2 to node #1 type linear Fy = -10*kN;
add load # 3 to node #1 type linear Fz = -10*kN;
```

The force `type` refers to the functional dependence in time (or pseudo-time) that the force will have. The possible functional forms have been listed before. Listed are additional parameters which define these forces.

1. `linear`

   Receives no extra parameters. In this case the magnitude of the force is interpreted as the magnitude of the force after one second of time (or pseudo-time) has passed.

2. `path`

   How to add path loads is in the next page.

Modeling, Loads: Nodal Path Loads

To add forces which follow a path other than linear, we have the `path_series`, for equally spaced time series data, and `path_time_series` for variable spaced time series data.

The commands are:

```
add load # <.> to node # <.> type path_series
  FORCETYPE = <force or moment scale factor>
  time_step = <T>
  series_file = "STRING";
```

```
add load # <.> to node # <.> type path_time_series
  FORCETYPE = <force or moment scale factor>
  series_file = "STRING";
```

As before, `FORCETYPE` can be `Fx`, `Fy`, `Fz`, `Mx`, `My`, `Mz`, `F_fluidx`, `F_fluidy`, `F_fluidz`.

The format of the series_file is one column of text for the equally spaced case (`path_series`) and double column, one for time and second one for data values, for (`path_time_series`).

Modeling, Loads: Nodal Loads From Reactions

Loads can be added from reactions.

The command is:

```
add load # <.> to node # <.>  type from_reactions;
add load # <.> to all nodes type from_reactions;
```

The load # is a unique number assigned to each load. The node # is the number of a node which has already been defined. This DSL applies an external load equal to the reaction calculated at that node. It is useful, for stage loading where a constrained dof gets relaxed. The first command add load for a specified node whereas, the second command applies load for all nodes.

For example:

```
add load # 3 to node #5  type from_reactions;
```

Adds an external load to node 5 from its reaction force calculated in previous stage.

```
add load # 3 to all nodes type from_reactions;
```

Adds an external load to all nodes from their reaction force calculated in previous stage.

Modeling, Loads: Selfweight Element Load

```
add load # <.>
to element # <.>
type self_weight
use acceleration field # <.>;
```

NOTE: since the gravity acceleration field is $g = 9.81\mathrm{m/s}^2$, meaning that there is an increment of $9.81\mathrm{m/s}$ of velocity each second (please note that this defines a rate of increase in velocity), gravity is then applied in 1 second! This is sometimes (most of the time) too harsh numerically! It helps if one defines an acceleration field of say $0.0981\mathrm{m/s}^2$ and then apply it in 100 seconds. This is to be done in command `add acceleration field ...` on page 184.

Modeling, Loads: Selfweight Nodal Load

```
add load # <.> to node # <.> type self_weight use acceleration field ↩
   # <.>;
```

NOTE: For this command to take effect, there should be concentrated mass defined at the node.

Modeling, Loads: 8 Node Brick Surface Load with the Constant Pressure

Surface of 8 node brick element with same pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>) with magnitude <Pa>;
```

Note: This command works for the dry `8NodeBrick` element and the coupled `8NodeBrick_upU` element. For the coupled upU element, this command applies all surface load on the solid phase, simulating a drained surface loading condition.

A new command for undrained surface loading on upU element will be added soon...

Modeling, Loads: 8 Node Brick Surface Load with Variable Pressure

Surface of 8 node brick element with variable pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>) with magnitudes ( <Pa> ,  <Pa> ,  <Pa> ,  <Pa>);
```

Modeling, Loads: 20Node Brick Surface Load with the Constant Pressure

Surface of 20 node brick element with same pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>, <.>, <.>, <.>, <.>) with magnitude  <Pa>;
```

Modeling, Loads: 20 Node Brick, Surface Load with Variable Pressure

Surface of 20 node brick element with variable pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>, <.>, <.>, <.>, <.>) with magnitudes ( <Pa> ,  <Pa> ,  ↩
   <Pa> ,  <Pa>,  <Pa>,  <Pa>,  <Pa>,  <Pa>);
```

Modeling, Loads: 27 Node Brick Surface Load with the Constant Pressure

Surface of 27 node brick element with same pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>, <.>, <.>, <.>, <.>, <.>) with magnitude  <Pa>;
```

Modeling, Loads: 27 Node Brick Surface Load with Variable Pressure

Surface of 27 node brick element with variable pressure magnitudes at all nodes:

```
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
   <.> , <.>, <.>, <.>, <.>, <.>, <.>) with magnitudes ( <Pa> ,  <Pa> ↩
   ,  <Pa> ,  <Pa>,  <Pa>,  <Pa>,  <Pa>,  <Pa>,  <Pa>);
```

Modeling, Loads: Removing Loads

Loads can be removed using:

```
remove load # <.>
```

Modeling, Loads: Domain Reduction Method, DRM

```
add load # <.> type domain reduction method hdf5_file = <string>;
add load # <.> type domain reduction method hdf5_file = <string> ↩
   scale_factor = <.>;
```

- `hdf5_file` HDF5 file with information for the DRM specification. See section....
- `scale_factor` Factor to linearly scale the motion.

Creating DRM input in HDF5 format. As shown in Fig.(1.5), eight components are required for the DRM input.

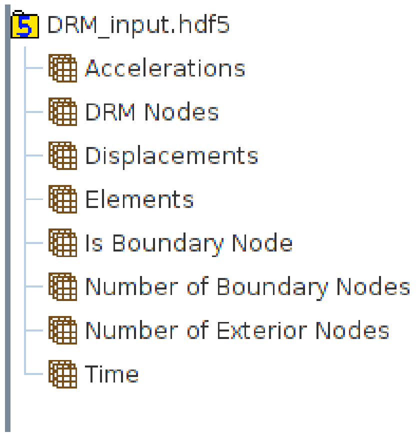


Figure 1.5: Components of DRM input in HDF5 format.

The name of the sub-folders must be exactly the same as shown here.

1. Elements: element numbers for DRM elements, a single layer of elements used to add the earthquake motion.
2. DRM Nodes: Node numbers for DRM elements.
3. Is Boundary Node: used to describe whether each of nodes in "DRM Nodes" is a boundary node or an exterior node.
   - If this value is "1", the corresponding node in "DRM Nodes" is a boundary node.
   - If this value is "0", the corresponding node in "DRM Nodes" is an exterior node in the DRM element.
4. Number of Boundary Nodes: the number of boundary nodes.

5. Number of Exterior Nodes: the number of exterior nodes.

6. Displacements: the displacement components of input earthquake motion on corresponding DRM Nodes. Displacements are a 2D array,

   - column number represents a time-step,
   - rows represents the displacement in one direction.

     If every node has 3 degrees of freedom (DOFs, say ux, uy, and uz), the first three rows represent the input displacements on first DRM node in directions of ux, uy, and uz. Then, next three rows represent the input displacements for the next node. So the total row number should be three times of the number of DRM Nodes.

7. Accelerations: same data structure as displacements, above.

8. Time: real time for each time-step in the input earthquake motion.

Python example script to generate the DRM HDF5-based input is given below. Please note that script only generates simplest possible rigid body motion, and that for any realistic motions, those will have to be created using 1C or 3C seismic motions codes, for example, SW4, SynAcc, fk, Hisada, EDT, MS ESSI, or even SHAKE for 1C motions.

```
# Created by Jose Antonio Abell Mena
# This  file  reads  old-format  DRM  input  files and translates them into new
# HDF5-based format.
#

# This    file  produces a rigid body input to the DRM layer. That is, all DRM
# nodes  have  same  X-direction displacement and acceleration. In this case a
# sine  wave  is  used.  This  is  not  realistic,  its just for demonstration
# purposes.  DRM  won't work in this case but can be used to verify input if a
# pseudo-static analysis is done (zero density on all elements and apply loads
# with transient analysis.)
# For  real  input  motions,  produced  using  some other means, say SW4, fk,
# Hisada or MS ESSI program, this simple program can be used as an example,
# where  DRM  input  file format used here can be (re) used, while those real
# motions are read form output of above mentioned programs.

```

```
import scipy as sp
import h5py
import time

# Write elements and nodes data
elements = sp.loadtxt("DRMelements.txt",dtype=sp.int32)
exterior_nodes = sp.loadtxt("DRMexterior.txt",dtype=sp.int32)
boundary_nodes = sp.loadtxt("DRMbound.txt",dtype=sp.int32)

Ne = sp.array(exterior_nodes.size)
Nb = sp.array(boundary_nodes.size)

Nt = Ne+Nb

all_nodes = sp.hstack((boundary_nodes, exterior_nodes))
is_boundary_node = sp.zeros(Nt, dtype=sp.int32)
is_boundary_node[0:Nb] = 1

h5file = h5py.File("small.h5.drminput","w")

h5file.create_dataset("Elements", data=elements)
h5file.create_dataset("DRM Nodes", data=all_nodes)

#  This  array  has  1  if the node at the corresponding position in ↩
   "DRM nodes"
#  array is a boundary node and zero if not
h5file.create_dataset("Is Boundary Node", data=is_boundary_node)

h5file.create_dataset("Number of Exterior Nodes", data=Ne)
h5file.create_dataset("Number of Boundary Nodes", data=Nb)

#  Write    timestamp    (time   format used is that of c "asctime" ↩
   Www Mmm dd
#  hh:mm:ss yyyy example: Tue Jan 13 10:17:09 2009)
localtime = time.asctime( time.localtime(time.time()) )
h5file.create_dataset("Created",data=str(localtime))

#  Generate motions
t = sp.linspace(0,10,1001)
w = 2*sp.pi/0.5
d = sp.sin(w*t)
a = -w**2*sp.sin(w*t)

#  Output accelerations, displacements and time-vector

#  Format is:
#
#  Array/matrix for Accelerations and Displacements has the following ↩
   shape
#    [3*(N_boundary_nodes + N_exterior_nodes)  ,  Ntimesteps]
#
#  where    component
#       A[3*n],     A[3*n+1],    A[3*n+2]
#   correspond   to accelerations/displacements in X, Y, and Z directions
#   at node n.
#   The location corresponding to node n is that of the n-th component ↩
   of array
#   "DRM Nodes"

#   Time vector

h5file.create_dataset("Time", data=t)

acc = h5file.create_dataset("Accelerations", (3*Nt,len(t)), ↩
   dtype=sp.double)
dis = h5file.create_dataset("Displacements", (3*Nt,len(t)), ↩
   dtype=sp.double)

for node_index in range(Nt):
 acc[3*node_index,:]   = a
 acc[3*node_index+1,:] = 0*a  #Zero acceleration in y and z
 acc[3*node_index+2,:] = 0*a
 dis[3*node_index,:]   = d
 dis[3*node_index+1,:] = 0*d  #Zero displacement in y and z
 dis[3*node_index+2,:] = 0*d

h5file.close()
```

Modeling, Wave Field for Creating DRM Loads: Add Wave Field

```
add wave field # <.> with
    acceleration_filename = <string>
    unit_of_acceleration = <L/T^2>
    displacement_filename = <string>
    unit_of_displacement = <L>
    add_compensation_time = <T>
    motion_depth = <L>
    monitoring_location = ↩
   <within_soil_layer|equivalent_rock_outcropping>
    soil_profile_filename = <string>
    unit_of_Vs = <L/T>
    unit_of_rho = <M/L^3>
    unit_of_damping = <absolute|percent>
    unit_of_thickness = <L>
    ;
```

Example adding a wave field

```
add wave field # 1 with
    acceleration_filename = "acc.txt"
    unit_of_acceleration = 1 * m/s^2
    displacement_filename = "dis.txt"
    unit_of_displacement = 1 * m
    add_compensation_time = 0.5 * s
    motion_depth = 0 * m
    monitoring_location = within_soil_layer
    soil_profile_filename = "soil_profile.txt"
    unit_of_Vs = 1 * m/s
    unit_of_rho = 1 * kg/m^3
    unit_of_damping = absolute
    unit_of_thickness = 1*m
    ;
```

where:

- `No (or #) <.>` is the unique wave field ID. The wave field ID does not have to be sequential, any unique positive integer number can be used. Each wave field is a 1C wave field. The wave field does not have a direction. Later, if users want to add load with the wave field, users should specify the direction with each wave field.
- `acceleration_filename` is the filename of a plain text file, which contains the acceleration of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding acceleration. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field does NOT conduct any base correction on the input motion, so the simulation

results may have permanent deformation after the earthquake. If users want to have base corrections, users should pre-process the earthquake motion by themselves.

- `displacement_filename` is the filename of a plain text file, which contains the displacement of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding displacement. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field does NOT conduct any base correction on the input motion, so the simulation results may have permanent deformation after the earthquake. If users want to have base corrections, users should pre-process the earthquake motion by themselves.

- `add_compensation_time` is a feature to add zero-motion in the beginning and at the end of the earthquake motion. Since the wave propagation theory is solving the wave equation in frequency domain (steady state), without additional zeros, the beginning and the end of wave may be mixed up. If the user does not want to add the additional zeros, user can specify 0*s.

- `motion_depth` is the depth of the input motion. Usually, the `motion_depth` is at the surface (namely, 0*m). Later, users can specify the request depth for deconvolution. However, users can also specify a specific depth of the input motion. In this case, users can request both convolution and deconvolution.

  – If the request depth is deeper than this input acceleration depth, the wave propagation will generate the deconvolution results.

  – If the request depth is shallower than this input acceleration depth, the wave propagation will generate the convolution results. It is recommended to add a small damping for wave convolution.

  The acceleration depth is the relative depth to the soil surface, so both negative and positive depth are acceptable and result in the same results.

- `monitoring_location` is the location of the earthquake monitoring station. When the monitoring location is within soil layer, the wave propagation is conducted inside the soil layer directly. When the monitoring location is equivalent rock outcropping, wave deconvolution is conducted back to the bedrock first and then propagate into the soil layers.

- `soil_profile_filename` contains the soil properties for each layer. The soil profile file should have four columns, which are the shear wave velocity, density, damping ratio and thickness of each layer respectively. The soil layers should be from the soil surface to the bedrock. The last layer is bedrock, which has three columns only. User should NOT give the thickness of the last layer.

  One Example of soil profile file is given below.

```
// Vs     rho     damp    thickness
200       2000    0.03    35
250       2000    0.04    35
2000      2400    0.05

```

Modeling, Wave Field for Creating DRM Loads: Deconvolution

This command performs deconvolution or convolution of given motions at surface or certain depth and writes accelerations, velocities and displacements in 3 directions, in files, that can then be used to create DRM loads.

```
generate wave propagation results of wave field
  # <.> at depth <L> to file <output_filename_prefix>
```

One example of deconvolution is

```
generate wave propagation results of wave field
  # 1 at depth -60*m to file "Northridge_record" ;
```

where

- `wave field # <.>` specifies the wave field number which will be used for wave propagation.
- `depth <L>` is the request depth of the output motion.
  - If the request depth is deeper than the input motion that defined in the wave field, this command will generate the deconvolution results.
  - If the request depth is shallower than the input motion that defined in the wave field, this command will generate the convolution results. It is recommended to add a small damping for wave convolution.

  The depth specifies the *relative* location between the soil surface and the request depth, which means both positive and negative depth are acceptable and will result in the same results.
- `output_filename_prefix` specified the prefix of the output filenames. This command will generate 3 output files, whose suffix are `at_str(depth)_acc.txt` , `at_str(depth)_vel.txt` , `at_str(depth)_dis.txt` .

Modeling, Wave Field for Creating DRM Input: Motions

This command performs deconvolution or convolution of given motions at surface or certain depth and directly generates DRM motions in 1, 2, or 3 directions.

```
generate DRM motion file from wave field
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

```
generate DRM motion file from wave field
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

```
generate DRM motion file from wave field
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

One example of deconvolution to DRM is

```
generate DRM motion file from wave field
  # 1 in direction ux
  soil_surface at z = 0*m
  hdf5_file = "input.hdf5" ;
```

where:

- `in direction <ux,uy,uz>` specifies the direction of the wave field. Each wave field is a 1C wave field. At most 3 wave fields can be associated with the load.
- `soil_surface` specifies the relation between the FEM coordinate systems and the soil profile depths inside the wave field. The soil surface should always be above the DRM nodes. Namely, soil surface is generally the surface between the soil and the structure, NOT the bedrock surface.
- `hdf5_file` specifies the HDF5 file which contain the information about the DRM elements and DRM nodes.

Modeling, Wave Field for Creating DRM Input: Forces

This command performs deconvolution or convolution of given motions at surface or certain depth and directly generates DRM motions and forces in 1, 2, or 3 directions.

```
generate DRM force file from wave field
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

```
generate DRM force file from wave field
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

```
generate DRM force file from wave field
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  # <.> in direction <ux|uy|uz>
  soil_surface at z = <L>
  hdf5_file = <string> ;
```

One example of deconvolution to DRM is

```
generate DRM force file from wave field
  # 1 in direction ux
  soil_surface at z = 0*m
  hdf5_file = "input.hdf5" ;
```

where:

- `in direction <ux,uy,uz>` specifies the direction of the wave field. Each wave field is a 1C wave field. At most 3 wave fields can be associated with the load.
- `soil_surface` specifies the relation between the FEM coordinate systems and the soil profile depths inside the wave field. The soil surface should always be above the DRM nodes. Namely, soil surface is generally the surface between the soil and the structure, NOT the bedrock surface.
- `hdf5_file` specifies the HDF5 file which contain the information about the DRM elements and DRM nodes.

Modeling, Wave Field for Creating DRM Loads: Add Inclined Plane Wave Field from Incident SV Wave Potential Magnitude

```
add wave field # <.> type inclined_plane_wave with
    anticlockwise_angle_of_SV_wave_plane_from <x|y|z> = <degrees>
    SV_incident_magnitude = <L^2>
    SV_incident_angle = <degrees>
    SV_incident_frequency = <1/T>
    motion_time_step = <T>
    number_of_time_steps = <.>
    soil_profile_filename = <string>
    soil_surface at <x|y|z> = <L>
    unit_of_vs_and_vp = <L/T>
    unit_of_rho = <M/L^3>
    unit_of_damping = <absolute|percent>
    unit_of_thickness = <L>
    ;
```

Example of adding an inclined plane wave field

```
add wave field # 1 type inclined_plane_wave with
  anticlockwise_angle_of_SV_wave_plane_from x= 30
  SV_incident_magnitude = 2*m^2
  SV_incident_angle = 60
  SV_incident_frequency = 5/s
  motion_time_step = 0.01*s
  number_of_time_steps = 600
  soil_profile_filename = "soil.txt"
  soil_surface at z = 0*m
  unit_of_vs_and_vp = 1*m/s
  unit_of_rho = 1*kg/m^3
  unit_of_damping = absolute
  unit_of_thickness = 1*m;
```

where:

- `No (or #) <.>` is the unique wave field ID/number. The wave field ID does not have to be sequential, any unique positive integer number can be used. Each wave field is an inclined plane SV wave field.
- `anticlockwise_angle_of_SV_wave_plane_from <x|y|z>` specifies the orientation of the inclined wave field propagation plane. User should give the anticlockwise angle in degrees between the wave propagation plane and the specified reference axis. The reference axis could be x or y or z. As shown in figure 1.7, the `anticlockwise_angle_of_SV_wave_plane_from` x axis is α.
- `SV_incident_magnitude` specifies the incident SV wave potential magnitude. The displacement magnitude of incident SV wave is related to the potential magnitude as follows: $|u| = \phi\omega/V_s$, where $|u|$ is the displacement magnitude, ϕ is potential magnitude, ω is incident angular frequency and V_s is the

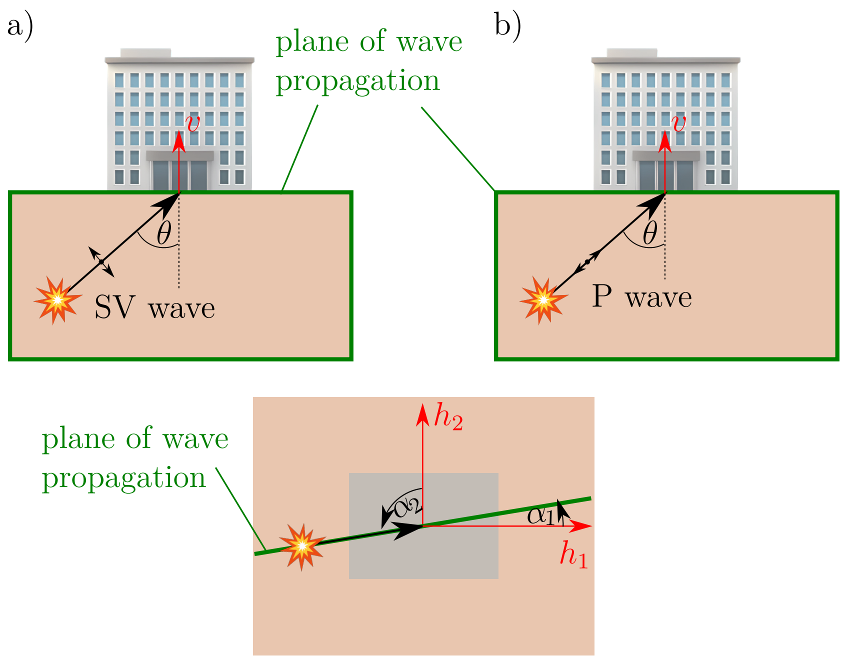


Figure 1.6: Orientation of an inclined plane wave with respect to the vertical, v, and horizontal, h_1, h_2, directions: a) a SV wave and b) a P-wave. The user defines v, h_1, h_2 directions. Either α_1 or α_2 can be input into the DSL command.

shear wave velocity of the incident soil/rock layer.

- `SV_incident_angle` specifies the inclination angle of incident SV wave, measured from vertical axis of wave plane to the wave propagation axis. In figure 1.7, the incident angle of SV wave is θ.
- `motion_time_step` is the time step/interval used for discretizing the harmonic motion into time domain.
- `number_of_time_steps` is the number of total time steps for the discretized harmonic motion.
- `soil_profile_filename` is a file name for a file that contains the soil properties for each layer. The soil profile file should have fives columns: (i) shear wave velocity, (ii) compressional wave velocity, (iii) density, (iv) damping ratio and (v) thickness of each layer respectively. The soil layers count from the soil surface to the bedrock. The last layer is bedrock, which has four columns only. User should NOT give the thickness of the last layer, as it extends into halfspace.

  One Example of soil profile file is given below.

```
  // Vs     Vp     rho      damp    thickness
     200    333    2000     0.02          100
     250    408    2000     0.02          200
    2000   3400    2400     0.02

```

- `soil_surface at <x|y|z>` defines the location of soil surface in the global coordinate system of Real-ESSI.

Modeling, Wave Field for Creating DRM Loads: Add Inclined Plane Wave Field from Incident SV Wave Time Series Signal

```
add wave field # <.> type inclined_plane_wave with
    anticlockwise_angle_of_SV_wave_plane_from <x|y|z> = <degrees>
    SV_incident_acceleration_filename = <string>
    unit_of_acceleration = <L/T^2>
    SV_incident_displacement_filename = <string>
    unit_of_displacement = <L>
    SV_incident_angle = <degrees>
    add_compensation_time = <T>
    source_location = (<T>, <T>, <T>)
    soil_profile_filename = <string>
    soil_surface at <x|y|z> = <L>
    unit_of_vs_and_vp = <L/T>
    unit_of_rho = <M/L^3>
    unit_of_damping = <absolute|percent>
    unit_of_thickness = <L>
    ;
```

Example of adding an inclined plane wave field

```
add wave field # 1 type inclined_plane_wave with
  anticlockwise_angle_of_SV_wave_plane_from x = 0
  SV_incident_acceleration_filename = "Kobe_acc.txt"
  unit_of_acceleration = 1*m/s^2
  SV_incident_displacement_filename = "Kobe_disp.txt"
  unit_of_displacement = 1*m
  SV_incident_angle = 15
  add_compensation_time = 0.5*s
  source_location = (-150*m, 0*m, -100*m)
  soil_profile_filename = "soil_profile.txt"
  soil_surface at z = 0*m
  unit_of_vs_and_vp = 1*m/s
  unit_of_rho = 1*kg/m^3
  unit_of_damping = absolute
  unit_of_thickness = 1*m;
```

where:

- `No (or #) <.>` is the unique wave field ID/number. The wave field ID does not have to be sequential, any unique positive integer number can be used. Each wave field is an inclined plane SV wave field.
- `anticlockwise_angle_of_SV_wave_plane_from <x|y|z>` specifies the orientation of the inclined wave field propagation plane. User should give the anticlockwise angle in degrees between the wave propagation plane and the specified reference axis. The reference axis could be x or y or z. As shown in figure 1.7, the `anticlockwise_angle_of_SV_wave_plane_from` x axis is α.
- `SV_incident_acceleration_filename` is the filename of a plain text file, which contains the acceler-

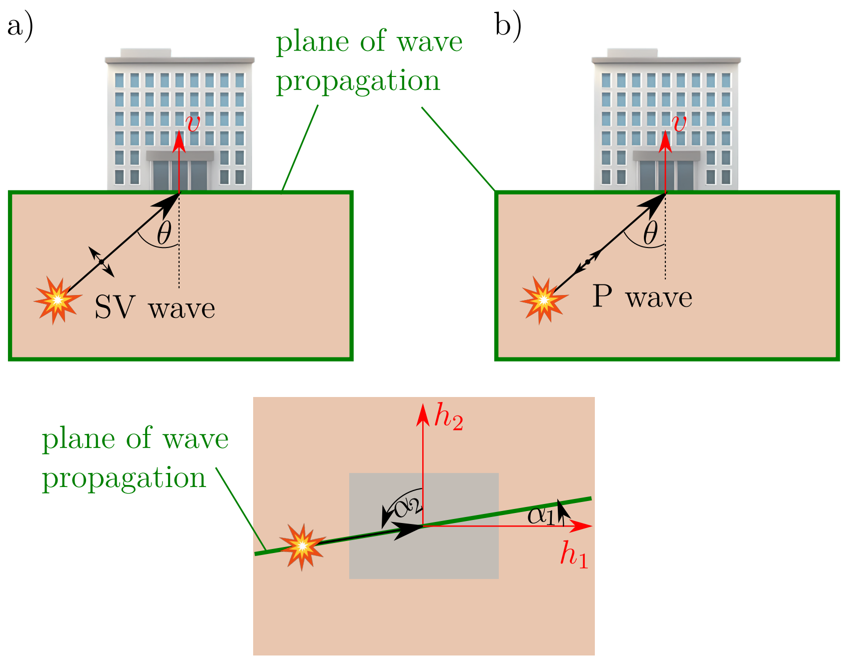


Figure 1.7: Orientation of an inclined plane wave with respect to the vertical, v, and horizontal, h_1, h_2, directions: a) a SV wave and b) a P-wave. The user defines v, h_1, h_2 directions. Either α_1 or α_2 can be input into the DSL command.

ation of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding acceleration. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field implementation in Real-ESSI does NOT conduct any baseline correction on the input motion. The users should perform baseline correction for earthquake motions by themselves.

- `SV_incident_displacement_filename` is the filename of a plain text file, which contains the displacement of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding displacement. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field implementation in Real-ESSI does NOT conduct any baseline correction on the input motion. The users should perform baseline correction for earthquake motions by themselves.

- `SV_incident_angle` specifies the inclination angle of incident SV wave, measured from vertical axis of wave plane to the wave propagation axis. In figure 1.7, the incident angle of SV wave is θ.

- `add_compensation_time` is a feature to add zero-motion in the beginning and at the end of the earthquake motion. If the user does not want to add the additional zeros, user can specify compensation time as 0*s.

- source_location specify the location of seismic source, where the seismic motion is input as in SV_incident_acceleration_filename and SV_incident_displacement_filename, it is used for determining phase of the wave, and the source location can be inside or outside of the model.

- soil_profile_filename is a file name for a file that contains the soil properties for each layer. The soil profile file should have fives columns: (i) shear wave velocity, (ii) compressional wave velocity, (iii) density, (iv) damping ratio and (v) thickness of each layer respectively. The soil layers count from the soil surface to the bedrock. The last layer is bedrock, which has four columns only. User should NOT give the thickness of the last layer, as it extends into half-space.

  One Example of soil profile file is given below.

```
 // Vs     Vp     rho      damp   thickness
    200    333    2000     0.02         100
    250    408    2000     0.02         200
   2000   3400    2400     0.02

```

- soil_surface at <x|y|z> defines the location of soil surface in the global coordinate system of Real-ESSI.

Modeling, Wave Field for Creating DRM Loads: Add Inclined Plane Wave Field from Incident P Wave Potential Magnitude

```
add wave field # <.> type inclined_plane_wave with
    anticlockwise_angle_of_P_wave_plane_from <x|y|z> = <degrees>
    P_incident_magnitude = <L^2>
    P_incident_angle = <degrees>
    P_incident_frequency = <1/T>
    motion_time_step = <T>
    number_of_time_steps = <.>
    soil_profile_filename = <string>
    soil_surface at <x|y|z> = <L>
    unit_of_vs_and_vp = <L/T>
    unit_of_rho = <M/L^3>
    unit_of_damping = <absolute|percent>
    unit_of_thickness = <L>
    ;
```

Example adding an inclined plane wave field

```
add wave field # 1 type inclined_plane_wave with
  anticlockwise_angle_of_P_wave_plane_from x= 30
  P_incident_magnitude = 2*m^2
  P_incident_angle = 60
  P_incident_frequency = 5/s
  motion_time_step = 0.01*s
  number_of_time_steps = 600
  soil_profile_filename = "soil.txt"
  soil_surface at z = 0*m
  unit_of_vs_and_vp = 1*m/s
  unit_of_rho = 1*kg/m^3
  unit_of_damping = absolute
  unit_of_thickness = 1*m;
```

where:

- `No (or #) <.>` is the unique wave field ID/number. The wave field ID does not have to be sequential, any unique positive integer number can be used. Each wave field is an inclined plane P wave field.
- `anticlockwise_angle_of_P_wave_plane_from <x|y|z>` specifies the orientation of the inclined wave propagation plane. User should give the anticlockwise angle in degrees between the wave propagation plane and the specified reference axis. The reference axis could be x or y or z. As shown in figure 1.7, the `anticlockwise_angle_of_P_wave_plane_from` x axis is α.
- `P_incident_magnitude` specifies the incident P wave potential magnitude. The displacement magnitude of incident P wave is related to the potential magnitude as following: $|u| = \phi\omega/V_p$, where $|u|$ is the displacement magnitude, ϕ is potential magnitude, ω is incident angular frequency and V_p is the

compressional wave velocity of the incident layer.

- `P_incident_angle` specifies the inclination of incident P wave. The angle is measured from vertical axis of wave plane to the wave propagation axis. In figure 1.7, the incident angle of P wave is θ.
- `motion_time_step` is the time interval when discretized the harmonic motion into time domain.
- `number_of_time_steps` is the number of total time steps for the discretized harmonic motion.
- `soil_profile_filename` is a file name for a file that contains the soil properties for each layer. The soil profile file should have fives columns: (i) shear wave velocity, (ii) compressional wave velocity, (iii) density, (iv) damping ratio and (v) thickness of each layer respectively. The soil layers count from the soil surface to the bedrock. The last layer is bedrock, which has four columns only. User should NOT give the thickness of the last layer, as it extends into halfspace.

  One Example of soil profile file is given below.

```
// Vs     Vp     rho      damp    thickness
   200    333    2000      0.02          100
   250    408    2000      0.02          200
  2000   3400    2400      0.02

```

- `soil_surface at <x|y|z>` defines the location of soil surface in the global coordinate system of Real-ESSI.

Modeling, Wave Field for Creating DRM Loads: Add Inclined Plane Wave Field from Incident P Wave Time Series Signal

```
add wave field # <.> type inclined_plane_wave with
    anticlockwise_angle_of_P_wave_plane_from <x|y|z> = <degrees>
    P_incident_acceleration_filename = <string>
    unit_of_acceleration = <L/T^2>
    P_incident_displacement_filename = <string>
    unit_of_displacement = <L>
    P_incident_angle = <degrees>
    add_compensation_time = <T>
    source_location = (<T>, <T>, <T>)
    soil_profile_filename = <string>
    soil_surface at <x|y|z> = <L>
    unit_of_vs_and_vp = <L/T>
    unit_of_rho = <M/L^3>
    unit_of_damping = <absolute|percent>
    unit_of_thickness = <L>
    ;
```

Example of adding an inclined plane wave field

```
add wave field # 1 type inclined_plane_wave with
  anticlockwise_angle_of_P_wave_plane_from x = 0
  P_incident_acceleration_filename = "Kobe_acc.txt"
  unit_of_acceleration = 1*m/s^2
  P_incident_displacement_filename = "Kobe_disp.txt"
  unit_of_displacement = 1*m
  P_incident_angle = 15
  add_compensation_time = 0.5*s
  source_location = (-150*m, 0*m, -100*m)
  soil_profile_filename = "soil_profile.txt"
  soil_surface at z = 0*m
  unit_of_vs_and_vp = 1*m/s
  unit_of_rho = 1*kg/m^3
  unit_of_damping = absolute
  unit_of_thickness = 1*m;
```

where:

- `No (or #) <.>` is the unique wave field ID/number. The wave field ID does not have to be sequential, any unique positive integer number can be used. Each wave field is an inclined plane P wave field.
- `anticlockwise_angle_of_P_wave_plane_from <x|y|z>` specifies the orientation of the inclined wave field propagation plane. User should give the anticlockwise angle in degrees between the wave propagation plane and the specified reference axis. The reference axis could be x or y or z. As shown in figure 1.7, the `anticlockwise_angle_of_P_wave_plane_from` x axis is α.
- `P_incident_acceleration_filename` is the filename of a plain text file, which contains the acceler-

ation of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding acceleration. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field implementation in Real-ESSI does NOT conduct any baseline correction on the input motion. The users should perform baseline correction for earthquake motions by themselves.

- `P_incident_displacement_filename` is the filename of a plain text file, which contains the displacement of the input motion. The file should have two columns, where the first column is the accumulated time and the second column is the corresponding displacement. For the DRM loading from a wave field, if the simulation time is longer than the earthquake motion, the remaining simulation will continue with zero motions. The wave field implementation in Real-ESSI does NOT conduct any baseline correction on the input motion. The users should perform baseline correction for earthquake motions by themselves.

- `P_incident_angle` specifies the inclination angle of incident P wave, measured from vertical axis of wave plane to the wave propagation axis. In figure 1.7, the incident angle of P wave is θ.

- `add_compensation_time` is a feature to add zero-motion in the beginning and at the end of the earthquake motion. If the user does not want to add the additional zeros, user can specify compensation time as 0*s.

- `source_location` specify the location of seismic source, where the seismic motion is input as in `P_incident_acceleration_filename` and `P_incident_displacement_filename`, it is used for determining phase of the wave, and the source location can be inside or outside of the model.

- `soil_profile_filename` is a file name for a file that contains the soil properties for each layer. The soil profile file should have fives columns: (i) shear wave velocity, (ii) compressional wave velocity, (iii) density, (iv) damping ratio and (v) thickness of each layer respectively. The soil layers count from the soil surface to the bedrock. The last layer is bedrock, which has four columns only. User should NOT give the thickness of the last layer, as it extends into half-space.

  One Example of soil profile file is given below.

```
// Vs     Vp     rho      damp    thickness
  200    333    2000      0.02          100
  250    408    2000      0.02          200
 2000   3400    2400      0.02

```

- `soil_surface at <x|y|z>` defines the location of soil surface in the global coordinate system of Real-ESSI.

Modeling, Wave Field for Creating DRM Loads: DRM Inclined Motion

This command generates inclined DRM motion with pre-defined inclined wave field.

```
generate DRM motion file from wave field # <.> hdf5_file = <string>;
```

One example of generating inclined DRM motion is:

```
generate DRM motion file from wave field # 1 hdf5_file = ↩
   "DRMinput.hdf5";
```

where

- `wave field # <.>` specifies the inclined plane wave field number which will be used for wave propagation.
- `hdf5_file` specifies the HDF5 file which contains the geometric information about the DRM elements and DRM nodes.

Modeling, Imposed Motions: through Loads, Motion Time History, Constant Time Step

Impose motions (displacements, velocities and accelerations) through loads. This one is used if time increment is constant during the analysis. Input files have one column only, corresponding file for displacements, velocities, and accelerations.

```
add load # <.> type imposed motion to node # <.> dof DOFTYPE
time_step = <T>
displacement_scale_unit = <L>
displacement_file = "filename"
velocity_scale_unit = <L/T>
velocity_file = "filename"
acceleration_scale_unit = <L/L^2>
acceleration_file = "filename";
```

The above command generates load to the corresponding node to get the applied imposed motion.

Modeling, Imposed Motions: through Loads, Stochastic Motion Time History, Constant Time Step

Impose stochastic motions (uncertain displacements, velocities and accelerations) through stochastic loads. This one is used if time increment is constant during the analysis.

```
add load # <.> type imposed random motions to node # <.> dof DOFTYPE
time_step = <T>
displacement_scale_unit = <L>
displacement_file = "filename"
velocity_scale_unit = <L/T>
velocity_file = "filename"
acceleration_scale_unit = <L/L^2>
acceleration_file = "filename"
penalty_stiffness = <N/L>
using double product # <.>;
```

where

- `DOFTYPE` specify the dof to impose the uncertain motion. It can be either `ux`, `uy` or `uz`.
- `time_step` specify the time step of the imposed uncertain motion.
- `displacement_scale_unit` specify the scale unit of the imposed uncertain displacement polynomial chaos (PC) coefficients.
- `displacement_file` specify the filename of a text file containing PC coefficients of uncertain displacement random process. The number of rows of the file content should be equal to total number of polynomial chaos basis of the displacement random process. The number of columns of the file content should be equal to total number of time steps of the displacement random process. The value at the i^{th} row and j^{th} column of the file gives the PC coefficient of the i^{th} PC basis of the displacement random process at the j^{th} time step.
- `velocity_scale_unit` specify the scale unit of the imposed uncertain velocity polynomial chaos (PC) coefficients.
- `velocity_file` specify the filename of a text file containing PC coefficients of uncertain velocity random process. The number of rows of the file content should be equal to total number of polynomial chaos basis of the velocity random process. The number of columns of the file content should be equal to total number of time steps of the velocity random process. The value at the i^{th} row and j^{th} column of the file gives the PC coefficient of the i^{th} PC basis of the velocity random process at the j^{th} time step.
- `acceleration_scale_unit` specify the scale unit of the imposed uncertain acceleration polynomial chaos (PC) coefficients.

- `acceleration_file` specify the filename of a text file containing PC coefficients of uncertain acceleration random process. The number of rows of the file content should be equal to total number of polynomial chaos basis of the acceleration random process. The number of columns of the file content should be equal to total number of time steps of the acceleration random process. The value at the i^{th} row and j^{th} column of the file gives the PC coefficient of the i^{th} PC basis of the acceleration random process at the j^{th} time step.
- `penalty_stiffness` specify the penalty stiffness for the input of uncertain motion using penalty method. The penalty stiffness is expected to be several magnitudes, e.g., $10^3 \sim 10^6$, larger than the elemental stiffness.
- `double product #` specify the ID of the double product that would be used in the formation of stochastic force. In stochastic finite element method (FEM), the first PC basis for this double product should come from the PC representation of uncertain FEM system response, e.g., uncertain structural displacement. The second PC basis for this double product should come from the uncertain imposed motion representation.

Modeling, Imposed Motions: through Loads, Stochastic Random Process Motions, Constant Time Step

Impose a defined random process motions.

This one is used if time increment is constant during the analysis.

```
add load # <.> type imposed random motions to node # <.> dof DOFTYPE
time_step = <T>
uncertain_displacement = random field # <.>
displacement_scale_unit = <L>
penalty_stiffness = <N/L>
using double product # <.>;
```

where

- DOFTYPE specify the dof to impose the uncertain motion. It can be either ux, uy or uz.
- time_step specify the time step of the imposed uncertain motion.
- uncertain_displacement specify the imposed uncertain motion through a defined random field/process.
- displacement_scale_unit specify the scale unit of the imposed uncertain displacement.
- penalty_stiffness specify the penalty stiffness for the input of uncertain motion using penalty method. The penalty stiffness is expected to be several magnitudes, e.g., $10^3 \sim 10^6$, larger than the elemental stiffness.
- double product # specify the ID of the double product that would be used in the formation of stochastic force. In stochastic finite element method (FEM), the first PC basis for this double product should come from the PC representation of uncertain FEM system response, e.g., uncertain structural displacement. The second PC basis for this double product should come from the uncertain imposed motion representation.

Modeling, Imposed Motions: through Loads, Motion Time History, Variable Time Step

Impose motions (displacements, velocities and accelerations) through loads. This one is used if time increment is variable during the analysis. Input files have two columns, first column is time and the second column in corresponding file for displacements, velocities, and accelerations. Time steps have to be the same in each file.

```
add load # <.> type imposed motion to node # <.> dof DOFTYPE
displacement_scale_unit = <displacement>
displacement_file = "filename"
velocity_scale_unit = <velocity>
velocity_file = "filename"
acceleration_scale_unit = <acceleration>
acceleration_file = "filename";
```

The above command generates load to the corresponding node to get the applied imposed motion.

Modeling, Imposed Motions: Adding Load for Uniform Acceleration Time History

Defines a non-inertial reference frame from which all displacements are measured. This reference frame (fixed to the base of the model) accelerates according to a given acceleration record. All output quantities are derived from this relative coordinate system (not-inertial). To get total displacements, the twice-integrated acceleration record must be added to the results.

The command is:

```
add load # <.> type uniform acceleration to all nodes dof <.>
  time_step = <T>
  scale_factor = <L/T^2>
  initial_velocity = <L/T>
  acceleration_file = <string>;
```

Where

- `time_step` Is the time step of the record in time units.
- `scale_factor` Is a dimensionless factor with which the record is scaled before it's applied.
- `initial_velocity` Initial velocity for all translational DOFs of the system.
- `acceleration_file` String containing the path (relative or absolute) to the record text file.

File format is a single value of the record in acceleration units (m/s/s) per line for each time step. If a time-step different from the record is used for analysis, then the record is interpolated linearly.

Modeling, Imposed Motions: Remove Imposed Motions

Motions can be removed using:

```
remove imposed motion # <.>
```

Modeling, Random Variable: Adding Gaussian Random Variables

Gaussian random variable can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Gaussian distribution mean = <.> ↩
   standard_deviation = <.>;
```

where:

- mean is the mean of the Gaussian random variable
- standard_deviation is the standard deviation of the Gaussian random variable

For example:

```
add random variable # 1 with Gaussian distribution mean = 3.0 ↩
   standard_deviation = 1.0;
```

Adds a Gaussian random variable 1 with mean equal to 3.0 and standard deviation equal to 1.0.

Modeling, Random Variable: Adding Gaussian Random Variables with Location

Gaussian random variable with spatial location can be added for probabilistic analysis. The location information of the defined random variable is important to calculate the correlation structure of random field, that can consist of many random variables.

The command is:

```
add random variable # <.> with Gaussian distribution mean = <.> ↩
   standard_deviation = <.> at (<L>, <L>, <L>);
```

where:

- `mean` is the mean of the Gaussian random variable
- `standard_deviation` is the standard deviation of the Gaussian random variable

For example:

```
add random variable # 1 with Gaussian distribution mean = 3.0 ↩
   standard_deviation = 1.0 at (3*m, 0*m, 0*m);
```

Adds a Gaussian random variable 1 with mean equal to 3.0 and standard deviation equal to 1.0 at location $x = 3$m, $y = 0$m and $z = 0$m.

Modeling, Random Variable: Adding Lognormal Random Variables

Lognormal random variable can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Lognormal distribution mean = <.> ↩
   standard_deviation = <.>;
```

where:

- `mean` is the mean of the lognormal random variable
- `standard_deviation` is the standard deviation of the lognormal random variable

For example:

```
add random variable # 1 with Lognormal distribution mean = 3.0 ↩
   standard_deviation = 1.0;
```

Adds a Lognormal random variable 1 with mean equal to 3.0 and standard deviation equal to 1.0.

Modeling, Random Variable: Adding Lognormal Random Variables with Location

Lognormal random variable with spatial location can be added for probabilistic analysis. The location information of the defined random variable is important to calculate the correlation structure of random field, that can consist of many random variables.

The command is:

```
add random variable # <.> with Lognormal distribution mean = <.> ↩
   standard_deviation = <.> at (<L>, <L>, <L>);
```

where:

- `mean` is the mean of the lognormal random variable
- `standard_deviation` is the standard deviation of the lognormal random variable

For example:

```
add random variable # 1 with Lognormal distribution mean = 3.0 ↩
   standard_deviation = 1.0 at (3*m, 0*m, 0*m);
```

Adds a Lognormal random variable 1 with mean equal to 3.0 and standard deviation equal to 1.0 at location $x = 3$m, $y = 0$m and $z = 0$m.

Modeling, Random Variable: Adding Lognormal Random Variables using Logarithmic Input

Lognormal random variable can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Lognormal distribution lognormal_mean ↩
   = <.> lognormal_standard_deviation = <.>;
```

where:

- `lognormal_mean`: μ is the mean of the natural logarithm of the lognormal random variable X
- `lognormal_standard_deviation`: σ is the standard deviation of the natural logarithm of the lognormal random variable X

In other words, for lognormal distributed random variable X with parameters μ and σ, we have:

$$ln(X) \sim N(\mu, \sigma) \tag{1.34}$$

It is noted that the mean m and variance v of lognormal random variable X is related to parameters μ and σ as follows:

$$m = e^{\mu + \sigma^2/2} \tag{1.35}$$

$$v = e^{2\mu + \sigma^2}(e^{\sigma^2} - 1) \tag{1.36}$$

For example:

```
add random variable # 1 with Lognormal distribution lognormal_mean = ↩
   3.0 lognormal_standard_deviation = 1.0;
```

adds a Lognormal random variable 1. The natural logarithm of such random variable follows Gaussian distribution with mean equal to 3.0 and standard deviation equal to 1.0.

Modeling, Random Variable: Adding Lognormal Random Variables using Logarithmic Input with Location

Lognormal random variable with spatial location can be added for probabilistic analysis. The location information of the defined random variable is important to calculate the correlation structure of random field, which can consist of many random variables.

The command is:

```
add random variable # <.> with Lognormal distribution lognormal_mean ↩
   = <.> lognormal_standard_deviation = <.> at (<L>, <L>, <L>);
```

where:

- `lognormal_mean`: μ is the mean of the natural logarithm of the lognormal random variable X
- `lognormal_standard_deviation`: σ is the standard deviation of the natural logarithm of the lognormal random variable X

In other words, for lognormal distributed random variable X with parameters μ and σ, we have:

$$ln(X) \sim N(\mu, \sigma) \tag{1.37}$$

It is noted that the mean m and variance v of lognormal random variable X is related to parameters μ and σ as follows:

$$m = e^{\mu+\sigma^2/2} \tag{1.38}$$

$$v = e^{2\mu+\sigma^2}(e^{\sigma^2} - 1) \tag{1.39}$$

For example:

```
add random variable # 1 with Lognormal distribution lognormal_mean = ↩
   3.0 lognormal_standard_deviation = 1.0 at (3*m, 0*m, 0*m);
```

Adds a Lognormal random variable 1 at location $x = 3$m, $y = 0$m and $z = 0$m. The natural logarithm of such random variable follows Gaussian distribution with mean equal to 3.0 and standard deviation equal to 1.0.

Modeling, Random Variable: Adding Gamma Random Variables using Shape and Scale Parameters

Random variable following Gamma distribution can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Gamma distribution shape_parameter = ↩
   <.> scale_parameter = <.>;
```

where:

- `shape_parameter` is the shape parameter of the Gamma random variable
- `scale_parameter` is the scale parameter of the Gamma random variable

For example:

```
add random variable # 1 with Gamma distribution shape_parameter = 5.0 ↩
   scale_parameter = 2.0;
```

Adds a Gamma random variable 1 with the shape parameter equal to 5.0 and scale parameter equal to 2.0.

Modeling, Random Variable: Adding Gamma Random Variables using Shape and Scale Parameters with Location

Random variable following Gamma distribution can be added for probabilistic analysis.

The location information of the defined random variable is important to calculate the correlation structure of random field, that can consist of many random variables.

The command is:

```
add random variable # <.> with Gamma distribution shape_parameter = ↩
   <.> scale_parameter = <.> at (<L>, <L>, <L>);
```

where:

- `shape_parameter` is the shape parameter of the Gamma random variable
- `scale_parameter` is the scale parameter of the Gamma random variable

For example:

```
add random variable # 1 with Gamma distribution shape_parameter = 5.0 ↩
   scale_parameter = 2.0 at (3*m, 0*m, 0*m);
```

Adds a Gamma random variable 1 with the shape parameter equal to 5.0 and scale parameter equal to 2.0 at location $x = 3$m, $y = 0$m and $z = 0$m.

Modeling, Random Variable: Adding Gamma Random Variables using Mean and Standard Deviation Parameters

Random variable for given mean and standard deviation parameter following Gamma distribution can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Gamma distribution mean = <.> ↩
   standard_deviation = <.>;
```

where:

- `mean` is the mean of the Gamma random variable
- `standard_deviation` is the standard deviation of the Gamma random variable

For example:

```
add random variable # 1 with Gamma distribution mean = 5.0 ↩
   standard_deviation = 2.0;
```

Adds a Gamma random variable 1 with mean equal to 5.0 and standard deviation equal to 2.0.

Modeling, Random Variable: Adding Gamma Random Variables using Mean and Standard Deviation Parameters with Location

Random variable for given mean and standard deviation parameter following Gamma distribution can be added for probabilistic analysis.

The location information of the defined random variable is important to calculate the correlation structure of random field, that can consist of many random variables.

The command is:

```
add random variable # <.> with Gamma distribution mean = <.> ↩
   standard_deviation = <.> at (<L>, <L>, <L>);
```

where:

- mean is the mean of the Gamma random variable
- standard_deviation is the standard deviation of the Gamma random variable

For example:

```
add random variable # 1 with Gamma distribution mean = 5.0 ↩
   standard_deviation = 2.0 at (3*m, 0*m, 0*m);
```

Adds a Gamma random variable 1 with mean equal to 5.0 and standard deviation equal to 2.0 at location $x = 3$m, $y = 0$m and $z = 0$m.

Modeling, Random Variable: Adding Weibull Random Variables using Shape and Scale Parameters

Random variable following Weibull distribution can be added for probabilistic analysis.

The command is:

```
add random variable # <.> with Weibull distribution shape_parameter = ↩
   <.> scale_parameter = <.>;
```

where:

- shape_parameter is the shape parameter of the Weibull random variable
- scale_parameter is the scale parameter of the Weibull random variable

For example:

```
add random variable # 1 with Weibull distribution shape_parameter = ↩
   5.0 scale_parameter = 2.0;
```

Adds a Weibull random variable 1 with the shape parameter equal to 5.0 and scale parameter equal to 2.0.

Modeling, Random Variable: Adding Weibull Random Variables using Shape and Scale Parameters with Location

Random variable following Weibull distribution can be added for probabilistic analysis.

The location information of the defined random variable is important to calculate the correlation structure of random field, which can consist of many random variables.

The command is:

```
add random variable # <.> with Weibull distribution shape_parameter = ↩
   <.> scale_parameter = <.> at (<L>, <L>, <L>);
```

where:

- shape_parameter is the shape parameter of the Weibull random variable
- scale_parameter is the scale parameter of the Weibull random variable

For example:

```
add random variable # 1 with Weibull distribution shape_parameter = ↩
   5.0 scale_parameter = 2.0 at (3*m, 0*m, 0*m);
```

adds a Weibull random variable 1 with the shape parameter equal to 5.0 and scale parameter equal to 2.0 at location $x = 3$m, $y = 0$m and $z = 0$m.

Modeling, Random Variable: Remove Random Variables

Remove random variables.

The command is:

```
remove random variable # <.> ;
```

For example:

```
remove random variable # 2;
```

Remove random variable 2 from the analysis.

Modeling, Random Variable: Hermite Polynomial Chaos Expansion

Hermite polynomial chaos expansion Xiu (2010) can be performed for random variable with any type of distribution.

The command is:

```
Hermite polynomial chaos expansion to random variable # <.> with ↩
   order <.>;
```

where:

- order specifies the order of Hermite polynomial chaos expansion

For example:

```
Hermite polynomial chaos expansion to random variable # 1 with order 6;
```

Performs Hermite polynomial chaos expansion to random variable 1 using Hermite polynomial chaos up to order 6.

Modeling, Random Variable: Output Hermite Polynomial Chaos Expansion Result

A HDF5 (.hdf5) file contains computed polynomial chaos coefficients of Hermite polynomial chaos expansion for random variable can be generated.

The command is:

```
generate Hermite polynomial chaos expansion file from random variable ↩
   # <.> hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the output hdf5 file.

The generated hdf5 file contains two datasets:

- Dataset **PC** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis. $\boldsymbol{PC_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} multidimensional Hermite PC basis.
- Dataset **PC Coefficients** is a column vector. The i^{th} component of **PC Coefficients** is the polynomial chaos coefficient corresponding to the i^{th} PC base as described by **PC**.

For example:

```
generate Hermite polynomial chaos expansion file from random variable ↩
   # 2 hdf5_file = "PC_RV1.hdf5";
```

Generate HDF5 file named "PC_RV2.hdf5" that contains the computed polynomial chaos coefficients of Hermite polynomial chaos expansion of random variable 2.

Modeling, Random Variable: Hermite Polynomial Chaos Expansion & Output Results

Hermite polynomial chaos expansion Xiu (2010) can be performed for random variable with any type of distribution. A HDF5 (.hdf5) file contains computed polynomial chaos coefficients of Hermite polynomial chaos expansion for random variable can be generated.

The command is:

```
generate Hermite polynomial chaos expansion file from random variable ↩
   # <.> with order <.> hdf5_file = "file_name";
```

where:

- `order` specifies the order of Hermite polynomial chaos expansion
- `file_name` is a string that specifies the name of the output hdf5 file.

The generated hdf5 file contains two datasets:

- Dataset **PC** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis. $\boldsymbol{PC_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} multidimensional Hermite PC basis.
- Dataset **PC Coefficients** is a column vector. The i^{th} component of **PC Coefficients** is the polynomial chaos coefficient corresponding to the i^{th} PC base as described by **PC**.

For example:

```
generate Hermite polynomial chaos expansion file from random variable ↩
   # 1 with order 6 hdf5_file = "PC_RV1.hdf5";
```

Perform Hermite polynomial chaos expansion to random variable 1 using Hermite polynomial chaos up to order 6 and generate HDF5 file named "PC_RV1.hdf5" that contains the computed polynomial chaos coefficients.

Modeling, Random Field: Adding Random Field with Dimension and Order

Random field with specific Hermite polynomial chaos dimension and order can be added for probabilistic analysis.

The command is:

```
add random field # <.> with Hermite polynomial chaos dimension <.> ↩
   order <.>;
```

where:

- `dimension` defines the dimension of Hermite polynomial chaos expansion of the random field
- `order` defines the order of Hermite polynomial chaos expansion of the random field

For example:

```
add random field # 1 with Hermite polynomial chaos dimension 4 order 3;
```

adds random field 1 with Hermite polynomial chaos expansion of dimension 4 and order 3.

Modeling, Random Field: Define Global Dimension Index of Random Field

Define the global dimension index of local Hermite polynomial chaos (PC) dimension for the uncertainty characterization of the random field.

If the global dimension index is not specified, by default Real-ESSI takes the ID of local Hermite polynomial chaos (PC) dimension as the global dimension index.

Please note that correctly specifying global dimension index for local Hermite PC dimensions of the random field is very important, especially when there are multiple random fields exist in the system and need to compute the triple products of Hermite PC basis of these random fields.

The command is:

```
define random field # <> Hermite polynomial chaos dimension # <> as ↩
    global dimension # <>;
```

where:

- `Hermite polynomial chaos dimension` defines the local dimension ID for Hermite polynomial chaos (PC) basis of the random field. It should be an integer no more than the total number of dimensions adopted in the Hermite polynomial chaos (PC) Karhunen Loève expansion of the random field.
- `global dimension` defines the corresponding global dimension index for the local Hermite PC dimension

For example:

```
define random field # 1 Hermite polynomial chaos dimension # 1 as ↩
    global dimension # 10;
```

defines the global dimension index of local Hermite PC dimension 1 of random field 1 is 10.

Modeling, Random Field: Define Global Dimension Index of Random Field from File Input

Define the global dimension index of local Hermite polynomial chaos (PC) dimension for the uncertainty characterization of the random field using inputs from a text file.

If the global dimension index is not specified, by default Real-ESSI takes the ID of local Hermite polynomial chaos (PC) dimension as the global dimension index.

Please note that correctly specifying global dimension index for local Hermite PC dimensions of the random field is very important, especially when there are multiple random fields exist in the system and need to compute the triple products of Hermite PC basis of these random fields.

The command is:

```
define random field # <.> Hermite polynomial chaos dimension from ↩
   dimension_file = "file_name";
```

where:

- dimension_file specifies the name of a text file that contains two columns: The first column is local dimension ID of Hermite PC basis; The second column is corresponding global dimension ID for the local dimension of Hermite PC basis. Comments lines starts with "//"

For example:

```
define random field # 1 Hermite polynomial chaos dimension from ↩
   dimension_file = "dimension_info_RF1.txt";
```

defines the global dimension index of local Hermite PC dimensions for random field 1 with input from a text file "dimension_info_RF1.txt".

An example file of "dimension_info_RF1.txt" is provided below:

```
//=================================================================
// This file specify the global dimension index of local dimensions
// of Hermite PC basis
// File should have two columns separated by spaces:
// The first column is local KL dimension ID
// The second column is the global KL dimension ID
//=================================================================
1 10
2 11
3 12
4 13
```

Modeling, Random Field: Set Number of Polynomial Chaos Terms of Random Field

Specify the number of polynomial chaos terms of a random field involved in the stochastic finite element analysis. By default, the full polynomial chaos basis of a random field would be used for uncertainty propagation. The specified number of polynomial chaos terms in this command is used for truncation of polynomial chaos basis.

The command is:

```
set random field # <.> polynomial_chaos_terms = <.>;
```

where:

- `polynomial_chaos_terms` defines the number of truncated Hermite polynomial chaos basis of the random field

For example:

```
set random field # 1 polynomial_chaos_terms = 100;
```

Set the number of truncated Hermite polynomial chaos basis of random field 1 to be 100.

Modeling, Random Field: Adding Random Field with Zero Correlation

Random field with uncorrelated random variables can be added for probabilistic analysis.

The command is:

```
add random field # <.> with zero correlation;
```

Modeling, Random Field: Adding Random Field with Exponential Correlation

Random field with exponential correlation can be added for probabilistic analysis.

The command is:

```
add random field # <.> with exponential correlation ↩
   correlation_length = <L> ;
```

where:

- `correlation_length` l_c defines the correlation length of random field such that the correlation $\rho(RV_i, RV_j)$ of any two random variables RV_i and RV_j is given as:

$$\rho(RV_i, RV_j) = exp(-d/l_c) \tag{1.40}$$

Variable d is the Euclidean distance between RV_i and RV_j, that is calculated from the spatial locations of random variables within the random field.

For example:

```
add random field # 1 with exponential correlation correlation_length ↩
   = 10*m;
```

adds an exponentially correlated random field number 1 with correlation length 10m.

Modeling, Random Field: Adding Random Field with Triangular Correlation

Random field with triangular correlation can be added for probabilistic analysis.

The command is:

```
add random field # <.> with triangular correlation correlation_length ↩
   = <L> ;
```

where:

- `correlation_length` l_c defines the correlation length of random field such that the correlation $\rho(RV_i, RV_j)$ of any two random variables RV_i and RV_j is given as:

$$\rho(RV_i, RV_j) = \max\{1 - \mathrm{d}/\mathrm{l_c},\, 0\} \tag{1.41}$$

Variable d is the Euclidean distance between RV_i and RV_j, that is calculated from the spatial locations of random variables within the random field.

For example:

```
add random field # 1 with triangular correlation correlation_length = ↩
   10*m;
```

Adds an triangular correlated random field number 1 with correlation length 10m.

Modeling, Random Field: Adding Random Field with Exponentially Damped Cosine Correlation

Random field with exponentially damped cosine correlation can be added for probabilistic analysis.

The command is:

```
add random field # <.> with exponentially damped cosine correlation ↩
   correlation_length = <L> ;
```

where:

- `correlation_length` l_c defines the correlation length of random field such that the correlation $\rho(RV_i, RV_j)$ of any two random variables RV_i and RV_j is given as:

$$\rho(RV_i, RV_j) = exp(-d/l_c) * cos(d/l_c) \tag{1.42}$$

Variable d is the Euclidean distance between RV_i and RV_j, that is calculated from the spatial locations of random variables within the random field.

For example:

```
add random field # 1 with exponentially damped cosine correlation ↩
   correlation_length = 10*m;
```

adds an exponentially damped cosine correlated random field number 1 with correlation length 10m.

Modeling, Random Field: Adding Random Field with Gaussian Correlation

Random field with Gaussian correlation can be added for probabilistic analysis.

The command is:

```
add random field # <.> with Gaussian correlation correlation_length = ↩
   <L> ;
```

where:

- `correlation_length` l_c defines the correlation length of random field such that the correlation $\rho(RV_i, RV_j)$ of any two random variables RV_i and RV_j is given as:

$$\rho(RV_i, RV_j) = exp(-d^2/l_c^2) \tag{1.43}$$

Variable d is the Euclidean distance between RV_i and RV_j, that is calculated from the spatial locations of random variables within the random field.

For example:

```
add random field # 1 with Gaussian correlation correlation_length = ↩
   10*m;
```

adds a random field number 1 with Gaussian correlation and correlation length 10m.

Modeling, Random Field: Remove Random Fields

Remove random Fields.

The command is:

```
remove random field # <.> ;
```

For example:

```
remove random field # 2;
```

Remove random field 2 from the analysis.

Modeling, Random Field: Adding Random Variable to Random Field

Add random variable to random field.

The command is:

```
add random variable # <.> to random field # <.>;
```

For example:

```
add random variable # 2 to random field # 1;
```

Adds random variable 2 to random field 1.

Modeling, Random Field: Remove Random Variable From Random Field

Remove random variable from random field.

The command is:

```
remove random variable # <.> from random field # <.>;
```

For example:

```
remove random variable # 2 from random field # 1;
```

Remove random variable 2 from random field 1.

Modeling, Random Field: Hermite Polynomial Chaos Karhunen Loève Expansion

Perform Hermite polynomial chaos Karhunen Loève expansion for random field of any arbitrary marginal distribution and correlation structure according to Sakamoto and Ghanem (2002).

The command is:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.>;
```

Where:

- `dimension`: specifies the number of dimensions of Hermite polynomial chaos to capture the correlation structure of the random field
- `order`: specifies the order of Hermite polynomial chaos to capture the marginal distribution of the random field

For example:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # 1 ↩
   with Hermite polynomial chaos dimension 4 order 3;
```

Perform the Hermite polynomial chaos Karhunen Loève expansion for random field 1 using Hermite polynomial chaos of dimension 4 and order 3.

Modeling, Random Field: Hermite Polynomial Chaos Karhunen Loève Expansion with Inverse Order

Perform Hermite polynomial chaos Karhunen Loève expansion for random field of any arbitrary marginal distribution and correlation structure according to Sakamoto and Ghanem (2002).

The user can explicitly state the order used in the inversion of underlying Gaussian correlation kernel.

The command is:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   correlation_kernel_inverse_order = <.>;
```

Where:

- `dimension`: specifies the number of dimensions of Hermite polynomial chaos to capture the correlation structure of the random field
- `order`: specifies the order of Hermite polynomial chaos to capture the marginal distribution of the random field
- `correlation_kernel_inverse_order`: specifies the order used in the inversion of underlying Gaussian correlation kernel. For the exact Gaussian kernel inversion, set up `correlation_kernel_inverse_order` equal to `order` of Hermite polynomial chaos. `correlation_kernel_inverse_order` should not exceed `order` of Hermite polynomial chaos. If `correlation_kernel_inverse_order` is not stated, by default linear Gaussian kernel inversion, i.e., `correlation_kernel_inverse_order` equal to 1, is performed as the approximation of higher order inversion. See Sakamoto and Ghanem (2002) for more details.

For example:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # 1 ↩
   with Hermite polynomial chaos dimension 4 order 2 ↩
   correlation_kernel_inverse_order = 2;
```

Perform the Hermite polynomial chaos Karhunen Loève expansion for random field 1 using Hermite polynomial chaos of dimension 4 and order 2. The 2^{nd} order Gaussian correlation kernel inversion is adopted.

Modeling, Random Field: Hermite Polynomial Chaos Karhunen Loève Expansion with Number of FE Elements Larger than Dimension of Hermite Polynomials

Perform Hermite polynomial chaos Karhunen Loève expansion for random field described by either Gaussian or lognormal distribution and Gaussian auto-correlation coefficient function. The PCE coefficients are computed using Eq. (11) from Sakamoto and Ghanem (2002).

This command should be used when the number of Gauss points (GPs), i.e., integration points, is much larger than the number of discrete locations needed to solve the eigenproblem of auto-covariance, that is, than the dimension of Hermite polynomials. This allows to save some computation time. In such case, the eigenproblem of auto-covariance function will be solved instead of the eigenproblem of auto-covariance matrix.

Here, "shear beam" element is used. It has only one GP, in the middle of an element. Hence the number of GPs is here equal to the number of FE elements. It is easier for a user to input the number of FE elements than to input the number of GPs.

The command is:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   correlation_kernel_inverse_order = 1 number_of_FE_elements = <.>;
```

Where:

- `dimension`: specifies the number of dimensions of Hermite polynomial chaos to capture the correlation structure of the random field, in other words, it is the number of discrete points used in the solution of the eigenproblem of auto-covariance
- `order`: specifies the order of Hermite polynomial chaos to capture the marginal distribution of the random field
- `correlation_kernel_inverse_order = 1`: does not specify anything and must be equal to 1
- `number_of_FE_elements`: here, "shear beam" element is used and it has only one GP, in the middle of an element, hence the number of FE elements is here equal to the number of GPs, the user must provide (via command `add random variable...`) the type of distribution (here, either Gaussian or lognormal), mean and standard deviation in the middle of each FE element (mean and standard deviation at discrete points used in the solution of the eigenproblem of auto-covariance function are interpolated using the values at GPs), they should be sorted for increasing coordinates in 1D

  `number_of_FE_elements = dimension` is equivalent to:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field ↩
   # <.> with Hermite polynomial chaos dimension <.> order <.> ;
```

and:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field ↩
   # <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   correlation_kernel_inverse_order = 1;
```

For example:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # 1 ↩
   with Hermite polynomial chaos dimension 4 order 2 ↩
   correlation_kernel_inverse_order = 1 number_of_FE_elements = 20;
```

Perform the Hermite polynomial chaos Karhunen Loève expansion for random field 1 using Hermite polynomial chaos of dimension 4 and order 2 with number of FE elements 20 (i.e., with 20 GPs, in the middle of elements).

Command:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   number_of_FE_elements = <.>;
```

with optional argument `number_of_FE_elements` cannot be defined because

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   correlation_kernel_inverse_order = <.>;
```

with optional argument `correlation_kernel_inverse_order` exists already.

Modeling, Random Field: Hermite Polynomial Chaos Karhunen Loève Expansion Using HDF5 Input

Add a random field with marginal distribution and correlation information defined in a given HDF5 (.hdf5) file. Perform Hermite polynomial chaos Karhunen Loève expansion for the random field.

The command is:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   hdf5_file = "file_name";
```

Where:

- `dimension`: specifies the number of dimensions of Hermite polynomial chaos to capture the correlation structure of the random field
- `order`: specifies the order of Hermite polynomial chaos to capture the marginal distribution of the random field
- `hdf5_file`: specifies the filename of the input HDF5 file that defines the marginal distribution and correlation information of the random field

The input HDF5 file should contain the following datasets:

- Dataset **Random Field** contains a single integer, which is the ID of the random field.
- Dataset **Marginal Mean** is a column vector specifying marginal mean of the random field corresponding to each random variable.
- Dataset **Marginal Variance** is a column vector specifying marginal variance of the random field for each random variable.
- Dataset **Marginal Distributions** is a column vector integers specifying the marginal distribution IDs of the random field for each random variable. Specifically, the ID is 1 for Gaussian distribution, 2 for Lognormal distribution, 3 for Gamma distribution and 4 for Weibull distribution.
- Dataset **Correlation** is a 2D array specifying correlation of the random field among random variables.
- Dataset **PC Order** contains a single integer, which specifies the order of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **PC Dimension** contains a single integer, which specifies the dimension of Hermite polynomial chaos (PC) Karhunen Loève expansion.

- Dataset **Index to Global Dimension** contains a column vector of integers, which specifies the index of corresponding global PC dimension for each local PC dimension used in the uncertainty expansion of the random field.

For example:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # 1 ↩
   with Hermite polynomial chaos dimension 4 order 4 hdf5_file = ↩
   "PC_RF1.hdf5";
```

Perform the Hermite polynomial chaos Karhunen Loève expansion for random field 1 using Hermite polynomial chaos of dimension 4 and order 4 with input marginal distribution and correlation information defined in HDF5 file "PC_RF1.hdf5".

Modeling, Random Field: Hermite Polynomial Chaos Karhunen Loève Expansion with Inverse Order Using HDF5 Input

Add a random field with marginal distribution and correlation information defined in a given HDF5 (.hdf5) file. Perform Hermite polynomial chaos Karhunen Loève expansion for the random field.

The user can explicitly state the order used in the inversion of underlying Gaussian correlation kernel.

The command is:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # ↩
   <.> with Hermite polynomial chaos dimension <.> order <.> ↩
   correlation_kernel_inverse_order = <.> hdf5_file = "file_name";
```

Where:

- `dimension`: specifies the number of dimensions of Hermite polynomial chaos to capture the correlation structure of the random field
- `order`: specifies the order of Hermite polynomial chaos to capture the marginal distribution of the random field
- `correlation_kernel_inverse_order`: specifies the order used in the inversion of underlying Gaussian correlation kernel. For the exact Gaussian kernel inversion, set up `correlation_kernel_inverse_order` equal to `order` of Hermite polynomial chaos. `correlation_kernel_inverse_order` should not exceed `order` of Hermite polynomial chaos. If `correlation_kernel_inverse_order` is not stated, by default linear Gaussian kernel inversion, i.e., `correlation_kernel_inverse_order` equal to 1, is performed as the approximation of higher order inversion. See Sakamoto and Ghanem (2002) for more details.
- `hdf5_file`: specifies the filename of the input HDF5 file that defines the marginal distribution and correlation information of the random field

The input HDF5 file should contain the following datasets:

- Dataset **Random Field** contains a single integer, which is the ID of the random field.
- Dataset **Marginal Mean** is a column vector specifying marginal mean of the random field corresponding to each random variable.
- Dataset **Marginal Variance** is a column vector specifying marginal variance of the random field for each random variable.

- Dataset **Marginal Distributions** is a column vector integers specifying the marginal distribution IDs of the random field for each random variable. Specifically, the ID is 1 for Gaussian distribution, 2 for Lognormal distribution, 3 for Gamma distribution and 4 for Weibull distribution.
- Dataset **Correlation** is a 2D array specifying correlation of the random field among random variables.
- Dataset **PC Order** contains a single integer, which specifies the order of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **PC Dimension** contains a single integer, which specifies the dimension of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **Index to Global Dimension** contains a column vector of integers, which specifies the index of corresponding global PC dimension for each local PC dimension used in the uncertainty expansion of the random field.

For example:

```
Hermite polynomial chaos Karhunen Loeve expansion to random field # 1 ↩
   with Hermite polynomial chaos dimension 4 order 4 ↩
   correlation_kernel_inverse_order = 3 hdf5_file = "PC_RF1.hdf5";
```

Perform the Hermite polynomial chaos Karhunen Loève expansion for random field 1 using Hermite polynomial chaos of dimension 4 and order 4. The 3^{rd} order Gaussian correlation kernel inversion is adopted. The input marginal distribution and correlation information are defined in HDF5 file "PC_RF1.hdf5".

Modeling, Random Field: Output Hermite Polynomial Chaos Karhunen Loève Expansion Result

A HDF5 (.hdf5) file contains all the information for Hermite polynomial chaos Karhunen Loève expansion for random field can be generated.

The command is:

```
generate Hermite polynomial chaos Karhunen Loeve expansion file from ↩
   random field # <.> hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the output hdf5 file.

The generated hdf5 file contains the following datasets:

- Dataset **Random Field** contains a single integer, which is the ID of the random field.
- Dataset **Random Variables** contains a column vector of integers, which are the IDs of the random variables that constitute the random field.
- Dataset **Marginal Mean** is a column vector specifying marginal mean of the random field corresponding to each random variable.
- Dataset **Marginal Variance** is a column vector specifying marginal variance of the random field for each random variable.
- Dataset **Marginal Distributions** is a column vector integers specifying the marginal distribution IDs of the random field for each random variable. Specifically, the ID is 1 for Gaussian distribution, 2 for Lognormal distribution, 3 for Gamma distribution and 4 for Weibull distribution.
- Dataset **Correlation** is a 2D array specifying correlation of the random field among random variables.
- Dataset **PC Order** contains a single integer, which specifies the order of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **PC Dimension** contains a single integer, which specifies the dimension of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **Index to Global Dimension** contains a column vector of integers, which specifies the index of corresponding global PC dimension for each local PC dimension used in the uncertainty expansion of the random field.

- Dataset **PC** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis. $\boldsymbol{PC_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} multidimensional Hermite PC basis.
- Dataset **PC Coefficients** is a 2D array. The j^{th} component of the i^{th} row is the polynomial chaos coefficient corresponding to the j^{th} PC base as described by **PC** for the i^{th} random variable specified in **Random Variables**.
- Dataset **PC Variance** is a column vector specifying the variances of Hermite PC basis.

For example:

```
generate Hermite polynomial chaos Karhunen Loeve expansion file from ↩
   random field # 1 hdf5_file = "PC_RF1.hdf5";
```

Generate HDF5 file named "PC_RF1.hdf5" that contains all the information for Hermite polynomial chaos Karhunen Loève expansion of random field 1.

Modeling, Random Field: Adding Random Field from Hermite Polynomial Chaos Karhunen Loève Expansion HDF5 File

Add a random field with marginal distribution, correlation information and multi-dimensional Hermite polynomial chaos (PC) coefficients specified in a given HDF5 (.hdf5) file.

The command is:

```
add random field # <.> with Hermite polynomial chaos Karhunen Loeve ↩
   expansion hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the input hdf5 file.

The input hdf5 file should contain the following datasets:

- Dataset **Random Field** contains a single integer, that represents the ID of the random field.
- Dataset **Random Variables** contains a column vector of integers, that are the IDs of the random variables that constitute the random field.
- Dataset **Marginal Mean** is a column vector specifying marginal mean of the random field corresponding to each random variable.
- Dataset **Marginal Variance** is a column vector specifying marginal variance of the random field for each random variable.
- Dataset **Marginal Distributions** is a column vector of integers specifying the marginal distribution IDs of the random field for each random variable. Specifically, the ID is 1 for Gaussian distribution, 2 for Lognormal distribution, 3 for Gamma distribution and 4 for Weibull distribution.
- Dataset **Correlation** is a 2D array specifying correlation of the random field among random variables.
- Dataset **PC Order** contains a single integer, that specifies the order of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **PC Dimension** contains a single integer, that specifies the dimension of Hermite polynomial chaos (PC) Karhunen Loève expansion.
- Dataset **Index to Global Dimension** contains a column vector of integers, that specify the index of corresponding global PC dimension for each local PC dimension used in the uncertainty expansion of the random field.

- Dataset **PC** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis. $\boldsymbol{PC_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} multidimensional Hermite PC basis.
- Dataset **PC Coefficients** is a 2D array. The j^{th} component of the i^{th} row is the polynomial chaos coefficient corresponding to the j^{th} PC base as described by **PC** for the i^{th} random variable specified in **Random Variables**.
- Dataset **PC Variance** is a column vector specifying the variances of Hermite PC basis.

For example:

```
add random field # 1 with Hermite polynomial chaos Karhunen Loeve ↩
   expansion hdf5_file = "PC_RF1.hdf5";
```

Add random field 1 with the marginal distribution, correlation structure and Hermite polynomial chaos Karhunen Loève expansion information defined in HDF5 file named "PC_RF1.hdf5".

Modeling, Random Field: Adding Random Field from Marginal Distribution and Correlation

Add a random field with specified marginal distribution and correlation information.

The command is:

```
add random field # <.> with <distribution_type> distribution
marginal_mean_file = "file_name"
marginal_standard_deviation_file = "file_name"
correlation_file = "file_name";
```

where:

- `distribution_type` is a string specifying the marginal distribution type of the random field, can be `Gaussian`, `Lognormal`, or `Gamma`.
- `marginal_mean_file` is a string specifying the name of a plain text file that contains a single column of marginal mean of the random field.
- `marginal_standard_deviation_file` is a string specifying the name of a plain text file that contains a single column of marginal standard deviation of the random field.
- `correlation_file` is a string specifying the name of a plain text file that contains a 2D array of the correlation structure of the random field.

Modeling, Random Field: Add Triple Product of Hermite Polynomial Chaos Basis

Compute and add triple product of Hermite polynomial chaos basis from three different random fields.

The command is:

```
add triple product # <.> with Hermite polynomial chaos from random ↩
   field (<.>, <.>, <.>);
```

For example:

```
add triple product # 1 with Hermite polynomial chaos from random ↩
   field (1, 2, 3);
```

Compute and add triple product #1 with Hermite polynomial chaos basis from random field 1, 2 and 3;

Modeling, Random Field: Add Double Product of Hermite Polynomial Chaos Basis

Compute and add double product of Hermite polynomial chaos basis from two different random fields.

The command is:

```
add double product # <.> with Hermite polynomial chaos from random ↩
   field (<.>, <.>);
```

For example:

```
add double product # 1 with Hermite polynomial chaos from random ↩
   field (2, 3);
```

Compute and add double product #1 with Hermite polynomial chaos basis from random field 2 and 3;

Modeling, Random Field: Generate Triple Product of Hermite Polynomial Chaos Basis

The computation of triple product of Hermite polynomial chaos basis for different random fields is a key part for stochastic finite element analysis.

A HDF5 (.hdf5) file contains triple product of Hermite polynomial chaos basis for random fields can be generated.

The command is:

```
generate triple product of Hermite polynomial chaos from random field ↩
   (<.>, <.>, <.>) hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the output HDF5 file.

The generated HDF5 file contains the following datasets:

- Dataset **PC1** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC1_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC1**.
- Dataset **PC1 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC1**.
- Dataset **PC1 Variance** is a column vector specifying the variances of basis **PC1**.
- Dataset **PC2** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC2_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC2**.
- Dataset **PC2 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC2**.
- Dataset **PC2 Variance** is a column vector specifying the variances of basis **PC2**.
- Dataset **PC3** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC3_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC3**.
- Dataset **PC3 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC3**.
- Dataset **PC3 Variance** is a column vector specifying the variances of basis **PC3**.

- Dataset **Triple Product** is a column vector containing the non-zero triple products of polynomial chaos basis from **PC1**, **PC2** and **PC3**.
- Dataset **Triple Product PC1 Index** is a column vector containing the indexes of polynomial chaos basis from **PC1** that contributes to the non-zero triple products in dataset **Triple Product**.
- Dataset **Triple Product PC2 Index** is a column vector containing the indexes of polynomial chaos basis from **PC2** that contributes to the non-zero triple products in dataset **Triple Product**.
- Dataset **Triple Product PC3 Index** is a column vector containing the indexes of polynomial chaos basis from **PC3** that contributes to the non-zero triple products in dataset **Triple Product**.

For example:

```
generate triple product of Hermite polynomial chaos from random field ↩
   (1, 2, 3) hdf5_file = "Triple_product_4(3)_4(3)_4(3).hdf5";
```

Compute the triple product of Hermite polynomial chaos basis of random field 1, 2 and 3 and write all the results into a HDF5 file named "Triple_product_4(3)_4(3)_4(3).hdf5";

Modeling, Random Field: Generate Double Product of Hermite Polynomial Chaos Basis

The computation of double product of Hermite polynoial chaos basis for different random fields is a key part for stochastic finite element analysis.

A HDF5 (.hdf5) file contains double product of Hermite polynomial chaos basis for random fields can be generated.

The command is:

```
generate double product of Hermite polynomial chaos from random field ↩
   (<.>, <.>) hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the output HDF5 file.

The generated HDF5 file contains the following datasets:

- Dataset **PC1** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC1_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC1**.
- Dataset **PC1 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC1**.
- Dataset **PC1 Variance** is a column vector specifying the variances of basis **PC1**.
- Dataset **PC2** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC2_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC2**.
- Dataset **PC2 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC2**.
- Dataset **PC2 Variance** is a column vector specifying the variances of basis **PC2**.
- Dataset **Double Product** is a column vector containing the non-zero double products of polynomial chaos basis from **PC1** and **PC2**.
- Dataset **Double Product PC1 Index** is a column vector containing the indexes of polynomial chaos basis from **PC1** that contributes to the non-zero double products in dataset **Double Product**.
- Dataset **Double Product PC2 Index** is a column vector containing the indexes of polynomial chaos basis from **PC2** that contributes to the non-zero double products in dataset **Double Product**.

For example:

```
generate double product of Hermite polynomial chaos from random field ↩
   (1, 2) hdf5_file = "doubleproduct_153(2)_150(1).hdf5";
```

Compute the triple product of Hermite polynomial chaos basis of random field 1 and 2 and write all the results into a HDF5 file named "doubleproduct_153(2)_150(1).hdf5";

Modeling, Random Field: Add Triple Product of Hermite Polynomial Chaos Basis Using HDF5 Input

Add triple product of Hermite polynomial chaos basis using HDF5 input.

The command is:

```
add triple product # <.> from hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the input HDF5 file.

The input HDF5 file should contain the following datasets:

- Dataset **PC1** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC1_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC1**.
- Dataset **PC1 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC1**.
- Dataset **PC1 Variance** is a column vector specifying the variances of basis **PC1**.
- Dataset **PC2** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC2_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC2**.
- Dataset **PC2 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC2**.
- Dataset **PC2 Variance** is a column vector specifying the variances of basis **PC2**.
- Dataset **PC3** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC3_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC3**.
- Dataset **PC3 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC3**.
- Dataset **PC3 Variance** is a column vector specifying the variances of basis **PC3**.
- Dataset **Triple Product** is a column vector containing the non-zero triple products of polynomial chaos basis from **PC1**, **PC2** and **PC3**.

- Dataset **Triple Product PC1 Index** is a column vector containing the indexes of polynomial chaos basis from **PC1** that contributes to the non-zero triple products in dataset **Triple Product**.
- Dataset **Triple Product PC2 Index** is a column vector containing the indexes of polynomial chaos basis from **PC2** that contributes to the non-zero triple products in dataset **Triple Product**.
- Dataset **Triple Product PC3 Index** is a column vector containing the indexes of polynomial chaos basis from **PC3** that contributes to the non-zero triple products in dataset **Triple Product**.

For example:

```
add triple product # 1 from hdf5_file = ↩
   "tripleproduct_3(2)_153(2)_153(2).hdf5";
```

Add triple product #1 using HDF5 input file named "tripleproduct_3(2)_153(2)_153(2).hdf5".

Modeling, Random Field: Add Double Product of Hermite Polynomial Chaos Basis Using HDF5 Input

Add double product of Hermite polynomial chaos basis using HDF5 input.

The command is:

```
add double product # <.> from hdf5_file = "file_name";
```

where:

- `file_name` is a string that specifies the name of the input HDF5 file.

The input HDF5 file should contain the following datasets:

- Dataset **PC1** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC1_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC1**.
- Dataset **PC1 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC1**.
- Dataset **PC1 Variance** is a column vector specifying the variances of basis **PC1**.
- Dataset **PC2** is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) basis of the first random field. $\boldsymbol{PC2_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} basis of **PC2**.
- Dataset **PC2 Index to Global Dimension** contains a column vector of integers, which specifies the global dimension index of each local PC dimension in basis **PC2**.
- Dataset **PC2 Variance** is a column vector specifying the variances of basis **PC2**.
- Dataset **Double Product** is a column vector containing the non-zero double products of polynomial chaos basis from **PC1** and **PC2**.
- Dataset **Double Product PC1 Index** is a column vector containing the indexes of polynomial chaos basis from **PC1** that contributes to the non-zero double products in dataset **Double Product**.
- Dataset **Double Product PC2 Index** is a column vector containing the indexes of polynomial chaos basis from **PC2** that contributes to the non-zero double products in dataset **Double Product**.

For example:

```
add double product # 1 from hdf5_file = ↩
    "doubleproduct_153(2)_150(1).hdf5";
```

Add double product #1 using HDF5 input file named "doubleproduct_153(2)_150(1).hdf5".

Modeling, Solid-Fluid Interaction: Adding Solid-Fluid Interface

For solid-fluid interaction analysis, solid fluid interface should be defined and added to the analysis domain.

The command is:

```
add solid fluid interface <string>
```

where:

- <string> specifies the name of the boundary of fluid domain that is solid fluid interface. It is noted that the boundary name should be consistent with the definition in the OpenFOAM input file at *constant/polyMesh/boundary*. More information about the organization and format of OpenFOAM input files can be found at OpenFOAM User Guide (OpenCFD Ltd, 2019).

For example:

```
add solid fluid interface "bottom_fluid_surface";
```

Adds fluid boundary named "bottom_fluid_surface" as one of the interface boundaries between solid domain and fluid domain.

Modeling, Solid-Fluid Interaction: Defining Solid-Fluid Interface, ESSI Element Nodes

For solid-fluid interaction analysis, solid fluid interface contains information about the Real-ESSI solid interface and OpenFOAM fluid interface. The Real-ESSI solid interface defines Real-ESSI interface nodes and faces.

Real-ESSI interface nodes can be defined as the following:

```
define solid fluid interface ESSI nodes <string>;
```

where:

- `<string>` specifies the plain text file name that contains the information about Real-ESSI interface nodes.

The format of such text file containing Real-ESSI interface nodes information is:

- Comment line starts with "//"
- Each line defining a Real-ESSI interface node has four entries separated by space(s):
  - 1st entry: Real-ESSI node ID;
  - 2nd entry: x coordinate of Real-ESSI interface node;
  - 3rd entry: y coordinate of Real-ESSI interface node;
  - 4th entry: z coordinate of Real-ESSI interface node;

For example:

```
define solid fluid interface ESSI nodes "ESSI_nodes_info.fei";
```

Defines Real-ESSI nodes at solid fluid interface with file named "ESSI_nodes_info.fei". An example file of "ESSI_nodes_info.fei" is provided below:

```
//======================================================
// Files contains information about ESSI nodes at solid fluid ↩
   interface, have 4 columns
// 1st column: ESSI node ID
// 2nd column: coordinate x
// 3rd column: coordinate y
// 4th column: coordinate z
//=======================================================
1 0.00 0.00 0.00
12 30.00 0.00 0.00
33 0.00 0.00 10.00
...
```

Modeling, Solid-Fluid Interaction: Defining Solid-Fluid Interface, ESSI Element Faces

For solid-fluid interaction analysis, solid fluid interface contains information about Real-ESSI solid interface and OpenFOAM fluid interface. The Real-ESSI solid interface defines Real-ESSI interface nodes and faces.

Real-ESSI interface faces are quads that can be defined as:

```
define solid fluid interface ESSI faces <string>;
```

where:

- `<string>` specifies the plain text file name that contains the information about Real-ESSI interface elements faces.

The format of such text file containing Real-ESSI interface element faces information is:

- Comment line starts with "//"
- Each line defining a Real-ESSI interface element face, i.e., a face of a brick element, in effect a quad consisting of four Real-ESSI interface nodes. Each line has six entries separated by spaces:
  - 1^{st} entry: Real-ESSI interface face ID;
  - 2^{nd} entry: Real-ESSI element ID that contains the Real-ESSI interface face;
  - 3^{rd} entry: Real-ESSI node ID for Real-ESSI interface face, i.e., a brick face, a quad, vertex 1;
  - 4^{th} entry: Real-ESSI node ID for Real-ESSI interface face, i.e., a brick face, a quad, vertex 2;
  - 5^{th} entry: Real-ESSI node ID for Real-ESSI interface face, i.e., a brick face, a quad, vertex 3;
  - 6^{th} entry: Real-ESSI node ID for Real-ESSI interface face, i.e., a brick face, a quad, vertex 4;

  It is noted that the ordering of the four vertex Real-ESSI nodes is very important. The ordering should be taken such that the face normal vector points outwards to the fluid domain following the convention of right hand rule.

For example:

```
define solid fluid interface ESSI faces "ESSI_faces_info.fei";
```

Defines Real-ESSI faces at solid fluid interface with file named "ESSI_faces_info.fei". An example file of "ESSI_faces_info.fei" is provided below:

```
//================================================
// Files contains information about ESSI faces (quads) at solid fluid ↩
   interface, have 6 columns
// 1st column: ESSI face ID
// 2nd column: ESSI Element ID that ESSI face belongs to
// 3rd column: ESSI node ID for quad vertex 1
// 4th column: ESSI node ID for quad vertex 2
// 5th column: ESSI node ID for quad vertex 3
// 6th column: ESSI node ID for quad vertex 4
//================================================
1 276 1 25 272 5
2 277 25 26 273 272
3 278 26 27 274 273
4 279 27 28 275 274
...
```

Modeling, Solid-Fluid Interaction: Defining Solid-Fluid Interface FOAM Nodes

For solid-fluid interaction analysis, solid fluid interface contains information about the Real-ESSI solid interface and OpenFOAM fluid interface. The OpenFOAM fluid interface needs to define OpenFOAM interface nodes and faces.

OpenFOAM interface nodes can be defined as the following:

```
define solid fluid interface FOAM nodes <string>;
```

where:

- `<string>` specifies the plain text file name that contains the information about OpenFOAM interface nodes.

The format of such text file containing OpenFOAM interface nodes information is:

- Comment line starts with "//"
- Each line defining a OpenFOAM interface node has four entries separated by space(s):
  - 1^{st} entry: OpenFOAM node ID;
  - 2^{nd} entry: x coordinate of OpenFOAM interface node;
  - 3^{rd} entry: y coordinate of OpenFOAM interface node;
  - 4^{th} entry: z coordinate of OpenFOAM interface node;

For example:

```
define solid fluid interface FOAM nodes "foam_nodes_info.fei";
```

Defines OpenFOAM nodes at solid fluid interface with file named "foam_nodes_info.fei". An example file of "foam_nodes_info.fei" can be:

```
//=====================================================
// Files contains information about Foam nodes at solid fluid ↩
   interface, have 4 columns
// 1st column: Foam node ID
// 2nd column: coordinate x
// 3rd column: coordinate y
// 4th column: coordinate z
//=====================================================
1 0.00 0.00 0.00
12 30.00 0.00 0.00
33 0.00 0.00 10.00
...
```

Modeling, Solid-Fluid Interaction: Defining Solid-Fluid Interface FOAM Faces

For solid-fluid interaction analysis, solid fluid interface contains information about the Real-ESSI solid interface and OpenFOAM fluid interface. The OpenFOAM fluid interface needs to define OpenFOAM interface nodes and faces.

OpenFOAM interface faces are quads that can be defined as the following:

```
define solid fluid interface FOAM faces <string>;
```

where:

- `<string>` specifies the plain text file name that contains the information about OpenFOAM interface faces.

The format of such text file containing OpenFOAM interface faces information is:

- Comment line starts with "//"
- Each line defining a OpenFOAM interface face, i.e., a quad consisting of four OpenFOAM interface nodes. Each line has five entries separated by space(s):
  - 1^{st} entry: OpenFOAM face ID;
  - 2^{nd} entry: OpenFOAM node ID for OpenFOAM interface face, i.e., a quad, vertex 1;
  - 3^{rd} entry: OpenFOAM node ID for OpenFOAM interface face, i.e., a quad, vertex 2;
  - 4^{th} entry: OpenFOAM node ID for OpenFOAM interface face, i.e., a quad, vertex 3;
  - 5^{th} entry: OpenFOAM node ID for OpenFOAM interface face, i.e., a quad, vertex 4;

  It is noted that the ordering of the four vertex OpenFOAM nodes is very important. The ordering should be consistent with the OpenFOAM faces definition in the OpenFOAM input file at *constant/polyMesh/-faces*. Detailed information about the organization and format of OpenFOAM input files can be found at OpenFOAM User Guide (OpenCFD Ltd, 2019).

For example:

```
define solid fluid interface FOAM faces "foam_faces_info.fei";
```

Defines OpenFOAM faces at solid fluid interface with file named "foam_faces_info.fei". An example file of "foam_faces_info.fei" can be:

```
//=========================================
// Files contains information about Foam faces (quads) at solid fluid ↩
    interface, have 5 columns
```

```
// 1st column: Foam face ID
// 2rd column: Foam node ID for quad vertex 1
// 3th column: Foam node ID for quad vertex 2
// 4th column: Foam node ID for quad vertex 3
// 5th column: Foam node ID for quad vertex 4
//============================================
50 8 0 4 404
51 9 8 404 405
52 10 9 405 406
53 11 10 406 407
54 12 11 407 408
55 13 12 408 409
...
```

1.3.5 Simulation

Simulation, Solvers: Sequential Solvers

```
define solver sequential <profilespd|umfpack >;
```

Available sequential solvers are:

- `ProfileSPD` is used for symmetric matrices
- `UMFPack` is used for non-symmetric matrices and indefinite matrices

NOTE: USE THE SAME SOLVER FOR EACH ANALYSIS, FOR ALL LOAD STAGES!

Use the same solver, parallel or sequential, with same solver options, for all loading stages in an analysis. System matrices, mass, damping and stiffness and packaged in a different way for different solvers, and different solver options, so changing solver type between different stages will affect access to those matrices, and will affect results...

Simulation, Solvers: Parallel Solvers

```
define solver parallel petsc <petsc_options> ;
```

NOTE: USE THE SAME SOLVER FOR EACH ANALYSIS, FOR ALL LOAD STAGES!

Use the same solver, parallel or sequential, with same solver options, for all loading stages in an analysis. System matrices, mass, damping and stiffness and packaged in a different way for different solvers, and different solver options, so changing solver type between different stages will affect access to those matrices, and will affect results...

Direct Solvers

Command Example for a direct solver:

```
define solver parallel petsc "-ksp_type preonly -pc_type lu" ;
define solver parallel petsc "-pc_type lu ↩
   -pc_factor_mat_solver_package mumps" ;
define solver parallel petsc "-pc_type lu ↩
   -pc_factor_mat_solver_package superlu" ;
```

As shown in the Command Example, "-ksp_type" represents the solver type, "-pc_type" represents the preconditioner types. By defining "preonly", petsc will use the direct solver, and its type is defined in the preconditioner types. In addition, "lu" represents LU factorization in the direct solver. The solver package "mumps" is designed for finite-element methods, and can interleave Gauss elimination process with the assembly process of global stiffness from the local element stiffness matrices. It is also noted that "mumps" can solve symmetric indefinite matrices.

The solver package "superlu" pivots the large-scale sparse matrices to numerous small-scale dense matrices for acceleration.

Iterative Solvers

Command Example for an iterative solver:

```
define solver parallel petsc "-ksp_type gmres -pc_type jacobi";
define solver parallel petsc "-ksp_type cg -pc_type ilu";
```

PETSc contains many iterative solvers and preconditioner for large-scale problems, and they are all available in with Real-ESSI.

Tables 1.1 and 1.2 on next pages present a full set of options for iterative solvers and preconditioners.

Table 1.1: Available Parallel Iterative Solvers

Solver Name	Method
"richardson"	Richardson
"chebyshev"	Chebyshev
"cg"	Conjugate Gradient
"bicg"	BiConjugate Gradient
"gmres"	Generalized Minimal Residual
"fgmres"	Flexible Generalized Minimal Residual
"dgmres"	Deflated Generalized Minimal Residual
"gcr"	Generalized Conjugate Residual
"bcgs"	BiCGSTAB
"cgs"	Conjugate Gradient Squared
"tfqmr"	Transpose-Free Quasi-Minimal Residual (1)
"tcqmr"	Transpose-Free Quasi-Minimal Residual (2)
"cr"	Conjugate Residual
"lsqr"	Least Squares Method

Table 1.2: Available Parallel Iterative Preconditioners

Preconditioner Name	Method
jacobi	Jacobi
bjacobi	Block Jacobi
sor	SOR (and SSOR)
eisenstat	SOR with Eisenstat trick
icc	Incomplete Cholesky
ilu	Incomplete LU
asm	Additive Schwarz
gasm	Generalized Additive Schwarz
gamg	Algebraic Multigrid
bddc	Balancing Domain Decomposition by Constraints
ksp	Linear solver
composite	Combination of preconditioners

For more available solver options please consult the PETSc documentation (`http://www.mcs.anl.gov/petsc/petsc-current/docs/manual.pdf`).

Simulation: Static Solution Advancement

```
simulate <.> steps using static algorithm;
```

Simulation: Dynamic Solution Advancement with the Constant Time Step

```
simulate <.> steps using transient algorithm time_step = <T>;
```

Simulation: Dynamic Solution Advancement with Variable Time Step

```
simulate <.> steps using variable transient algorithm
  time_step = <T>
  minimum_time_step = <.>
  maximum_time_step = <.>
  number_of_iterations = <.>
```

Simulation: Generalized Eigenvalue Analysis

At any given point in an analysis a generalized eigenvalue analysis of the system can be performed, based on the current mass and tangent stiffness matrices. The command to do this is:

```
simulate using eigen algorithm number_of_modes = <.>;
```

The first `number_of_modes` eigenvalues are displayed on screen after the analysis is performed. If more eigenvalues are requested than degrees-of-freedom the system has, the excess reported values are set to NaN (not a number).

Description of output for nodes of different dof types can be found in section 206.5.6.

Simulation: Displacement Control

```
define static integrator displacement_control using node # <.> dof ↩
   DOFTYPE increment <L>;
```

Simulation: Load, Control, Factor Increment

```
define load factor increment <.>;
```

Simulation: Dynamic Integrator, Newmark Method

```
define dynamic integrator Newmark  with gamma = <.> beta = <.>;
```

See also the list of the reserved keywords from Section 1.7 on page 347.

Simulation: Dynamic Integrator, Hilber Hughes Taylor, HHT, α Method

```
define dynamic integrator Hilber_Hughes_Taylor with alpha = <.>;
```

See also the list of the reserved keywords from Section 1.7 on page 347.

Simulation: Absolute Convergence Criteria

```
define convergence test
  < Absolute_Norm_Unbalanced_Force | ↩
   Absolute_Norm_Displacement_Increment >
  tolerance = <.>
  maximum_iterations =  <.>;
```

This command sets the convergence criteria for global iterative solvers. If the system-of-equation to be solved is

$$K_T \Delta U = \Delta R$$

where K_T is the current tangent stiffness operator/matrix, ΔU is the displacement increment, and ΔR is the residual. The convergence criteria is based on:

- The l^2 norm of the displacement increment: $\|\Delta U\|_2 < TOL$.
- The l^2 norm of the unbalanced force: $\|\Delta R\|_2 < TOL$.

The convergence test should be defined before the algorithms.

Simulation: Average Convergence Criteria

```
define convergence test ↩
   <Average_Norm_Unbalanced_Force|Average_Norm_Displacement_Increment>
tolerance = <.>
maximum_iterations =  <.> ;
```

This command sets the convergence criteria for global iterative solvers. If the system-of-equation to be solved is

$$K_T \Delta U = \Delta R$$

Where K_T is the current tangent stiffness operator (dynamic tangent for dynamic analysis), ΔU is the displacement increment, and ΔR is the residual. The convergence criteria can be based off

- The average l^2 norm of the displacement increment: $\|\Delta U\|_2/\sqrt{N} < TOL$.
- The average l^2 norm of the unbalanced force: $\|\Delta R\|_2/\sqrt{N} < TOL$.

where N is the number of DOFs in the system-of-equations.

The convergence test should be defined before the algorithms.

Simulation: Relative Convergence Criteria

```
define convergence test ↩
   <Relative_Norm_Unbalanced_Force|Relative_Norm_Displacement_Increment>
tolerance = <.>
minimum_absolute_tolerance = <.>
maximum_iterations =  <.> ;
```

This command sets the convergence criteria for global iterative solvers. If the system-of-equation to be solved is

$$K_T \Delta U = \Delta R$$

Where K_T is the current tangent stiffness operator (dynamic tangent for dynamic analysis), ΔU is the displacement increment, and ΔR is the residual. The convergence criteria can be based on

- The relative l^2 norm of the displacement increment: $\|\Delta U\|_2 / \|U_0\|_2 < TOL$ or $\|\Delta U\|_2 < MIN\_ABS\_TOL$.
- The relative l^2 norm of the unbalanced force: $\|\Delta R\|_2 / \|R_0\|_2 < TOL$ or $\|\Delta R\|_2 < MIN\_ABS\_TOL$.

Where,
R_0 is the external force in the beginning
U_0 is the solution after the first iteration.
Since U_0 is zero before the first iteration, the relative norm of the displacement increment in the first iteration would be equal to 1.

The convergence test should be defined before the algorithms.

Simulation: Solution Algorithms

```
define algorithm < With_no_convergence_check | linear_elastic | ↩
   Newton | Modified_Newton | Newton_With_LineSearch >;
```

```
define algorithm < Newton_With_Subincrement >
  using minimum_time_step = <.> ;
```

If the current specified load factor $\Delta\lambda$ (for static) or time step Δt (for dynamic) fails to achieve the convergence in the specified maximum number of iterations, the algorithm `Newton_With_Subincrement` will subdivide the current step into two sub steps of load increment $\Delta\lambda^{new} = \Delta\lambda/2$ (for static) or time step $\Delta t^{new} = \Delta t/2$ (for dynamic).

- `minimum_time_step` specifies the allowed minimum load factor $\Delta\lambda$ (for static) or time step Δt (for dynamic), that the algorithm should sub-divide to achieve convergence. If the subdivided step size becomes less than the `minimum_time_step`, the algorithm returns failure to convergence.

Note: If any Newton algorithm is used, the convergence test should be defined before the algorithms.

Simulation: Constitutive Integration Algorithm

Starting with version 03-NOV-2015, NDMaterial class of materials require explicit specification of the constitutive integration algorithm. This is done with the command:

```
define NDMaterial constitutive integration algorithm Forward_Euler;
```

```
define NDMaterial constitutive integration algorithm ↩
   Forward_Euler_Subincrement
  number_of_subincrements = <.> ;
```

```
define NDMaterial constitutive integration algorithm Backward_Euler
  yield_function_relative_tolerance  = <.>
  stress_relative_tolerance = <.>
  maximum_iterations = <.>;
```

```
define NDMaterial constitutive integration algorithm ↩
   Backward_Euler_Subincrement
  yield_function_relative_tolerance  = <.>
  stress_relative_tolerance = <.>
  maximum_iterations = <.>
  allowed_subincrement_strain = <.> ;
```

The command specifies the method, tolerances and maximum number of iterations used to do material point integrations. The parameters are:

- `number_of_subincrements` Specify the number of subincrements in forward Euler subincrement algorithm.
- `yield_function_relative_tolerance` Specify the relative tolerance of the yield surface value in the family of backward Euler algorithm.
- `stress_relative_tolerance` Specify the relative stress tolerance in the family of backward Euler algorithm. The stress increment is within this tolerance for each step unless the integration fails. Frobenius norm is used to calculate the stress norm.
- `maximum_iterations` Specify the maximum number of iterations in backward Euler algorithm.
- `allowed_subincrement_strain` defines the maximum value of allowed strain increment in backward Euler subincrement method. If one of strain component increments is greater than the user-defined allowed strain increment, strain increment will be divided into subincrements based on the allowed subincrement. For example, if the `strain_increment` is 0.05, and the `allowed_subincrement_strain` is 0.01. The number of subincrements will be $0.05/0.01 = 5$. A small allowed subincrement leads to more

accurate results, however, it takes more time. For the simple nonlinear materials, like von Mises linear hardening, the allowed subincrement can be as big as 5 percent. For the complicated nonlinear materials, like hyperbolic Drucker-Prager Armstrong-Frederick hardening material, the allowed subincrement should be much smaller in the range of 1E-4.

Simulation: Status Check

All simulate commands set the variable SIMULATE_EXIT_FLAG automatically upon exit. This flag can be used to check whether the simulation concluded normally (SIMULATE_EXIT_FLAG $= 0$), failed (SIMULATE_EXIT_FLAG ↩
< 0), or finished with warnings (SIMULATE_EXIT_FLAG > 0).

For example, the following simulations will fail.

```
atmospheric_pressure = 101325*Pa;

pstart = 3000*kPa;

//SAniSand 2004 calibration for Toyoura Sand.
add material # 1 type sanisand2004
    mass_density =  2100.0 * kg / m^3
    e0 =  0.735
    sanisand2004_G0 = 125.                         poisson_ratio = 0.05
    sanisand2004_Pat = atmospheric_pressure
    sanisand2004_p_cut = 0.1*atmospheric_pressure
    sanisand2004_Mc = 1.25                         sanisand2004_c = 0.712
    sanisand2004_lambda_c = 0.019                  sanisand2004_xi = 0.7
    sanisand2004_ec_ref = 0.934                    sanisand2004_m = 0.01
    sanisand2004_h0 = 7.05                         sanisand2004_ch = 0.968
    sanisand2004_nb = 1.1                          sanisand2004_A0 = 0.704
    sanisand2004_nd = 3.5                          sanisand2004_z_max = 4.
    sanisand2004_cz = 600.
    initial_confining_stress = 1*Pa  ;

simulate constitutive testing DIRECT_STRAIN
    use material # 1
    scale_factor = 1.
    series_file = "increments.txt"
    sigma0 = ( -pstart*kPa , -pstart*kPa , -pstart*kPa , 0*Pa , 0*Pa ↩
   , 0*Pa )
    verbose_output = 1;


if(SIMULATE_EXIT_FLAG == 0)
{
    print "All Good!";
}
else
{
    print "Something went wrong. Error code = ";
    print SIMULATE_EXIT_FLAG;
}

bye;
```

The above simulation fails because the integration method for the constitutive model is not set (see 1.3.5). Therefore, the second branch of the 'if' statement will execute.

Simulation: Save State

Save ESSI system state to a file, to prepare for a restart.

```
 save model;
```

This command will save the state of a model, an ESSI system, in file. Filename for the save file will be created from a model name, loading stage name, and current loading time.

For example, for a model that contains the following commands in the input file:

```
model name "ESSI_model";
. . .
new loading stage "Loading_stage_2";
. . .
simulate 100 steps using transient algorithm time_step = 0.005*s;

save model;
```

will be saved in file with the following name:

```
ESSI_model_Loading_stage_2_at_time_0.5second_RESTART.essi
```

since there were 100 steps with $\Delta t = 0.005$s, and that advances the solution to $t = 0.5$s.

Simulation: Restart Simulation

Restart simulation after stage or a step, from a saved ESSI system model file.

```
restart model using file "filename";
```

Here, ESSI system model is saved in a file `filename`, see command for saving model on page 304.

For example, to restart simulation from a saved file described above, restart will be initiated in a new input file by using the following command:

```
restart model using file ↩
   "ESSI_model_Loading_stage_2_at_time_0.5second_RESTART.essi";
```

All the results from previous loading stages will be saved in the restart file. From here on, analyst can start new loading stages, etc.

Simulation: Return Value for `simulate` Command

Simulate command, `simulate`, returns status of simulation progress. For each successful step, `simulate` returns value 0 while for a failed step it returns -1. This is useful as analyst can control solution process, and change algorithm if predefined algorithm fails to converge.

For example the example if listing 1.8, simulation part of a larger examples, will perform a change of stepping algorithm from the load control to displacement control upon failure of load control to converge.

```
step=0;
Nsteps = 100;
define load factor increment 0.01; // Start with load-control

simulation_status=simulate 1 steps using static algorithm;

while (step<(Nsteps-1))
  {
    if(simulation_status>=0) // Converged, continue using load-control
      {
        simulation_status=simulate 1 steps using static algorithm;
      }
    else // Not converged, so change to displacement-control
     {
       define static integrator displacement_control using node # 1 ↩
  dof ux increment 1E-3*m;
       simulate 1 steps using static algorithm;
     }
    step=step+1;
  }

```

Figure 1.8: Interactive simulation control using feedback (return value) from the `simulate` command.

It should be noted that the idea for interactive control of simulation process comes from FEAP (Zienkiewicz and Taylor, 1991) and later from OpenSEES (Mazzoni et al., 2002) where it was implemented with early extension of OpenSees command language with using Tcl in early 2000s.

An example of the above feedback mechanism is provided below

```
model name "vm";
add material # 1 type vonMises
    mass_density = 0.0*kg/m^3
    elastic_modulus = 2E7*N/m^2
    poisson_ratio = 0.0
    von_mises_radius = 1E5*Pa
    kinematic_hardening_rate = 0*Pa
    isotropic_hardening_rate = 0*Pa;
// define the node:
add node # 1 at (0*m,0*m,1*m)  with 3 dofs;
add node # 2 at (1*m,0*m,1*m)  with 3 dofs;
add node # 3 at (1*m,1*m,1*m)  with 3 dofs;
add node # 4 at (0*m,1*m,1*m)  with 3 dofs;
add node # 5 at (0*m,0*m,0*m)  with 3 dofs;
add node # 6 at (1*m,0*m,0*m)  with 3 dofs;
add node # 7 at (1*m,1*m,0*m)  with 3 dofs;
add node # 8 at (0*m,1*m,0*m)  with 3 dofs;
// Define the element.
add element # 1 type 8NodeBrick using 2 Gauss points each direction ↩
   with nodes (1, 2, 3, 4, 5, 6, 7, 8) use material # 1;

new loading stage "shearing";
//fix the bottom totally
fix node # 5 dofs all;
fix node # 6 dofs all;
fix node # 7 dofs all;
fix node # 8 dofs all;
// Fix the other 2 directions on the top.
fix node # 1 dofs uy uz ;
fix node # 2 dofs uy uz ;
fix node # 3 dofs uy uz ;
fix node # 4 dofs uy uz ;
add load # 101 to node # 1 type linear Fx =  40 * kN;
add load # 102 to node # 2 type linear Fx =  40 * kN;
add load # 103 to node # 3 type linear Fx =  40 * kN;
add load # 104 to node # 4 type linear Fx =  40 * kN;
define solver UMFPack;
//define algorithm With_no_convergence_check ↩
   ;Norm_Displacement_Increment;Norm_Unbalance
define convergence test Absolute_Norm_Displacement_Increment
    tolerance = 1E-3
    maximum_iterations =  5
    ;
define algorithm Newton;
define NDMaterial constitutive integration algorithm Backward_Euler
    yield_function_relative_tolerance =  1E-7
    stress_relative_tolerance =  1E-7
    maximum_iterations = 100;

// ↩
   ***********************************************************************
step=0;
```

```
Nsteps = 10;
define load factor increment 1/Nsteps; // Start with load-control
// *********************************************************
// Simulate with status check:
// *********************************************************
mystatus=simulate 1 steps using static algorithm;
while (step<(Nsteps-1)){
    step=step+1;
    if(mystatus>=0){ // Converged, so continue using load-control
        mystatus=simulate 1 steps using static algorithm;
    }
    else{ // Not converged, so change to displacement-control
        define static integrator displacement_control using node # 1 dof ux increment 1E-3*m ;
        simulate 1 steps using static algorithm;
    }
}

bye;
```

Resulting terminal output, showing a switch between two solution control mechanisms is provided below:

```



  The Finite Element Interpreter

  MS ESSI
  Earthquake Soil Structure Interaction Simulator

  Sequential processing mode.

Version Name   : Academic Version. Release date: Apr 14 2017 at 17:19:55. Tag: c24e557a56
Version Branch : yuan
Compile Date   : Apr 15 2017 at 20:28:11
Compile User   : yuan
Compile Sysinfo: cml01 4.4.0-72-generic x86_64 GNU/Linux
Runtime User   : Runtime Sysinfo: Time Now       : Apr 15 2017 at 21:15:40

Static startup tips:
 * Remember: Every command ends with a semicolon ';'.
 * Type 'quit;' or 'exit;' to finish.
 * Run 'essi -h' to see available command line options.

Including: "main.fei"


Model name is being set to "vm"
```

```




Starting new stage: shearing

changing previous_stage_name from  to shearing
Setting set_constitutive_integration_method = 2

Starting sequential static multi-step analysis
==========================================================================
Creating analysis ↩
   model.....................................................................
Checking constraint ↩
   handler...................................................................P
Checking ↩
   numberer..................................................................
Checking analysis ↩
   algorithm.................................................................
Checking system of equation ↩
   handler...........................................................Pass!
Checking static integration ↩
   handler...........................................................Pass!


 Writing Initial Conditions and   (0) - Outputting mesh.

Static Analysis: [    1/1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 1.6396e-12
                     Absolute Norm deltaU: 0.0032
                     Average  Norm deltaF: 8.1981e-13
                     Average  Norm deltaU: 0.0016
                     Relative Norm deltaF: 2.0495e-16
                     Relative Norm deltaU: 0.0032
  [iteration 2    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 4.5475e-13
                     Absolute Norm deltaU: 5.2683e-19
                     Average  Norm deltaF: 2.2737e-13
                     Average  Norm deltaU: 2.6341e-19
                     Relative Norm deltaF: 5.6843e-17
                     Relative Norm deltaU: 1.6463e-16

> Analysis End ↩
   --------------------------------------------------------------------------

Starting sequential static multi-step analysis
==========================================================================
Creating analysis ↩
   model.....................................................................
Checking constraint ↩
```

```
   handler.........................................................P
Checking ↩
   numberer.........................................................
Checking analysis ↩
   algorithm........................................................
Checking system of equation ↩
   handler...........................................................Pass!
Checking static integration ↩
   handler...........................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 2.7285e-12
                     Absolute Norm deltaU: 0.0032
                     Average  Norm deltaF: 1.3642e-12
                     Average  Norm deltaU: 0.0016
                     Relative Norm deltaF: 3.4106e-16
                     Relative Norm deltaU: 0.0032
  [iteration 2    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3.5225e-12
                     Absolute Norm deltaU: 7.8429e-19
                     Average  Norm deltaF: 1.7612e-12
                     Average  Norm deltaU: 3.9214e-19
                     Relative Norm deltaF: 4.4031e-16
                     Relative Norm deltaU: 2.4509e-16

> Analysis End ↩
   ------------------------------------------------------------------------

Starting sequential static multi-step analysis
==========================================================================
Creating analysis ↩
   model............................................................
Checking constraint ↩
   handler.........................................................P
Checking ↩
   numberer.........................................................
Checking analysis ↩
   algorithm........................................................
Checking system of equation ↩
   handler...........................................................Pass!
Checking static integration ↩
   handler...........................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 1.819e-12
                     Absolute Norm deltaU: 0.0032
                     Average  Norm deltaF: 9.0949e-13
                     Average  Norm deltaU: 0.0016
                     Relative Norm deltaF: 2.2737e-16
                     Relative Norm deltaU: 0.0032
  [iteration 2    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 2.5724e-12
                     Absolute Norm deltaU: 5.0807e-19
                     Average  Norm deltaF: 1.2862e-12
                     Average  Norm deltaU: 2.5403e-19
                     Relative Norm deltaF: 3.2155e-16
                     Relative Norm deltaU: 1.5877e-16

> Analysis End ↩
   -------------------------------------------------------------------------

Starting sequential static multi-step analysis
==========================================================================
Creating analysis ↩
   model.......................................................................
Checking constraint ↩
   handler....................................................................P
Checking ↩
   numberer....................................................................
Checking analysis ↩
   algorithm...................................................................
Checking system of equation ↩
   handler.......................................................Pass!
Checking static integration ↩
   handler.......................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.0032
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0016
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.0032
  [iteration 2    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.001253
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0006265
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.39156
  [iteration 3    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.001253
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0006265
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.39156
  [iteration 4    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.001253
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0006265
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.39156
  [iteration 5    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.001253
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0006265
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.39156
  [iteration     5/5    ]  Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)     !!!FAILED TO CONVERGE!!! ↩
   [EXITING..]
                     Absolute Norm deltaF: 3132.5
                     Absolute Norm deltaU: 0.001253
                     Average  Norm deltaF: 1566.2
                     Average  Norm deltaU: 0.0006265
                     Relative Norm deltaF: 0.39156
                     Relative Norm deltaU: 0.39156
NewtonRaphson::solveCurrentStep() -the ConvergenceTest object failed ↩
   in test()

Static Analysis: [1    /1    ] The Algorithm failed at load factor 0.4
> Analysis End ↩
   ------------------------------------------------------------------------

Starting sequential static multistep analysis
===========================================================================
Creating analysis ↩
   model.......................................................................
Checking constraint ↩
   handler.....................................................................P
Checking ↩
   numberer....................................................................
Checking analysis ↩
   algorithm...................................................................
Checking system of equation ↩
   handler.........................................................Pass!
Checking static integration ↩
   handler.........................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
```

```
   Displacement Increment::(tol: 0.001)
                      Absolute Norm deltaF: 9310.6
                      Absolute Norm deltaU: 2.6478e-19
                      Average  Norm deltaF: 4655.3
                      Average  Norm deltaU: 1.3239e-19
                      Relative Norm deltaF: 0.42857
                      Relative Norm deltaU: 2.6478e-19

> Analysis End ↩
   ----------------------------------------------------------------------------------

Starting sequential static multistep analysis
=================================================================================================
Creating analysis ↩
   model.....................................................................................
Checking constraint ↩
   handler.................................................................................P
Checking ↩
   numberer..................................................................................
Checking analysis ↩
   algorithm.................................................................................
Checking system of equation ↩
   handler.......................................................................Pass!
Checking static integration ↩
   handler.......................................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                      Absolute Norm deltaF: 1437.5
                      Absolute Norm deltaU: 1.0012e-18
                      Average  Norm deltaF: 718.76
                      Average  Norm deltaU: 5.006e-19
                      Relative Norm deltaF: 0.10425
                      Relative Norm deltaU: 1.0012e-18

> Analysis End ↩
   ----------------------------------------------------------------------------------

Starting sequential static multistep analysis
=================================================================================================
Creating analysis ↩
   model.....................................................................................
Checking constraint ↩
   handler.................................................................................P
Checking ↩
   numberer..................................................................................
Checking analysis ↩
   algorithm.................................................................................
Checking system of equation ↩
   handler.......................................................................Pass!
Checking static integration ↩
```

```
   handler.............................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 112.08
                     Absolute Norm deltaU: 5.1789e-19
                     Average  Norm deltaF: 56.038
                     Average  Norm deltaU: 2.5895e-19
                     Relative Norm deltaF: 0.017652
                     Relative Norm deltaU: 5.1789e-19

> Analysis End ↩
   -------------------------------------------------------------------------

Starting sequential static multistep analysis
===========================================================================
Creating analysis ↩
   model.......................................................................
Checking constraint ↩
   handler.....................................................................P
Checking ↩
   numberer....................................................................
Checking analysis ↩
   algorithm...................................................................
Checking system of equation ↩
   handler.............................................................Pass!
Checking static integration ↩
   handler.............................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 7.142
                     Absolute Norm deltaU: 8.6792e-19
                     Average  Norm deltaF: 3.571
                     Average  Norm deltaU: 4.3396e-19
                     Relative Norm deltaF: 0.001399
                     Relative Norm deltaU: 8.6792e-19

> Analysis End ↩
   -------------------------------------------------------------------------

Starting sequential static multistep analysis
===========================================================================
Creating analysis ↩
   model.......................................................................
Checking constraint ↩
   handler.....................................................................P
Checking ↩
   numberer....................................................................
Checking analysis ↩
```

```
   algorithm.......................................................................
Checking system of equation ↩
   handler............................................................Pass!
Checking static integration ↩
   handler............................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 0.44693
                     Absolute Norm deltaU: 1.0155e-18
                     Average  Norm deltaF: 0.22347
                     Average  Norm deltaU: 5.0774e-19
                     Relative Norm deltaF: 8.9267e-05
                     Relative Norm deltaU: 1.0155e-18

> Analysis End ↩
   --------------------------------------------------------------------------------

Starting sequential static multistep analysis
==================================================================================
Creating analysis ↩
   model...........................................................................
Checking constraint ↩
   handler.....................................................................P
Checking ↩
   numberer........................................................................
Checking analysis ↩
   algorithm.......................................................................
Checking system of equation ↩
   handler............................................................Pass!
Checking static integration ↩
   handler............................................................Pass!

Static Analysis: [1    /1    ]
  [iteration 1    /5    ] Convergence Test: Absolute Norm ↩
   Displacement Increment::(tol: 0.001)
                     Absolute Norm deltaF: 0.027935
                     Absolute Norm deltaU: 2.1658e-19
                     Average  Norm deltaF: 0.013968
                     Average  Norm deltaU: 1.0829e-19
                     Relative Norm deltaF: 5.5866e-06
                     Relative Norm deltaU: 2.1658e-19

> Analysis End ↩
   --------------------------------------------------------------------------------
How polite! Bye, have a nice day!
```

Simulation: New Elastic Loading Case

For design applications, linear elastic analysis cases are performed and later combined, using factors of safety (see section 1.3.5 on page 317) to obtain sectional forces for design.

The command for elastic analysis is:

```
new elastic loading case <string> ;
```

One example is

```
new elastic loading case "case1" ;
```

In a new elastic loading case, all previous loads, load patterns are removed.

To guarantee a fresh start, all commit-displacement at nodes are reset to 0, and all commit-stress/strain at Gauss points are reset to 0.

The following components are kept unchanged in a new elastic loading case:

- material properties.
- mesh connectivity
- boundary conditions.
- acceleration fields.
- damping.

If users want to modify the mesh, a new model is suggested instead of a new elastic loading case.

Simulation: Combine Elastic Load Cases

For design applications, elastic load cases, that have been analyzed beforehand, can be superimposed, combined using factors of safety, to obtain internal forces that used for design.

The command for this is

```
combine elastic load cases
  hdf5_filenames_list = <string>
  load_factors_list = <string>
  output_filename = <string>
  ;
```

One example is

```
combine elastic load cases
  hdf5_filenames_list = "test_case1.h5.feioutput ↩
   test_case2.h5.feioutput"
  load_factors_list = "1.2 1.5"
  output_filename = "combine.h5.feioutput"
  ;
```

- `hdf5_filenames_list` specifies the list of HDF5 output filenames. The list should be separated by either space or comma.
- `load_factors_list` specifies the list of scale factors for each loading case. The list should be separated by either space or comma.
- `output_filename` specifies one output filename of the combined loading cases.

The number of specified files in `hdf5_filenames_list` should be equal to the number of scale factors (factors of safety) in `load_factors_list`.

Simulation, Dynamic Solution Advancement for Solid-Fluid Interaction

Dynamic analysis of solid-fluid interaction can be performed using:

```
simulate <.> steps using solid fluid interaction transient algorithm ↩
   time_step = <T>;
```

where:

- <.> is an integer specifying total number of time steps in transient solid fluid interaction analysis.
- time_step = <T> defines the time step for solid fluid interaction transient analysis.

For example:

```
simulate 300 steps using solid fluid interaction transient algorithm ↩
   time_step = 0.01*s;
```

Performs transient solid fluid interaction analysis for 300 steps with time step 0.01 s.

Simulation, Dynamic Solution Advancement for Stochastic Finite Element Method

Dynamic analysis of stochastic finite element modeling can be performed using:

```
simulate <.> steps using stochastic transient algorithm time_step = <T>;
```

where:

- `<.>` is an integer specifying total number of time steps in transient stochastic finite element analysis.
- `time_step = <T>` defines the time step for stochastic finite element transient analysis.

Please note that the stochastic transient algorithm is different from the general transient algorithm in section 1.3.5 in the formulation of unbalanced load for each time step. The stochastic transient algorithm uses directly the incremental external loads to compute the incremental displacements, while the general transient algorithm accounts for the correction from resisting forces in the formulation of unbalanced forces.

For deterministic and probabilistic, linear elastic problems, both transient algorithms would produce the same response. Stochastic transient algorithm is more efficient because there is no need to compute resisting forces.

For deterministic, nonlinear inelastic problems, the general transient algorithm is more accurate due to the corrections from resisting forces. The accuracy of stochastic transient algorithm can be improved using smaller loading increments. For probabilistic, nonlinear inelastic problems, the accuracy of the general transient algorithm can only be guaranteed if the number of polynomial chaos terms used in probabilistic constitutive modeling is equal or close enough to the number of polynomial chaos terms in global level. Otherwise, it is recommended to use the stochastic transient algorithm for dynamic analysis of stochastic finite element modeling.

For example:

```
simulate 300 steps using stochastic transient algorithm time_step = ↩
   0.01*s;
```

Performs transient stochastic finite element analysis for 300 steps with time step 0.01s.

Simulation, Sobol Sensitivity Analysis

Sobol sensitivity analysis can be performed using:

```
Sobol sensitivity analysis of node # <.> dof DOFTYPE peak response ↩
   from random field # <.>
pc_coefficient_hdf5 = "pc_coefficient_hdf5_file_name"
output_hdf5 = "output_hdf5_file_name";
```

where:

- `node #` specify the node tag.
- `DOFTYPE` specify the dof to perform sensitivity analysis. It can be either `ux`, `uy` or `uz`.
- `random field #` specify the random field polynomial chaos bases of the stochastic nodal response.
- `pc_coefficient_hdf5` specify the name of a hdf5 file that contains simulation results of polynomial chaos coefficients.
- `output_hdf5` specify the name of the output hdf5 file for sensitivity analysis.

The output hdf5 format for sensitivity analysis is given as below:

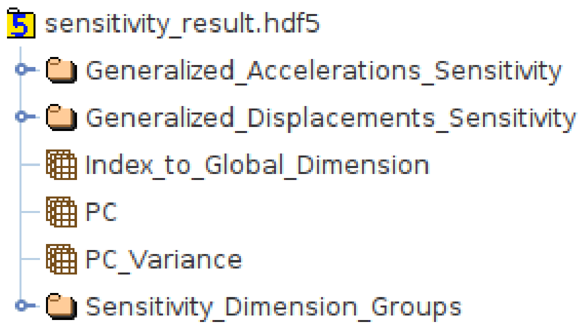

sensitivity_result.hdf5
Generalized_Accelerations_Sensitivity
Generalized_Displacements_Sensitivity
Index_to_Global_Dimension
PC
PC_Variance
Sensitivity_Dimension_Groups

Figure 1.9: Overall data structure of output hdf5 file for sensitivity analysis.

Figure 1.9 shows the overall data structure organization of the output hdf5 file of sensitivity analysis.

- **Generalized_Accelerations_Sensitivity** data group:

  Contains Sobol sensitivity analysis results for stochastic nodal acceleration response. It contains the following datasets and data groups as shown in Figure 1.10.

  - **Component_Sobol_Indexes** dataset:

    Is a column vector containing the computed Sobol Indexes for each component of polynomial chaos (PC) bases.

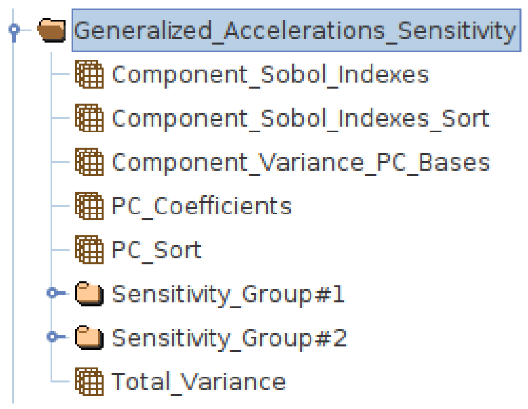

Generalized_Accelerations_Sensitivity
Component_Sobol_Indexes
Component_Sobol_Indexes_Sort
Component_Variance_PC_Bases
PC_Coefficients
PC_Sort
Sensitivity_Group#1
Sensitivity_Group#2
Total_Variance

Figure 1.10: Datasets and data groups in **Generalized_Accelerations_Sensitivity** data group.

– **Component_Sobol_Indexes_Sort** dataset:

Is a column vector containing the computed Sobol Indexes for each component of polynomial chaos (PC) bases, in descending order.

– **Component_Variance_PC_Bases** dataset:

Is a column vector containing the computed variance for each component of polynomial chaos (PC) bases.

– **PC_Coefficients** dataset:

Is a column vector containing the polynomial chaos coefficients corresponding to PC bases specified in **PC** dataset.

– **PC_Sort** dataset:

Is a 2D array that describes the sorted PC bases corresponding to **Component_Sobol_Indexes_Sort** dataset. **PC_Sort**$_{ij}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} sorted, PC basis.

– **Total_Variance** dataset:

Is a scalar, variance of nodal stochastic response.

In addition to the above datasets, there will be sub data group(s) containing sensitivity analysis results corresponding to each of the defined sensitivity dimension groups. For example, we have two sub data groups **Sensitivity_Group#1** and **Sensitivity_Group#2** for this specific hdf5 output for sensitivity analysis. Within these sub data groups, taking **Sensitivity_Group#1** as an example, the output data is organized as shown in Figure 1.11.

It includes the following datasets:

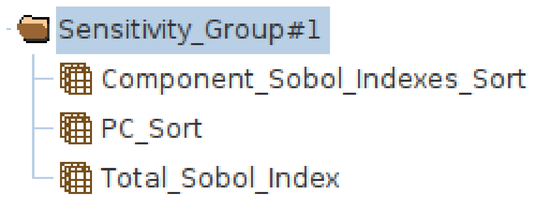


Figure 1.11: Datasets in **Sensitivity_Group#1**.

* **Component_Sobol_Indexes_Sort** dataset:

  Is a column vector containing the computed Sobol Indexes for part of polynomial chaos (PC) bases specified through the sensitivity dimension group, in descending order.

* **PC_Sort** dataset:

  Is a 2D array that describes the sorted, part of PC bases specified through the sensitivity dimension group, corresponding to **Component_Sobol_Indexes_Sort** dataset. **PC_Sort**$_{\boldsymbol{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} sorted, PC basis.

* **Total_Sobol_Index** dataset:

  Is a scalar, total Sobol sensitivity index for PC bases specified in the sensitivity dimension group.

- **Generalized_Displacements_Sensitivity** data group:

  Contains Sobol sensitivity analysis results for stochastic nodal displacement response. The configuration of data structure for **Generalized_Displacements_Sensitivity** data group is the same as **Generalized_Accelerations_Sensitivity** data group.

- **Index_to_Global_Dimension** dataset:

  Contains a column vector of integers, which specifies the global dimension IDs for the polynomial chaos bases used to represent the nodal stochastic response.

- **PC** dataset:

  Is a 2D array that describes the multi-dimensional Hermite polynomial chaos (PC) bases for representing the nodal stochastic response. $\boldsymbol{PC_{ij}}$ denotes the order of polynomial chaos dimension ξ_j that contributes to the i^{th} multidimensional Hermite PC basis.

- **PC_Variance** dataset:

  Is a column vector specifying the variances of Hermite PC basis.

- **Sensitivity_Dimension_Groups** data group:

  Contains the information about the sensitivity dimension groups defined for sensitivity analysis. Each sensitivity dimension group would be defined by a dataset within the data group as shown in Figure 1.12. Each dataset contains a column vector of integers, specifying the dimension IDs in specific sensitivity dimension group.

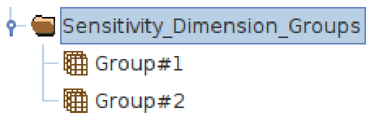


Figure 1.12: Datasets in **Sensitivity_Dimension_Groups** data group.

Simulation: 3D 3C Wave Field Inversion

```
generate domain reduction method motion file from ↩
   3D_3C_wave_field_inversion
    target_nodes_filename = <string>
    target_motions_filename = <string>
    time_step = <T>
    hdf5_file = <string>;
```

Example:

```
generate domain reduction method motion file from ↩
   3D_3C_wave_field_inversion
    target_nodes_filename = "Target_Nodes.txt"
    target_motions_filename = "Target_Motions.txt"
    time_step = 0.01*s
    hdf5_file = "DRM_Input_from_Inverse_Motion.hdf5";
```

where:

- `target_nodes_filename` is the file name for a file that contains the list of nodes, represented by their tags, where target motions are designated.

  One example of target nodes file is given below.

```
  5
  15
  25
  35
  46
  48
  50
  52

```

- `target_motions_filename` is the file name for a file that contains the list of target motions at the corresponding target nodes. Note that the length, or number of rows, and the ordering of the target motions file must be the same as those of the target nodes file.

  One example of target motions file is given below.

```
  Displacement_1000steps_with_CT.txt
  Displacement_1000steps_with_CT.txt
  Displacement_1000steps_with_CT.txt
  Displacement_1000steps_with_CT.txt
  Zero_Displacement_1000steps_with_CT.txt
  Zero_Displacement_1000steps_with_CT.txt
  Zero_Displacement_1000steps_with_CT.txt
  Zero_Displacement_1000steps_with_CT.txt
```

Time series of target motion is defined in each of the file listed in `target_motions_filename`.

- `time_step` is the time step/interval corresponding to the target motions.
- `hdf5_file` specifies the HDF5 file which contains the geometric information about the DRM elements and DRM nodes. This is also the file in which the DRM forces obtained from 3D wave field inversion are stored. Then this file can be used in future simulations as the DRM input. See previous DRM-related DSLs for the format of this file.

1.3.6 Output Options

Real-ESSI Simulator outputs total displacements at all the nodes, as well total stress, total strain and total plastic strain at all the Gauss points of the element in each time step of each stage of loading. Real-ESSI also outputs any/all other element output in addition to the integration/Gauss point output. Generally, 3-D elements have only integration/Gauss point outputs and structure elements have only element output. The output options are reset to the default options in the beginning of each loading stage. More information about output organization is given in section 206.2.

Output Options: Enable/Disable Output

This option is used to enable or disable the outputting of results from all nodes and elements to HDF5 (.feioutput) output file.

Note:- By default output is always enabled for each loading stage.

Command to disable output is

```
disable all output;
```

Command to enable output is

```
enable all output;
```

Output Options: Enable/Disable Element Output

This option is used to enable or disable the outputting of element results from all elements to HDF5 (.feioutput) output file, per stage of loading.

Note:- By default all results from elements are output for each loading stage, so this option can be used to enable or disable output per loading stage.

Command to disable element output is

```
disable element output;
```

Command to enable element output is

```
enable element output;
```

Output Options: Enable/Disable Displacement Output

This option is used to enable or disable the displacement output at nodes to HDF5 (.feioutput) file.

Note:- By default displacement output is enabled.

Command to disable displacement output is

```
disable displacement output;
```

Command to enable displacement output is

```
enable displacement output;
```

Output Options: Enable/Disable Acceleration Output

This option is used to enable or disable the acceleration output at nodes to HDF5 (.feioutput) file.

Note:- By default acceleration output is disabled.

Command to disable acceleration output is

```
disable acceleration output;
```

Command to enable acceleration output is

```
enable acceleration output;
```

Output Options: Enable/Disable Asynchronous Output

This option is used to enable or disable the asynchronous method of writing output to HDF5 (.feioutput) file.

Note:- By default asynchronous output is disabled. Asynchronous output is an advanced output feature. Asynchronous output is suitable for I/O-bound simulation.

Command to disable asynchronous output is

```
disable asynchronous output;
```

Command to enable asynchronous output is

```
enable asynchronous output;
```

Output Options: Output Every n Steps

This option is used to output results at intervals of n time steps.

Note:- By default results are output for every time step.

Command to enable output only at n^{th} time step interval

```
output every <.> steps;
```

For example: To output only at interval of two time steps for a simulation of 100 steps. One can write

```
output every 2 steps;
```

This will only output for steps 2,4,6,... until 100th step.

Output Options: Output Support Reactions

This option is used to output reactions at constrained supports.

Note:- By default output reactions at constrained supports are disabled.

Command to enable reactions for support is

```
output support reactions;
```

1.4 Checking the Model

Real-ESSI provides model check capability:

```
check model ;
```

This command will cycle over all the domain components, including Nodes, Elements, Loads, Constraints, etc. and execute the `checkModel()` function for each. Each domain component writes/reports to the terminal and to the *essi.log* file, if an error is found. For example, bricks will report when the computed Jacobian is negative and other similar errors. Nodes that are not connected will be reported as well. If the diagnostic log is empty, it means that the mesh has passed all tests. Additionally, an output HDF5 file is produced that can be used to display the mesh and do further visual inspections of the model. This file will have initial conditions as outputs for element sand nodes.

Command `check model;` represents a dry run through the model that is used to check the model before a full analysis. Model check is highly recommended before initial stages of a full analysis are executed.

1.5 Constitutive Testing

Material models can be tested using constitutive drivers which exercise single material models. RealE-SSI implements two such drivers.

1. Bardet Driver. Bardet-type constraints can be used to simulate conditions such as drained or undrained triaxial testing with strain or stress control or direct shear testing with shear control.

2. Direct Strain Driver. This driver applies a given strain history (specified by the user) to a material model.

Both these drivers produce identical output: the files `Stress.feioutput` and `Strain.feioutput` which contain stress and strain tensor components at each step. Additionally, the drivers may print out material internal information to the file `Material_Output.feioutput`. For the stress and strain files, each line of these files contain the stresses and strains organized in the following manner:

`Stress.feioutput` $\rightarrow \sigma_{11}\ \sigma_{22}\ \sigma_{33}\ \sigma_{12}\ \sigma_{13}\ \sigma_{23}$.

`Strain.feioutput` $\rightarrow \epsilon_{11}\ \epsilon_{22}\ \epsilon_{33}\ \epsilon_{12}\ \epsilon_{13}\ \epsilon_{23}$.

The Bardet driver has the following format.

```
 simulate constitutive testing BARDETMETHOD use material # <.>
   scale_factor = <.>
   series_file = <string>
   sigma0 = ( <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , ↩
 <F/L^2> )
   verbose_output = <.>
```

Where,

- `BARDETMETHOD` can have any one of the following values:
  - `CONSTANT_P_TRIAXIAL_LOADING_STRAIN_CONTROL`: Triaxial loading with p kept constant. In this case the input file is interpreted as strain increments in the ϵ_{11} component.
  - `DRAINED_TRIAXIAL_LOADING_STRESS_CONTROL`: Drained Triaxial loading. In this case the input file is interpreted as stress increments in the σ_{11} component.
  - `DRAINED_TRIAXIAL_LOADING_STRAIN_CONTROL`: Drained Triaxial loading. In this case the input file is interpreted as strain increments in the ϵ_{11} component.
  - `UNDRAINED_TRIAXIAL_LOADING_STRAIN_CONTROL`: Undrained Triaxial loading. In this case the input file is interpreted as strain increments in the ϵ_{11} component.
  - `UNDRAINED_TRIAXIAL_LOADING_STRESS_CONTROL`: Undrained Triaxial loading. In this case the input file is interpreted as stress increments in the σ_{11} component.

  - UNDRAINED_SIMPLE_SHEAR_LOADING_STRAIN_CONTROL: Undrained simple-shear loading. In this case the input file is interpreted as angular strain increments in the $\gamma_{12} = 2\epsilon_{12}$ component.

- scale_factor: Can be used to scale the series file arbitrarily.
- series_file: String specifying the path to the file containing the increments (might be interpreted as strain or stress depending on the method chosen). Each line of the file contains one increment.
- sigma0: Components of the initial stress for the material, given in the order: $(\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{12}, \sigma_{13}, \sigma_{23})$.
- verbose_output(=N) Whether the driver should print extra information about the material model every N steps. If Takes value 0 (no output) or N (do output every N increments). Each material implements its own output, so the format of the Material_Output.feioutput file is variable and material dependent.

The direct strain driver has the following format.

```
simulate constitutive testing DIRECT_STRAIN use material # <.>
  scale_factor = <.>
  series_file = <string>
  sigma0 = ( <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , ↩
 <F/L^2> )
  verbose_output = <.>
```

Where al the arguments are the same as the Bardet driver. In this case each line of the file contains all six components of the strain increment to be applied. For example:
series_file = "increments.txt" where each line in increments.txt contains $d\epsilon_{11}$ $d\epsilon_{22}$ $d\epsilon_{33}$ $d\epsilon_{12}$ $d\epsilon_{13}$ $d\epsilon_{23}$.

1.6 List of Available Commands (tentative, not up to date)

```
add acceleration field # <.> ax = <accel> ay = <accel> az = <aaccel> ;
add constraint equal_dof with master node # <.> and slave node # <.> ↩
   dof to constrain <.>;
add constraint equal_dof with node # <.> dof <.> master and node # ↩
   <.> dof <.> slave;
add damping # <.> to element # <.>;
add damping # <.> to node # <.>;
add damping # <.> type Caughey3rd with a0 = <1/time> a1 = <time> a2 = ↩
   <time^3> stiffness_to_use = ↩
   <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
add damping # <.> type Caughey4th with a0 = <1/time> a1 = <time> a2 = ↩
   <time^3> a3 = <time^5> stiffness_to_use = ↩
   <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
add damping # <.> type Rayleigh with a0 = <1/time> a1 = <time> ↩
   stiffness_to_use = ↩
   <Initial_Stiffness|Current_Stiffness|Last_Committed_Stiffness>;
add domain reduction method loading # <.> hdf5_file = <string> ↩
   scale_factor = <.>;
add domain reduction method loading # <.> hdf5_file = <string>;
add element # <.> type 20NodeBrick using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use ↩
   material # <.>;
add element # <.> type 20NodeBrick with nodes (<.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>) use material # <.>;
add element # <.> type 20NodeBrick_up using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use ↩
   material # <.> and porosity = <.> alpha = <.>  rho_s = <M/L^3>  ↩
   rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  k_z = <L^3T/M>  ↩
   K_s = <stress> K_f = <stress>;
add element # <.> type 20NodeBrick_up with nodes (<.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = <.>  ↩
   rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  ↩
   k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 20NodeBrick_upU using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>)  use ↩
   material # <.> and porosity = <.> alpha = <.>  rho_s = <M/L^3>  ↩
   rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  k_z = <L^3T/M>  ↩
   K_s = <stress> K_f = <stress>;
add element # <.> type 20NodeBrick_upU with nodes (<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = ↩
   <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = ↩
   <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 27NodeBrick using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>) use material # <.>;
add element # <.> type 27NodeBrick with nodes (<.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use material # <.>;
add element # <.> type 27NodeBrick_up using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> ↩
   alpha = <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y ↩
   = <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 27NodeBrick_up with nodes (<.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = <.>  ↩
   rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  ↩
   k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 27NodeBrick_upU using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> ↩
   alpha = <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y ↩
   = <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 27NodeBrick_upU with nodes (<.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
   <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = ↩
   <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = ↩
   <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 3NodeShell_ANDES with nodes (<.>, <.>, <.>) ↩
   use material # <.> thickness = <l> ;
add element # <.> type 4NodeShell_ANDES with nodes (<.>, <.>, <.>, ↩
   <.>) use material # <.> thickness = <l> ;
add element # <.> type 4NodeShell_MITC4 with nodes (<.>, <.>, <.>, ↩
   <.>) use material # <.> thickness = <L>;
add element # <.> type 4NodeShell_NewMITC4 with nodes (<.>, <.>, <.>, ↩
   <.>) use material # <.> thickness = <L>;
add element # <.> type 8_27_NodeBrick using <.> Gauss points each ↩
   direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>) use material # <.>;
add element # <.> type 8_27_NodeBrick with nodes (<.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use material # <.>;
add element # <.> type 8_27_NodeBrick_up using <.> Gauss points each ↩
    direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> ↩
    alpha = <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y ↩
    = <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 8_27_NodeBrick_up with nodes (<.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = ↩
    <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = ↩
    <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 8_27_NodeBrick_upU using <.> Gauss points each ↩
    direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> ↩
    alpha = <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y ↩
    = <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 8_27_NodeBrick_upU with nodes (<.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>) use material # <.> and porosity = <.> alpha = ↩
    <.>  rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = ↩
    <L^3T/M>  k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 8NodeBrick using <.> Gauss points each ↩
    direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use ↩
    material # <.>;
add element # <.> type 8NodeBrick with nodes (<.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>) use material # <.>;
add element # <.> type 8NodeBrick_up using <.> Gauss points each ↩
    direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use ↩
    material # <.> porosity = <.> alpha = <.>  rho_s = <M/L^3>  rho_f ↩
    = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  k_z = <L^3T/M>  K_s = ↩
    <stress> K_f = <stress>;
add element # <.> type 8NodeBrick_up with nodes (<.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>) use material # <.> porosity = <.> alpha = <.>  ↩
    rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  ↩
    k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type 8NodeBrick_upU using <.> Gauss points each ↩
    direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use ↩
    material # <.> porosity = <.> alpha = <.>  rho_s = <M/L^3>  rho_f ↩
    = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  k_z = <L^3T/M>  K_s = ↩
    <stress> K_f = <stress>;
add element # <.> type 8NodeBrick_upU with nodes (<.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>) use material # <.> porosity = <.> alpha = <.>  ↩
    rho_s = <M/L^3>  rho_f = <M/L^3> k_x = <L^3T/M>  k_y = <L^3T/M>  ↩
    k_z = <L^3T/M>  K_s = <stress> K_f = <stress>;
add element # <.> type beam_9dof_elastic with nodes (<.>, <.>) ↩
    cross_section = <area> elastic_modulus = <F/L^2> shear_modulus = ↩
    <F/L^2> torsion_Jx = <length^4> bending_Iy = <length^4> bending_Iz ↩
    = <length^4> mass_density = <M/L^3>  xz_plane_vector = (<.>, <.>, ↩
    <.> ) joint_1_offset = (<L>, <L>, <L> ) joint_2_offset = (<L>, ↩
    <L>, <L> );
add element # <.> type beam_displacement_based with nodes (<.>, <.>) ↩
    with # <.> integration_points use section # <.> mass_density = ↩
    <M/L^3> IntegrationRule = "" xz_plane_vector = (<.>, <.>, <.> ) ↩
    joint_1_offset = (<L>, <L>, <L> ) joint_2_offset = (<L>, <L>, <L> );
add element # <.> type beam_elastic with nodes (<.>, <.>) ↩
    cross_section = <area> elastic_modulus = <F/L^2> shear_modulus = ↩
    <F/L^2> torsion_Jx = <length^4> bending_Iy = <length^4> bending_Iz ↩
    = <length^4> mass_density = <M/L^3>  xz_plane_vector = (<.>, <.>, ↩
    <.> ) joint_1_offset = (<L>, <L>, <L> ) joint_2_offset = (<L>, ↩
    <L>, <L> );
add element # <.> type beam_elastic_lumped_mass with nodes (<.>, <.>) ↩
    cross_section = <area> elastic_modulus = <F/L^2> shear_modulus = ↩
    <F/L^2> torsion_Jx = <length^4> bending_Iy = <length^4> bending_Iz ↩
    = <length^4> mass_density = <M/L^3>  xz_plane_vector = (<.>, <.>, ↩
    <.> ) joint_1_offset = (<L>, <L>, <L> ) joint_2_offset = (<L>, ↩
    <L>, <L> );
add element # <.> type BeamColumnDispFiber3d with nodes (<.>, <.>) ↩
    number_of_integration_points = <.> section_number = <.> ↩
    mass_density = <M/L^3>  xz_plane_vector = (<.>, <.>, <.> ) ↩
    joint_1_offset = (<L>, <L>, <L> ) joint_2_offset = (<L>, <L>, <L> );
add element # <.> type HardContact with nodes (<.>, <.>) ↩
    axial_stiffness = <F/L> shear_stiffness = <F/L> normal_damping = ↩
    <F/L> tangential_damping = <F/L>  friction_ratio = <.>  ↩
    contact_plane_vector = (<.>, <.>, <.> );
add element # <.> type HardWetContact with nodes (<.>, <.>) ↩
    axial_stiffness = <F/L> shear_stiffness = <F/L> normal_damping = ↩
    <F/L> tangential_damping = <F/L>  friction_ratio = <.>  ↩
    contact_plane_vector = (<.>, <.>, <.> );
add element # <.> type ShearBeam with nodes (<.>, <.>) cross_section ↩
    = <l^2> use material # <.>;
add element # <.> type SoftContact with nodes (<.>, <.>) ↩
    initial_axial_stiffness = <F/L> stiffening_rate = <m^-1> ↩
    shear_stiffness = <F/L> normal_damping = <F/L> tangential_damping ↩
    = <F/L>  friction_ratio = <.>  contact_plane_vector = (<.>, <.>, ↩
    <.> );
add element # <.> type SoftWetContact with nodes (<.>, <.>) ↩
    initial_axial_stiffness = <F/L> stiffening_rate = <m^-1> ↩
    shear_stiffness = <F/L> normal_damping = <F/L> tangential_damping ↩
    = <F/L>  friction_ratio = <.>  contact_plane_vector = (<.>, <.>, ↩
    <.> );
add element # <.> type truss with nodes (<.>, <.>) use material # <.> ↩
    cross_section = <length^2> mass_density = <M/L^3> ;
add element # <.> type variable_node_brick_8_to_27 using <.> Gauss ↩
    points each direction with nodes (<.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>, ↩
    <.>, <.>, <.>, <.>, <.>, <.>, <.>, <.>) use material # <.>;
add elements (<.>) to physical_element_group "string";
add fiber # <.> using material # <.> to section # <.>  ↩
    fiber_cross_section = <area> fiber_location = (<L>,<L>);
add imposed motion # <.> to node # <.> dof DOFTYPE ↩
    displacement_scale_unit = <displacement> displacement_file = ↩
    "disp_filename" velocity_scale_unit = <velocity> velocity_file = ↩
    "vel_filename" acceleration_scale_unit = <acceleration> ↩
    acceleration_file = "acc_filename";
add imposed motion # <.> to node # <.> dof DOFTYPE time_step = <t> ↩
    displacement_scale_unit = <length> displacement_file = ↩
    "disp_filename" velocity_scale_unit = <velocity> velocity_file = ↩
    "vel_filename" acceleration_scale_unit = <acceleration> ↩
    acceleration_file = "acc_filename";
add load # <.> to all elements type self_weight use acceleration ↩
    field # <.>;
add load # <.> to element # <.> type self_weight use acceleration ↩
    field # <.>;
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>) with magnitude <.>;
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>) with magnitudes (<.> , <.> , <.> , <.>);
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>, <.>, <.>, <.>, <.>) with magnitude <.>;
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>, <.>, <.>, <.>, <.>) with magnitudes (<.> , <.> , <.> , ↩
    <.>, <.>, <.>, <.>, <.>);
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>, <.>, <.>, <.>, <.>, <.>) with magnitude <.>;
add load # <.> to element # <.> type surface at nodes (<.> , <.> , ↩
    <.> , <.>, <.>, <.>, <.>, <.>, <.>) with magnitudes (<.> , <.> , ↩
    <.> , <.>, <.>, <.>, <.>, <.>, <.>);
add load # <.> to node # <.> type from_reactions;
add load # <.> to node # <.> type linear FORCETYPE = <force or ↩
   moment>; //FORCETYPE = Fx Fy Fz Mx My Mz F_fluid_x F_fluid_y ↩
   F_fluid_z
add load # <.> to node # <.> type path_series FORCETYPE = <force or ↩
   moment> time_step = <time> series_file = "filename";
add load # <.> to node # <.> type path_time_series FORCETYPE = <force ↩
   or moment> series_file = "filename";
add load # <.> to node # <.> type self_weight use acceleration field ↩
   # <.>;
add mass to node # <.> mx = <mass> my = <mass> mz = <mass> Imx = ↩
   <mass*length^2> Imy = <mass*length^2> Imz = <mass*length^2>;
add mass to node # <.> mx = <mass> my = <mass> mz = <mass>;
add material # <.> type CamClay mass_density = <M/L^3> M = <.> lambda ↩
   = <.> kappa = <.> e0 = <.> p0 = <F/L^2> Poisson_ratio = <.> ↩
   initial_confining_stress = <F/L^2>
add material # <.> type DruckerPrager mass_density = <M/L^3> ↩
   elastic_modulus = <F/L^2> poisson_ratio = <.> druckerprager_k = <> ↩
   kinematic_hardening_rate = <F/L^2> isotropic_hardening_rate = ↩
   <F/L^2> initial_confining_stress = exp;
add material # <.> type DruckerPragerArmstrongFrederickLE ↩
   mass_density = <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = ↩
   <.> druckerprager_k = <> armstrong_frederick_ha = <F/L^2> ↩
   armstrong_frederick_cr = <F/L^2> isotropic_hardening_rate = ↩
   <F/L^2> initial_confining_stress = <F/L^2>;
add material # <.> type DruckerPragerArmstrongFrederickNE ↩
   mass_density = <M/L^3> DuncanChang_K = <.> DuncanChang_pa = ↩
   <F/L^2> DuncanChang_n = <.> DuncanChang_sigma3_max = <F/L^2> ↩
   DuncanChang_nu = <.> druckerprager_k = <> armstrong_frederick_ha = ↩
   <F/L^2> armstrong_frederick_cr = <F/L^2> isotropic_hardening_rate ↩
   = <F/L^2> initial_confining_stress = <F/L^2>;
add material # <.> type DruckerPragerNonAssociateArmstrongFrederick ↩
   mass_density = <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = ↩
   <.> druckerprager_k = <> armstrong_frederick_ha = <F/L^2> ↩
   armstrong_frederick_cr = <F/L^2> isotropic_hardening_rate = ↩
   <F/L^2> initial_confining_stress = <F/L^2> plastic_flow_xi = <> ↩
   plastic_flow_kd = <> ;
add material # <.> type DruckerPragerNonAssociateLinearHardening ↩
   mass_density = <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = ↩
   <.> druckerprager_k = <> kinematic_hardening_rate = <F/L^2> ↩
   isotropic_hardening_rate = <F/L^2> initial_confining_stress = ↩
   <F/L^2> plastic_flow_xi = <> plastic_flow_kd = <> ;
add material # <.> type DruckerPragervonMises mass_density = <M/L^3> ↩
   elastic_modulus = <F/L^2> poisson_ratio = <.> druckerprager_k = <> ↩
   kinematic_hardening_rate = <F/L^2> isotropic_hardening_rate = ↩
   <F/L^2> initial_confining_stress = exp;
```

```
add material # <.> type linear_elastic_crossanisotropic mass_density ↩
   = <mass_density> elastic_modulus_horizontal = <F/L^2> ↩
   elastic_modulus_vertical = <F/L^2> poisson_ratio_h_v = <.> ↩
   poisson_ratio_h_h = <.> shear_modulus_h_v = <F/L^2>;
add material # <.> type linear_elastic_isotropic_3d mass_density = ↩
   <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = <.>;
add material # <.> type linear_elastic_isotropic_3d_LT mass_density = ↩
   <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = <.>;
add material # <.> type roundedMohrCoulomb mass_density = <M/L^3> ↩
   elastic_modulus = <F/L^2> poisson_ratio = <.> RMC_m = <.> RMC_qa = ↩
   <F/L^2> RMC_pc = <F/L^2> RMC_e = <.> RMC_eta0 = <.> RMC_Heta = ↩
   <F/L^2> initial_confining_stress = <F/L^2>
add material # <.> type sanisand2004 mass_density = <M/L^3> e0 = <.> ↩
   sanisand2004_G0 = <.> poisson_ratio = <.> sanisand2004_Pat = ↩
   <stress>  sanisand2004_p_cut = <.>  sanisand2004_Mc = <.>  ↩
   sanisand2004_c = <.> sanisand2004_lambda_c = <.> sanisand2004_xi = ↩
   <.>  sanisand2004_ec_ref = <.>  sanisand2004_m = <.>  ↩
   sanisand2004_h0 = <.> sanisand2004_ch = <.>  sanisand2004_nb = <.> ↩
   sanisand2004_A0 = <.> sanisand2004_nd = <.> sanisand2004_z_max = ↩
   <.>  sanisand2004_cz = <.> initial_confining_stress = <stress> ;
add material # <.> type sanisand2004_legacy mass_density = <M/L^3> e0 ↩
   = <.> sanisand2004_G0 = <.> poisson_ratio = <.> sanisand2004_Pat = ↩
   <stress>  sanisand2004_p_cut = <.>  sanisand2004_Mc = <.>  ↩
   sanisand2004_c = <.> sanisand2004_lambda_c = <.> sanisand2004_xi = ↩
   <.>  sanisand2004_ec_ref = <.>  sanisand2004_m = <.>  ↩
   sanisand2004_h0 = <.> sanisand2004_ch = <.>  sanisand2004_nb = <.> ↩
   sanisand2004_A0 = <.> sanisand2004_nd = <.> sanisand2004_z_max = ↩
   <.>  sanisand2004_cz = <.> initial_confining_stress = <stress>  ↩
   algorithm = <explicit|implicit>  number_of_subincrements = <.>  ↩
   maximum_number_of_iterations = <.>  tolerance_1 = <.>  tolerance_2 ↩
   = <.>;
add material # <.> type sanisand2008 mass_density = <M/L^3>  e0 = <.> ↩
    sanisand2008_G0 = <.>  sanisand2008_K0 = <.> sanisand2008_Pat = ↩
   <stress> sanisand2008_k_c = <.>  sanisand2008_alpha_cc = <.> ↩
   sanisand2008_c = <.>  sanisand2008_xi = <.>  sanisand2008_lambda = ↩
   <.>  sanisand2008_ec_ref = <.>  sanisand2008_m = <.>  ↩
   sanisand2008_h0 = <.>  sanisand2008_ch = <.>  sanisand2008_nb = ↩
   <.>  sanisand2008_A0 = <.> sanisand2008_nd = <.>  sanisand2008_p_r ↩
   = <.>  sanisand2008_rho_c = <.>  sanisand2008_theta_c = <.>  ↩
   sanisand2008_X = <.>  sanisand2008_z_max = <.>  sanisand2008_cz = ↩
   <.>  sanisand2008_p0 = <stress>  sanisand2008_p_in = <.>  ↩
   algorithm = <explicit|implicit>  number_of_subincrements = <.>  ↩
   maximum_number_of_iterations = <.>  tolerance_1 = <.>  tolerance_2 ↩
   = <.>;
```

```
add material # <.> type uniaxial_concrete02 compressive_strength = ↩
   <F/L^2> strain_at_compressive_strength = <.> crushing_strength = ↩
   <F/L^2>  strain_at_crushing_strength = <.> lambda = <.> ↩
   tensile_strength = <F/L^2> tension_softening_stiffness = <F/L^2>;
add material # <.> type uniaxial_elastic elastic_modulus = <F/L^2> ↩
   viscoelastic_modulus = <mass / length / time> ;
add material # <.> type uniaxial_steel01 yield_strength = <F/L^2> ↩
   elastic_modulus = <F/L^2> strain_hardening_ratio = <.>  a1 = <.>  ↩
   a2 = <.>  a3 = <>  a4 = <.> ;
add material # <.> type uniaxial_steel02 yield_strength = <F/L^2> ↩
   elastic_modulus = <F/L^2> strain_hardening_ratio = <.> R0 = <.> ↩
   cR1 = <.> cR2 = <.>  a1 = <.>  a2 = <.>  a3 = <>  a4 = <.> ;
add material # <.> type vonMises mass_density = <M/L^3> ↩
   elastic_modulus = <F/L^2> poisson_ratio = <.> von_mises_radius = ↩
   <F/L^2> kinematic_hardening_rate = <F/L^2> ↩
   isotropic_hardening_rate = <F/L^2> ;
add material # <.> type vonMisesArmstrongFrederick mass_density = ↩
   <M/L^3> elastic_modulus = <F/L^2> poisson_ratio = <.> ↩
   von_mises_radius = <> armstrong_frederick_ha = <F/L^2> ↩
   armstrong_frederick_cr = <F/L^2> isotropic_hardening_rate = ↩
   <F/L^2> ;
add node # <.> at (<length>,<length>,<length>)  with <.> dofs;
add nodes (<.>) to physical_node_group "string";
add section # <.> type elastic3d elastic_modulus = <F/L^2> ↩
   cross_section = <L^2> bending_Iz = <L^4> bending_Iy=<L^4> ↩
   torsion_Jx=<L^4> ;
add section # <.> type Elastic_Membrane_Plate elastic_modulus = ↩
   <F/L^2> poisson_ratio = <.> thickness = <length> mass_density = ↩
   <M/L^3>;
add section # <.> type FiberSection TorsionConstant_GJ = <F*L^2>
add section # <.> type Membrane_Plate_Fiber thickness = <length> use ↩
   material # <.>;
add single point constraint to node # <.> dof to constrain <dof_type> ↩
   constraint value of <corresponding unit>;
add uniform acceleration # <.> to all nodes dof <.> time_step = <T> ↩
   scale_factor = <.> initial_velocity = <L/S> acceleration_file = ↩
   <string>;
check mesh filename;
compute reaction forces;
define algorithm With_no_convergence_check / Newton / Modified_Newton;
define convergence test Norm_Displacement_Increment / ↩
   Energy_Increment / Norm_Unbalance / ↩
   Relative_Norm_Displacement_Increment / Relative_Energy_Increment / ↩
   Relative_Norm_Unbalance tolerance = <.> maximum_iterations = <.> ↩
   verbose_level = <0>|<1>|<2>;
```

```
define dynamic integrator Hilber_Hughes_Taylor with alpha = <.>;
define dynamic integrator Newmark with gamma = <.> beta = <.>;
define load factor increment <.>;
define NDMaterial constitutive integration algorithm Forward_Euler;
define NDMaterial constitutive integration algorithm ↩
   Forward_Euler_Subincrement number_of_subincrements =<.>;
define NDMaterial constitutive integration algorithm ↩
   Forward_Euler|Forward_Euler_Subincrement|Backward_Euler|Backward_Euler_Subin
   yield_function_relative_tolerance  = <.> stress_relative_tolerance ↩
   = <.> maximum_iterations = <.>;
define physical_element_group "string";
define physical_node_group "string";
define solver ProfileSPD / UMFPack;
define static integrator displacement_control using node # <.> dof ↩
   DOFTYPE increment <length>;
disable asynchronous output;
disable element output;
disable output;
enable asynchronous output;
enable element output;
enable output;
fix node # <.> dofs <.>;
fix node # <.> dofs all;
free node # <.> dofs <.>;
help;
if (.) { } else {};
if (.) { };
model name "name_string";
new loading stage "name_string";
output every <.> steps;
output non_converged_iterations;
output support reactions;
print <.>;
print element # <.>;
print node # <.>;
print physical_element_group "string";
print physical_node_group "string";
remove constraint equal_dof node # <.>;
remove displacement from  node # <.>;
remove element # <.>;
remove imposed motion # <.>;
remove load # <.>;
remove node # <.>;
remove physical_node_group "string";
remove strain from element # <.>;
remove physical_element_group "string";
runTest;
set output compression level to <.>;
simulate <.> steps using static algorithm;
simulate <.> steps using transient algorithm time_step = <time>;
simulate <.> steps using variable transient algorithm time_step = ↩
   <time> minimum_time_step = <time> maximum_time_step = <time> ↩
   number_of_iterations = <.>;
simulate constitutive testing BARDETMETHOD use material # <.> ↩
   scale_factor = <.> series_file = <string>  sigma0 = ( <F/L^2> , ↩
   <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> )  verbose_output ↩
   = <.>
simulate constitutive testing constant mean pressure triaxial strain ↩
   control use material # <.> strain_increment_size = <.> ↩
   maximum_strain = <.> number_of_times_reaching_maximum_strain = <.>;
simulate constitutive testing DIRECT_STRAIN use material # <.> ↩
   scale_factor = <.> series_file = <string>  sigma0 = ( <F/L^2> , ↩
   <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> , <F/L^2> ) verbose_output = ↩
   <.>
simulate constitutive testing drained triaxial strain control use ↩
   material # <.> strain_increment_size = <.> maximum_strain = <.> ↩
   number_of_times_reaching_maximum_strain = <.>;
simulate constitutive testing undrained simple shear use material # ↩
   <.> strain_increment_size = <.> maximum_strain = <.> ↩
   number_of_times_reaching_maximum_strain = <.>;
simulate constitutive testing undrained triaxial stress control use ↩
   material # <.> strain_increment_size = <.> maximum_strain = <.> ↩
   number_of_times_reaching_maximum_strain = <.>;
simulate constitutive testing undrained triaxial use material # <.> ↩
   strain_increment_size = <.> maximum_strain = <.> ↩
   number_of_times_reaching_maximum_strain = <.>;
simulate using eigen algorithm number_of_modes = <.>;
ux uy uz Ux Uy Uz rx ry rz;
while (.) { };
whos;
```

1.7 List of reserved keywords

The following keywords are reserved and cannot be used as variables in a script or interactive session. Doing so would result in a syntax error.

First Order (commands)

```
a0
a1
a2
a3
a4
acceleration
acceleration_depth
acceleration_file
acceleration_filename
acceleration_scale_unit
add
algorithm
algorithm
all
all
allowed_subincrement_strain
alpha
alpha1
alpha2
and
angle
armstrong_frederick_cr
armstrong_frederick_ha
asynchronous
at
ax
axial_penalty_stiffness
axial_stiffness
axial_viscous_damping
ay
az
bending_Iy
bending_Iz
beta
Beta
beta_min
case
cases
characteristic_strength
check
chi
cohesion
combine
compression
compressive_strength
```

```
compressive_yield_strength
compute
confinement
confinement_strain
constitutive
constrain
constraint
contact_plane_vector
control
convergence
cR1
cR2
cross_section
crushing_strength
Current_Stiffness
cyclic
damage_parameter_An
damage_parameter_Ap
damage_parameter_Bn
damping
define
depth
dilatancy_angle
dilation_angle_eta
dilation_scale
direction
disable
displacement
displacement_file
displacement_scale_unit
dof
dofs
dofs
domain
druckerprager_k
DuncanChang_K
DuncanChang_n
DuncanChang_nu
DuncanChang_pa
DuncanChang_sigma3_max
DYNAMIC_DOMAIN_PARTITION
e0
each
elastic
elastic_modulus
elastic_modulus_horizontal
elastic_modulus_vertical
element
elements
else
enable
every
```

```
factor
fiber
fiber_cross_section
fiber_location
field
file
fix
fluid
free
friction_angle
friction_ratio
from
gamma
Gamma
Gauss
generate
GoverGmax
h_in
hardening_parameters_of_yield_surfaces
hardening_parameters_scale_unit
hdf5_file
hdf5_filenames_list
help
if
imposed
Imx
Imy
Imz
in
inclined
increment
initial_axial_stiffness
initial_confining_stress
initial_elastic_modulus
initial_shear_modulus
initial_shear_stiffness
initial_velocity
integration
integration_points
IntegrationRule
integrator
interface
isotropic_hardening_rate
joint_1_offset
joint_2_offset
K_f
K_s
k_x
k_y
k_z
kappa
kd_in
```

```
kinematic_hardening_rate
lambda
level
line_search_beta
line_search_eta
line_search_max_iter
liquefaction_Alpha
liquefaction_c_h0
liquefaction_Dir
liquefaction_dre1
liquefaction_Dre2
liquefaction_EXPN
liquefaction_gamar
liquefaction_mdc
liquefaction_mfc
liquefaction_pa
liquefaction_pmin
load
load_factors_list
loading
local_y_vector
local_z_vector
M
M_in
magnitude
magnitudes
mass
mass_density
master
material
max_axial_stiffness
maximum_iterations
maximum_number_of_iterations
maximum_strain
maximum_stress
maximum_time_step
method
minimal
minimum_time_step
model
model
moment_x_stiffness
moment_y_stiffness
monotonic
motion
mu
mx
my
mz
name
NDMaterial
new
```

```
newton_with_subincrement
node
nodes
number_of_cycles
number_of_files
number_of_increment
number_of_integration_points
number_of_iterations
number_of_layers
number_of_modes
number_of_subincrements
number_of_times_reaching_maximum_strain
of
output
output
output_filename
p0
parallel
peak_friction_coefficient_limit
peak_friction_coefficient_rate_of_decrease
penalty_stiffness
pi1
pi2
pi3
plastic_deformation_rate
plastic_flow_kd
plastic_flow_xi
plot
point
points
poisson_ratio
poisson_ratio_h_h
poisson_ratio_h_v
porosity
print
propagation
pure
R0
radiuses_of_yield_surface
radiuses_scale_unit
rate_of_softening
reduction
reference_pressure
remove
rempve
residual_friction_coefficient
restart
restart_files
results
rho_a
rho_f
rho_s
```

```
rho_w
RMC_e
RMC_eta0
RMC_Heta
RMC_m
RMC_pc
RMC_qa
RMC_shape_k
rounded_distance
runTest
sanisand2004_A0
sanisand2004_c
sanisand2004_ch
sanisand2004_cz
sanisand2004_ec_ref
sanisand2004_G0
sanisand2004_h0
sanisand2004_lambda_c
sanisand2004_m
sanisand2004_Mc
sanisand2004_nb
sanisand2004_nd
sanisand2004_p_cut
sanisand2004_Pat
sanisand2004_xi
sanisand2004_z_max
sanisand2008_A0
sanisand2008_alpha_cc
sanisand2008_c
sanisand2008_ch
sanisand2008_cz
sanisand2008_ec_ref
sanisand2008_G0
sanisand2008_h0
sanisand2008_K0
sanisand2008_k_c
sanisand2008_lambda
sanisand2008_m
sanisand2008_nb
sanisand2008_nd
sanisand2008_p0
sanisand2008_p_in
sanisand2008_p_r
sanisand2008_Pat
sanisand2008_rho_c
sanisand2008_theta_c
sanisand2008_X
sanisand2008_xi
sanisand2008_z_max
save
scale_factor
SCOTCHGRAPHPARTITIONER
```

```
section
section_number
sequential
series_file
set
shear
shear_length_ratio
shear_modulus
shear_modulus_h_v
shear_stiffness
shear_viscous_damping
shear_zone_thickness
ShearStrainGamma
sigma0
simulate
single
size_of_peak_plateau
sizes_of_yield_surfaces
slave
slave
soil
soil_profile_filename
soil_surface
solid
solver
stage
steps
steps
stiffening_rate
stiffness_to_use
strain
strain_at_compressive_strength
strain_at_crushing_strength
strain_hardening_ratio
strain_increment_size
stress
stress_increment_size
stress_relative_tolerance
sub-stepping
surface
surface_vector_relative_tolerance
tensile_strength
tensile_yield_strength
tension_softening_stiffness
test
test
testing
thickness
time_step
to
tolerance_1
tolerance_2
```

```
torsion_Jx
torsional_stiffness
TorsionConstant_GJ
total_number_of_shear_modulus
total_number_of_yield_surface
triaxial
type
uniaxial
uniaxial_material
uniform
unit_of_acceleration
unit_of_damping
unit_of_rho
unit_of_vs
use
using
value
velocity_file
velocity_scale_unit
verbose_output
viscoelastic_modulus
von_mises_radius
wave
wave1c
wave3c
while
whos
with
xi_in
xz_plane_vector
yield_function_relative_tolerance
yield_strength
yield_surface_scale_unit
x
y
z
```

Second Order (inside commands)

```
20NodeBrick
20NodeBrick_up
20NodeBrick_upU
27NodeBrick
27NodeBrick_up
27NodeBrick_upU
3NodeShell_ANDES
4NodeShell_ANDES
4NodeShell_MITC4
4NodeShell_NewMITC4
8_27_NodeBrick
8_27_NodeBrick_up
8_27_NodeBrick_upU
```

```
8NodeBrick
8NodeBrick_fluid_incompressible_up
8NodeBrick_up
8NodeBrick_upU
Absolute_Norm_Displacement_Increment
Absolute_Norm_Unbalanced_Force
arclength_control
Average_Norm_Displacement_Increment
Average_Norm_Unbalanced_Force
Backward_Euler
BARDETMETHOD
beam_9dof_elastic
beam_displacement_based
beam_elastic
beam_elastic_lumped_mass
BeamColumnDispFiber3d
BearingElastomericPlasticity3d
BFGS
BondedContact
CamClay
Caughey3rd
Caughey4th
constant mean pressure triaxial strain control
Cosserat8NodeBrick
Cosserat_linear_elastic_isotropic_3d
Cosserat_von_Mises
DIRECT_STRAIN
displacement_control
DOFTYPE
domain reduction method
drained triaxial strain control
DruckerPrager
DruckerPragerArmstrongFrederickLE
DruckerPragerArmstrongFrederickNE
DruckerPragerMultipleYieldSurface
DruckerPragerMultipleYieldSurfaceGoverGmax
DruckerPragerNonAssociateArmstrongFrederick
DruckerPragerNonAssociateLinearHardening
DruckerPragervonMises
dynamic
eigen
elastic3d
Elastic_Membrane_Plate
ElasticFourNodeQuad
Energy_Increment
equal_dof
F_fluid_x
F_fluid_y
F_fluid_z
FiberSection
ForceBasedCoupledHardContact
ForceBasedCoupledSoftContact
```

```
ForceBasedElasticContact
ForceBasedHardContact
ForceBasedSoftContact
FORCETYPE
Forward_Euler
Forward_Euler_Subincrement
from_reactions
Fx
Fy
Fz
Hilber_Hughes_Taylor
HyperbolicDruckerPragerArmstrongFrederick
HyperbolicDruckerPragerLinearHardening
HyperbolicDruckerPragerNonAssociateArmstrongFrederick
HyperbolicDruckerPragerNonAssociateLinearHardening
linear
linear_elastic_crossanisotropic
linear_elastic_isotropic_3d
linear_elastic_isotropic_3d_LT
Membrane_Plate_Fiber
Modified_Newton
Mx
My
Mz
Newmark
Newton
non_converged_iterations
NonlinearFourNodeQuad
Norm_Displacement_Increment
Norm_Unbalance
Parallel
path_series
path_time_series
petsc
petsc_options_string
physical_element_group
physical_node_group
Pisano
PlaneStressLayeredMaterial
PlaneStressRebarMaterial
PlasticDamageConcretePlaneStress
pressure
ProfileSPD
Rayleigh
reaction forces
reactions
Relative_Energy_Increment
Relative_Norm_Displacement_Increment
Relative_Norm_Unbalance
Relative_Norm_Unbalanced_Force
roundedMohrCoulomb
RoundedMohrCoulombMultipleYieldSurface
```

```
sanisand2004
sanisand2004_legacy
sanisand2008
self_weight
ShearBeam
solid fluid interaction transient
static
StressBasedCoupledHardContact_ElPPlShear
StressBasedCoupledHardContact_NonLinHardShear
StressBasedCoupledHardContact_NonLinHardSoftShear
StressBasedCoupledSoftContact
StressBasedCoupledSoftContact_ElPPlShear
StressBasedCoupledSoftContact_NonLinHardShear
StressBasedCoupledSoftContact_NonLinHardSoftShear
StressBasedHardContact_ElPPlShear
StressBasedHardContact_NonLinHardShear
StressBasedHardContact_NonLinHardSoftShear
StressBasedSoftContact_ElPPlShear
StressBasedSoftContact_NonLinHardShear
StressBasedSoftContact_NonLinHardSoftShear
SuperElementLinearElasticImport
support
surface
transient
truss
TsinghuaLiquefactionModelCirclePiPlane
TsinghuaLiquefactionModelNonCirclePiPlane
UMFPack
undrained simple shear
undrained triaxial
undrained triaxial stress control
uniaxial_concrete02
uniaxial_elastic
uniaxial_steel01
uniaxial_steel02
variable transient
variable_node_brick_8_to_27
vonMises
vonMisesArmstrongFrederick
vonMisesMultipleYieldSurface
vonMisesMultipleYieldSurfaceGoverGmax
With_no_convergence_check

beta
gamma
delta

ux
uy
uz
rx
ry
```

```
rz
Ux
Uy
Uz
p
M
m
kg
s
cm
mm
km
Hz
Minute
Hour
Day
Week
ms
ns
N
kN
Pa
kPa
MPa
GPa
pound
lbm
lbf
inch
in
feet
ft
yard
mile
psi
ksi
kip
g
pi

NUMBER_OF_NODES
NUMBER_OF_ELEMENTS
CURRENT_TIME
NUMBER_OF_SP_CONSTRAINTS
NUMBER_OF_MP_CONSTRAINTS
NUMBER_OF_LOADS
IS_PARALLEL
SIMULATE_EXIT_FLAG
then
while
do
let
```

```
vector

cos
sin
tan
cosh
sinh
tanh
acos
asin
atan
atan2
sqrt
exp
log10
ceil
fabs
floor
log
```

1.8 Integrated Development Environment (IDE) for DSL

1.9 Mesh Generation using GiD

1. Download the latest version of GiD from `http://www.gidhome.com/`, and also get a temporary license (or purchase it...).
2. Download essi.gid.tar.gz, unpack it (`tar -xvzf essi.gid.tar.gz`) in `problemtypes` directory that is located in GiD's root directory.
3. When you run GiD, you will see `essi` in "Data > Problem types", and can start using it...
4. A simple movie with instructions for mesh generation is available: (Link to a movie, 11MB).

1.10 Model Development and Mesh Generation using gmesh

1.11 Model Input File Editing using Sublime

http://www.sublimetext.com/

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