Application of LS-DYNA® in Structural Fatigue Analysis and Post-processing with LS-PrePost®

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Abstract

This paper provides a general introduction of frequency domain features in LS-DYNA in structural fatigue analysis and post-processing of the results with LS-PrePost.

Fatigue is the progressive and localized structural damage that occurs when the material is subjected to cyclic loadings. Fatigue damage and failure are very common in industries. Some studies have suggested that over 80% of all mechanical failure of metal are attributable to fatigue.

Starting from 971 R7 version of LS-DYNA, a series of features have been implemented in LS-DYNA to provide fatigue and durability analysis for metal structures, under various vibration loading conditions. The analysis provides cumulative damage ratio, expected fatigue life and fatigue cycles for the structures, based on the Palmgren-Miner rule and material's S-N curve. With the recent updates in LS-PrePost (4.2, 4.3), a new interface has been added to provide the fringe plot of the fatigue variables, which greatly simplifies the post-processing of the results and makes the result analysis easier.

Some examples are provided to demonstrate the effectiveness and convenience in running LS-DYNA and LS-PrePost for fatigue analysis and results post-processing.

Introduction

Metal fatigue is a common reason for structure failure in many industry areas. Fatigue is defined as the progressive and localized structural damage that occurs when a material is subjected to cyclic loading [1]. The study of fatigue began in the 19th century when several serious fatigue failures were reported and the first laboratory investigations were carried out [2]. Wilhelm Albert published the first article on fatigue in 1837. In 1953 and 1954, the world's first commercial jetliner, the de Havilland Comet airliner, suffered from disaster as three planes broke up soon after taking off. This tragedy and many other accidents force people to put more efforts into the study of metal fatigue problems and apply the findings in new designs.

To help LS-DYNA users to work on fatigue and durability analysis, a series of features for vibration fatigue analysis have been implemented to LS-DYNA since version 971 R7. They are based on Palmgren-Miner rule of cumulative damage model and material's S-N fatigue curves.

$$R = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{1}$$

In equation (1)

- n_i is the number of stress cycles at stress level S_i during the loading history.

- N_i is the number of stress cycles for material fatigue failure at stress level S_i (this is obtained from S-N curve).
- *R* is the cumulative damage ratio, which is the cumulative fraction of life consumed by exposure to the *k* different stress levels.

The numbers of stress cycles n_i can obtained in frequency domain, using the random vibration solver or the steady state dynamics solver. The fatigue analysis results are provided as the fringe plots of cumulative damage ratio, expected fatigue life and many other variables pertaining to the fatigue state of structures or parts. The results are saved in D3FTG binary database, which can be accessed by LS-PrePost 4.2 or 4.3.

Keywords

To run random vibration fatigue, the following keywords are needed

FREQUENCY_DOMAIN_RANDOM_VIBRATION_*{FATIGUE}
*DATABASE_FREQUENCY_BINARY_D3PSD
*DATABASE_FREQUENCY_BINARY_D3RMS
*DATABASE_FREQUENCY_BINARY_D3FTG
*MAT_ADD_FATIGUE

In addition, some other keywords are needed to perform implicit eigenvalue analysis, prior to running the random vibration analysis. They include

*CONTROL_IMPLICIT_GENERAL
*CONTROL_IMPLICIT_EIGENVALUE

Etc.

One can see that the random vibration fatigue feature is an extension of the random vibration feature, with several new parameters (and a new Card, which is Card 6) to define some necessary information in order to run fatigue analysis.

Typical cards for *FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE looks like

$#	mdmin	mdmax	fnmin	fnmax	restrt	mftg	restrm	inftg
	1	20	0.	2000.		1		
$#	dampf	lcdam	lctyp	dmpmas	dmpstf	dmptyp		
	0.01							
$#	vaflag	method	unit	umlt	vapsd	varms	npsd	nftg
	1	1			1	1		
$#	ldtyp	ipanelu	ipanelv	temper	texpos	ldflag	sntype	strsf
					3600.			
$#	sid	stype	dof	ldpsd	ldvel	ldflw	ldspn	cid
			3	2001				
$#	pid	lcid	ptype	ltype	a	b	sthres	snlimt
	100	-1			1.e+06	3	0.01	1

Where “mftg” is a flag for selecting fatigue analysis method. It can be

EQ.1: Steinberg’s three-band method
EQ.2: Dirlik method
EQ.3: Narrow band method
EQ.4: Wirsching method

EQ.5: Chaudhury and Dover method
EQ.6: Tunna method
EQ.7: Hancock method

More details of the fatigue analysis methods can be found in [3] and [4].

“nftg” defines how many S-N curves are present in the structure. The S-N fatigue curve is a property of material and it is unique for each material model. For a comprehensive structure with multiple material models, like a car, it is common to have multiple S-N curves involved. If nftg is larger than 0, then Card 6 which defines the S-N curves need to be repeated “nftg” times. If ntg=-999, S-N curves will be defined through the keyword *MAT_ADD_FATIGUE. User only needs to define S-N curves for the parts or set of elements that he or she wants to run fatigue analysis. User does not have to define S-N curves and run fatigue analysis for the whole structure.

“texpos” is the time of exposure for the structure to the PSD loading.

In Card 6, “pid” defines the Part ID, or Part Set ID, or Element (solid, shell, beam, thick shell) Set ID that the current S-N curve applies for. If “lcid” is a positive number, it defines the S-N fatigue curve ID. If “lcid” = -1, the following equation is used to define the S-N fatigue curve:

$$N \cdot S^b = a \tag{2}$$

If “lcid” = -2, the S-N curve is defined as a log function:

$$\log(S) = a - b \cdot \log(N) \tag{3}$$

In equations (2) and (3), N is the number of stress cycles for fatigue failure. S is the stress range or stress amplitude; a and b are material constants which are dependent on material type, temperature, surface treatment and many other environmental factors.

The S-N curves are usually obtained by lab testing. Most fatigue tests are conducted under alternating loading and stress with 0 mean stress (fully reversed test). A lot of empirical equations have been introduced to estimate mean stress effects on S-N curves.

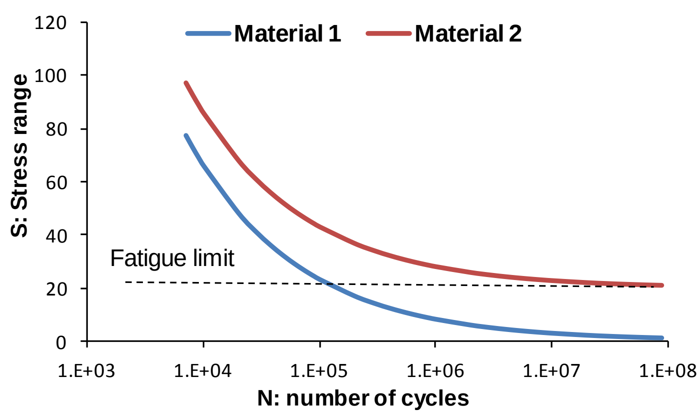

Figure 1. Typical S-N fatigue curves

“sthres” is the threshold stress for the S-N curve. It is usually the last point on the S-N curve. “snlimt” defines how to estimate the number of cycles for failure if the stress is lower than “sthres”. For conservative consideration, we can use the “*N*” at the threshold stress as the “*N*” for such lower stresses (snlimt=0); or we can do extrapolation from the last two points on S-N curve to get the “*N*” for the lower stresses (snlimt=1) or simply assume that the “*N*” is infinity (∞) for the lower stresses (snlimt=2). For snlimt=2, it is assumed that the material’s S-N curve will become horizontal (e.g. material 2 in Figure 1), which means there is a fatigue (endurance) limit. For this type of material, if the stress level is lower than the fatigue (endurance) limit, there is little damage to the material no matter how many stress cycles there will be. This is true for ferrous alloys and titanium alloys. Other structural metals such as aluminum and copper, do not have a distinct limit and will eventually fail even from small stress amplitudes.

A multi-slope S-N curve can be defined using *MAT_ADD_FATIGUE, which looks like

$#	mid	lcid	ltype	a	b	sthres	snlimt	sntype
	200131	-1		1.e+06	3	0.826		
$#				ai	bi	sthresi		
				1.1e+06	2.5	0.505		

To define S-N curve with multiple slopes, the S-N curve is split into several segments and each segment is defined by a set of parameters a_i, b_i and $sthres_i$. Up to 8 segments can be defined. The lower limit of the i-th segment is represented by the threshold stress $sthres_i$.

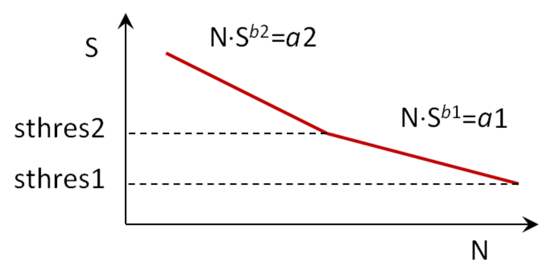

Figure 2. S-N fatigue curve with multiple slopes

To run steady state vibration (sine sweep) fatigue, the following keywords are needed:

FREQUENCY_DOMAIN_SSD_*{FATIGUE}
*DATABASE_FREQUENCY_BINARY_D3SSD
*DATABASE_FREQUENCY_BINARY_D3FTG
*MAT_ADD_FATIGUE

Typical cards for *FREQUENCY_DOMAIN_SSD_FATIGUE looks like

$#	mdmin	mdmax	fnmin	fnmax	restmd	restdp	lcflag	relatv
	1	20	0.	2000.				
$#	dampf	lcdam	lctyp	dmpmas	dmpstf	dmpflg		
	0.01							
$#						nout	notyp	nova
$#	nid	ntyp	dof	vad	lc1	lc2	lc3	vid
			3	2	1001	1002	1003	

Post-processing of the analysis results

Significant updates have been made in LS-PrePost 4.2 and 4.3 to support post-processing of the fatigue analysis results. The binary databases D3PSD, D3RMS and D3FTG are all accessible to LS-PrePost. Particularly the following state data are included in D3FTG.

1. Cumulative damage ratio
2. Expected fatigue life
3. Zero-crossing frequency with positive slope
4. Peak-crossing frequency
5. Irregularity factor
6. Expected fatigue cycles

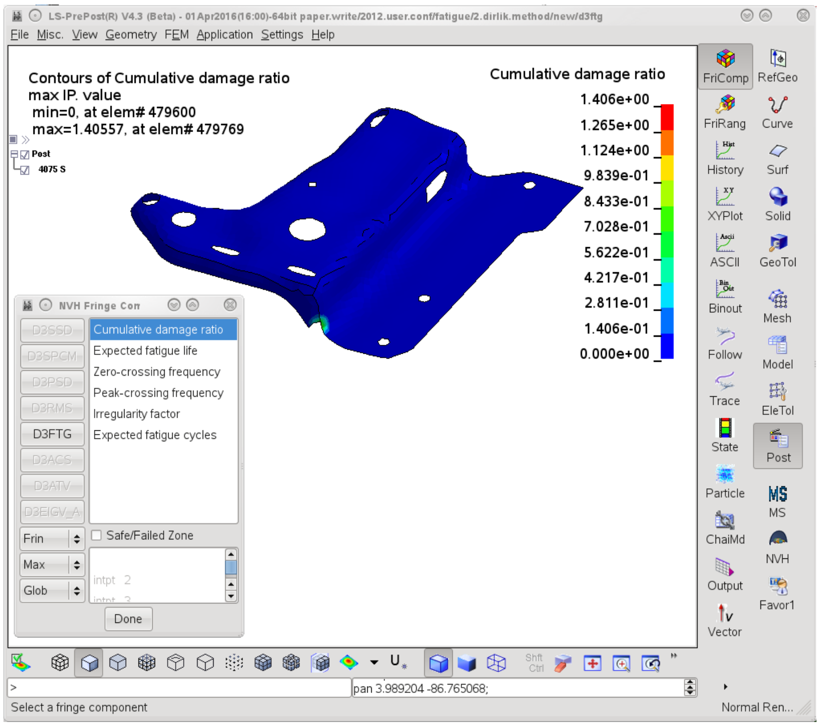

Figure 3. New GUI in LS-PrePost for fatigue result analysis

These results will show up in "FriComp" in "Post" module in LS-PrePost. Particularly, a "Safe/Failed Zone" check box is added. When the "Safe/ Failed Zone" check box is checked, the whole model is partitioned into two zones: the red zone is the area where the cumulative damage ratio is larger than 1, which means that the elements there have failed due to fatigue; the blue zone is the area where the cumulative damage ratio is less than 1, which means those elements are still safe, after the loading history. This check box can help user to capture the failure area easily and quickly.

For "Expected fatigue life", a "Log10 Scale" check box is provided. This is because the expected fatigue life can span from a few seconds to much longer time, like days. For example, if some parts of the structure are rigid and have no any stress, the "expected fatigue life" can go to infinity. With the "Log10 Scale" tool, LS-PrePost can make the fringe plot at the lower "expected fatigue life" and at the higher "expected fatigue life" more distinguishable.

Example 1: random vibration fatigue

The first example considers a metal bracket model shown in Figure 4. It is constrained to shaker table for a random vibration test. It is fixed through the two small holes (marked as red in Figure 4).

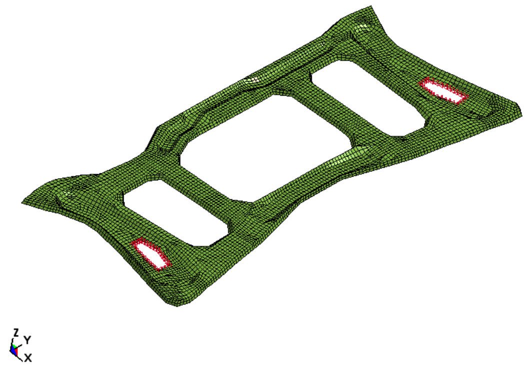

Figure 4. A bracket model constrained to shaker table

The S-N curve is represented by the equation

$$N \cdot S^{2.5} = 1.56 \times 10^{8} \tag{4}$$

The model is subjected to base acceleration PSD excitation. The acceleration PSD curve is shown in Figure 5.

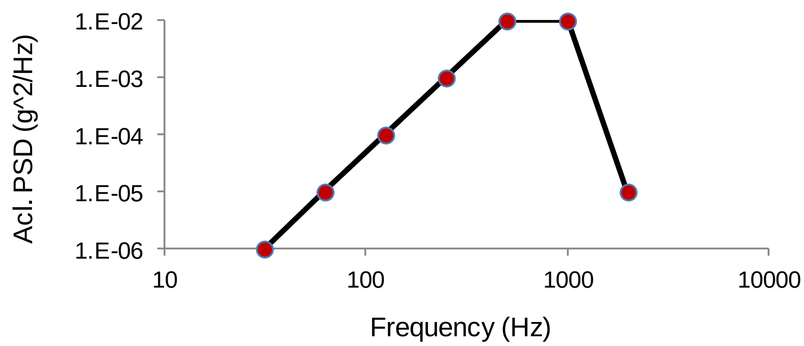

Figure 5. The acceleration PSD curve

The duration of excitation is set to be 1 hour. For the first loading case, we consider the acceleration in z-direction only.

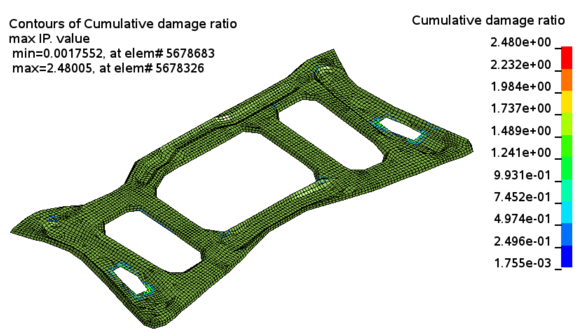

Figure 6. Cumulative damage ratio for z-acceleration PSD loading only

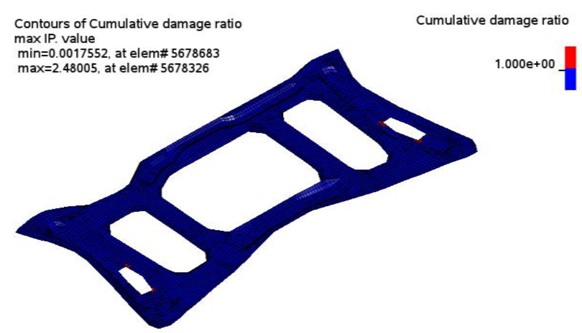

Figure 7. Safe / Failed zone for z-acceleration PSD loading only

Dirlik method is employed to perform fatigue analysis in this example. Von-mises stress is used as the stress index.

Figure 6 shows the cumulative damage ratio fringe plot under the z-directional acceleration excitation. The peak value of the cumulative damage ratio is around 2.48. This indicates that the model will fail due to fatigue in the test. The peak value appears at the edge of one constrained hole. This suggests that the initial crack will take place at that location.

To show the safe / failed zone clearly, one can check the "Safe / Failed Zone" box in the popup dialog (see Figure 3). The safe / failed zone for this model is shown in Figure 7.

The expected fatigue life of the structure can be found in Figure 8. It is the time or duration each element can survive under the current PSD loading condition. The minimum value of the expected fatigue life in the model is around 1451.58 seconds, which is shorter than the exposure time ("texpos"). This also indicates that the model will fail during the 1 hour (3600 seconds) vibration test. The location for the minimum expected fatigue life is same as the location for the maximum cumulative damage ratio (element ID 5678326).

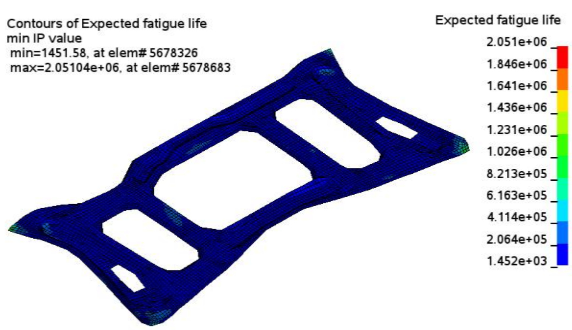

Figure 8. Expected fatigue life for z-acceleration PSD loading only

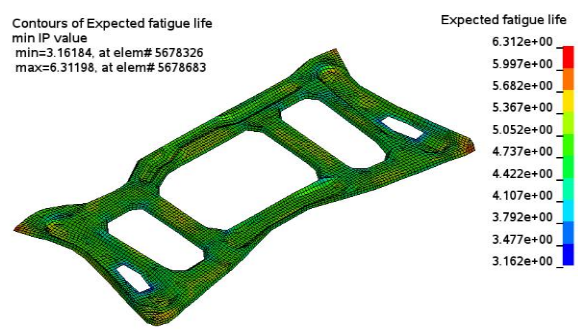

Figure 9. Expected fatigue life for z-acceleration PSD loading only (in log scale)

To show the expected fatigue life in log scale (see Figure 9), one need to check the "Log10 Scale" box in the popup dialog (see Figure 10).

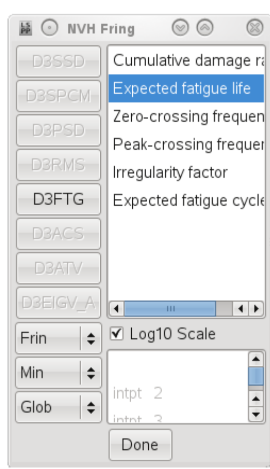

Figure 10. Safe / Failed Zone check box in D3FTG popup dialog

Using the "inftg" option, one can accumulate the damage on the structure from multiple loading cases. For example, the same structure shown in Figure 4 can be subjected to base acceleration PSD in x-, y- and z-direction sequentially. When we run fatigue analysis for the last loading case (e.g. acceleration in z-direction), we can set "inftg"=2 and put the path and name for the binary databases for the previous fatigue results (due to acceleration in x- and y-directions) into Card 7 of *FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE. The Card 7 is needed only if "inftg" > 0 and it should be repeated "inftg" times. The total cumulative damage ratio fringe plot due to the three loading cases can be found in Figure 11.

Figure 11. Cumulative damage ratio for x-, y- and z-acceleration PSD loading cases

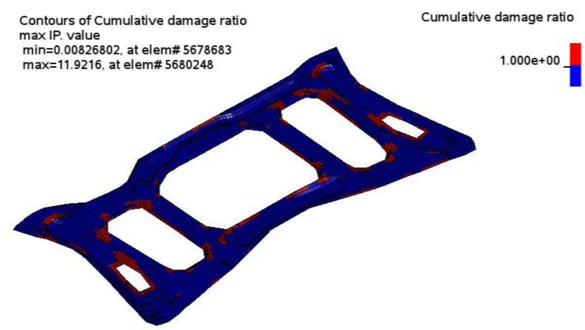

Figure 12. Safe / Failed zone for x-, y- and z-acceleration PSD loading cases

Figure 12 shows the safe / failed zone as the final result of the three loading cases. As we can see, the hole edge area has a higher chance for failure than other areas in this test.

Example 2: steady state vibration fatigue

The second example is about the fatigue analysis of a solid structure (a simplified auto front bumper model), in a steady state vibration test.

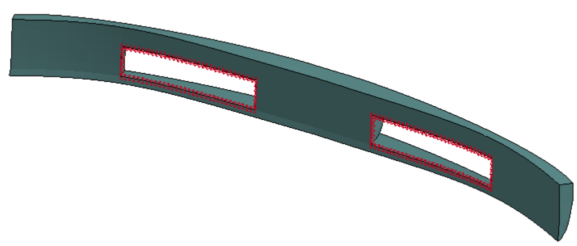

Figure 13. A front bumper model in steady state vibration

The bumper is subjected to continuous vibration from ground excitation during driving. It is assumed that the bumper is constrained to auto frame by the edge of the two holes (see the red nodes shown in Figure 13).

The material's S-N curve is defined by *DEFINE_CURVE, and shown in Figure 14.

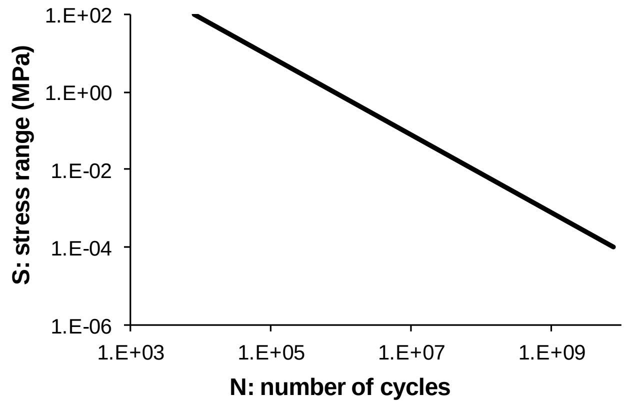

Figure 14. S-N curve for the bumper model

The base acceleration spectrum is given in Table 1 (see below).

Frequency (Hz)	Amplitude (g)	Duration (sec.)
200	1.0	600
300	1.0	600
400	1.0	600
500	1.0	600
600	1.0	600
700	1.0	600
800	1.0	600
900	1.0	600
1000	1.0	600
1100	1.0	600
1200	1.0	600
1300	1.0	600
1400	1.0	600
1500	1.0	600

Table 1. Base acceleration spectrum

The cumulative damage ratio fringe plot can be found in Figure 15.

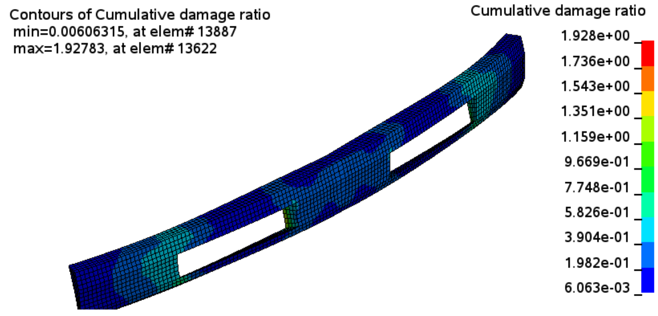

Figure 15. Cumulative damage ratio fringe plot for the bumper

To locate the failed zone quickly, one can use the "Safe / Failed zone" check box and get the failed zone indicated by red elements as below (Figure 16).

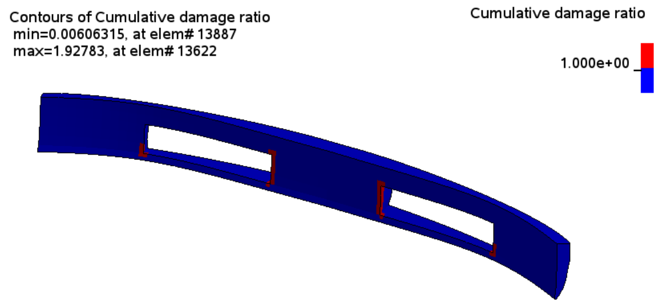

Figure 16. Safe / Failed zone under the steady state vibration

One can see that the failed elements are almost the same elements which are constrained to shaker table directly. For those elements we expect higher stress concentration due to the constraints and that is the reason for the higher chance for fatigue failure at the same location.

Conclusion

A series of fatigue and durability analysis features have been implemented in LS-DYNA. It is based on frequency domain approach and offers effective and efficient tools for fatigue analysis for random vibration and steady state vibration cases. Material's S-N fatigue curves are used in the analysis. As the result, the cumulative damage ratio, the expected fatigue life and many other information pertaining to fatigue status are provided. All the results are saved in binary database D3FTG. With the recent updates in LS-PrePost (4.2, 4.3), a new GUI has been added to show the fringe plot of the fatigue variables. This greatly simplifies the post-processing of the results and makes the fatigue results evaluation much easier.

Two simple examples are included in the paper to show the procedure of running fatigue analysis with LS-DYNA, and performing the post-processing of the results with LS-PrePost. Two different loading cases are considered: random vibration and steady state vibration.

For the future development, the fatigue analysis based on E-N curve will be studied. The strain based methods will further extend the capabilities of LS-DYNA in fatigue and durability analysis, especially for the cases with higher stress and plastic strains.

Acknowledgements

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References

1. http://en.wikipedia.org/wiki/Fatigue_(material).
2. Jaap Schijve (editor). Fatigue of structures and materials. *Springer*. 2009.
3. Arnaud Ringeval, Yun Huang, Random Vibration Fatigue Analysis with LS-DYNA, *Proceedings of the 12th International LS-DYNA Users Conference*, Detroit, 2012.

4. LS-DYNA Keyword User’s Manual, Version 8.0 (Created March 2015), LSTC.