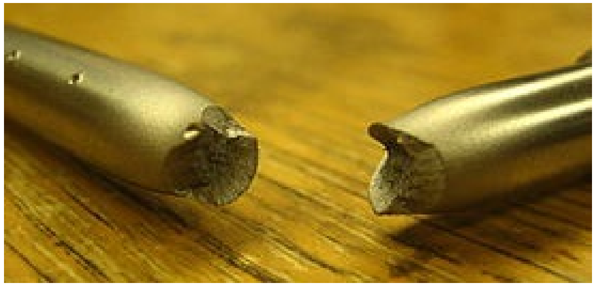
German LS-DYNA Forum 2018

Updated fatigue analysis with LS-DYNA®



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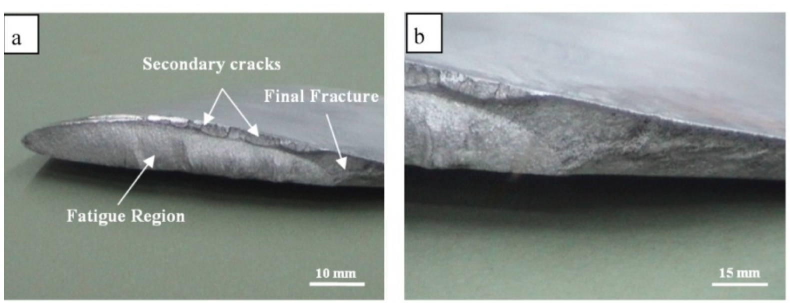
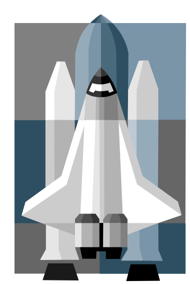
Outline

1) Introduction

What is fatigue?

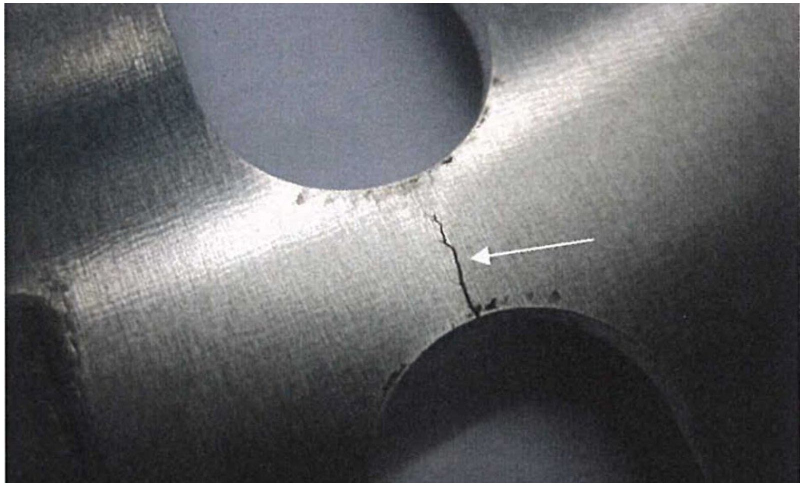
- ❑ Fatigue is a process in which damage accumulates due to the repetitive application of loads that may be well below the yield point.
- ❑ Fatigue is a complex process involving many steps but it can be broken down into initiation and propagation of fatigue cracks.
- ❑ It is estimated that fatigue failures are responsible for 90% of all metallic failures.
- ❑ For many years, fatigue has been a significant and challenging problem for engineers, especially for those who design structures such as aircrafts, railroad vehicles, automotives, bridges, pressure vessels, and cranes.





How to run fatigue analysis?

- Fatigue analysis can be performed in time domain and frequency domain.
- Two frequency domain approaches based on **random vibration theory and steady state vibration (SSD) theory** have been implemented in LS-DYNA for fatigue and durability analysis.
- Recently we implemented time domain fatigue, including one **based on stress** and the other **based on strain.**



List of LS-DYNA keywords for fatigue analysis

*FATIGUE

*FATIGUE_MEAN_STRESS_CORRECTION

*FATIGUE_MULTIAXIAL

*FATIUGE_SUMMATION

*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE

*FREQUENCY_DOMAIN_SSD_FATIGUE

*DATABASE_FREQUENCY_BINARY_D3FTG

*INITIAL_STRESS_SOLID (SHELL, TSHELL, BEAM)

*INITIAL_FATIGUE_DAMAGE_RATIO

*MAT_ADD_FATIGUE

2) S-N curve and E-N curve

S-N curve (high cycle, low stress)

***MAT_ADD_FATIGUE**

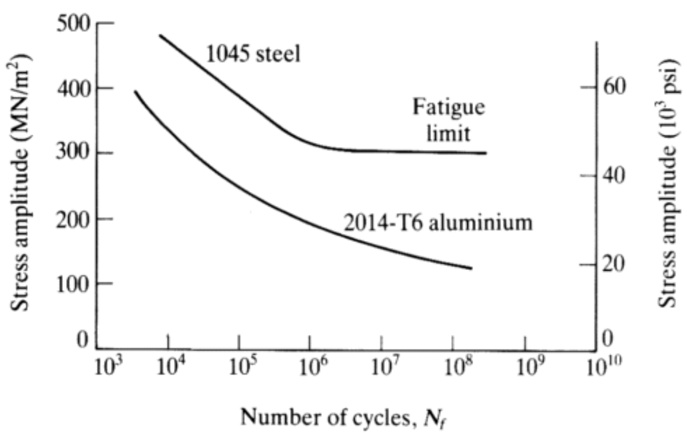
Card 1	1	2	3	4	5	6	7	8
Variable	MID	LCID	LTYPE	A	B	STHRES	SNLIMT	SNTYPE
Type	I	I	I	F	F	F	I	I
Default	none	-1	0	0.0	0.0	none	0	0

- By ***DEFINE_CURVE**
- By equation

$$N \cdot S^m = a$$

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

N: number of cycles for fatigue failure
S: stress



Source of information: http://www.efunda.com

- Fatigue life of stress below fatigue threshold

SNLIMT *Fatigue life for stress lower than the lowest stress on S-N curve.*
EQ.0: use the life at the last point on S-N curve
EQ.1: extrapolation from the last two points on S-N curve
EQ.2: infinity.

Multi S-N curves *(for multiple mean stress)*

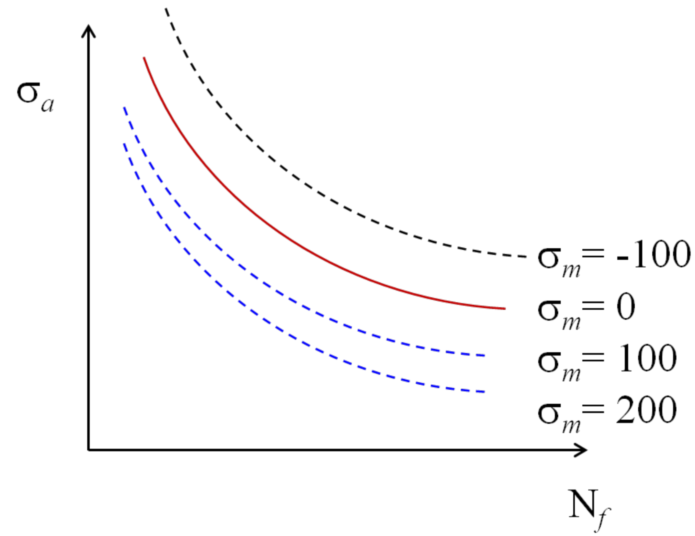
*MAT_ADD_FATIGUE

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



This parameter can be mean stress, temperature … (potentially)

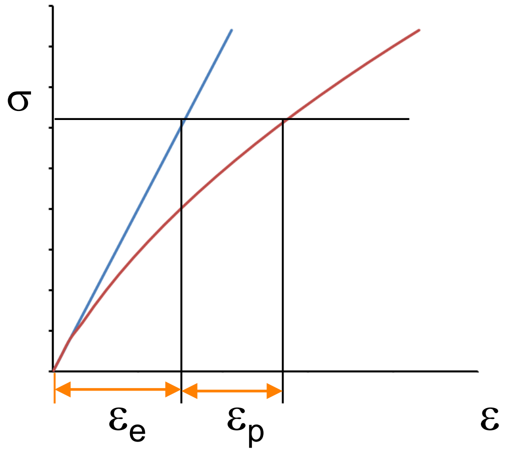
E-N curve *(low cycle, high stress)*

*MAT_ADD_FATIGUE_EN

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	

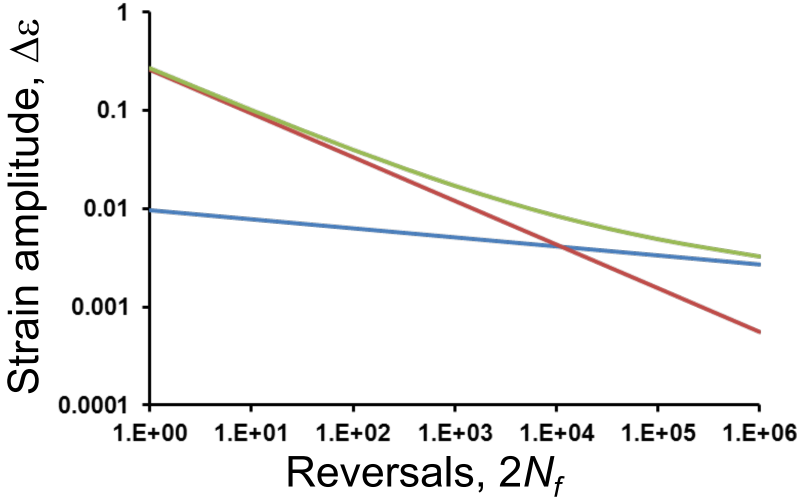
Cyclic stress strain curve

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



Local strain–life relationship

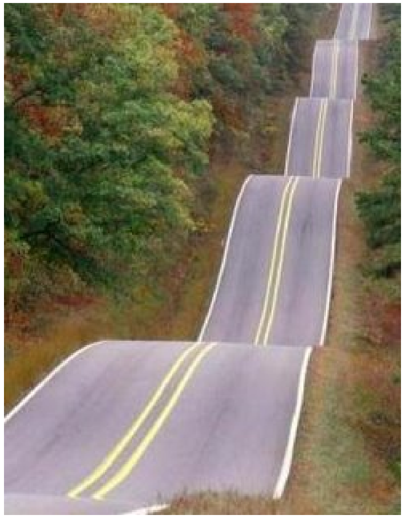
$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

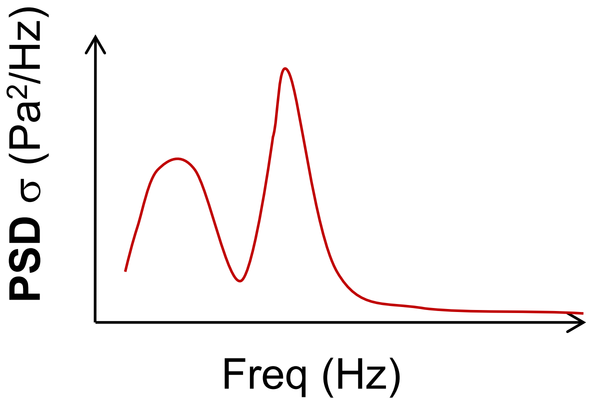


3) Random vibration fatigue

Introduction

- Structures and mechanical components are frequently subjected to the oscillating loads which are random in nature. Random vibration theory has been introduced for more than three decades to deal with all kinds of random vibration behavior.
- The stress PSD represents the frequency domain approach input into the fatigue. This is a scalar function that describes how the power of the time signal is distributed among frequencies.





Overview of random fatigue feature

- Keyword *FREQUENCY_DOMAIN_RANDOM_VIBRATION_*FATIGUE*
- Calculate fatigue life of structures under random vibration
- Based on S-N fatigue curve
- Based on probability distribution & Miner's Rule of Cumulative Damage Ratio

$$R = \sum_{\sigma_i} \frac{n_i}{N_i}$$

- Schemes:
  - ✓ *Steinberg's Three-band technique considering the number of stress cycles at the 1σ, 2σ, and 3σ levels.*
  - ✓ *Dirlik method based on the 4 Moments of PSD.*
  - ✓ *Narrow band method*
  - ✓ *Wirsching method*
  - ✓ …

PDF
(*probability density function*)

Keywords

FREQUENCY_DOMAIN_RANDOM_VIBRATION_*FATIGUE

Additional card for FATIGUE keyword options.

Card 6	1	2	3	4	5	6	7	8
Variable	MFTG	NFTG	SNTYPE	TEXPOS	STRSF	INFTG		
Type	I	I	I	F	F	I		
Default	0	1	0	0.0	0.0	0		

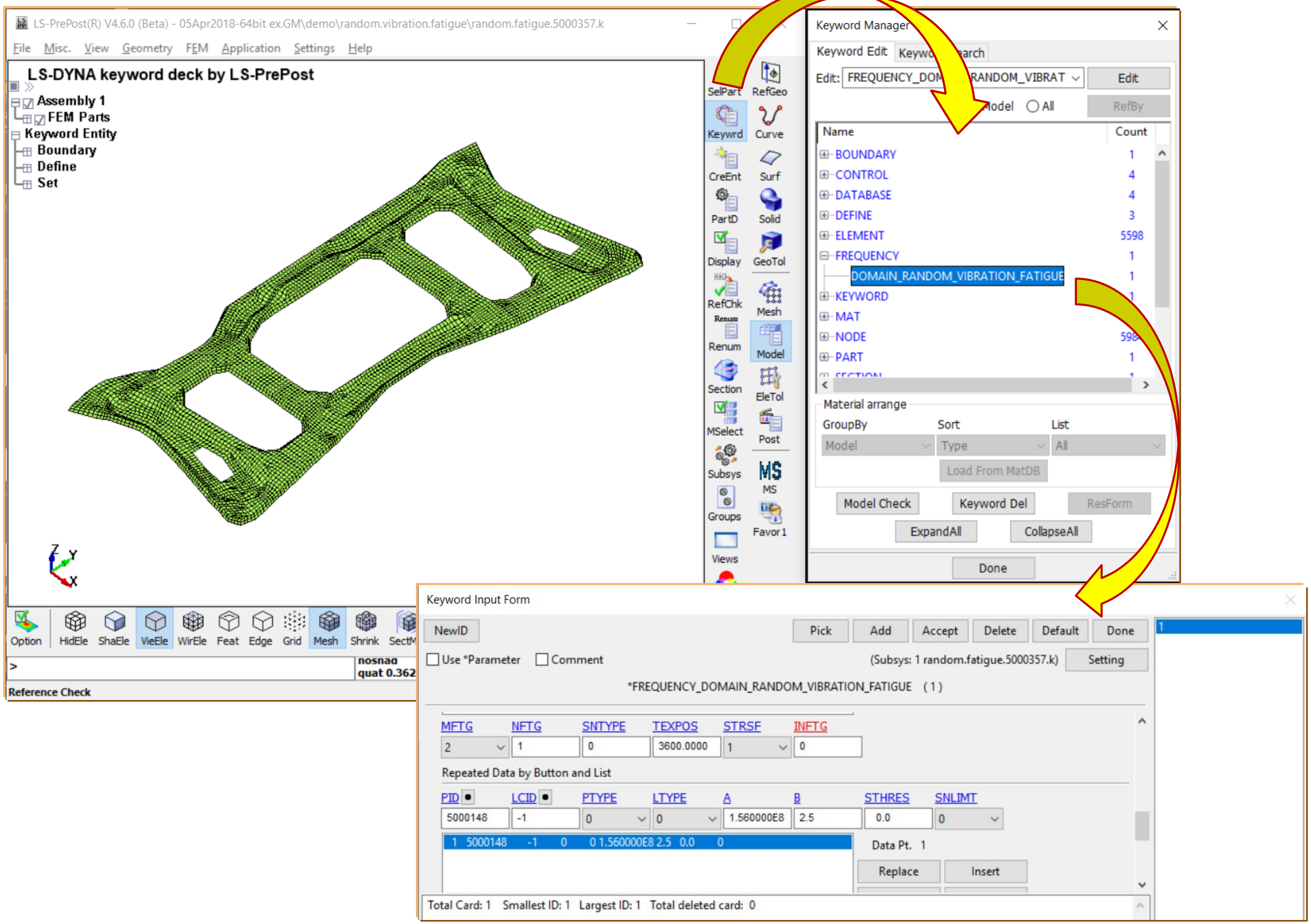
Repeat Card 7 "NFTG" times if multiple S-N fatigue curves are present.

Card 7	1	2	3	4	5	6	7	8
Variable	PID	LCID	PTYPE	LTYPE	A	B	STHRES	SNLIMT
Type	I	I	I	I	F	F	F	I
Default			0	0			0.	0

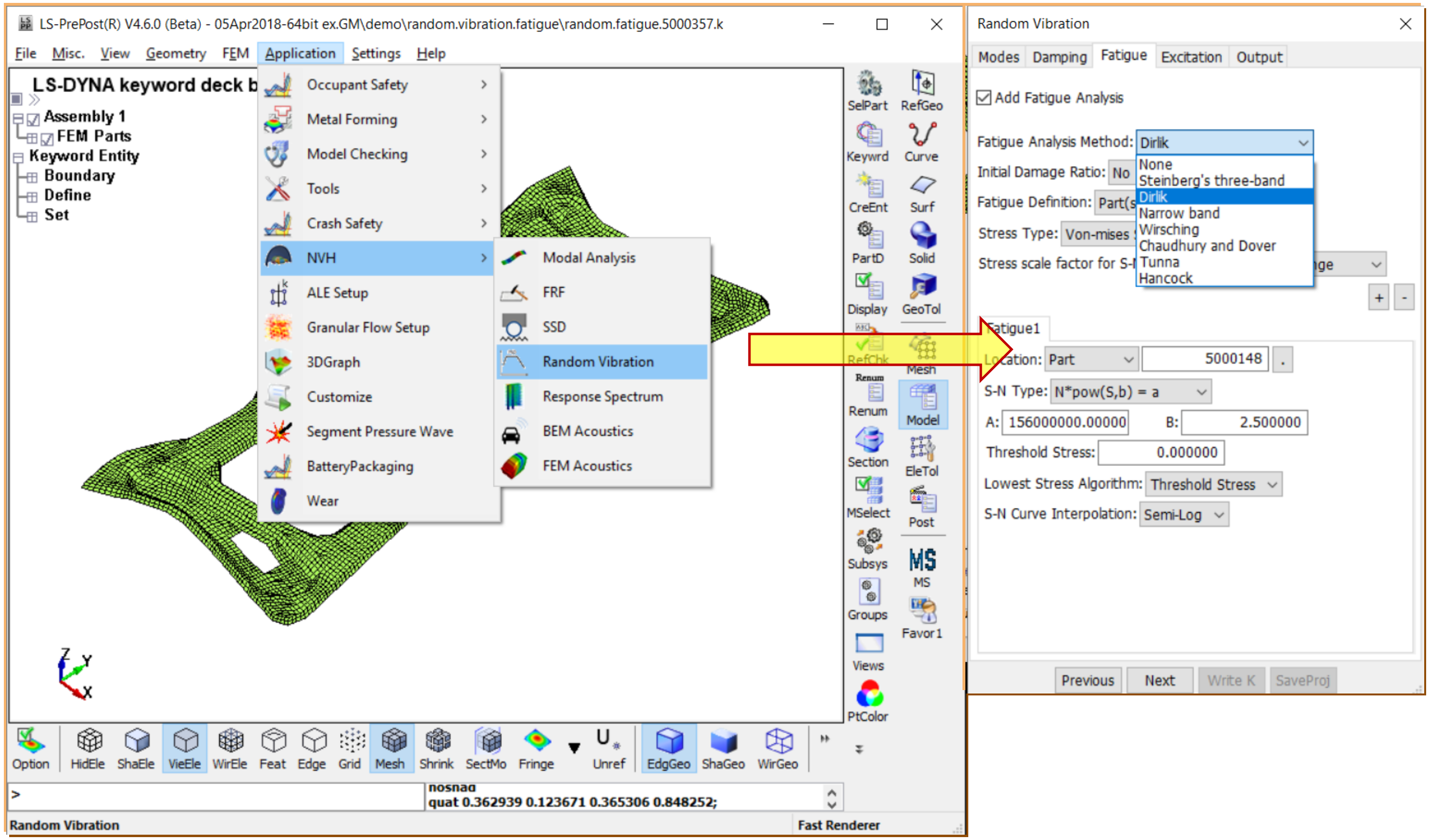
*MAT_ADD_FATIGUE (used if NFTG=-999)

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		0	0.0	0.0	none	0	0

EZ set up by "keyword manager"



EZ set up by "Application"



Analysis methods

- Steinberg's Three band technique

  Assuming no stress cycle beyond 3σ values.

- Dirlik method

  Dirlik, 1985, empirical closed form solution, using the Monte Carlo technique; widely applicable

- Narrow band method

  Bendat, 1964, applicable for narrow band fatigue only

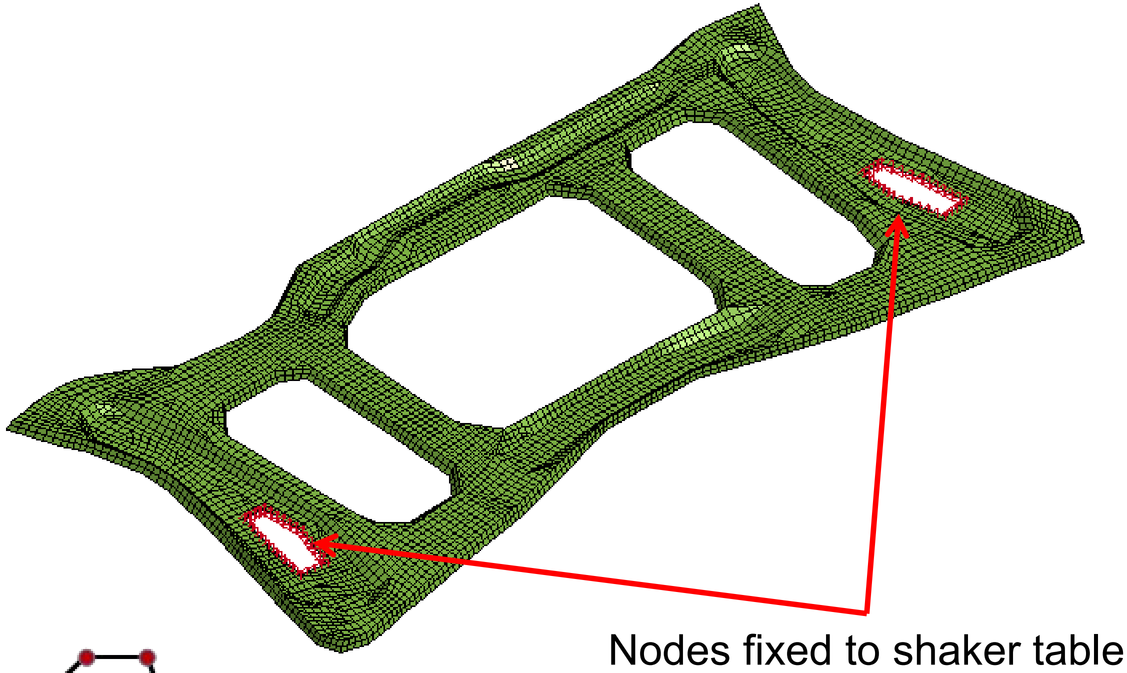
- Wirsching method
- Chaudhury and Dover method
- Tunna method
- Hancock method
- Lalanne method

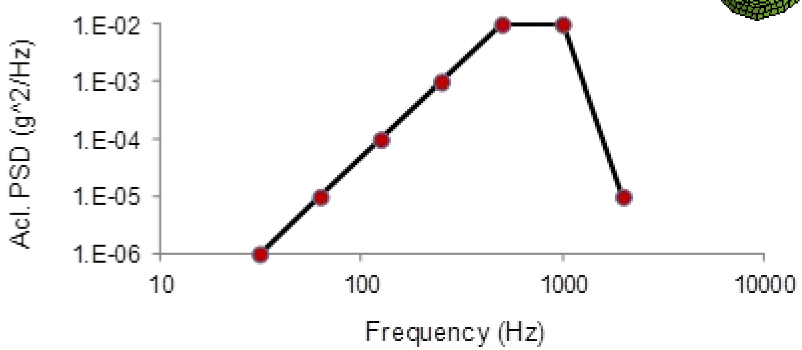
The Winsching, Chaudhury, Tunna and Hancock methods are based on empirical correction factors for the narrow band method, and are applicable to different industries.

Examples of random vibration fatigue

Steel
$\rho = 7890\ \text{kg/m}^3$
$E = 2.1\times10^5\ \text{MPa}$
$\nu = 0.3$

Time of exposure: 1 hour



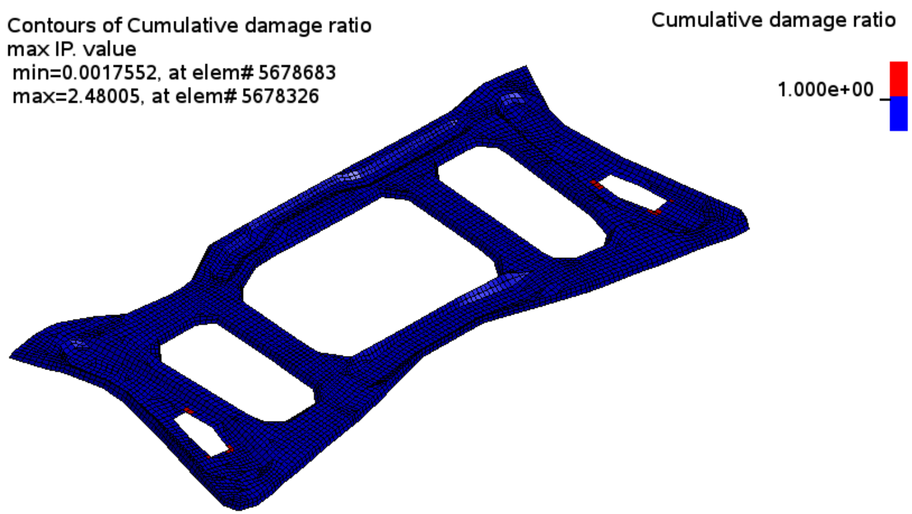


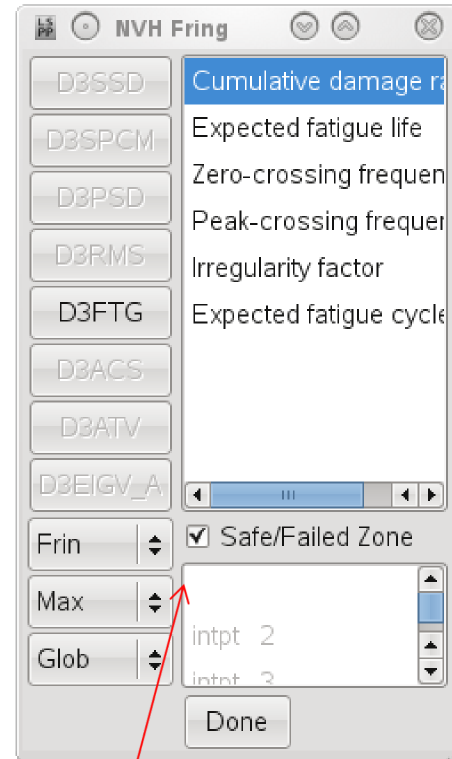
Z-acceleration PSD

S-N curve is defined by

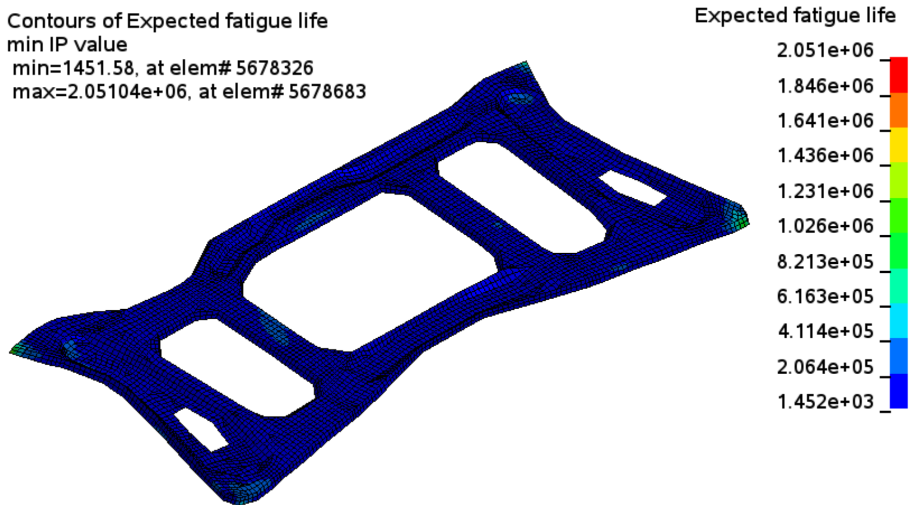
$$N \cdot S^{2.5} = 1.56\times10^{8}$$

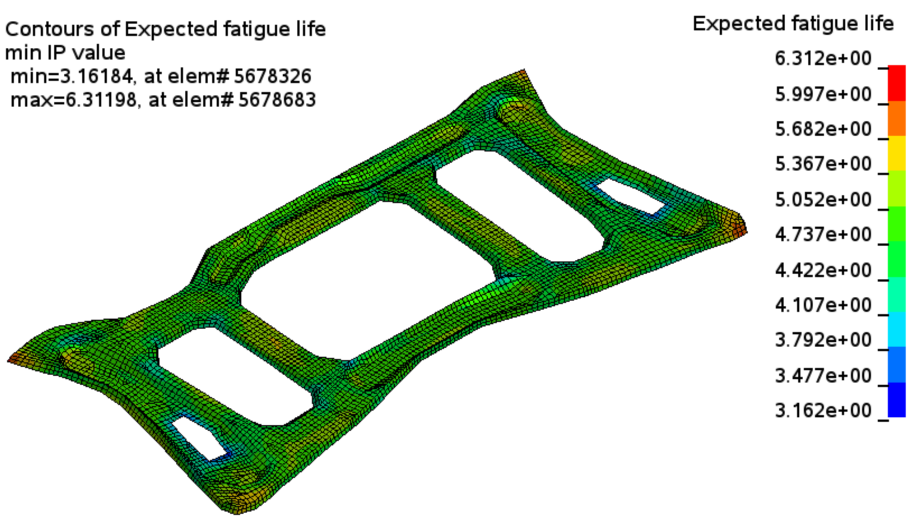
Result file: d3ftg (accessible to LS-PrePost)

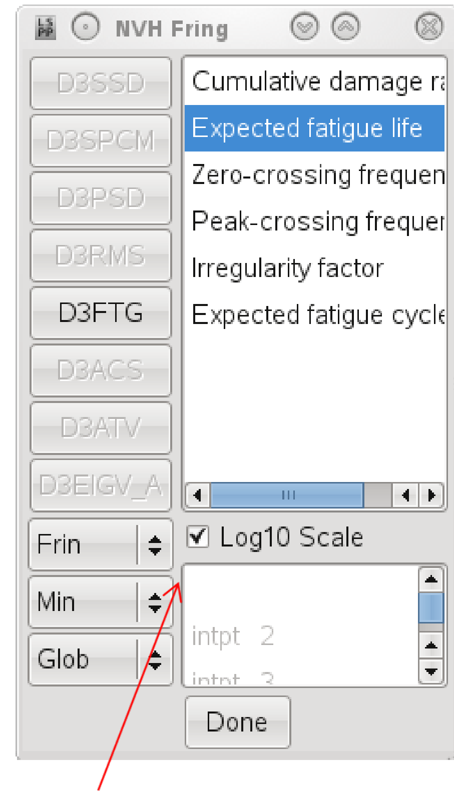




The Safe/Failed zone function can help user to locate the fatigue failed zone quickly.

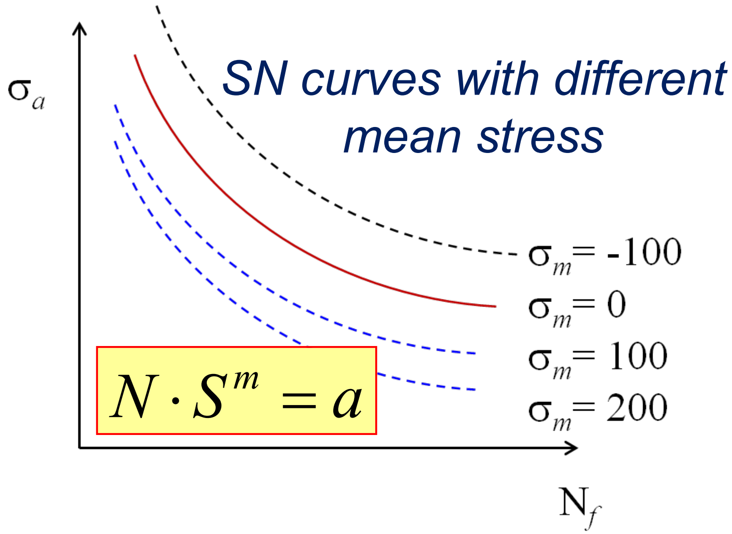






The log10 scale can be helpful to show the fringe of expected fatigue life, which may have a huge span of values.

Mean stress correction



***FATIGUE_MEAN_STRESS_CORRECTION**

Card 1	1	2
Variable	METHOD	
Type	I	

Card 2	1	2
Variable	MID	SIGMA
Type	I	F

METHOD
EQ.0: Goodman equation
EQ.1: Soderberg equation
EQ.2: Gerber equation
EQ.3: Goodman tension only
EQ.4: Gerber tension only
EQ.11: Morrow equation
EQ.12: Smith-Watson-Topper equation

- ❑ Completely reversed tests
- ❑ Mean stress correction equations

Goodman

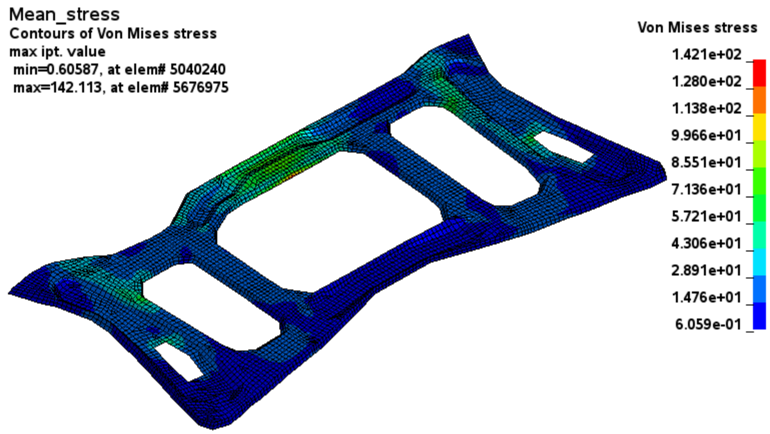
$$S = \frac{\sigma_a}{1 - \sigma_m / \sigma_u}$$

Soderberg

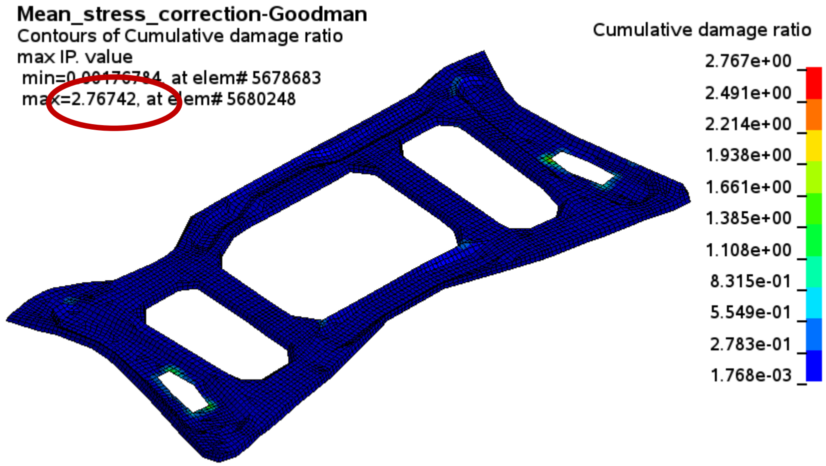
$$S = \frac{\sigma_a}{1 - \sigma_m / \sigma_y}$$

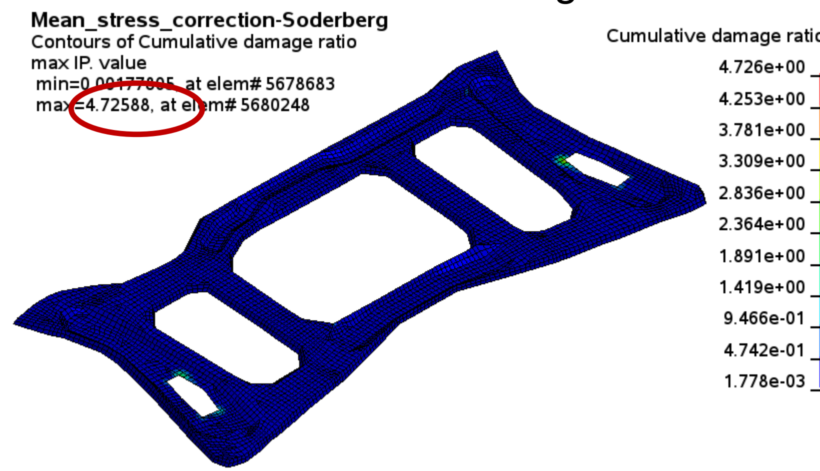
Gerber

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



- ✓ Mean stress is introduced by ***INITIAL_STRESS_SHELL** ***INITIAL_STRESS_SOLID …**
- ✓ Mean stress correction method is set by ***FATIGUE_MEAN_STRESS_CORRECTION**
- ✓ Mean stress can come from thermal stress, gravity loading, or residual stress from metal forming…

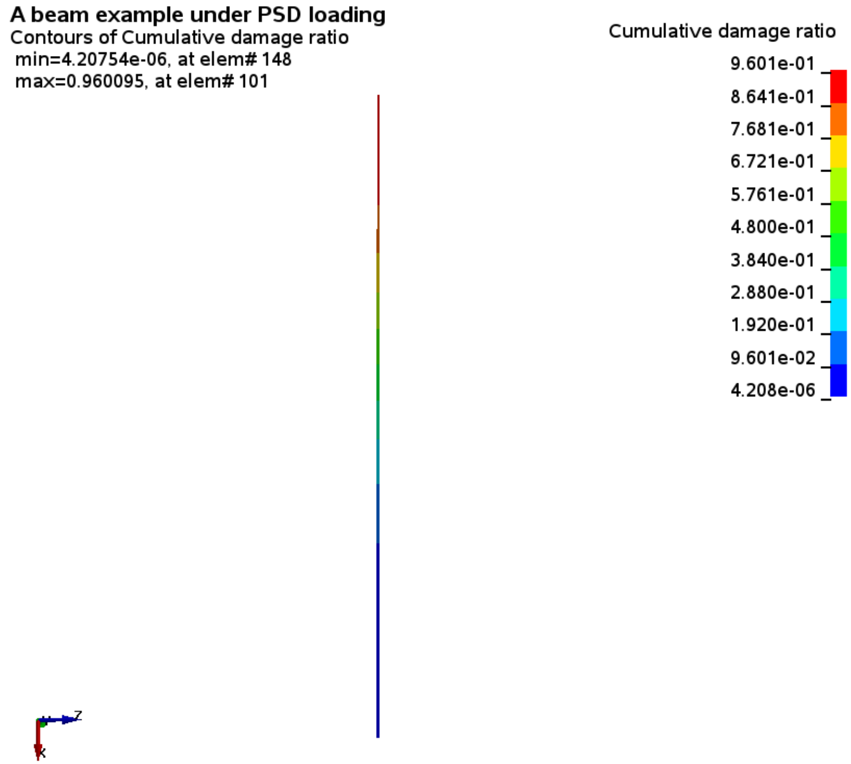


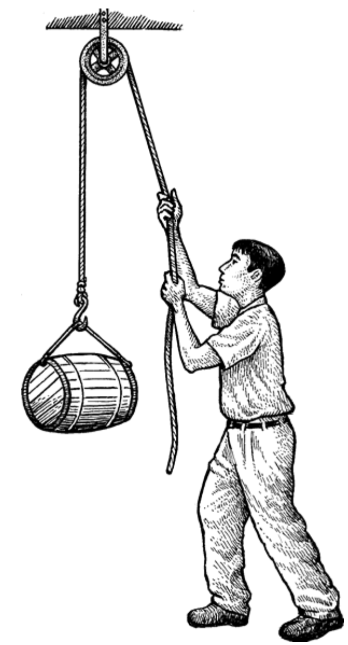


No mean stress correction	2.480
Goodman	2.767
Soderberg	4.726
Gerber	2.510

Yield strength (MPa)	250
Ultimate strength (MPa)	450

Fatigue analysis with beam elements





*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE

*DATABASE_EXTENT_BINARY

$#	neiph	neips	maxint	strflg	sigflg	epsflg	rltflg	engflg
	0	0	3	0	1	1	1	1
$#	cmpfl	ieverp	beamip	dcomp	shge	stssz	n3thdt	ialemat
	0	0	1	1	1	1	2	1
$#	nintsld	pkp_sen	sclp	unused	msscl	therm	intout	nodout
	0	0	1.0000	0	0	0	STRESS	STRESS

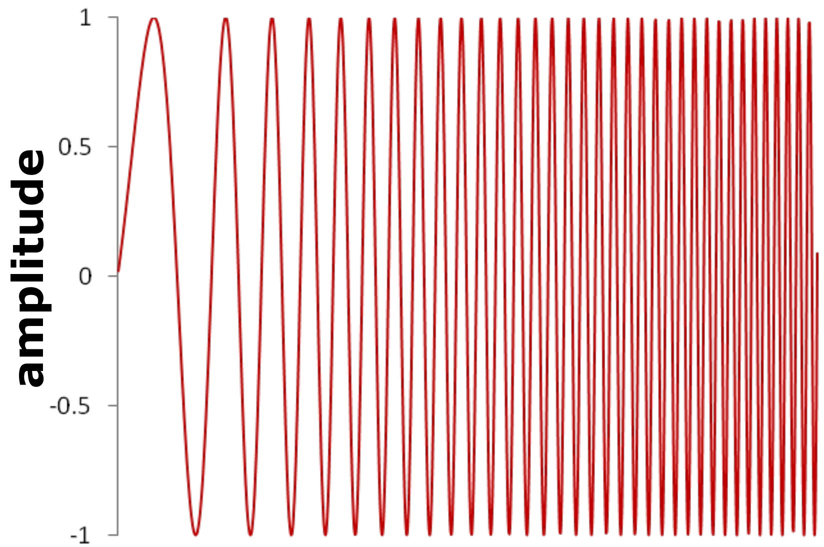
4) SSD fatigue

Introduction

FREQUENCY_DOMAIN_SSD_*FATIGUE

- Calculate fatigue life of structures under steady state vibration (e.g. sine sweep)
- Based on S-N fatigue curve
- Based on Miner's Rule of Cumulative Damage Ratio
- Rainflow counting algorithm for each frequency for one period

$$R = \sum_i \frac{n_i}{N_i}$$



Sine sweep

Keyword

FREQUENCY_DOMAIN_SSD_*FATIGUE

Card 3	1	2	3	4	5	6	7	8
Variable					STRTYP	NOUT	NOTYP	NOVA
Type					I	I	I	I
Default					0	0	0	0

Card 4	1	2	3	4	5	6	7	8
Variable	NID	NTYP	DOF	VAD	LC1	LC2	LC3	VID
Type	I	I	F	F	I	I	I	I
Default	none	0	none	none	none	none	0	0

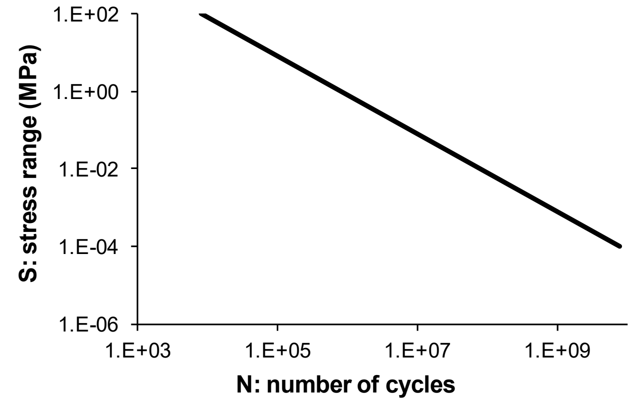
VARIABLE	DESCRIPTION
STRTYP	Stress type used in fatigue analysis = 0 Von Mises stress = 1 Maximum principal stress = 2 Maximum shear stress
LC3	Load Curve ID defining load duration for each frequency. This parameter is optional and is only needed for simulating sine sweep vibration

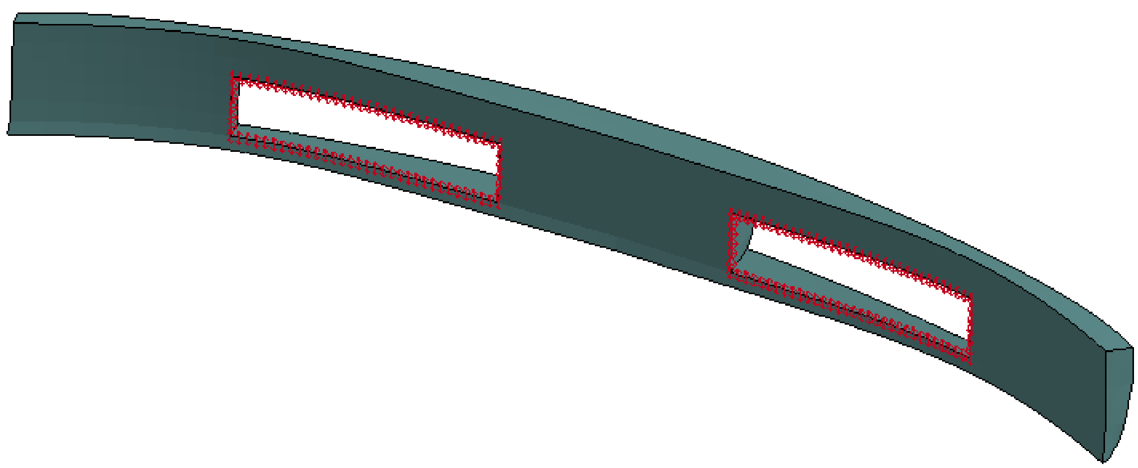
Example of SSD fatigue

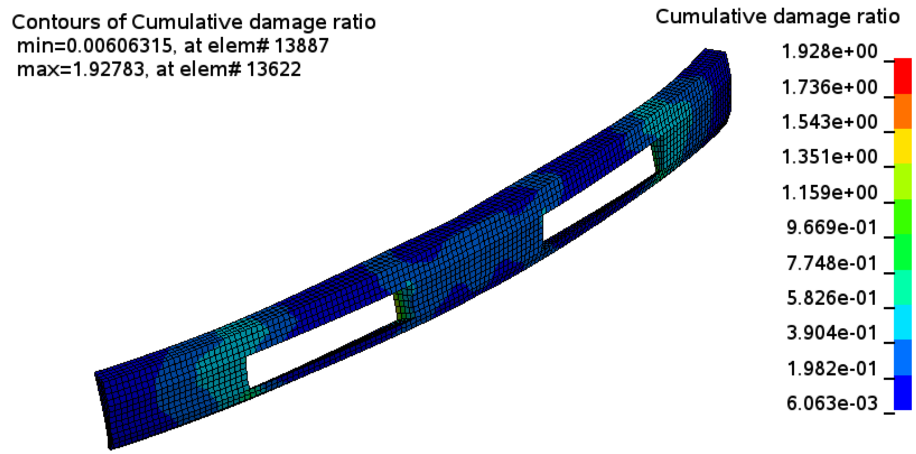
Loading condition

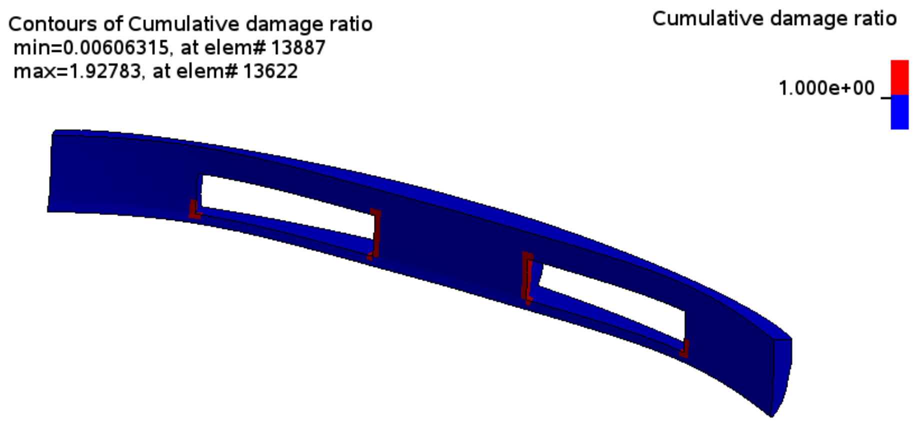
Freq (Hz)	Acl (g)	Duration (sec)
200	1.0	600
300	1.0	600
400	1.0	600
500	1.0	600
…	…	…
1500	1.0	600

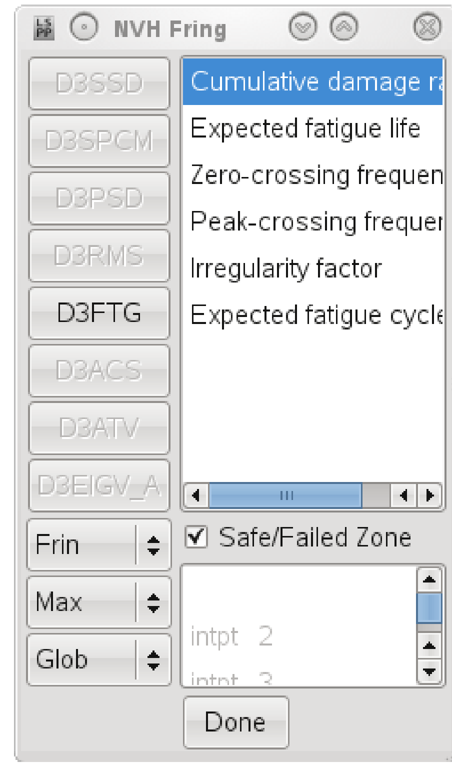
SN fatigue curve





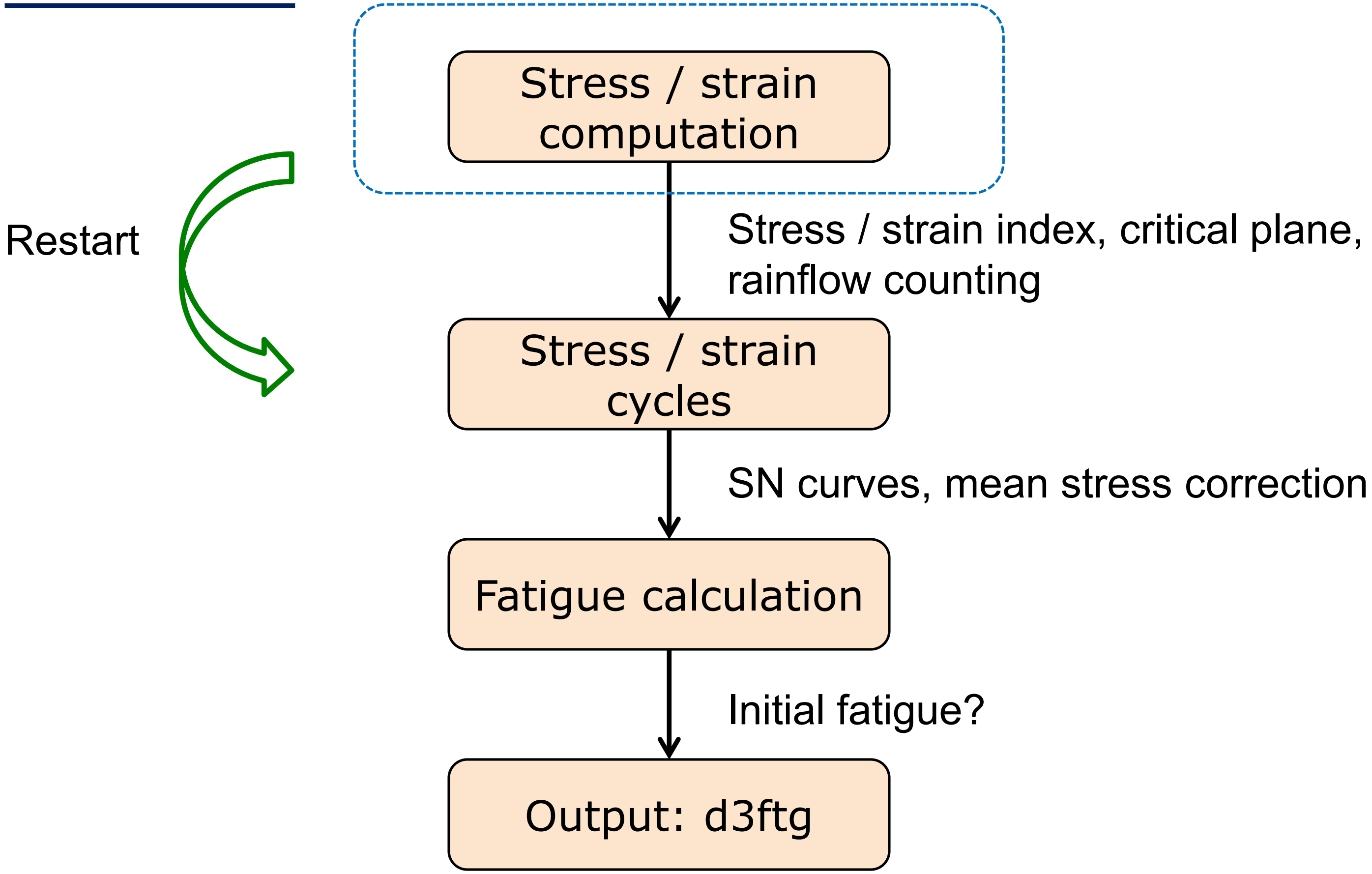

Contours of Cumulative damage ratio
min=0.00606315, at elem# 13887
max=1.92783, at elem# 13622
Cumulative damage ratio
1.928e+00
1.736e+00
1.543e+00
1.351e+00
1.159e+00
9.669e-01
7.748e-01
5.826e-01
3.904e-01
1.982e-01
6.063e-03


Contours of Cumulative damage ratio
min=0.00606315, at elem# 13887
max=1.92783, at elem# 13622
Cumulative damage ratio
1.000e+00


NVH Fring
D3SSD
D3SPCM
D3PSD
D3RMS
D3FTG
D3ACS
D3ATV
D3EIGV_A
Cumulative damage ra
Expected fatigue life
Zero-crossing frequen
Peak-crossing frequer
Irregularity factor
Expected fatigue cycle
Safe/Failed Zone
Frin
Max
Glob
intpt 2
Done

5) Time domain fatigue

Flow chart



Keyword

FATIGUE_*OPTION

Card 1	1	2	3	4	5	6	7	8
Variable	SSID	SSTYPE						
Type	I	I						

Card 2	1	2	3	4	5	6	7	8
Variable	DT							
Type	I							

Card 3	1	2	3	4	5	6	7	8
Variable	STRES	INDEX	RESTRT	TEXPOS				
Type	I	I	I	F				

VARIABLE	DESCRIPTION
STRES	Type of fatigue analysis variable: EQ.0: Stress (default) EQ.1: Strain

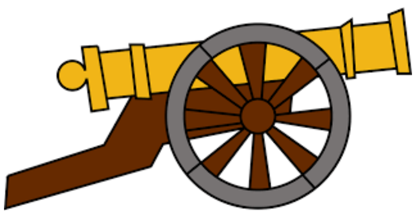
OPTION:

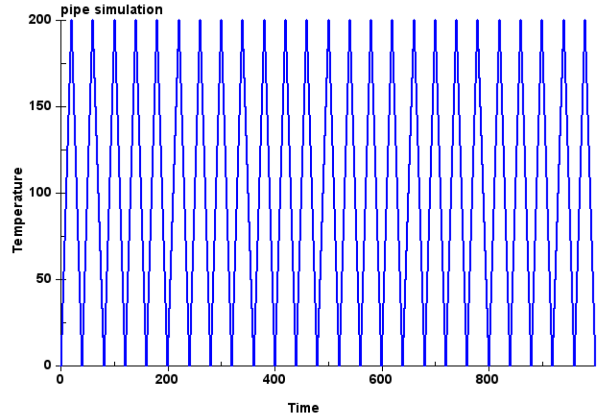
ELOUT

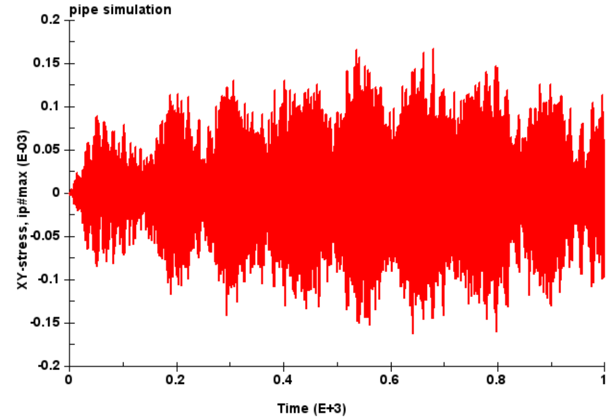
VARIABLE	DESCRIPTION
INDEX	Stress / strain index: EQ.0: Von-Mises stress/ strain EQ.1: Maximum principal stress/strain EQ.2: Maximum shear stress/strain EQ.-1: xx-stress/strain EQ.-2: yy-stress/strain EQ.-3: zz-stress/strain EQ.-4: xy-stress/strain EQ.-5: yz-stress/strain EQ.-6: zx-stress/strain

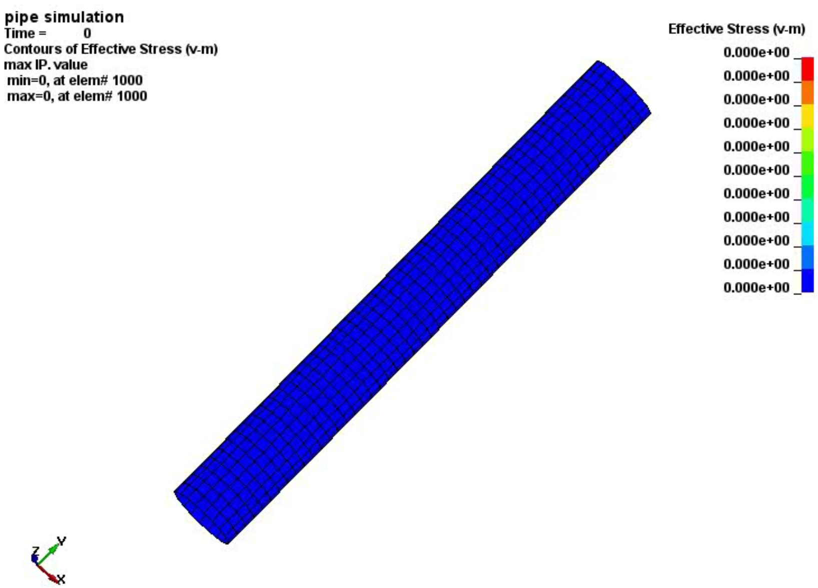
Stress based fatigue analysis

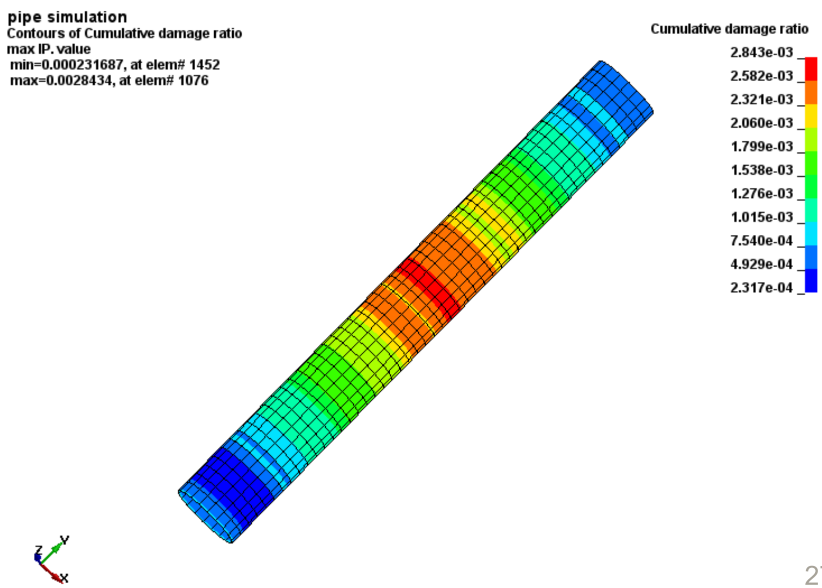
***LOAD_THERMAL_LOAD_CURVE**
***MAT_ELASTIC_PLASTIC_THERMAL**







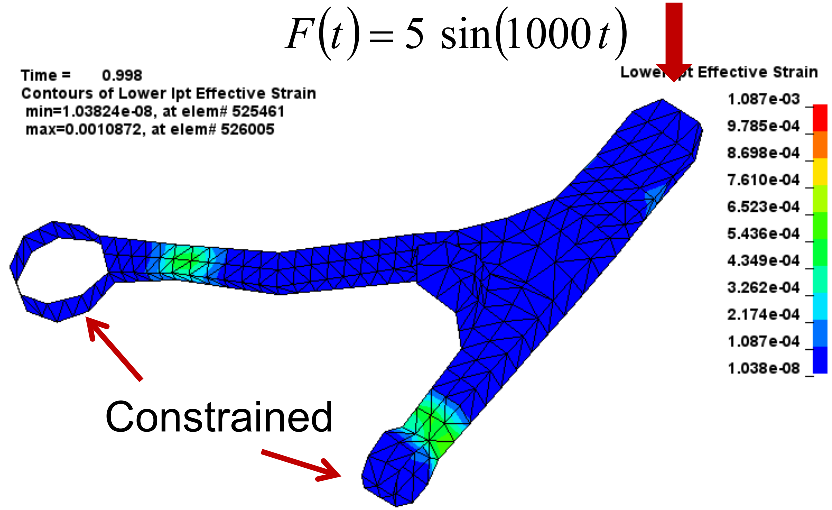


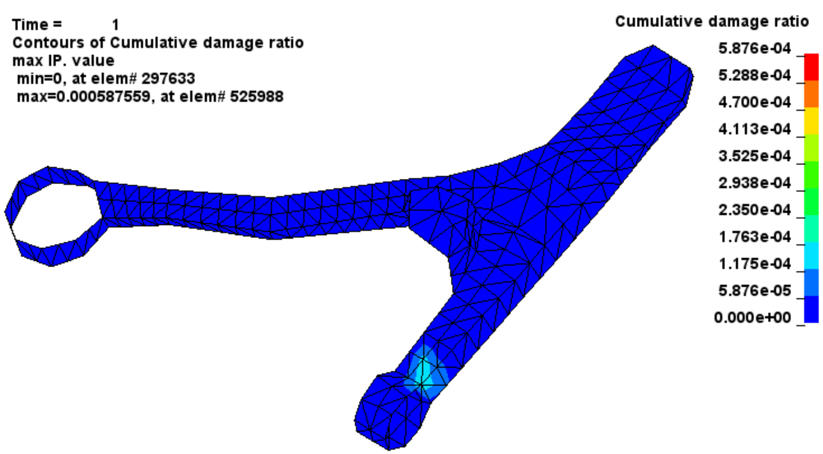


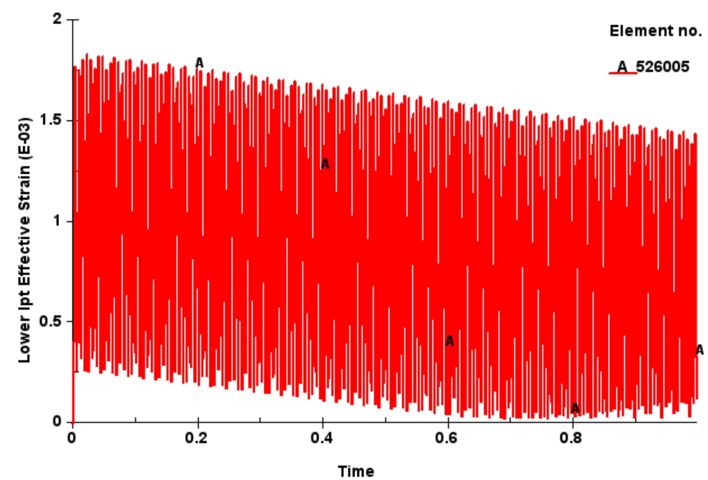
Strain based fatigue analysis

- This example studies the fatigue life of a metal bracket model, under cyclic nodal force excitation
- The location for maximum cumulative damage ratio, matches the location for maximum strain

$$F(t) = 5\ \sin(1000\,t)$$

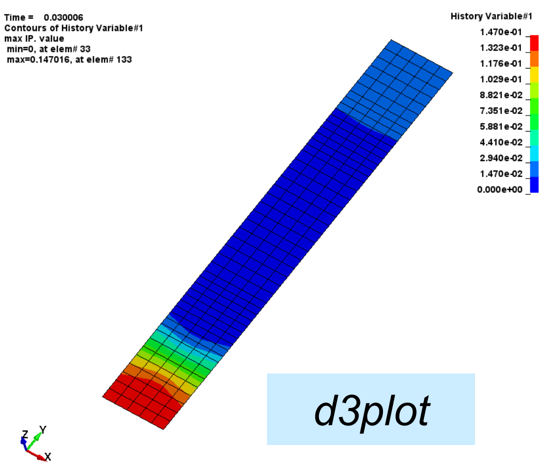




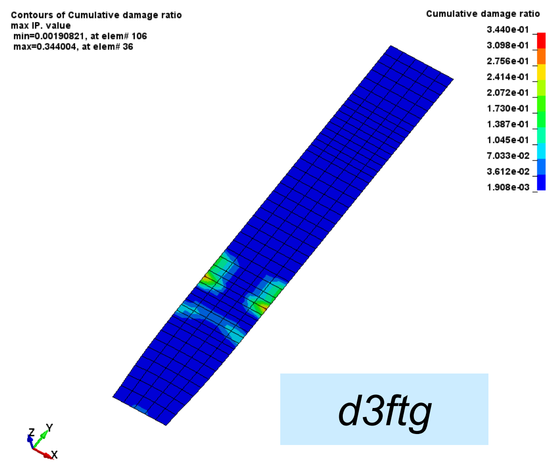


Initial damage ratio in fatigue

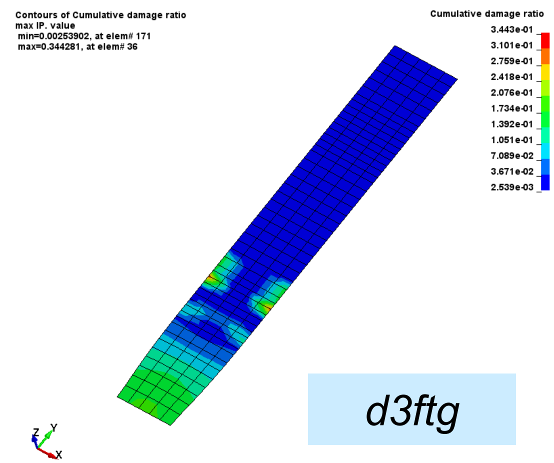
- Defined by ***INITIAL_FATIGUE_DAMAGE_RATIO**
  - Initial damage ratio can come from past fatigue analysis (d3ftg)
  - Initial damage ratio can come from transient preload (d3plot), e.g. ***MAT_ADD_EROSION**, ***MAT_ADD_DAMAGE_GISSMO**, etc.
- Summed up by ***FATIGUE_SUMMATION**



Damage from transient preload case (d3plot)



Damage ratio from fatigue load



Cumulative damage ratio from transient preload + fatigue load

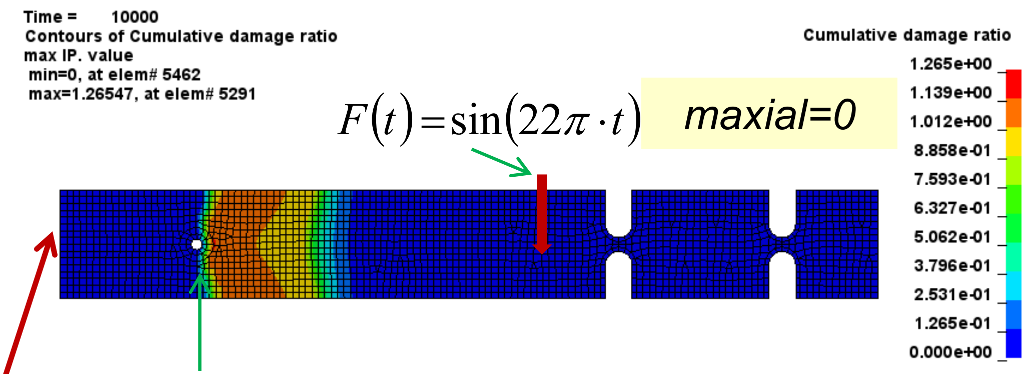
Multi-axial fatigue analysis

Stress / strain state is always three dimensional

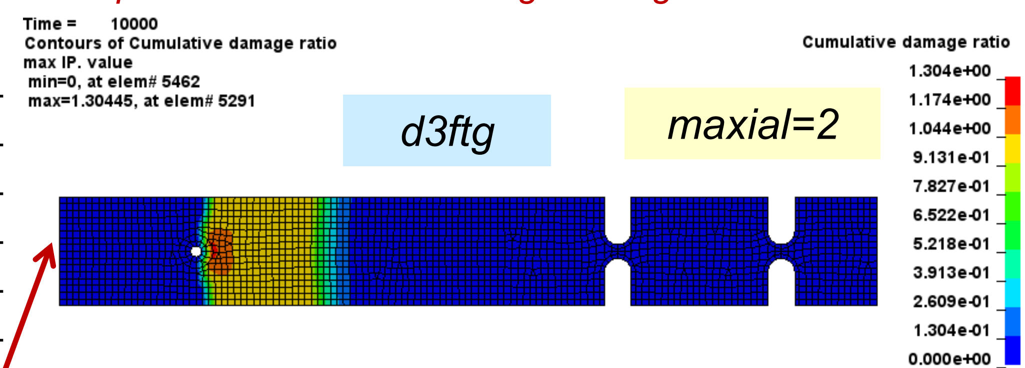
- A scalar index (e.g. von-mises stress, max principal stress) can be used
- Fatigue damage is computed on multiple planes and the max value is picked
- A critical plane is located and fatigue analysis is performed on the critical plane

```
*FATIGUE_ELOUT
$#     ssid     sstype
$
$#       dt
$
$#    stres      index
                                  1
*FATIGUE_MULTIAXIAL
$#   maxial     nplane
          1        180
```

maxial	nplane	Max damage ratio
0		1.26547
1	18	1.30282
1	36	1.30282
1	72	1.30327
1	180	1.30327
2		1.30445



The plate is constrained along the edge of the hole



6) Conclusion and future work

1. A bunch of time domain and frequency domain fatigue analysis methods have been implemented to LS-DYNA.
2. Validated by benchmark examples, users' problems …
3. Advantages:
   - ✓ A wide selection of stress / strain solvers (nonlinear, thermal, multi-physics, fluid-structure interaction, EM, CFD, explicit / implicit, etc.)
   - ✓ Integration of vibration and fatigue solvers in one code.
   - ✓ Manufacturing effects (e.g. residual stress) can be considered
   - ✓ Run fatigue analysis on part, set of parts, set of elements.
   - ✓ Post-processing: analysis results well supported by LS-PrePost
4. Future work:
   - ✓ Integration with LS-OPT / LS-TASC for structure's multi-disciplinary optimization (MDO).
   - ✓ Progressive fatigue computation and evolution of damage
   - ✓ More options for critical plane identification.

THANK YOU!