

German LS-DYNA Forum 2018

Updated fatigue analysis with LS-DYNA®



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17th October, 2018

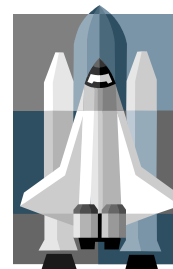
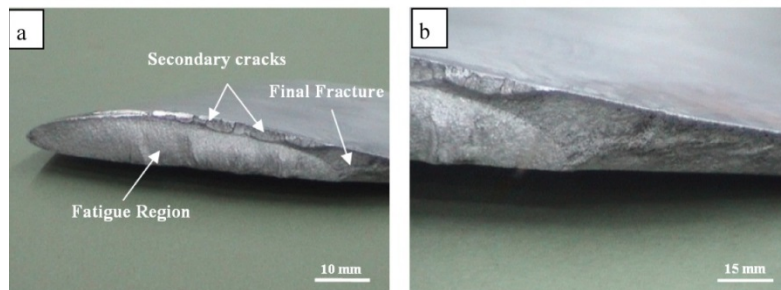
Outline

- 1) Introduction
- 2) S-N curve and E-N curve
- 3) Random vibration fatigue analysis
- 4) SSD fatigue analysis
- 5) Time domain fatigue analysis
- 6) Conclusion and future work

1) Introduction

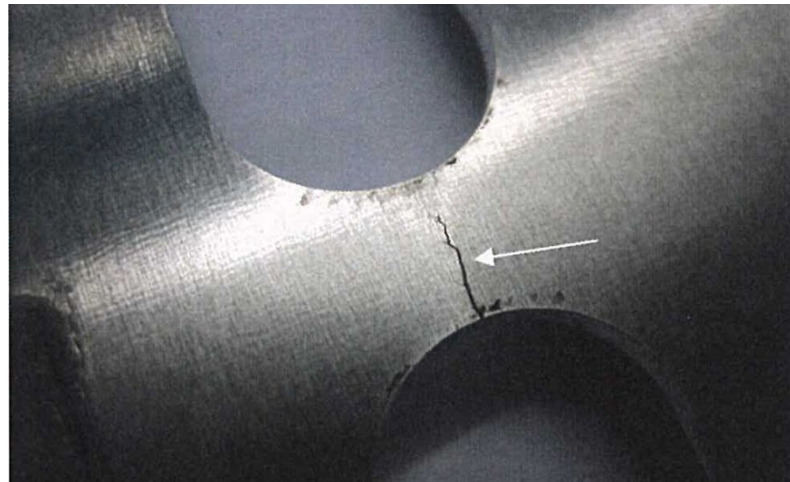
What is fatigue?

- ❑ 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

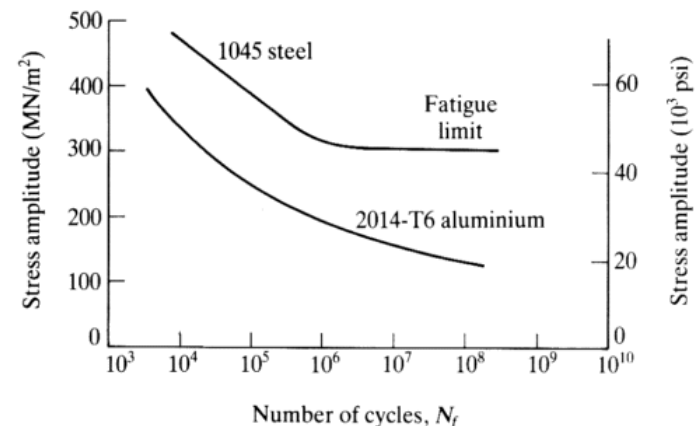
- Fatigue life of stress below fatigue threshold

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.



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

Multi S-N curves (for multiple mean stress)

*MAT_ADD_FATIGUE

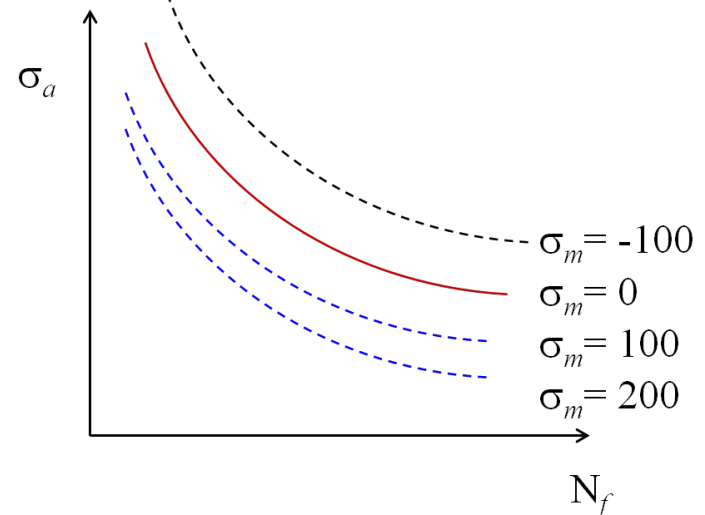
Card 1	1	2	3	4	5	6	7	8
Variable	MID	LCID	LTYPE	A	B	STHRES	SNLIMT	SNTYPE
Type	I	I	I	F	F	F	I	I
Default	none	-1	0	0.0	0.0	none	0	0

*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)

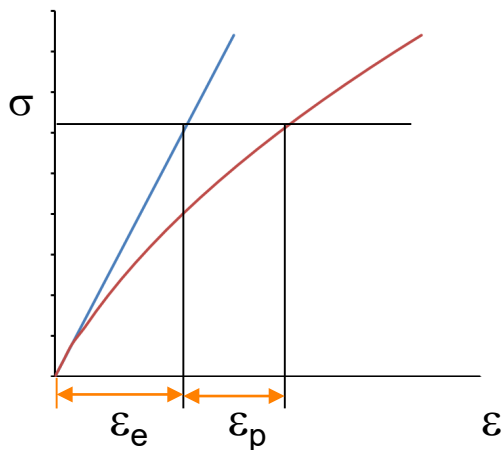
E-N curve (low cycle, high stress)

*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	

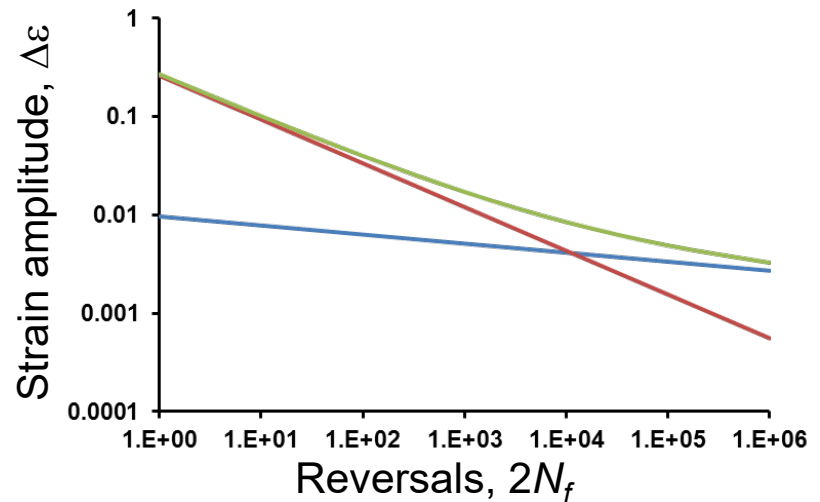
Cyclic stress strain curve

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



Local strain-life relationship

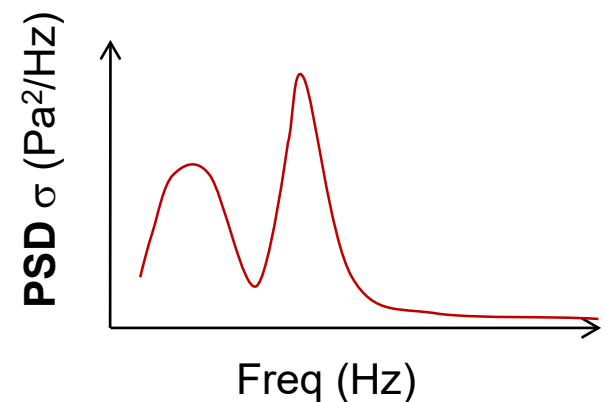
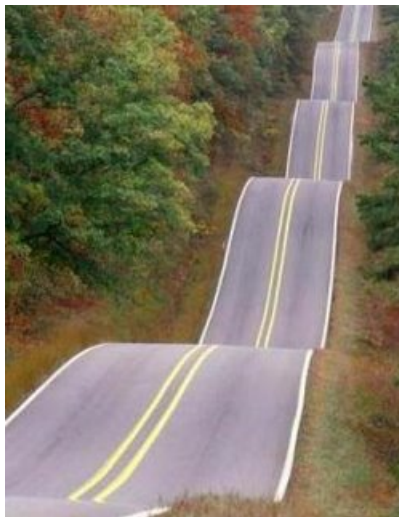
$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c$$



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"

The image shows the LS-PrePost (R) V4.6.0 (Beta) interface. The main window displays a 3D mesh of a mechanical part. The left sidebar shows the 'LS-DYNA keyword deck by LS-PrePost' tree with categories like Assembly 1, FEM Parts, Keyword Entity, Boundary, Define, and Set. The bottom toolbar includes options like Option, HidEle, ShaEle, VieEle, WirEle, Feat, Edge, Grid, Mesh, Shrink, and Sectv. The status bar shows 'nosnaa quat 0.362' and 'Reference Check'.

The 'Keyword Manager' dialog is open, showing a list of keywords and their counts. A yellow arrow points from the 'DOMAIN_RANDOM_VIBRATION_FATIGUE' keyword in this list to the 'Keyword Input Form' dialog.

The 'Keyword Input Form' dialog is titled 'Keyword Input Form' and shows the following data:

NewID: [] Pick Add Accept Delete Default Done [1] (Subsys: 1 random.fatigue.5000357.k) Setting

Use *Parameter Comment (*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE (1))

MFTG	NFTG	SNTYPE	TEXPOS	STRSE	INFTG
2	1	0	3600.0000	1	0

Repeated Data by Button and List

PID	LCID	PTYPE	LTYPE	A	B	STHRES	SNLIMT
5000148	-1	0	0	1.560000E8	2.5	0.0	0
1	5000148	-1	0	0.1560000E8	2.5	0.0	0

Data Pt. 1
Replace Insert

Total Card: 1 Smallest ID: 1 Largest ID: 1 Total deleted card: 0

EZ set up by “Application”

The image shows the LS-PrePost(R) V4.6.0 (Beta) interface. The 'Application' menu is open, and 'Random Vibration' is selected. The 'Random Vibration' dialog box is also open, showing the 'Fatigue' tab. The 'Add Fatigue Analysis' checkbox is checked. The 'Fatigue Analysis Method' is set to 'Dirlik'. The 'Initial Damage Ratio' is set to 'No'. The 'Fatigue Definition' is set to 'Part(s)'. The 'Stress Type' is set to 'Von-mises'. The 'Stress scale factor for S-N' is set to '1'. The 'Location' is set to 'Part' with a value of '5000148'. The 'S-N Type' is set to 'N*pow(S,b) = a'. The 'A' parameter is '156000000.00000' and the 'B' parameter is '2.500000'. The 'Threshold Stress' is '0.000000'. The 'Lowest Stress Algorithm' is 'Threshold Stress'. The 'S-N Curve Interpolation' is 'Semi-Log'. The status bar at the bottom shows 'nosnaa quat 0.362939 0.123671 0.365306 0.848252;'. The 'Fast Renderer' button is visible in the bottom right corner.

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

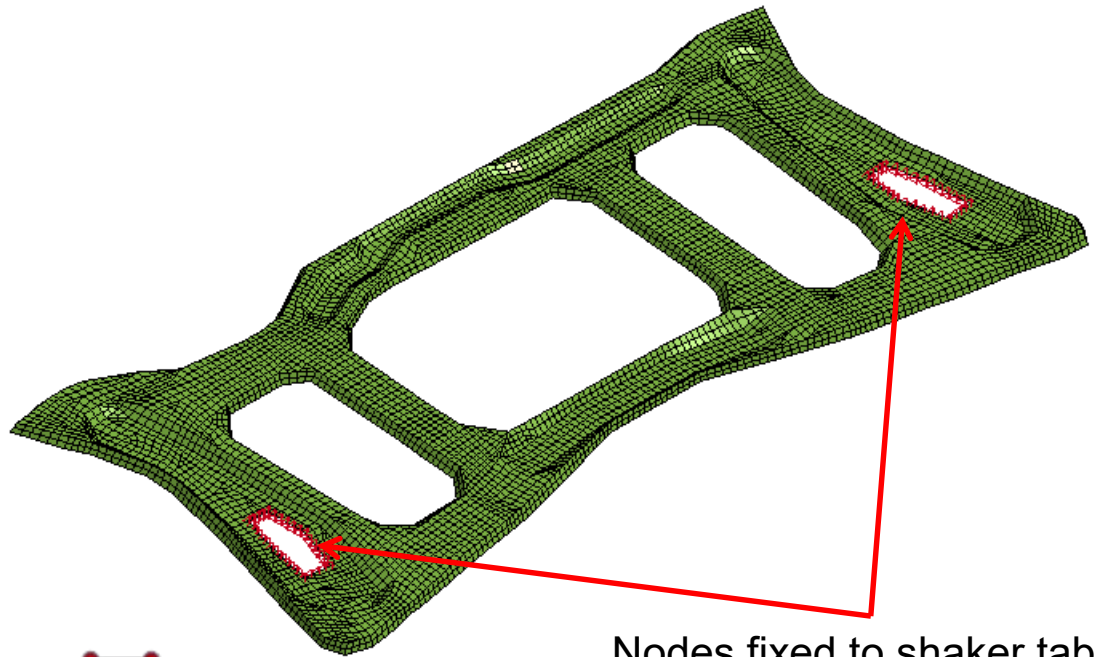
The Wirsching, Chaudhury, Tunna and Hancock methods are based on empirical correction factors for the narrow band method, and are applicable to different industries.

Examples of random vibration fatigue

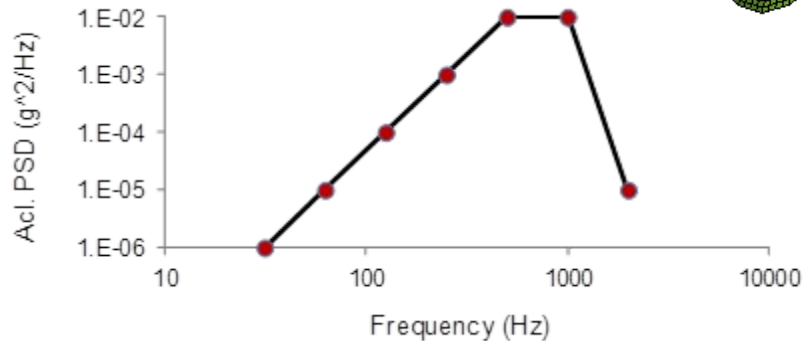
Steel

$\rho = 7890 \text{ kg/m}^3$
 $E = 2.1 \times 10^5 \text{ MPa}$
 $\nu = 0.3$

Time of exposure: 1 hour



Nodes fixed to shaker table



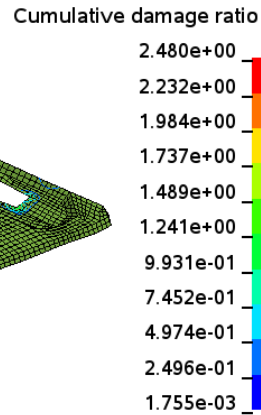
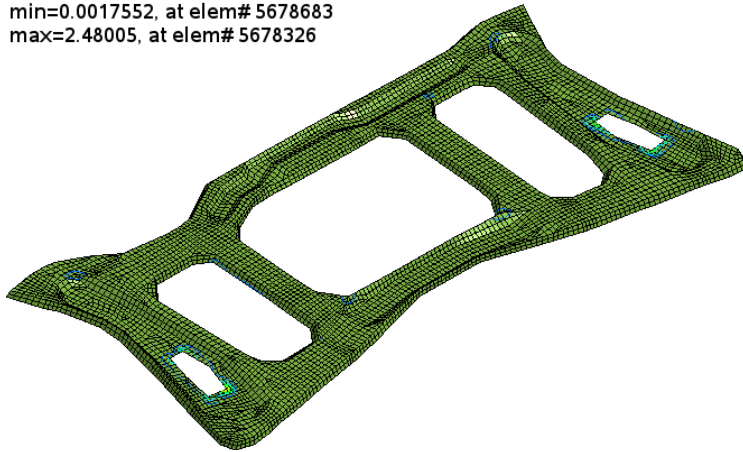
Z-acceleration PSD

S-N curve is defined by

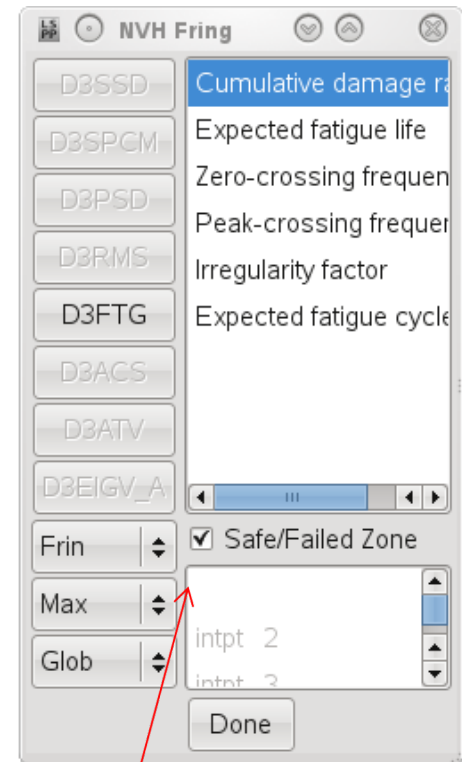
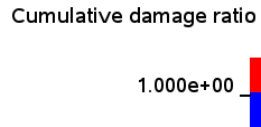
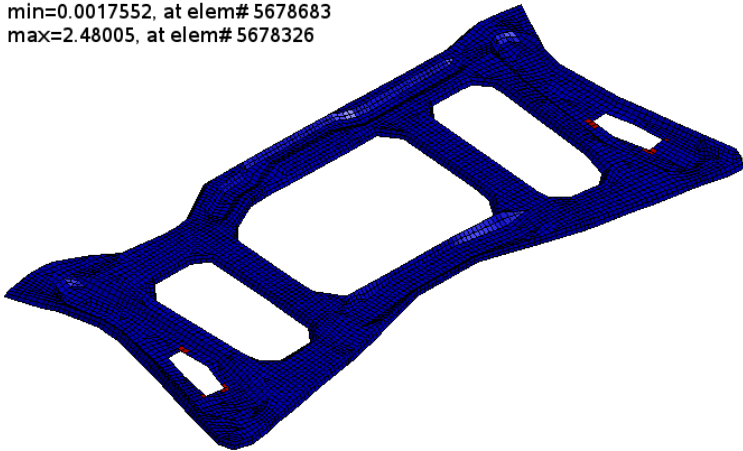
$$N \cdot S^{2.5} = 1.56 \times 10^8$$

Result file: d3ftg (accessible to LS-PrePost)

Contours of Cumulative damage ratio
max IP. value
min=0.0017552, at elem# 5678683
max=2.48005, at elem# 5678326

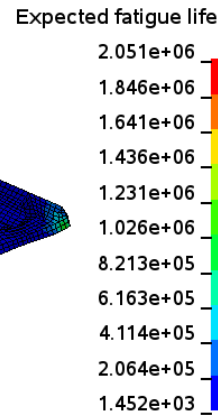
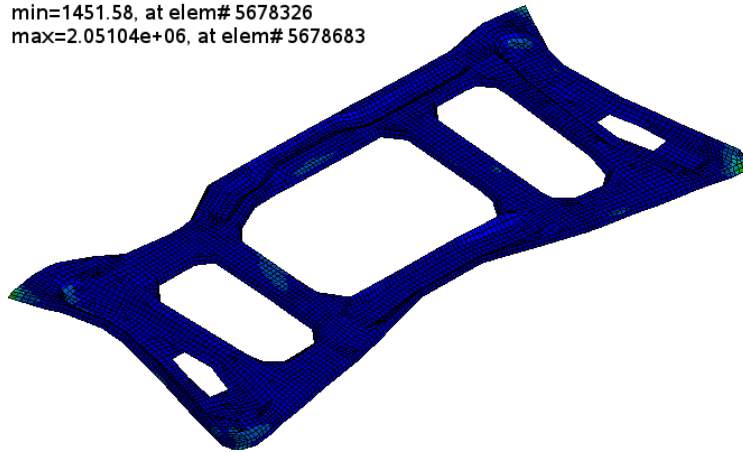


Contours of Cumulative damage ratio
max IP. value
min=0.0017552, at elem# 5678683
max=2.48005, at elem# 5678326

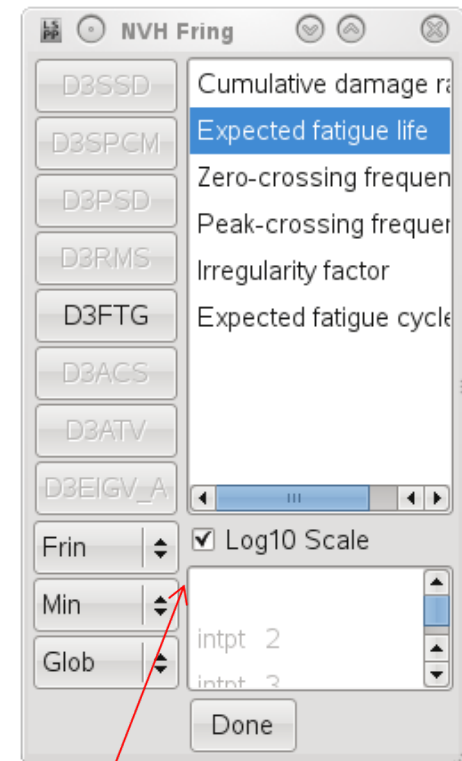
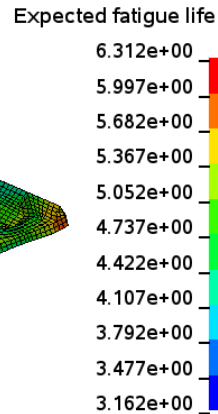
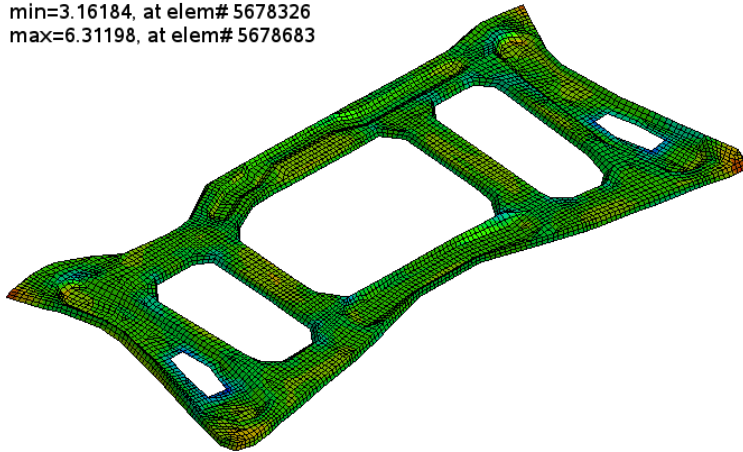


The Safe/Failed zone function can help user to locate the fatigue failed zone quickly.

Contours of Expected fatigue life
min IP value
min=1451.58, at elem# 5678326
max=2.05104e+06, at elem# 5678683

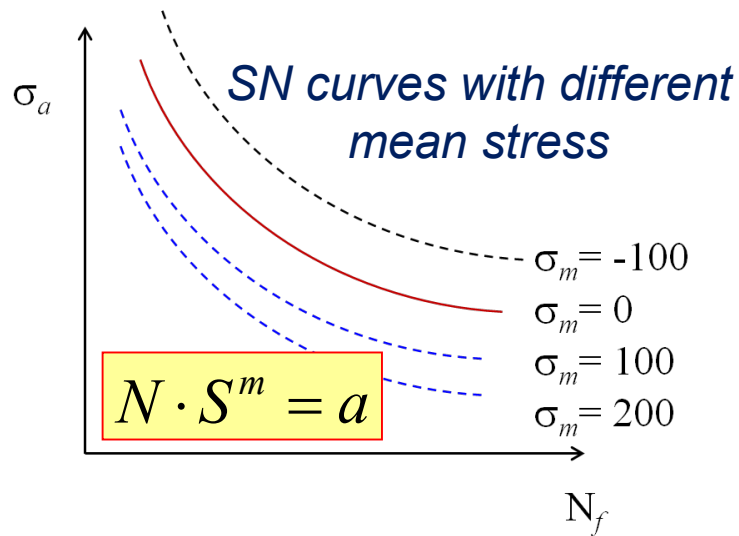


Contours of Expected fatigue life
min IP value
min=3.16184, at elem# 5678326
max=6.31198, at elem# 5678683



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

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

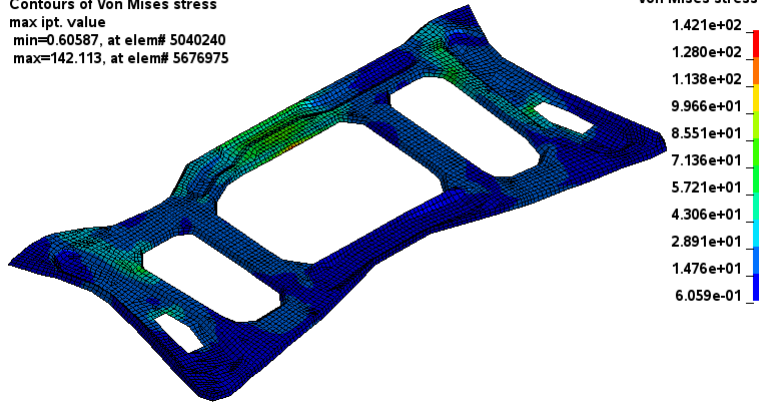
Soderberg

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

Gerber

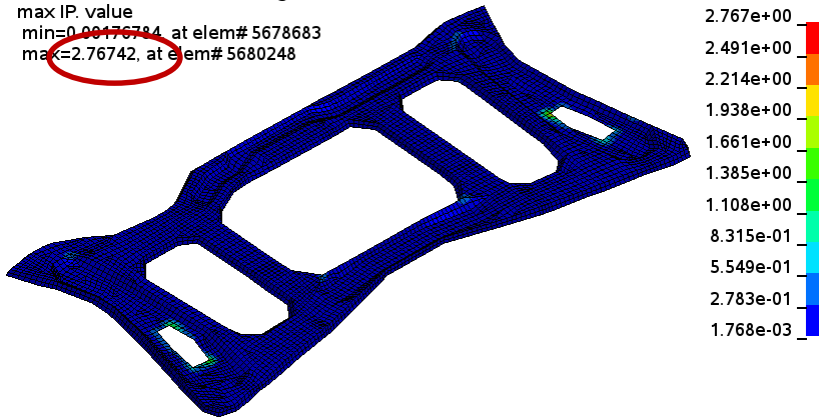
$$S = \frac{\sigma_a}{1 - (\sigma_m / \sigma_u)^2}$$

Mean_stress
Contours of Von Mises stress
max ipt. value
min=0.60587, at elem# 5040240
max=142.113, at elem# 5676975

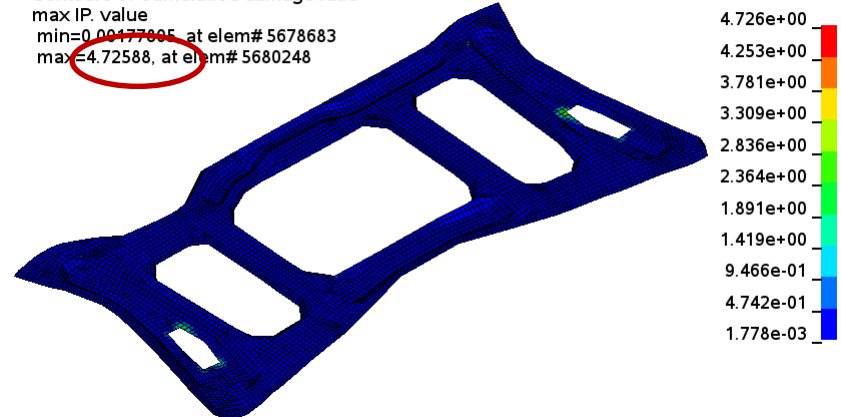


- ✓ Mean stress is introduced by
 - *INITIAL_STRESS_SHELL
 - *INITIAL_STRESS_SOLID ...
- ✓ Mean stress correction method is set by
 - *FATIGUE_MEAN_STRESS_CORRECTION
- ✓ Mean stress can come from thermal stress, gravity loading, or residual stress from metal forming...

Mean_stress_correction-Goodman
Contours of Cumulative damage ratio
max IP. value
min=0.00176784, at elem# 5678683
max=2.76742, at elem# 5680248



Mean_stress_correction-Soderberg
Contours of Cumulative damage ratio
max IP. value
min=0.00177005, at elem# 5678683
max=4.72588, at elem# 5680248



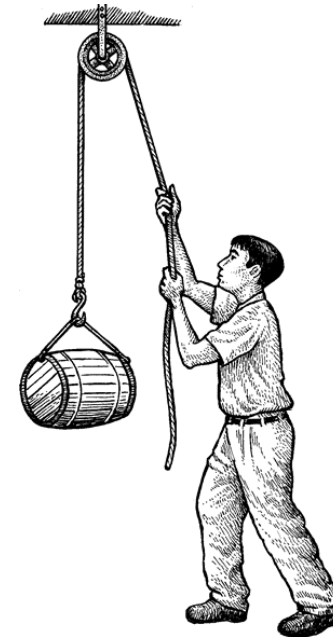
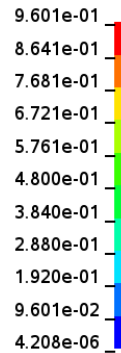
No mean stress correction	2.480
Goodman	2.767
Soderberg	4.726
Gerber	2.510

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

Fatigue analysis with beam elements

A beam example under PSD loading
 Contours of Cumulative damage ratio
 min=4.20754e-06, at elem# 148
 max=0.960095, at elem# 101

Cumulative damage ratio



***FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE**

***DATABASE_EXTENT_BINARY**

\$#	neiph	neips	maxint	strflg	sigflg	epsflg	rtflg	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	scip	unused	msscl	therm	intout	nodout
	0	0	1.0000	0	0	0	STRESS	STRESS

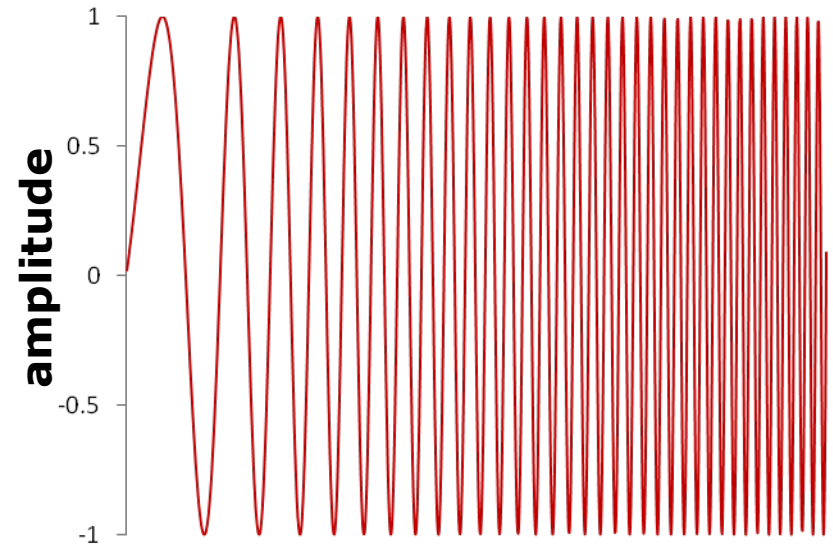
4) SSD fatigue

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

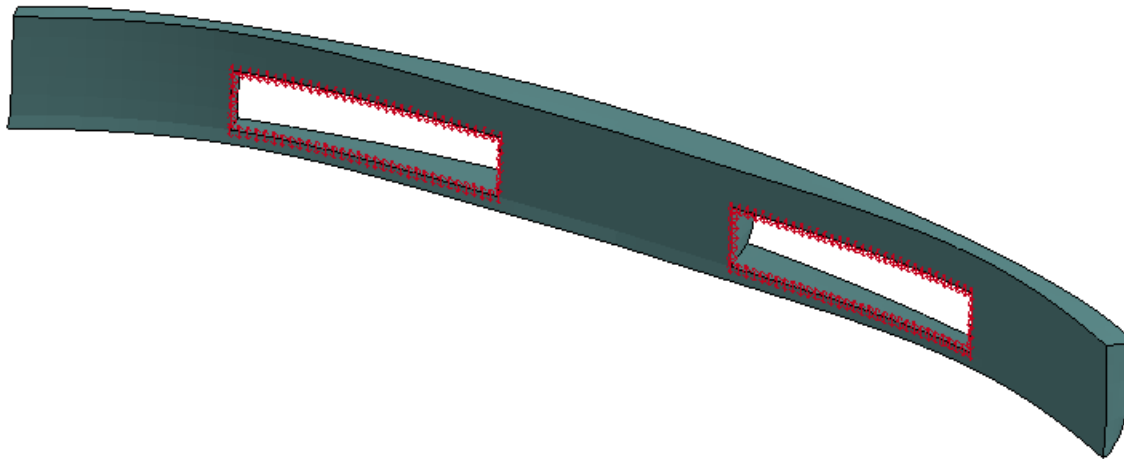
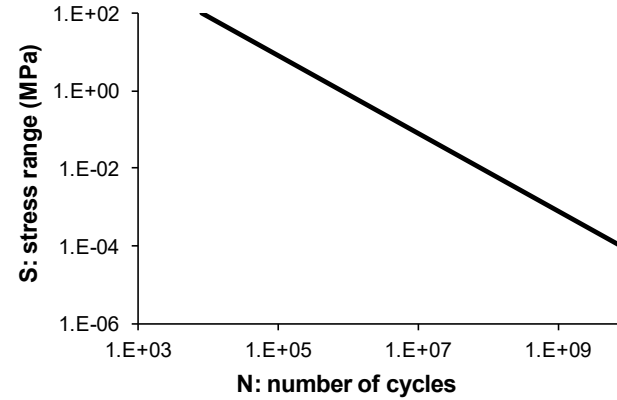
Load Curve ID defining load duration for each frequency. This parameter is optional and is only needed for simulating sine sweep vibration

Example of SSD fatigue

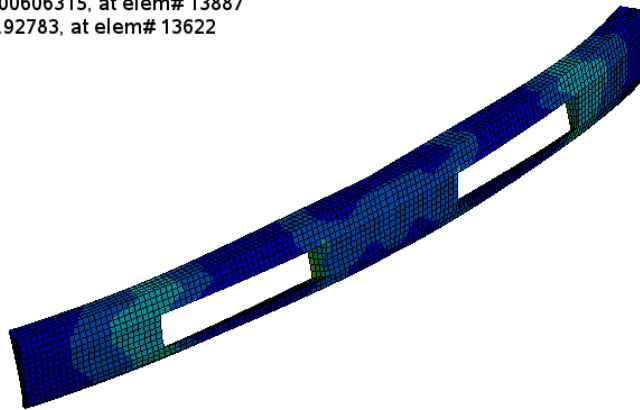
Loading condition

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

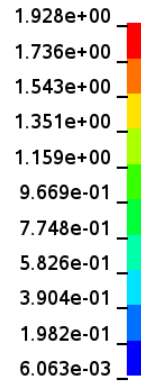
SN fatigue curve



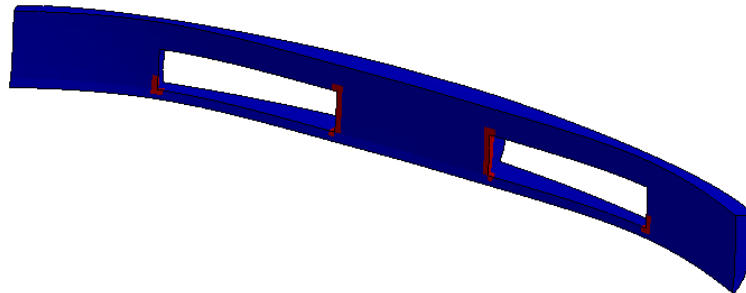
Contours of Cumulative damage ratio
min=0.00606315, at elem# 13887
max=1.92783, at elem# 13622



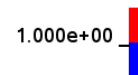
Cumulative damage ratio



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



Cumulative damage ratio



LS NVH Fring

D3SSD Cumulative damage ratio

D3SPGM Expected fatigue life

D3PSD Zero-crossing frequency

D3RMS Peak-crossing frequency

D3FTG Irregularity factor

D3ACS Expected fatigue cycle

D3ATV

D3EIGV_A

Frin Safe/Failed Zone

Max

Glob

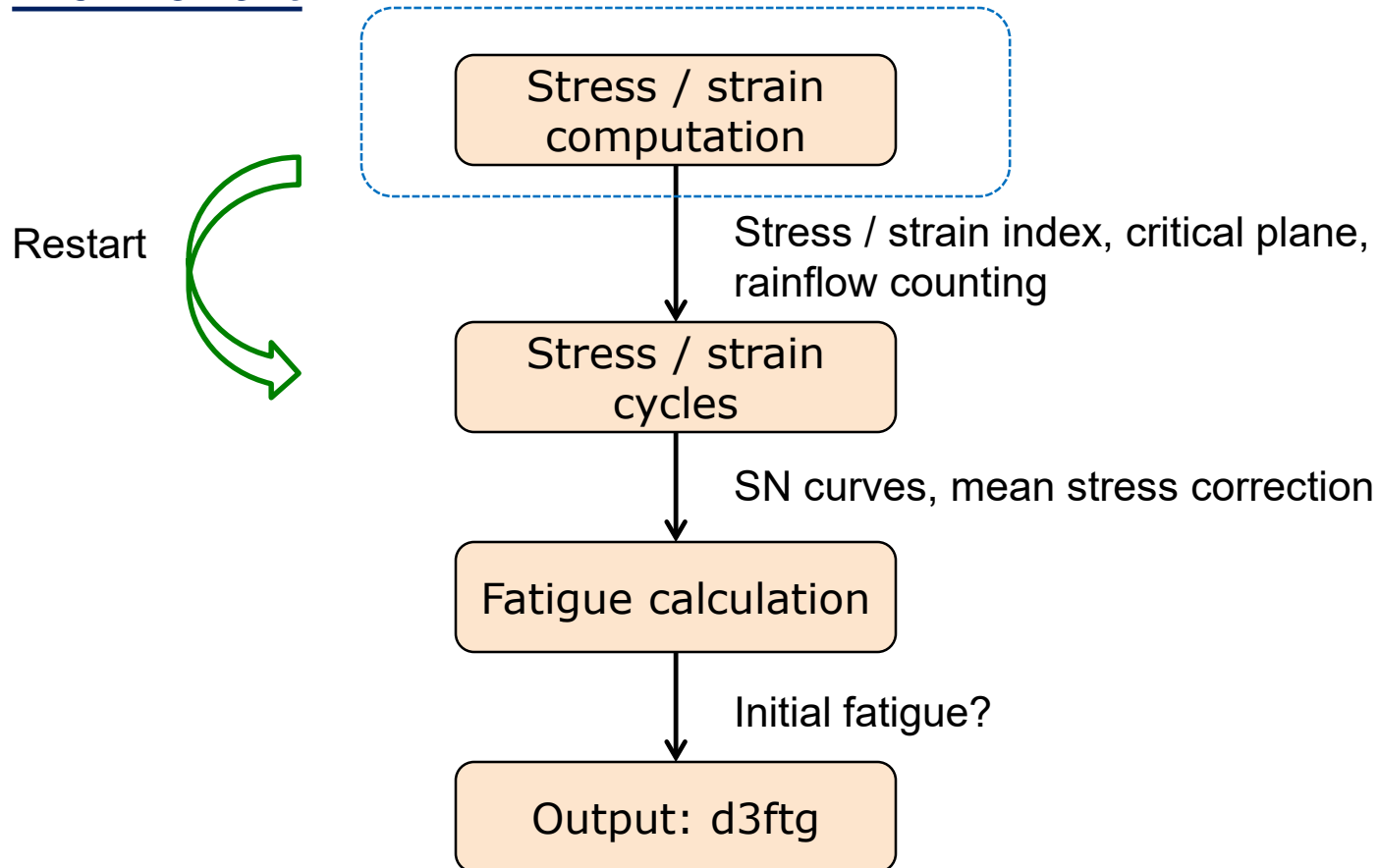
intpt 2

intnt 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							

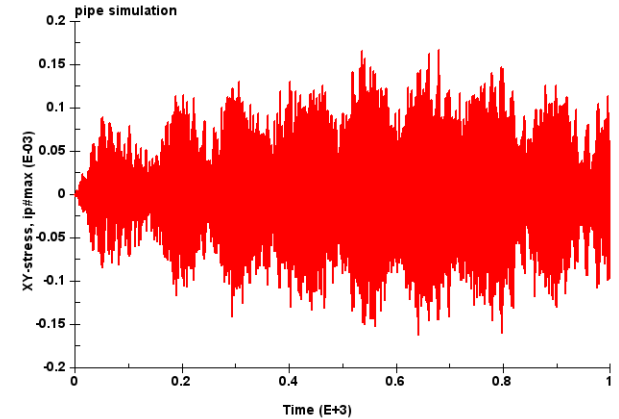
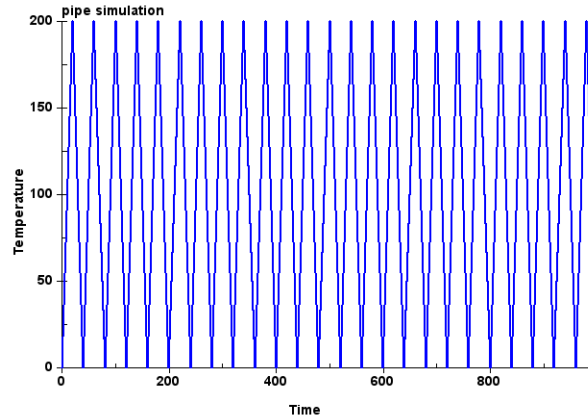
Card 3	1	2	3	4	5	6	7	8
Variable	STRES	INDEX	RESTR	TEXPOS				
Type	I	I	I	F				

<u>VARIABLE</u>	<u>DESCRIPTION</u>	<u>VARIABLE</u>	<u>DESCRIPTION</u>
STRES	Type of fatigue analysis variable: EQ.0: Stress (default) EQ.1: Strain	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
OPTION: ELOUT			

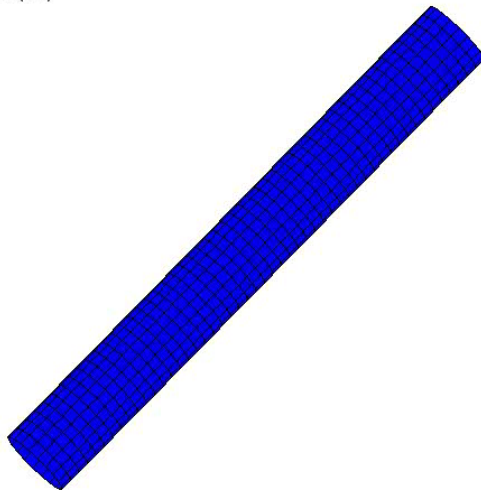
Stress based fatigue analysis

*LOAD_THERMAL_LOAD_CURVE

*MAT_ELASTIC_PLASTIC_THERMAL

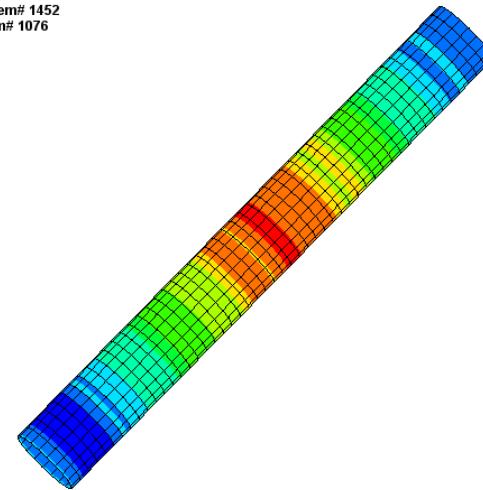


pipe simulation
Time = 0
Contours of Effective Stress (v-m)
max IP. value
min=0, at elem# 1000
max=0, at elem# 1000



Effective Stress (v-m)
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00

pipe simulation
Contours of Cumulative damage ratio
max IP. value
min=0.000231687, at elem# 1452
max=0.0028434, at elem# 1076

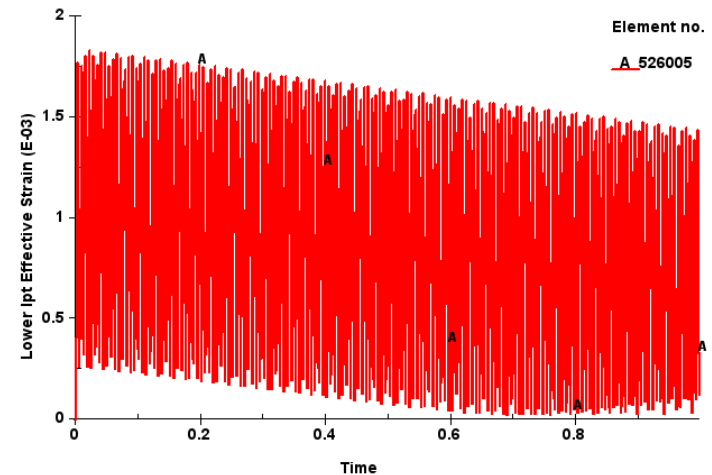
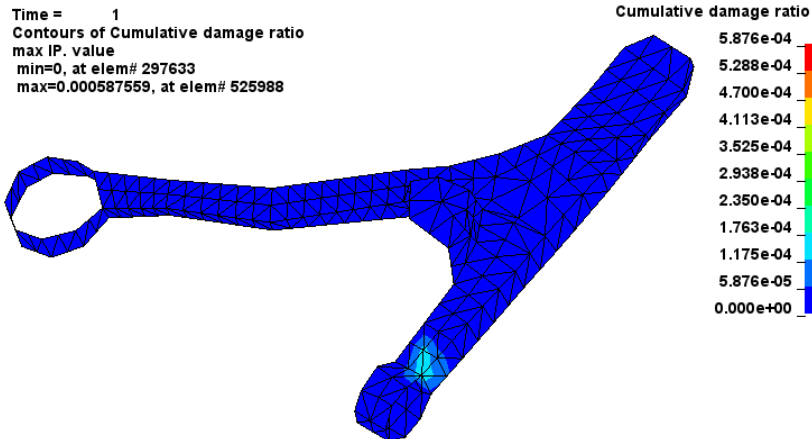
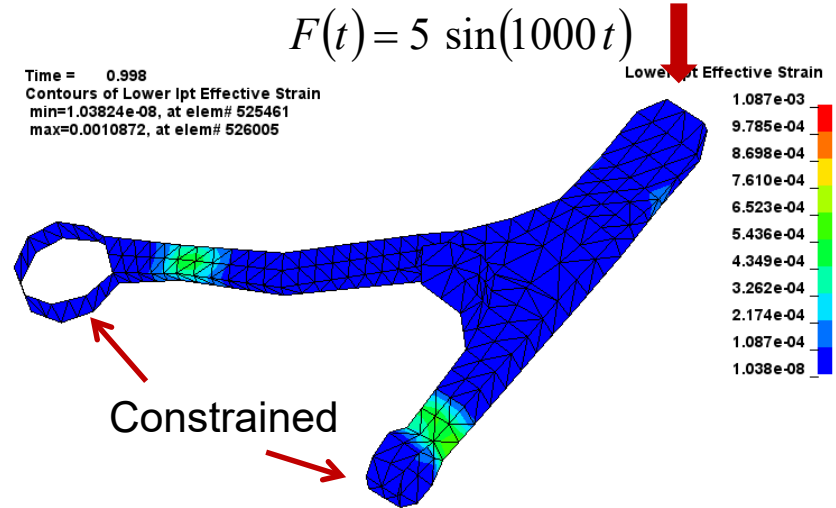


Cumulative damage ratio
2.843e-03
2.582e-03
2.321e-03
2.060e-03
1.799e-03
1.538e-03
1.276e-03
1.015e-03
7.540e-04
4.929e-04
2.317e-04



Strain based fatigue analysis

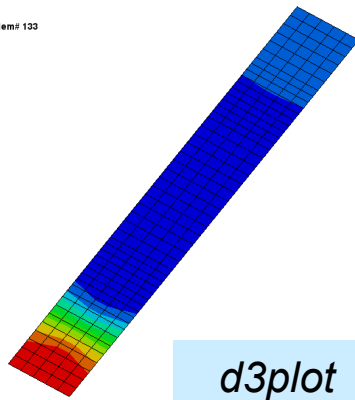
- This example studies the fatigue life of a metal bracket model, under cyclic nodal force excitation
- The location for maximum cumulative damage ratio, matches the location for maximum strain



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**

Time = 0.030006
Contours of History Variable#1
max IP. Value
min=0, at elem# 33
max=0.147016, at elem# 133

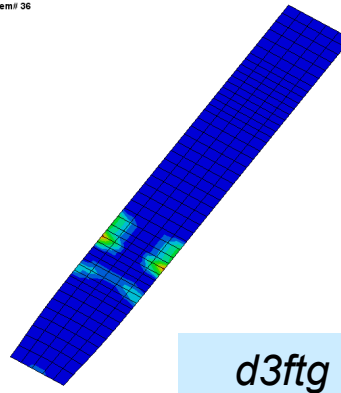


d3plot

Damage from transient preload case (d3plot)

History Variable#1
1.470e+01
1.323e+01
1.176e+01
1.029e+01
8.821e+02
7.351e+02
5.881e+02
4.410e+02
2.940e+02
1.470e+02
0.000e+00

Contours of Cumulative damage ratio
max IP. Value
min=0.00190821, at elem# 106
max=0.344004, at elem# 36

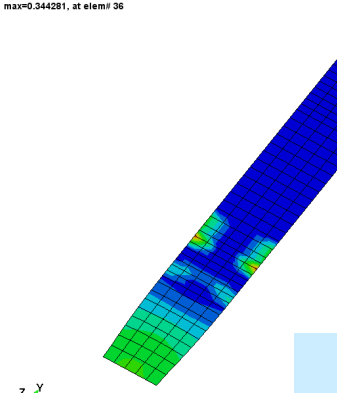


d3ftg

Damage ratio from fatigue load

Cumulative damage ratio
3.440e+01
3.098e+01
2.756e+01
2.414e+01
2.072e+01
1.730e+01
1.387e+01
1.045e+01
7.033e+02
3.612e+02
1.908e+03

Contours of Cumulative damage ratio
max IP. Value
min=0.00253902, at elem# 171
max=0.344281, at elem# 36



d3ftg

Cumulative damage ratio from transient preload + fatigue load

Cumulative damage ratio
3.442e+01
3.101e+01
2.759e+01
2.418e+01
2.076e+01
1.734e+01
1.392e+01
1.051e+01
7.089e+02
3.671e+02
2.539e+03

Multi-axial fatigue analysis

Stress / strain state is always three dimensional

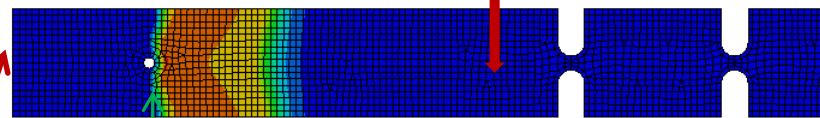
- A scalar index (e.g. von-mises stress, max principal stress) can be used
- Fatigue damage is computed on multiple planes and the max value is picked
- A critical plane is located and fatigue analysis is performed on the critical plane

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

Time = 10000
Contours of Cumulative damage ratio
max IP. value
min=0, at elem# 5462
max=1.26547, at elem# 5291

$$F(t) = \sin(22\pi \cdot t) \quad \text{maxial}=0$$

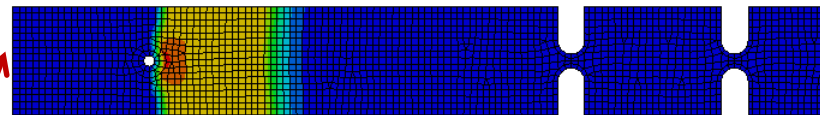


The plate is constrained along the edge of the hole

Time = 10000
Contours of Cumulative damage ratio
max IP. value
min=0, at elem# 5462
max=1.30445, at elem# 5291

d3ftg

maxial=2



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!