Time domain fatigue analysis in LS-DYNA R12

DYNAmore Nordic Webinar
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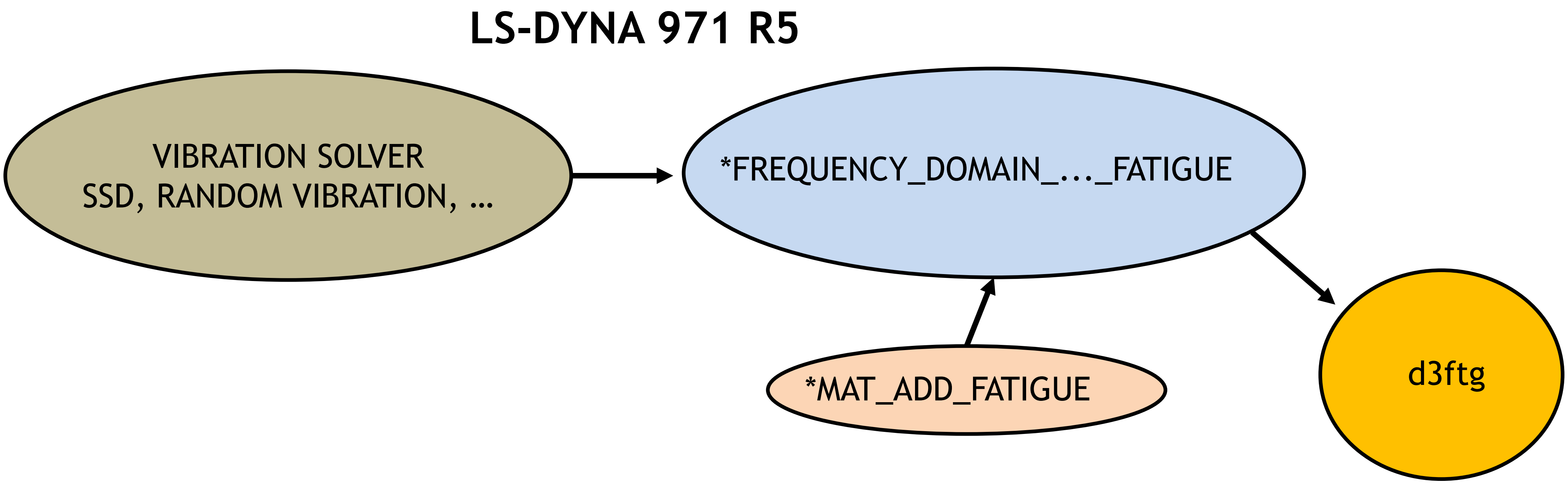
Agenda

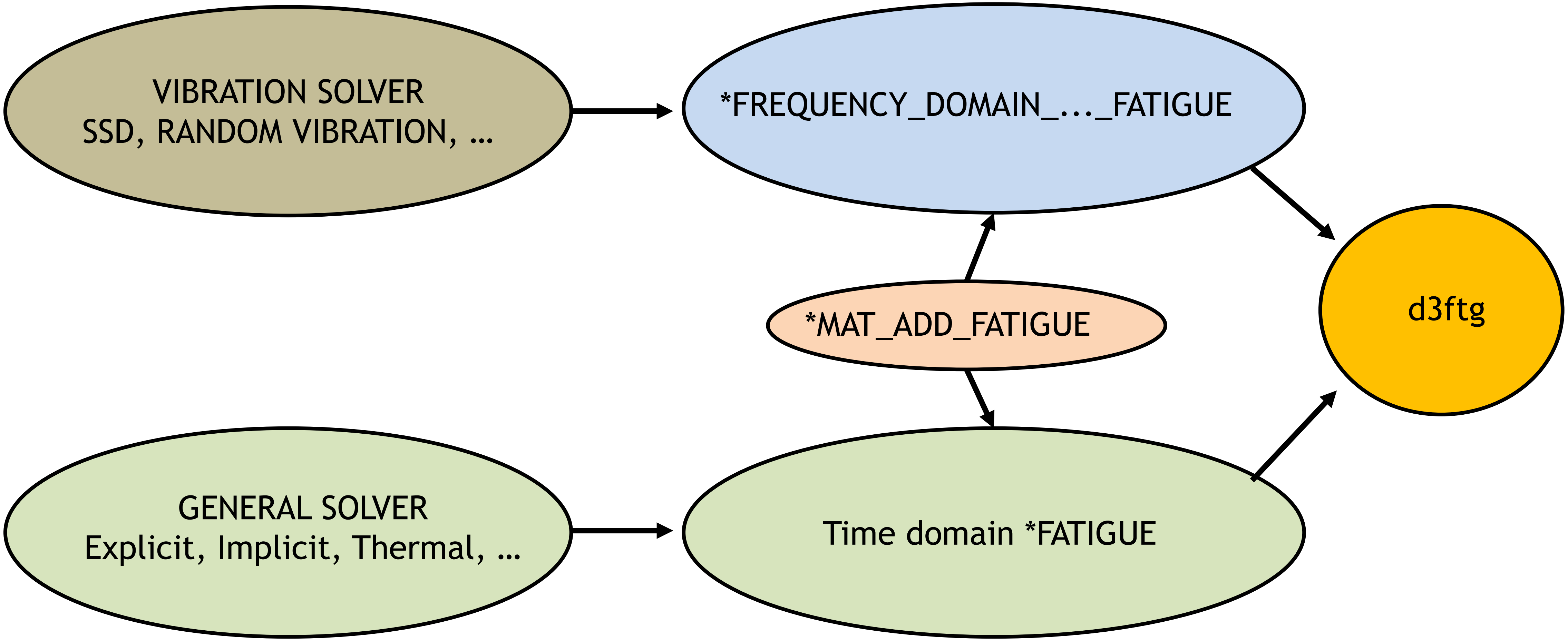
- Fatigue solvers in LS-DYNA
- Time domain fatigue solver - Compatibility
- Time domain fatigue solver – Flow chart
- Time domain fatigue solver – Keywords
- Time domain fatigue solver – Materials
- Time domain fatigue analysis – What is needed?
- Example – Notched bar
- Last words
- Useful sites - User support

Fatigue solvers in LS-DYNA



Fatigue solvers in LS-DYNA

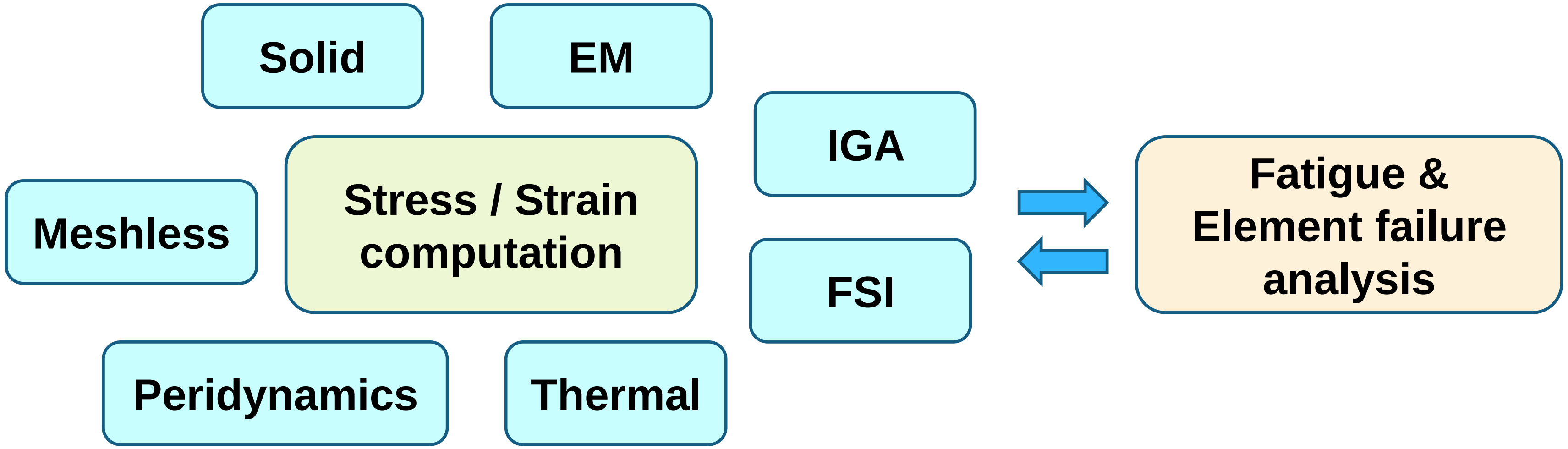
LS-DYNA R12!



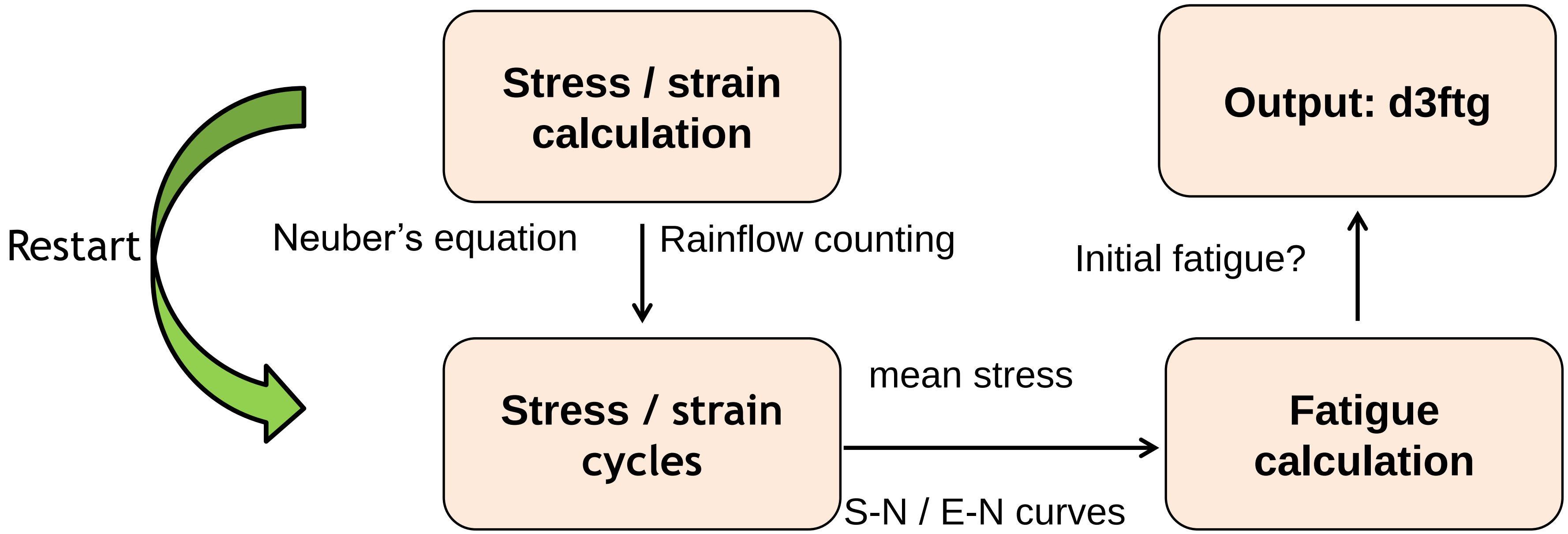
<u>Introduction of a time domain fatigue solver!</u>

Time domain fatigue solver – Compatibility

- Fully coupled by stress/strain computations to solvers
- SMP and MPP
- Linux and Windows
- Manufacturing effects can be considered
- Easy integration with LS-OPT / LS-TASC (**TBD!!**)



Time domain fatigue solver – Flow chart



Time domain fatigue solver - Keywords

- The time domain fatigue solver is activated by including the *FATIGUE_{OPTION}-keyword.
- Available keywords in R12 are:

FATIGUE_*{OPTION}

*FATIGUE_FAILURE

*FATIGUE_LOADSTEP R12!

*FATIGUE_MEAN_STRESS_CORRECTION

*FATIGUE_MULTIAXIAL R12!

*FATIGUE_SUMMATION

Additional keywords used in fatigue analysis:
*INITIAL_STRESS_{OPTION}
*INITIAL_FATIGUE_DAMAGE_RATIO
*MAT_ADD_FATIGUE

Time domain fatigue solver - Keywords

- *FATIGUE_{OPTION}
  - To activate solver
  - OPTION=D3PLOT or ELOUT is needed!

Card 3	1	2	3	4	5	6	7	8
Variable	STRSN	INDEX	RESTRT	TEXPOS				
Type	I	I	I	F				
Default	0	0	0	0.0				

Stress/Strain Binary Database Card. Card 3a is only read if RESTART = 1. It is optional.

Card 3a	1	2	3	4	5	6	7	8
Variable	FILENAME							
Type	C							

STRSN	Type of fatigue analysis variable: EQ.0: stress (default) EQ.1: strain
INDEX	Stress/strain index for performing fatigue analysis: EQ.0: von Mises stress/strain EQ.1: maximum principal stress/strain EQ.2: maximum shear stress/strain
RESTRT	Restart options. This flag is used to save an LS-DYNA transient analysis if the binary database for stress/strain time history data has been created in previous runs. See Remark 4. EQ.0: initial run EQ.1: restart with existing stress/strain binary database
TEXPOS	Exposure time. If this is 0, the exposure time is the same as ENDTIM in *CONTROL_TERMINATION.
DMGMIN	Minimum fatigue damage ratio for parts undergoing fatigue analysis: EQ.0: no change on computed fatigue damage ratio LT.0: for each part, the minimum fatigue damage ratio dumped to D3FTG is |DMGMIN| × the computed non-zero minimum fatigue damage ratio computed on the current part. GT.0: for each part, the minimum fatigue damage ratio dumped to D3FTG is DMGMIN.
FILENAME	Path and name of existing stress/strain binary database (such as d3plot or binout)

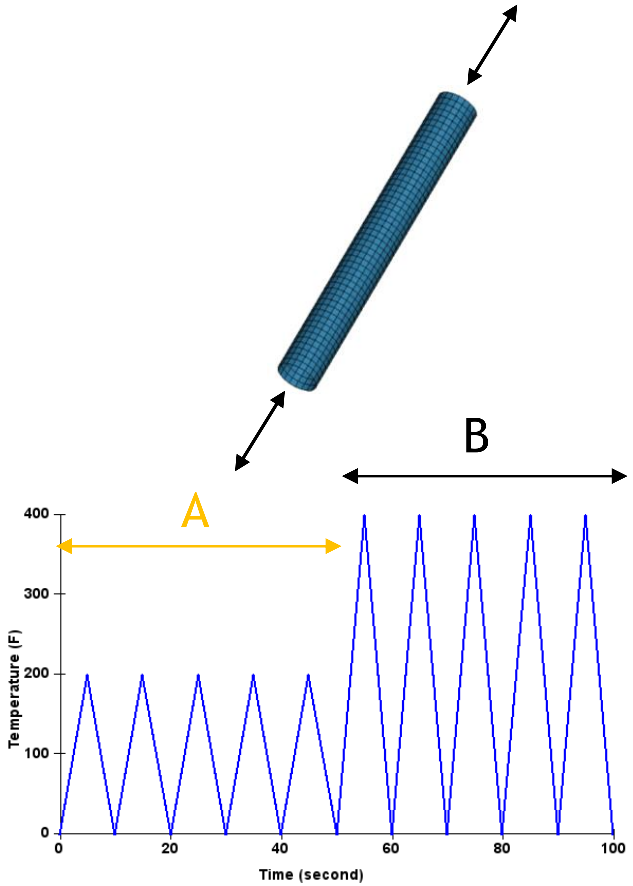
BINARY=2
on *DATABASE_ELOUT!

Time domain fatigue solver - Keywords

- *FATIGUE_LOADSTEP
- To define fatigue cycles, single or multiple
- Unique exposure time for each step
- Exclude part of solution

Card 1	1	2	3	4	5	6	7	8
Variable	TSTART	TEND	TEXPOS					
Type	F	F	F					
Default	none	none	0.0					

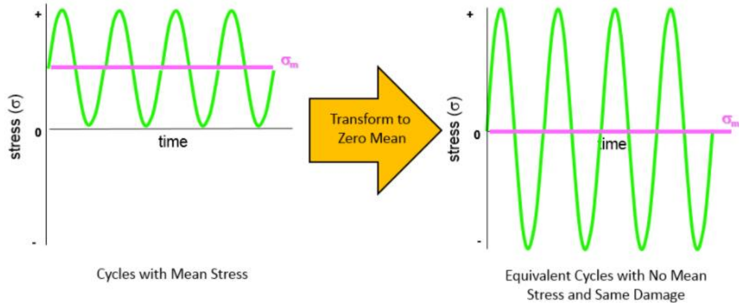
VARIABLE	DESCRIPTION
TSTART	Start time of current load step
TEND	End time of current load step
TEXPOS	Exposure time of current load step EQ.0.0: set to TEND – TSTART (default).




```
*FATIGUE_LOADSTEP
$#  tstart       tend    texpos
       0.0        50.    10000.
      50.0       100.    20000.
*DEFINE_CURVE
$#    lcid       sidr       sfa       sfo
       888          0       1.0       1.0
$#                 a1                  o1
                  0.0                 0.0
                  5.0               200.0
                 10.0                 0.0
                 15.0               200.0
                 20.0                 0.0
                 25.0               200.0
                 30.0                 0.0
                 35.0               200.0
                 40.0                 0.0
                 45.0               200.0
                 50.0                 0.0
                 55.0               400.0
                 60.0                 0.0
                 65.0               400.0
                 70.0                 0.0
                 75.0               400.0
                 80.0                 0.0
                 85.0               400.0
                 90.0                 0.0
                 95.0               400.0
                100.0                 0.0
```

Time domain fatigue solver - Keywords

- *FATIGUE_MEAN_STRESS_CORRECTION



Mean stress introduction by:
- Prestress
- Thermal load
- Gravity load
- Residual loads
- …

Card 1	1	2	3	4	5	6	7	8
Variable	METHOD							
Type	I							
Default	0							

Card 2	1	2	3	4	5	6	7	8
Variable	MID	SIGMA						
Type	I	F						
Default	none	none						

METHOD	Mean stress correction method: EQ.0: Goodman equation EQ.1: Soderberg equation EQ.2: Gerber equation EQ.3: Goodman tension only EQ.4: Gerber tension only EQ.5: Morrow equation (for correction on SN curve) EQ.11: Morrow equation (for correction on EN curve) EQ.12: Smith-Watson-Topper equation
MID	Material ID for which the current mean stress correction method is applied.
SIGMA	Ultimate tensile strength, σ_u, to be used in the Goodman equation (METHOD = 0, 3) or the Gerber equation (METHOD = 2, 4), yield strength, σ_y, to be used in the Soderberg equation (METHOD = 1), or true fracture strength, σ_f, to be used in the Morrow equation (METHOD = 5)

Goodman

$$S = \frac{\sigma_a}{1 - \sigma_m / \sigma_u}$$

Soderberg

$$S = \frac{\sigma_a}{1 - \sigma_m / \sigma_y}$$

Gerber

$$S = \frac{\sigma_a}{1 - (\sigma_m / \sigma_u)^2}$$

Time domain fatigue solver - Keywords

- *FATIGUE_MULTIAXIAL
- To account for multiaxial cyclic loading
- Multiplane-methods
  - Critical plane

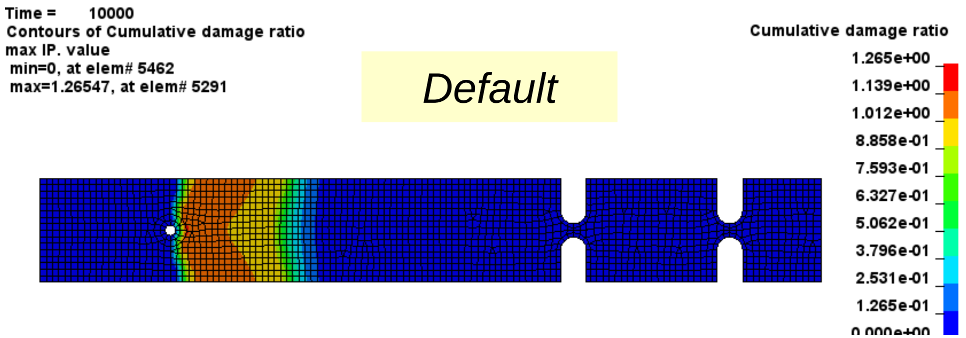
Card 1	1	2	3	4	5	6	7	8
Variable	MAXIAL	NPLANE						
Type	I	I						
Default	0	18						

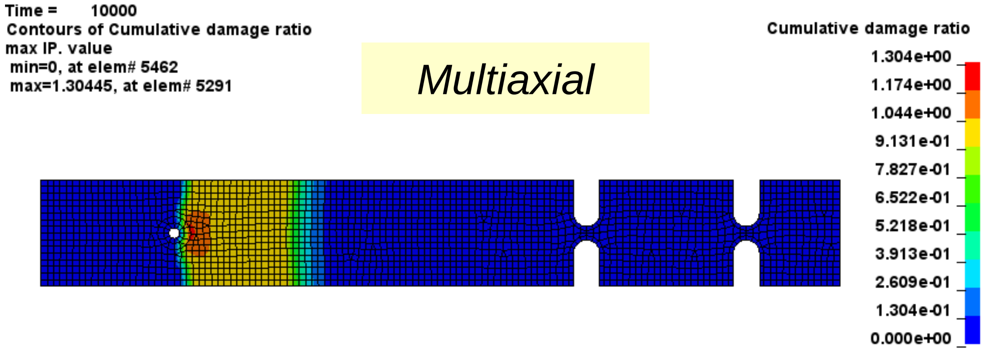
VARIABLE	DESCRIPTION
MAXIAL	Multiaxial fatigue analysis criterion: EQ.0: Fatigue analysis using equivalent stress or strain index (defined by INDEX in *FATIGUE) EQ.1: Fatigue analysis on multiple planes EQ.2: Fatigue analysis on critical plane which is determined by the highest 1st principal stress or strain
NPLANE	Number of planes for fatigue analysis (for MAXIAL = 1 only)

Example:

The stress state at a hole is always mutiaxial

$$F(t) = \sin(22\pi \cdot t)$$





Time domain fatigue solver - Keywords

- *INITIAL_FATIGUE_DAMAGE_RATIO_{OPTION}
  - Option = D3FTG or D3PLOT

*INITIAL_FATIGUE_DAMAGE_RATIO_D3FTG

Card 1	1	2	3	4	5	6	7	8
Variable	FILENAME							
Type	C							
Default	d3ftg							

FILENAME   Path and name of existing binary database for fatigue information

Time domain fatigue solver - Keywords

- *INITIAL_FATIGUE_DAMAGE_RATIO_{OPTION}
  - Option = D3FTG or D3PLOT

Card 1	1	2	3	4	5	6	7	8
Variable	FILENAME							
Type	C							
Default	d3plot							

VARIABLE	DESCRIPTION
FILENAME	Path and name of existing binary database for fatigue information

The d3plot option may be used to include damage from GISSMO-models or other transient preload cases.

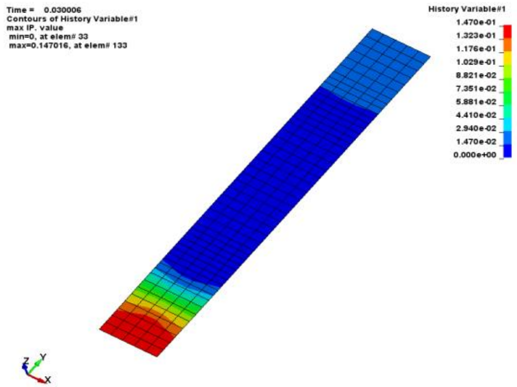
D3PLOT Card. Card 2 for the D3PLOT keyword option.

Card 2	1	2	3	4	5	6	7	8
Variable	NSTATE	NEIPHD	NEIPSD					
Type	I	I	I					
Default	1	1	1					

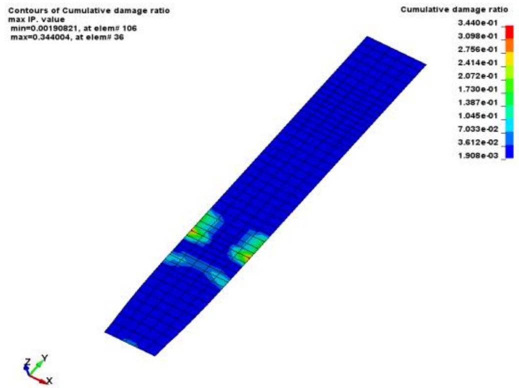
NSTATE	State ID in binary database (e.g. d3plot) for reading damage variables
NEIPHD	ID of additional integration point history variable which saves the damage for solid elements
NEIPSD	ID of additional integration point history variable which saves the damage for shell and thick shell elements

Time domain fatigue solver - Keywords

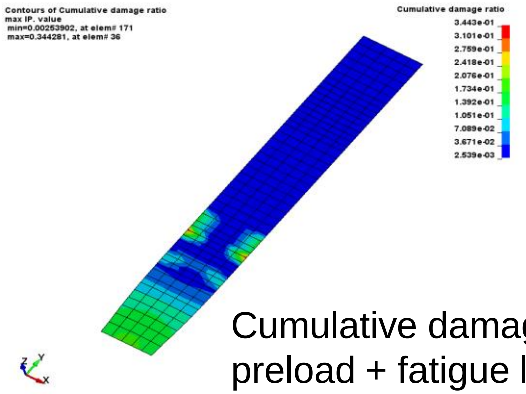
- *FATIGUE_SUMMATION
- To read in fatigue damage(d3ftg) defined by *INITIAL_FATIGUE_DAMAGE_RATIO and sum the damages to a total.



Damage from transient preload case (d3plot)



Damage ratio from fatigue load



Cumulative damage ratio from transient preload + fatigue load
*INITIAL_FATIGUE_DAMAGE_RATIO and *FATIGUE_SUMMATION

Time domain fatigue solver - Materials

- *MAT_ADD_FATIGUE - for S-N data (low stress, high cycle)

Card 1	1	2	3	4	5	6	7	8
Variable	MID	LCID	LTYPE	A	B	STHRES	SNLIMT	SNTYPE
Type	I	I	I	F	F	F	I	I
Default	none	-1	0	0.0	0.0	none	0	0

MID — Material ID for which the fatigue property applies

LCID — S-N fatigue curve ID:
- EQ.-1: S-N fatigue curve uses equation $NS^b = a$
- EQ.-2: S-N fatigue curve uses equation $\log(S) = a - b\log(N)$
- EQ.-3: S-N fatigue curve uses equation $S = a\,N^b$
- EQ.-4: S-N fatigue curve uses equation $S = a - b\log(N)$

LTYPE — Type of S-N curve:
- EQ.0: Semi-log interpolation (default)
- EQ.1: Log-log interpolation
- EQ.2: Linear-linear interpolation

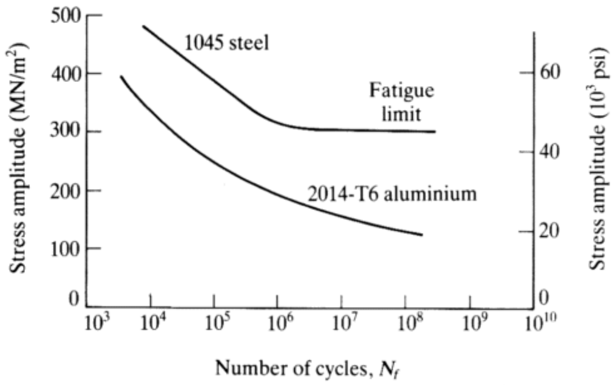
A — Material parameter a in S-N fatigue equation

B — Material parameter b in S-N fatigue equation

STHRES — Fatigue threshold stress

SNLIMT — SNLIMIT determines the algorithm used when stress is lower than STHRES.
- EQ.0: Use the life at STHRES
- EQ.1: *Ignored*
- EQ.2: Infinity

SNTYPE — Stress type of S-N curve.
- EQ.0: Stress range (default)
- EQ.1: Stress amplitude



$$\boxed{N \cdot S^m = a}$$

$$\boxed{\log(S) = a - b \cdot \log(N)}$$

Time domain fatigue solver - Materials

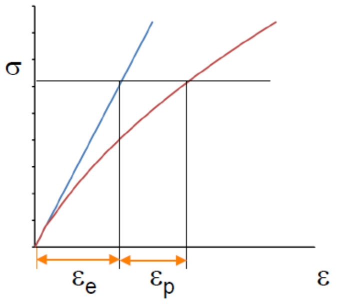
- *MAT_ADD_FATIGUE_EN - for E-N data (high stress, low cycle)

Card 1	1	2	3	4	5	6	7	8
Variable	MID	KP	NP	SIGMAP	EPSP	B	C	
Type	I	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	

MID	Material identification for which the fatigue property applies
KP	K', the cyclic strain hardening coefficient
NP	N', the cyclic strain hardening exponent
SIGMAP	σ_f', the fatigue strength coefficient
EPSP	ε_f', the fatigue ductility coefficient
BP	b', the fatigue strength exponent (Basquin's exponent)
CP	c', the fatigue ductility exponent (Coffin-Manson exponent)

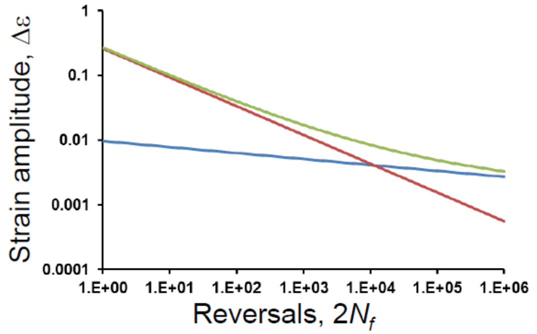
Cyclic stress strain curve

$$\boxed{\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{1/n'}}$$



Local strain–life relationship

$$\boxed{\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c}$$



Time domain fatigue solver - Materials

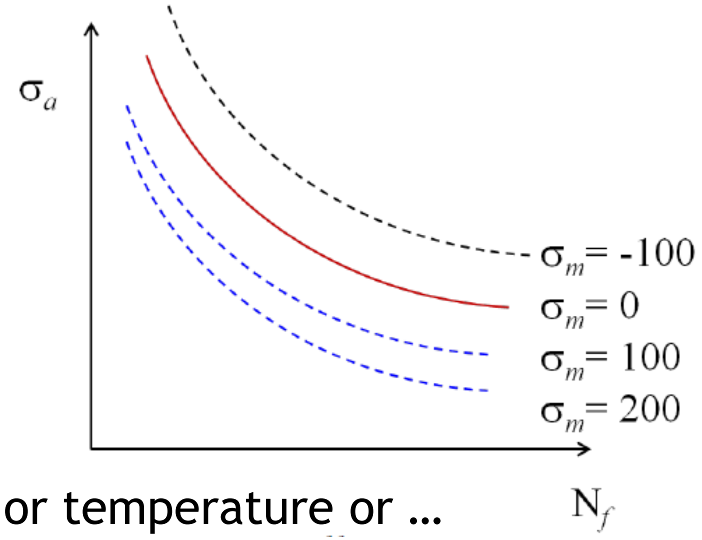
- *MAT_ADD_FATIGUE – Coming features

Card 1	1	2	3	4	5	6	7	8
Variable	MID	LCID	LTYPE	A	B	STHRES	SNLIMT	SNTYPE
Type	I	I	I	F	F	F	I	I
Default	none	-1	0	0.0	0.0	none	0	0

***DEFINE_TABLE**

```
*MAT_ADD_FATIGUE
$#      mid      lcid     ltype         a         b    sthres
       4075       100
*DEFINE_TABLE_2D
$#     tbid       sfa      offa
        100       1.0       0.0
$#                value                lcid
                 -100.0                1000
                    0.0                1001
                  100.0                1002
                  200.0                1003
*DEFINE_CURVE
$#     lcid      sidr       sfa       sfo      offa      offo
       1000         0       1.0       1.0       0.0       0.0
$ S-N fatigue curve for 1045 steel
$ semi-log interpolation
$#                   a1                  o1
                   10.0            46.41589
                  100.0            21.54435
```

SN curves with different mean stress



The value represents mean stress or temperature or …

Time domain fatigue solver – Output results

- *DATABASE_D3FTG
  - Fringe plot of fatigue results

Card 1	1	2	3	4	5	6	7	8
Variable	BINARY	DT						
Type	I	F						
Default	1	0.0						

*FATIGUE_D3PLOT & smp only today

BINARY — Flag for writing the binary plot file:

EQ.0: off

EQ.1: write the binary plot file d3ftg.

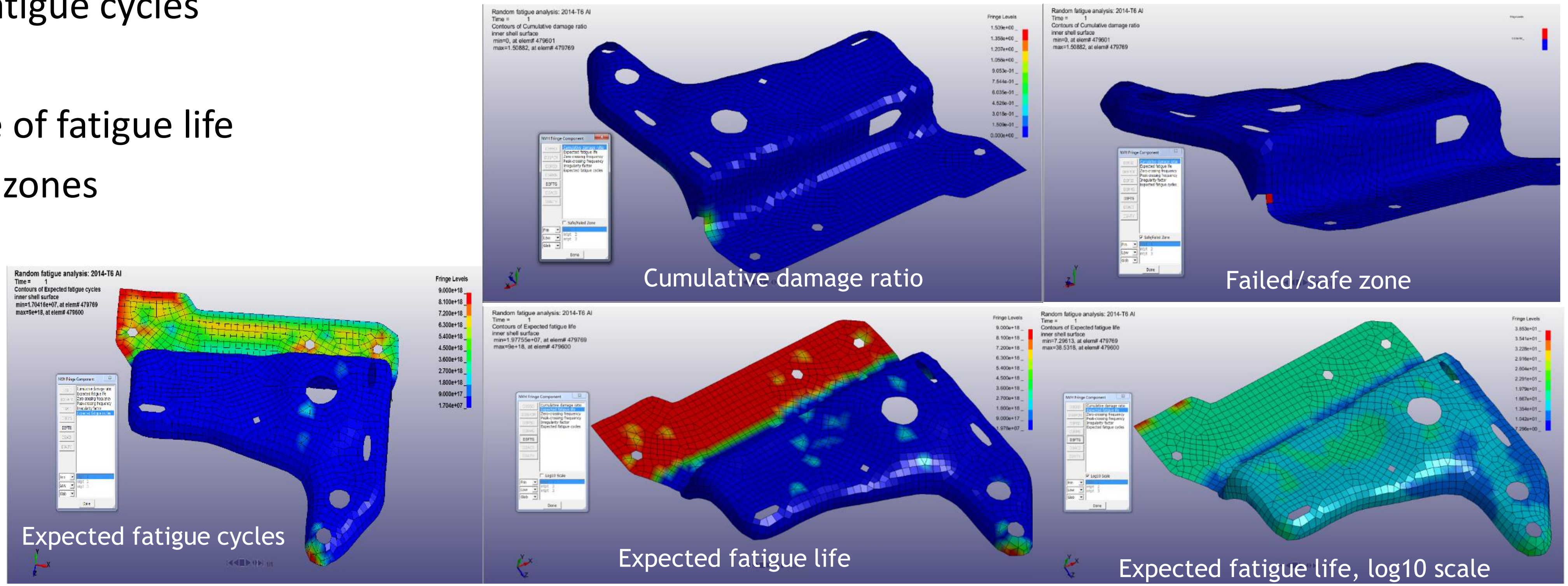
DT — Time interval between output states in time domain fatigue analysis (see *FATIGUE_{OPTION})

EQ.0.0: only fatigue results at the end of the analysis are output.

Time domain fatigue solver – Output results

- Fatigue results available
  - Cumulative damage ratio
  - Expected fatigue life
  - Expected fatigue cycles

  Also
  - Log10 scale of fatigue life
  - Failed/safe zones



Time domain fatigue analysis – What is needed?

Model & Load case

*CONTROL_...
*DATABASE_...
*NODE
*ELEMENT_...
*SECTION_..
*PART_...
*MAT_...
*LOAD_...
*...
*...
...

*FATIGUE_D3PLOT/ELOUT

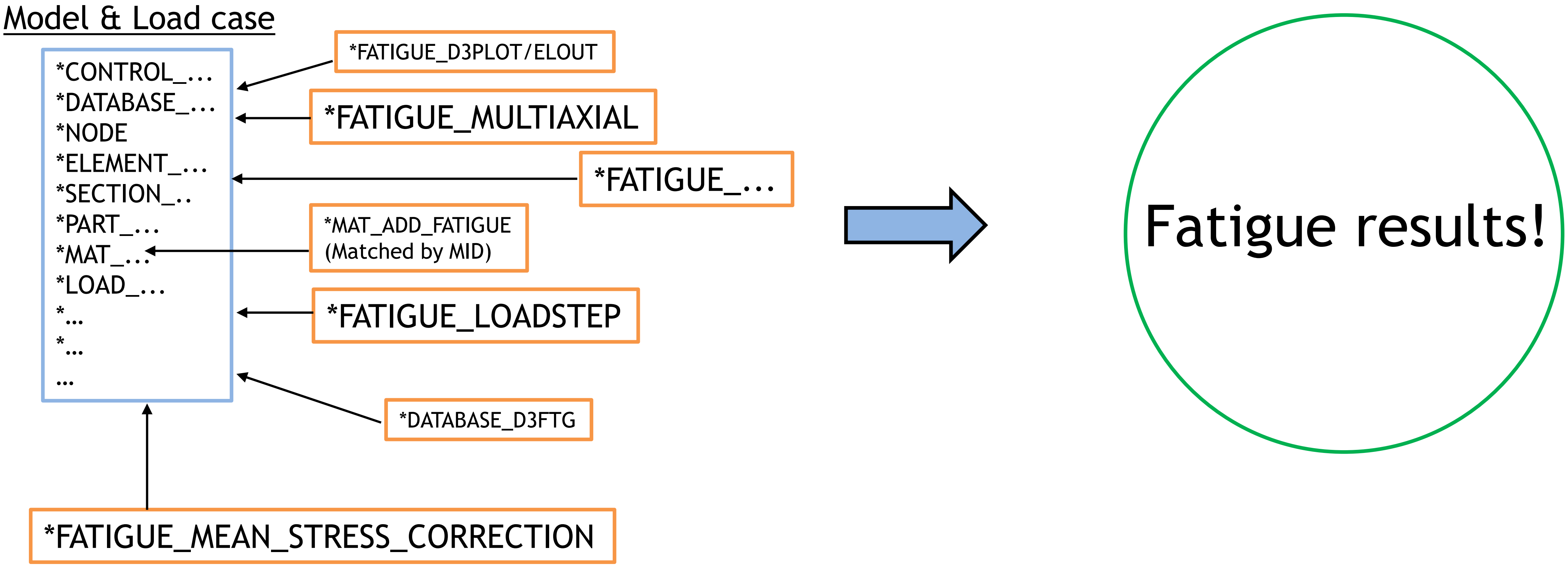
*MAT_ADD_FATIGUE
(Matched by MID)

*DATABASE_D3FTG

Fatigue results!

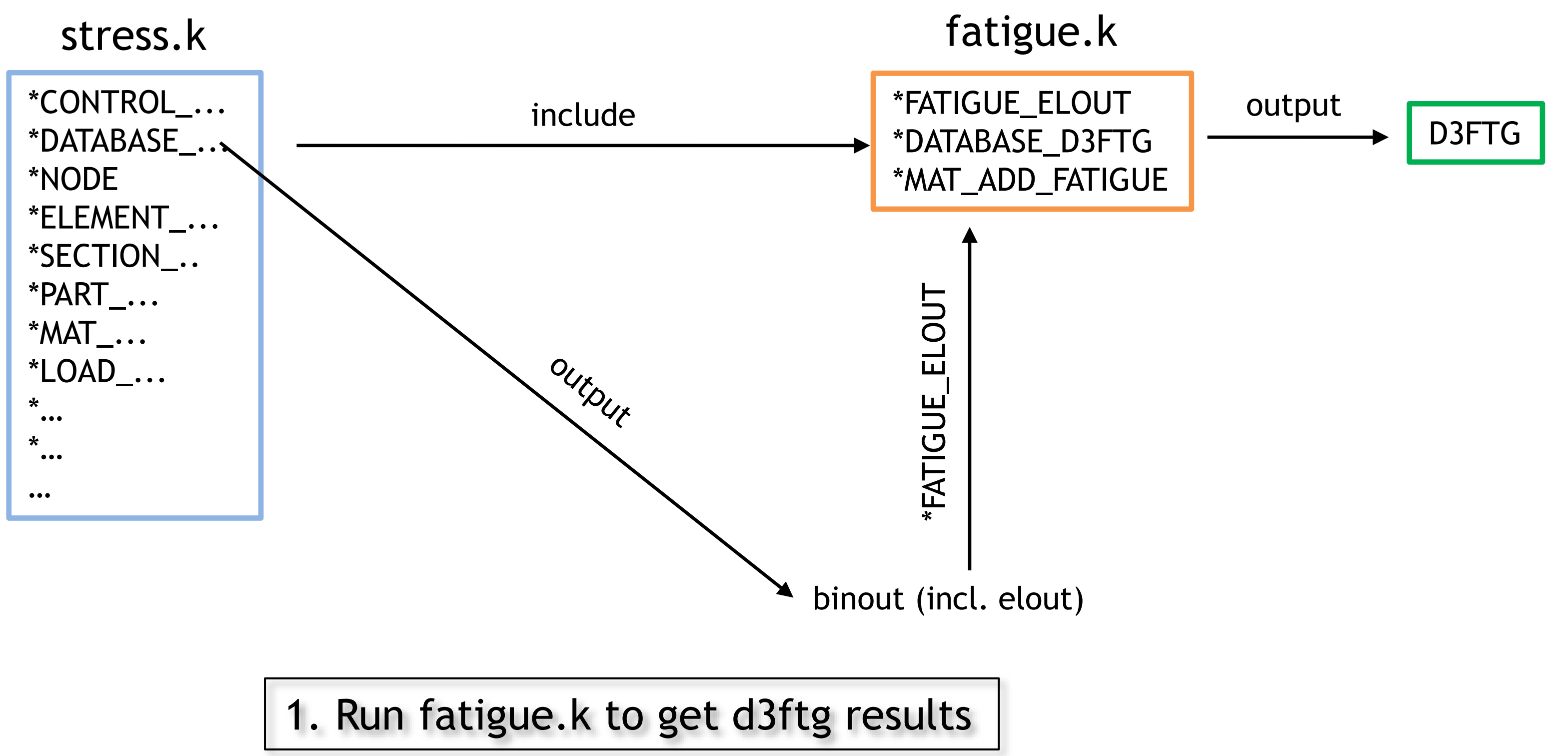
Time domain fatigue analysis – What is needed?

From this point you can choose to further refine and/or add on features to the fatigue analysis.



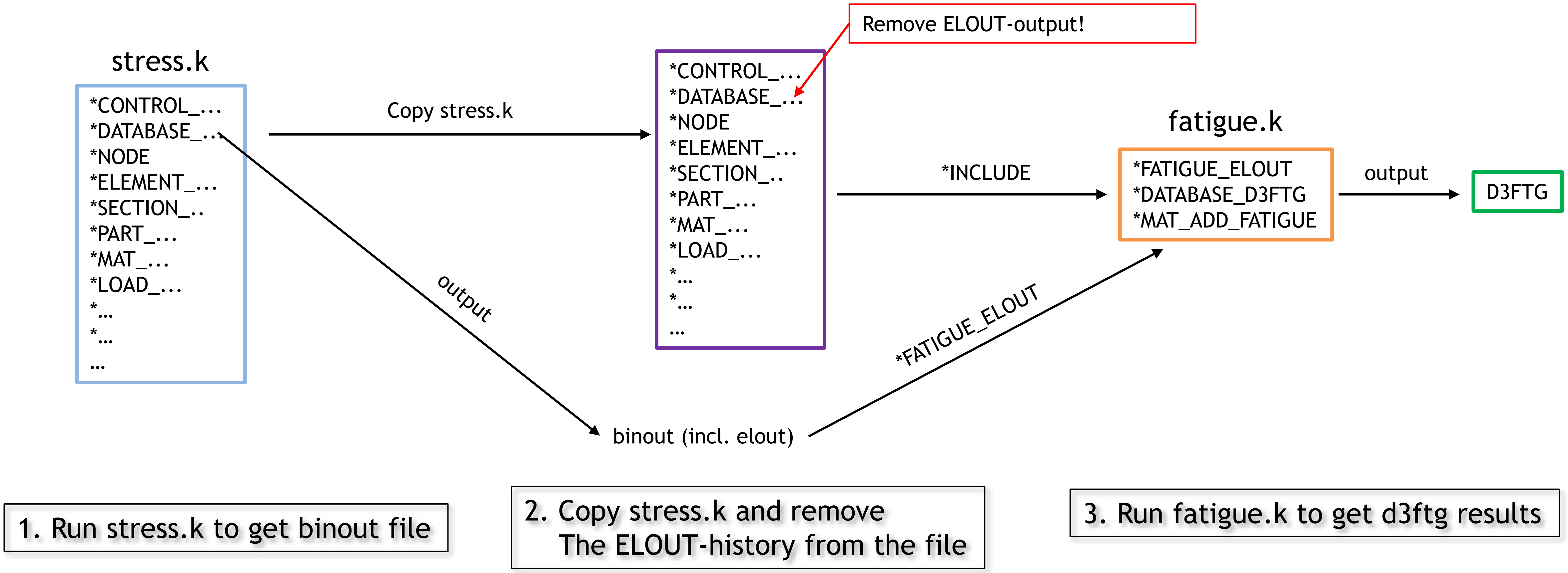
Example – Notched bar

- In this example the restart option is **not** used.
- It is then suggested that the fatigue-keywords are defined in a separate 'run-file', fatigue.k



Example – Notched bar

- In this example the restart option is used.
- It is then suggested that the fatigue-keywords are defined in a separate 'run-file', fatigue.k



Example – Notched bar

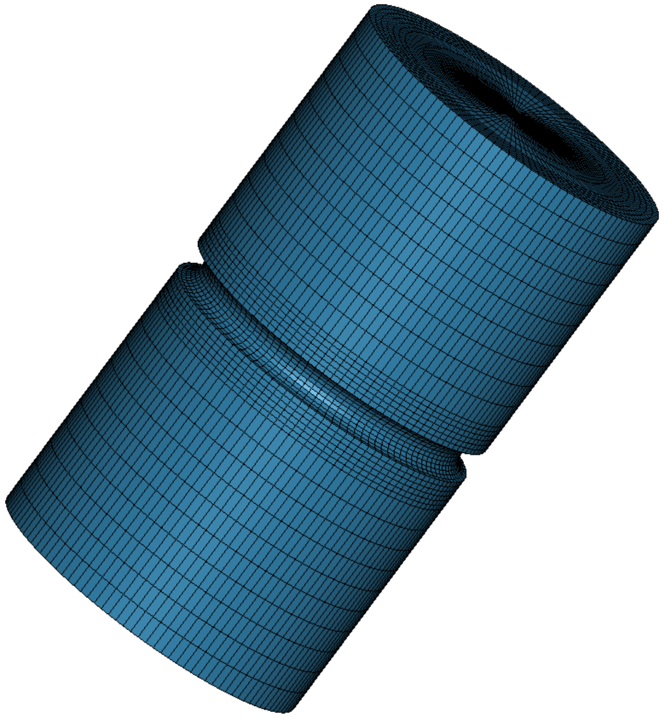
- Model
  - ELFORM = -1
  - *MAT_ELASTIC

*MAT_ELASTIC_(TITLE) (001)   (1)

TITLE

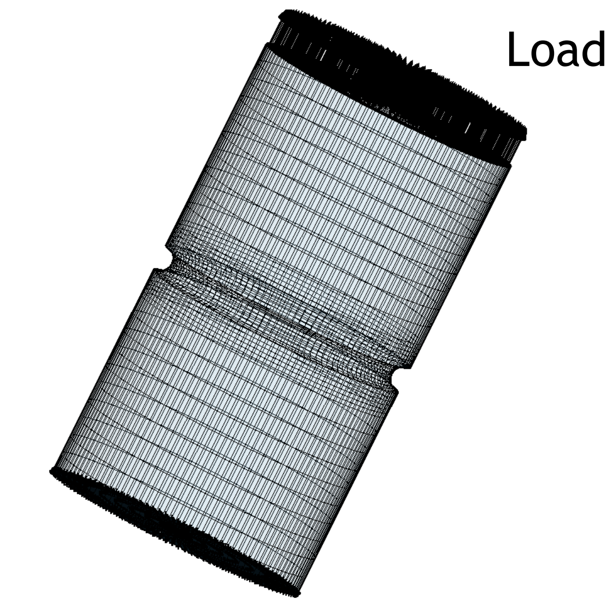
Generic steel

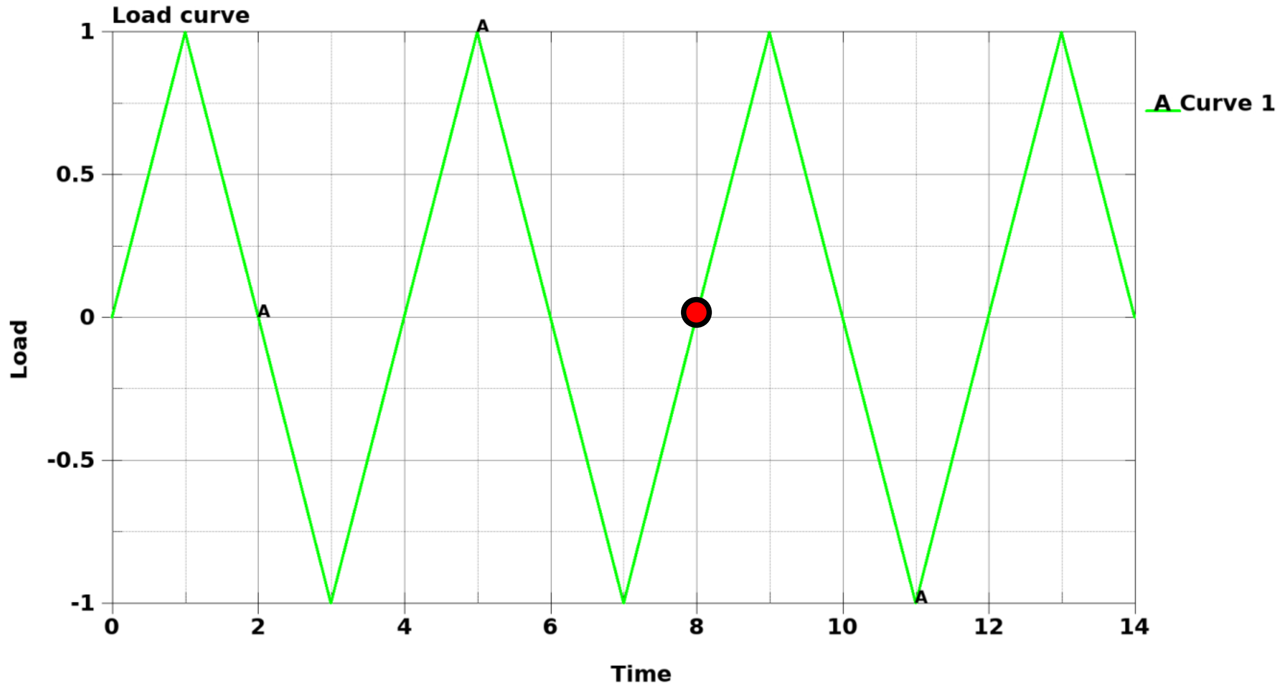
MID	RO	E	PR	DA	DB	NOT USED
2	7.850e-09	2.100e+05	0.3000000	0.0	0.0	0.0



Example – Notched bar

- Load case
  - Fixed BC
  - Fully reversed loading (no mean stress influence)





Termination time = 8 s

Example – Notched bar

- Fatigue set-up

Stress based

Restart with ELOUT-data

*FATIGUE_ELOUT (1)

1	STRSN	INDEX	RESTRT	TEXPOS	DMGMIN
	0	1	1	0.0	0.0

2	FILENAME	
	binout0000	Browse

Max. principal stress

*DATABASE_D3FTG (1)

1	BINARY	DT
	1	0.1000000

*FATIGUE_D3PLOT & smp only today

Model & Load case

*CONTROL_…
*DATABASE_…
*NODE
*ELEMENT_…
*SECTION_..
*PART_…
*MAT_…
*LOAD_…
*…
*…
…

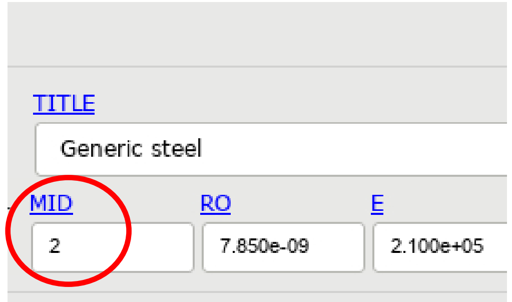
*FATIGUE_D3PLOT/ELOUT

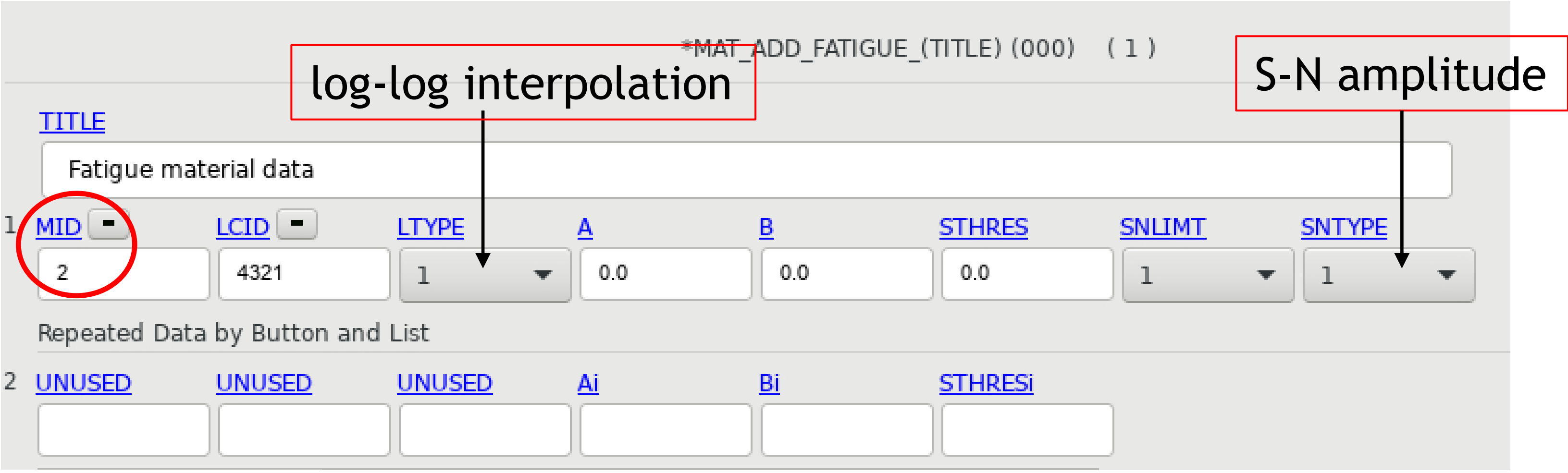
*MAT_ADD_FATIGUE
(Matched by MID)

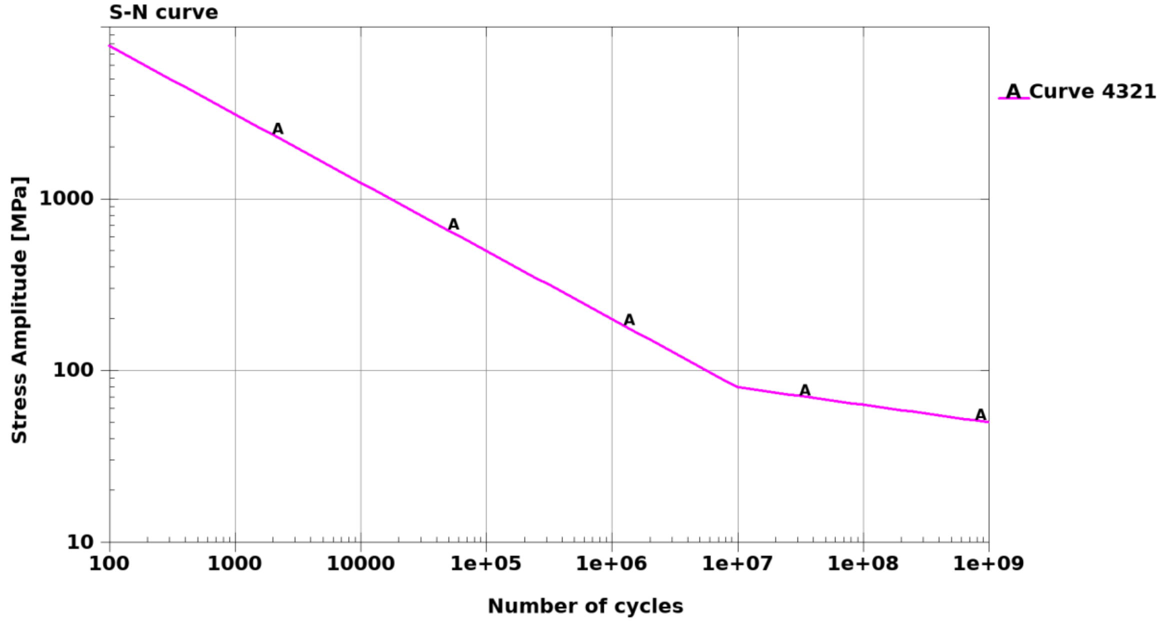
*DATABASE_D3FTG

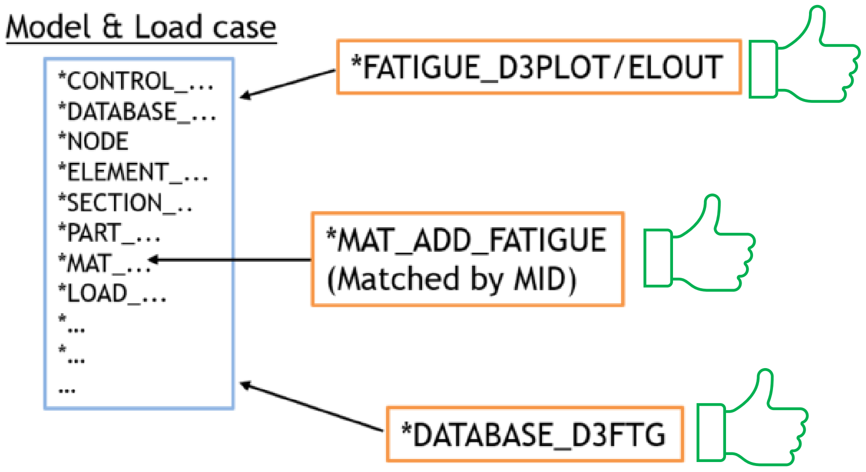
Example – Notched bar

- Fatigue material data





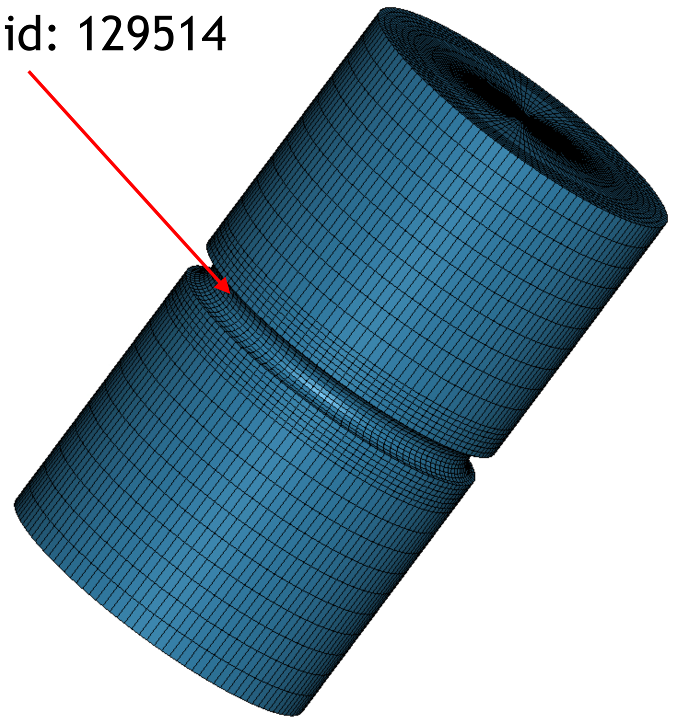


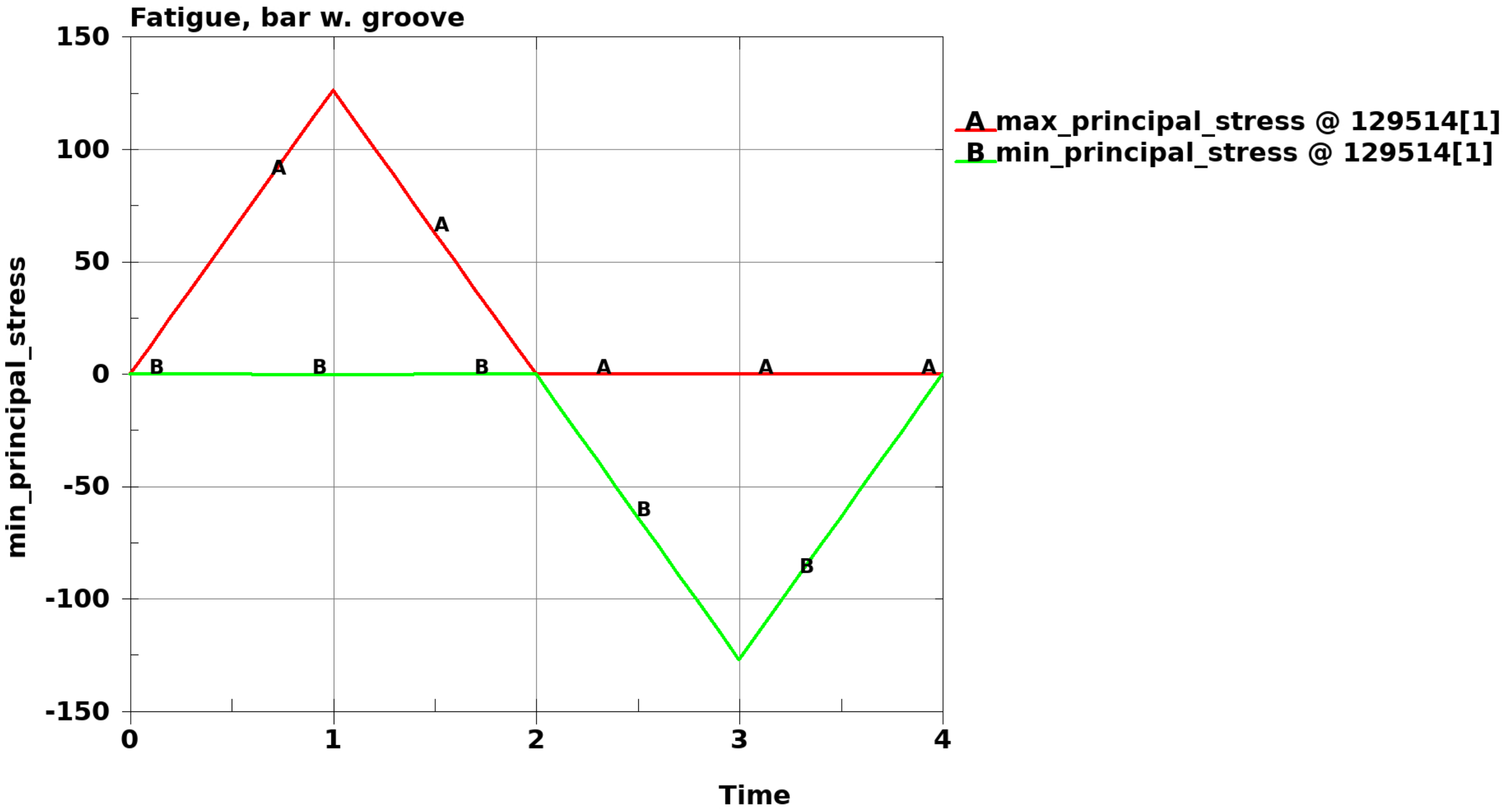


Example – Notched bar

- Run stress.k
- Check binout/elout

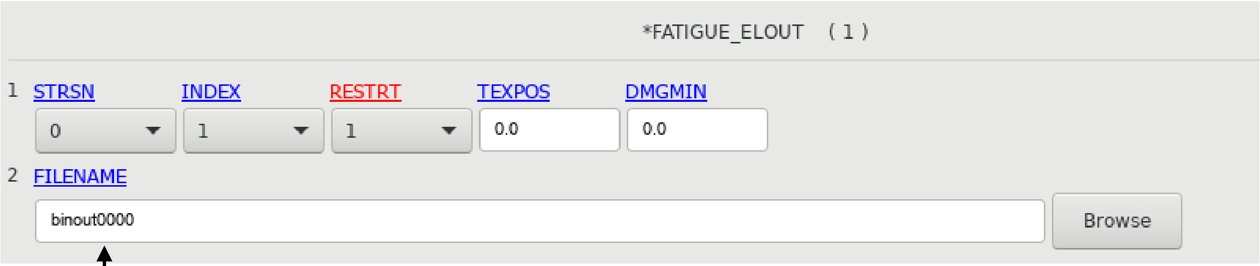
Element id: 129514





Example – Notched bar

- Copy stress.k



binout in run-directory!

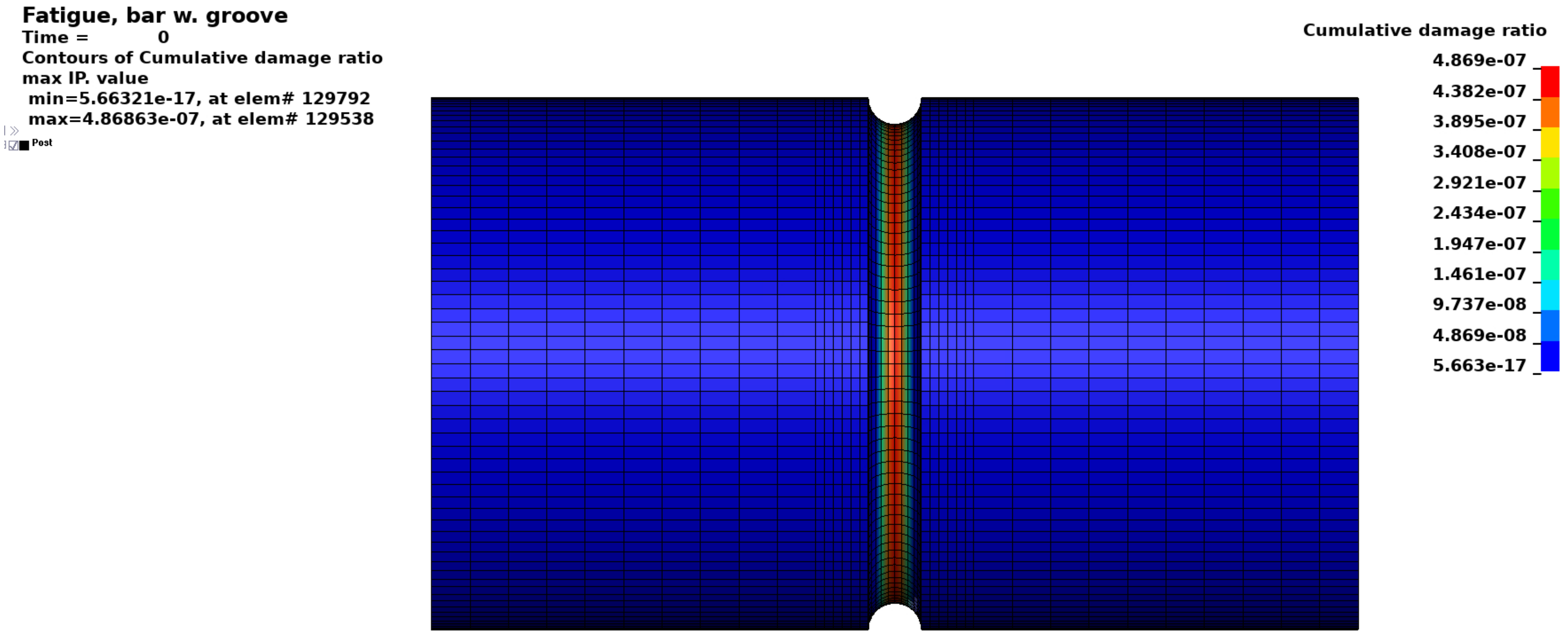
ELOUT **not** active!

Copy of stress.k

```
$*DATABASE_BNDOUT
$#        dt    binary      lcur     ioopt
$       0.01         0         0         1
$*DATABASE_ELOUT
$#        dt    binary      lcur     ioopt   option1   option2   option3   option4
$       0.01         2         0         1         0         0         0         0
$*DATABASE_GLSTAT
$#        dt    binary      lcur     ioopt
$       0.01         0         0         1
$*DATABASE_SPCFORC
$#        dt    binary      lcur     ioopt
$       0.01         0         0         1
$*DATABASE_HISTORY_SHELL_SET
$#       id1       id2       id3       id4       id5       id6       id7       id8
$          6         0         0         0         0         0         0         0
$*DATABASE_HISTORY_SOLID_SET
$#       id1       id2       id3       id4       id5       id6       id7       id8
$          5         0         0         0         0         0         0         0
*CONTROL_ACCURACY
$#       osu       inn    pidosu      iacc
           1         4         0         1
*CONTROL_ENERGY
$#      hgen      rwen    slnten     rylen     irgen
           2         2         2         2         2
```

Example – Notched bar

- Run fatigue.k
- View results in D3FTG



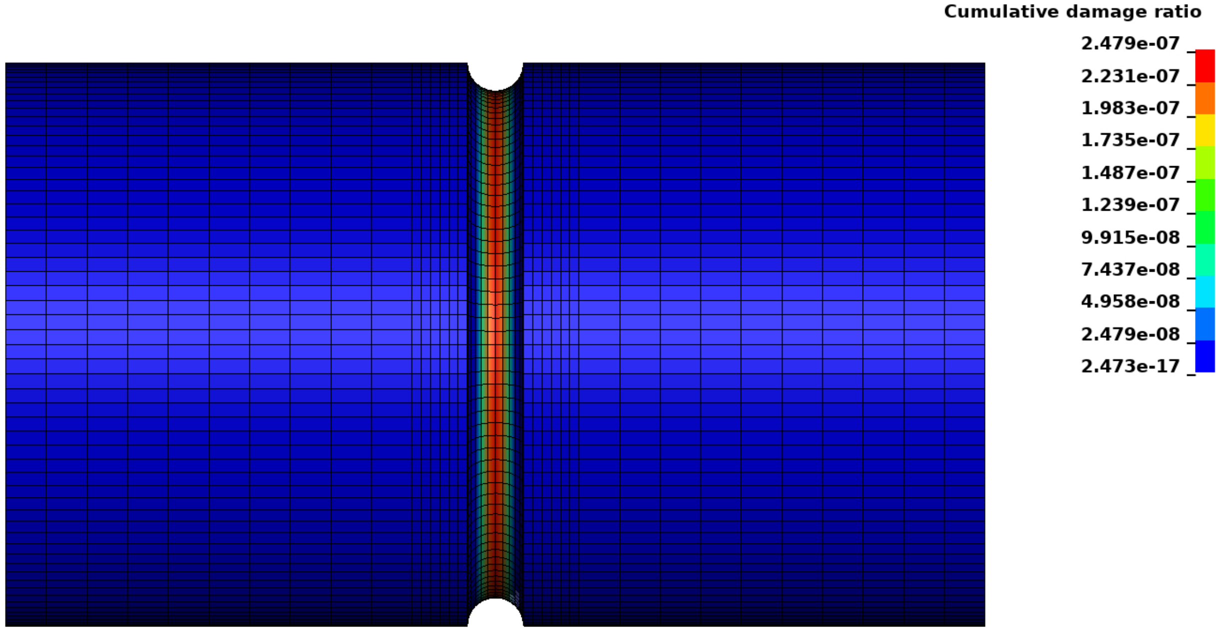
Example – Notched bar

- D3FTG

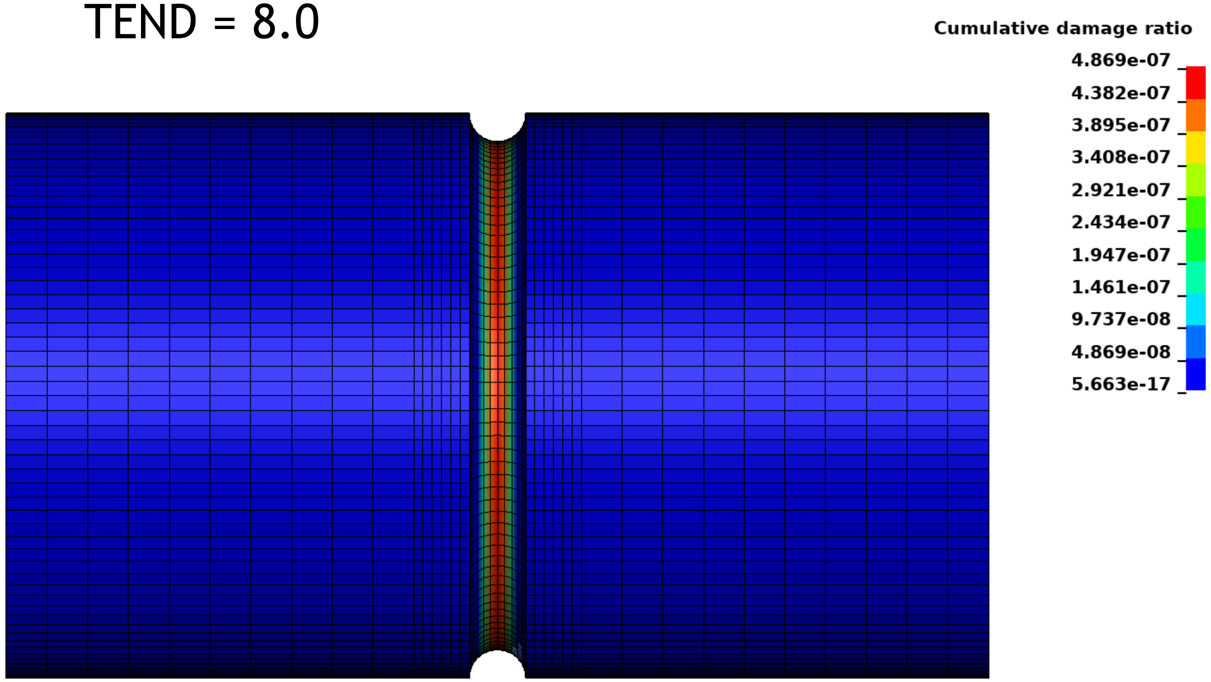
*FATIGUE_LOADSTEP

Card 1	1	2	3	4	5	6	7	8
Variable	TSTART	TEND	TEXPOS					
Type	F	F	F					
Default	none	none	0.0					

TSTART = 0.0
TEND = 4.0



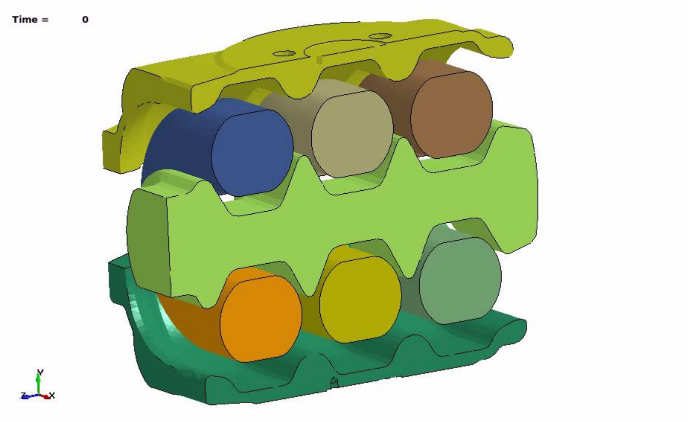
TSTART = 0.0
TEND = 8.0

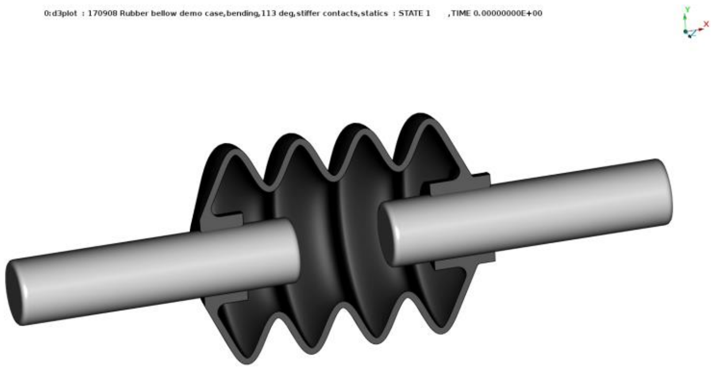


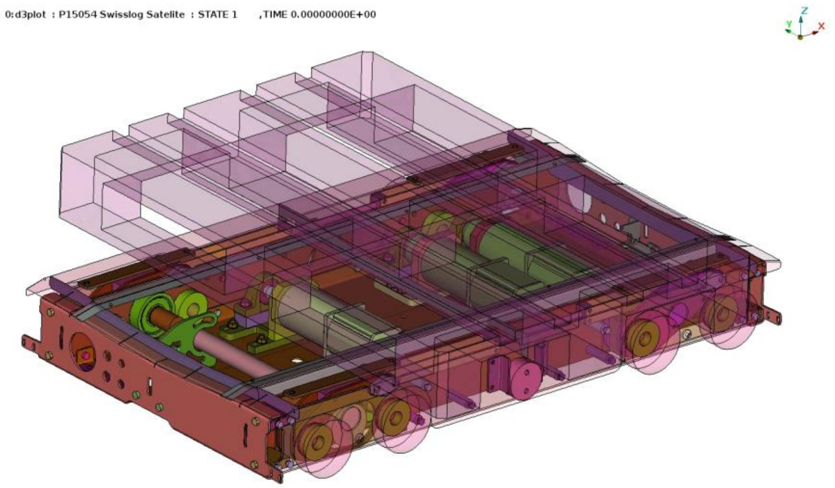
Last words

- Fatigue analysis of models containing…
  - Contacts
  - High order elements
  - Rubbers
  - Prestress
    - Inteference
    - Initial stress/force

… is now possible!







Courtesy of Kongsberg Automotive, Thule Sweden, Swisslog, Volvo GTT and Dellner Couplers

Useful sites - User support

- support@dynamore.se
  - Customer support
- www.dynaexamples.com
  - LS-DYNA example-models for different disciplines
- www.dynalook.com
  - Papers from LS-DYNA User’s conferences
- www.dynamore.se/en/training/seminars
  - Seminar and Webinar schedules

Thank you!

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