Recent Developments in Time Domain Fatigue Analysis with LS-DYNA®

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Abstract: A series of new options were implemented to the time domain fatigue analysis features since the last China LS-DYNA User's Conference in Shanghai, 2017. They include:

- Fatigue mean stress correction methods
- Load steps definition
- Fatigue damage evolution
- Fatigue failure simulation
- Multiaxial fatigue analysis
- Fatigue summation

This paper gives a brief review of these new options for time domain fatigue analysis with LS-DYNA. Some examples are provided to demonstrate the new feature of LS-DYNA, and show how to use this feature towards different loading cases.

Keywords: LS-DYNA, time domain, fatigue analysis

1 Fatigue mean stress correction methods

Mean stress has important effect on fatigue behavior of metal structures. Mean stress correction is necessary for accurate prediction of fatigue life of those metal structures. Under different mean stress, the SN curve of the same material can change quite a lot.

In LS-DYNA, two categories of mean stress correction methods are available.

Use equations to perform mean stress correction, based on the SN curves obtained by fully reversed testing (R = -1, or mean stress = 0). Following mean stress correction equations are available

- ➢ Goodman equation
- ➢ Soderberg equation
- ➢ Gerber equation
- ➢ Goodman tension only equation
- ➢ Gerber tension only equation
- ➢ Morrow equation (for fatigue analysis based on EN curve)
- ➢ Smith-Watson-Topper equation (for fatigue analysis based on EN curve)

Use *DEFINE_TABLE to define a family of SN curves. Each curve corresponds to a unique mean stress. In *MAT_ADD_FATIGUE keyword, use the table ID for the SN curve. When a mean stress is not represented by the existing SN curves, interpolation is performed to find the corresponding

number of cycles for failure N, for the given stress range or stress amplitude S, under current mean stress.
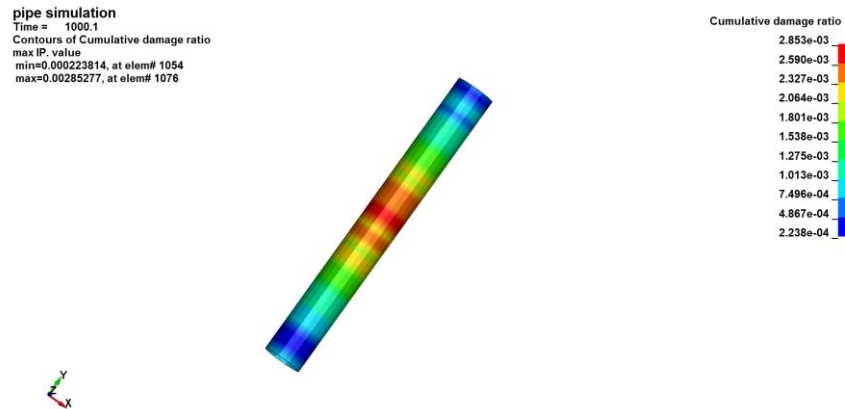

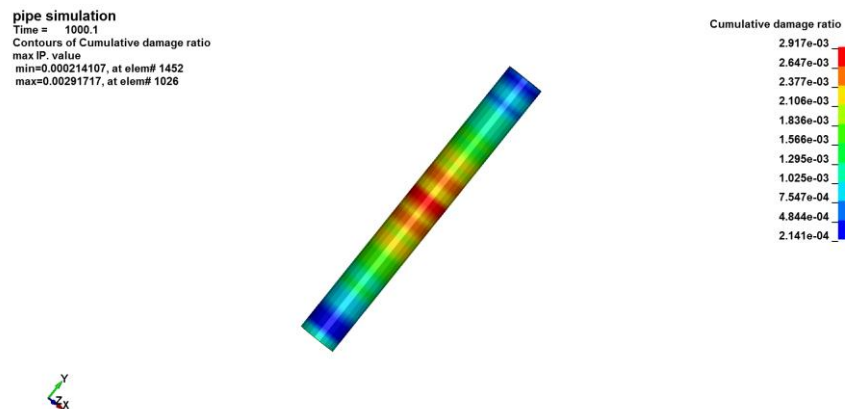Figure1. Damage ratio without mean stress correction

Figure2. Damage ratio with mean stress correction

Figure1 and 2 show a pipe model cumulative damage ratio comparison with and without mean stress correction. One can see that the original damage ratio is 0.002853 and the damage ratio is 0.002917 with mean stress correction.

2 Load steps definition

A new keyword ***FATIGUE_LOADSTEP** was implemented to define load steps in fatigue analysis.

One can choose which segments of loading history are needed in fatigue analysis. Sometimes user may want to skip the starting transient response in fatigue analysis, and use only the steady state cyclic response.

One can compute fatigue cumulative damage ratio for a long term load, based on representation on a shorter load step. The cumulative damage ratio, computed on the shorter load step, is multiplied by a scale factor (which is the ratio between the duration of real load and the duration of the representative load step), to provide estimation of the cumulative damage ratio for the real load, which could be much longer and be prohibitive to compute otherwise. Of course, it is assumed that stress / strain response in the shorter load step is a good representation of the behavior in the real load step. And the material properties don't change with the number of load cycles, or with the load

sequence. In other words, the fatigue behavior of the structure is linear.

The example pipe is modelled by ***MAT_ELASTIC_PLASTIC_THERMAL**. The thermal loading is defined by ***LOAD_THERMAL_LOAD_CURVE**. The keyword cards for ***FATIGUE_LOADSTEP** and other keywords for the load can be found in Figure 3. The thermal loading time history is in Figure4.

```
*FATIGUE_ELOUT
$#    ssid    sstype
$
$#      dt
$
$#   stres     index    restrt    texpos
          0         0
*DATABASE_D3FTG
$#  binary
         1
*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
```
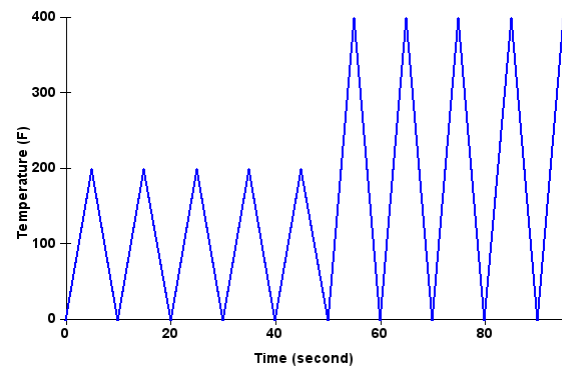

| Figure3. Keyword setting for running fatigue time step | Figure4. Thermal loading time history |

The pipe is subjected to two steps of cyclic thermal loading. For the first load step, the temperature varies between 0°F and 200°F and this lasts for 10000 seconds. For the second load step, the temperature varies between 0°F and 400°F and this lasts for 20000 seconds. It is very time consuming to run finite element simulation for the whole thermal loading history of 30000 seconds. To get a quick estimation of the cumulative damage ratio, we can reduce the duration for each load step to only 50 seconds, and multiply the cumulative damage ratio generated in each step by a scale factor which is the ratio between the real loading period and the reduced loading period.

Figure 5 shows the distribution of effective stress near the end of simulation. Figure 6 shows the cumulative damage ratio of the pipe, after the 30000 seconds thermal loading. One can see that the maximum values of the effective stress and the cumulative damage ratio appear near the bottom of the pipe, probably due to the stress concentration at the constraints.

<div style="display:flex">
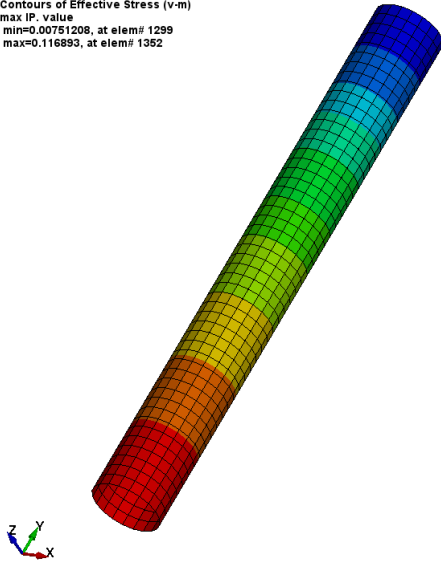
Figure5. Effective stress at the end of simulation
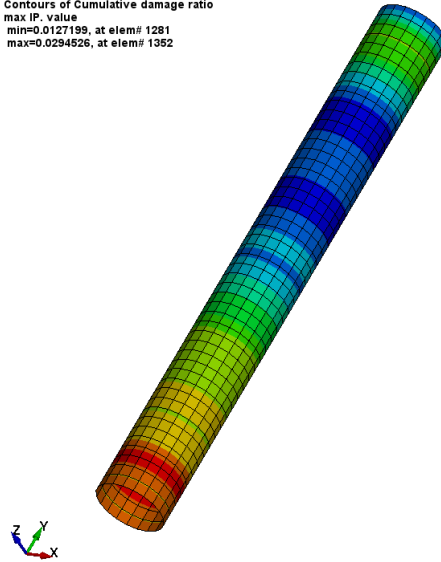
Figure6. Cumulative damage ratio

</div>

3 Fatigue damage evolution and fatigue failure simulation

To show fatigue damage evolution, a progressive fatigue analysis is needed. The corresponding keywords are ***DATABASE_D3FTG** and ***FATIGUE_FAILURE**.

3.1   Fatigue damage evolution

With a nonzero **DT** in ***DATABASE_D3FTG**, LS-DYNA can perform fatigue analysis and dump out d3ftg database every **DT** time. Multiple states are saved in d3ftg and can be plotted using LS-PrePost 4.7 or newer versions. Each state saves cumulative damage ratios for the whole structure at one time point. With this database, user can track the fatigue damage ratio evolution for the structure.

Figure7 shows an L-beam fixed to a bottom plate by four bolts. The plate is constrained to ground. Prescribed harmonic motion (displacement) is applied on the edge of the hole on the L-beam, in the vertical direction. The prescribed displacement time history is shown in Figure8.

The cumulative damage ratio fringe plots at time 0.01s, 0.02s and 0.03s are shown in Figure9. Constant color scale from 0 to 1.0 is used for all the plots so that one can easily compare the magnitude of the cumulative damage ratio, and trace the development of the damage. It is clear that the area at the lower edge of the hole experiences higher fatigue damage. The damage ratio increases with time and the damage area expands with time.
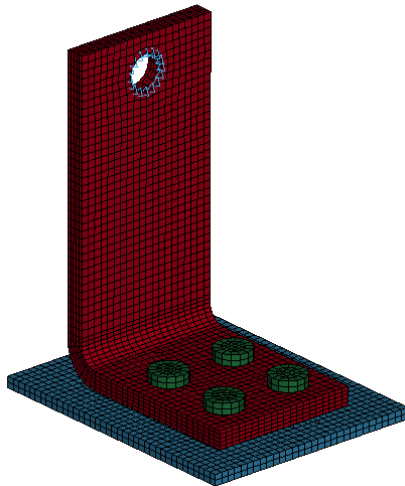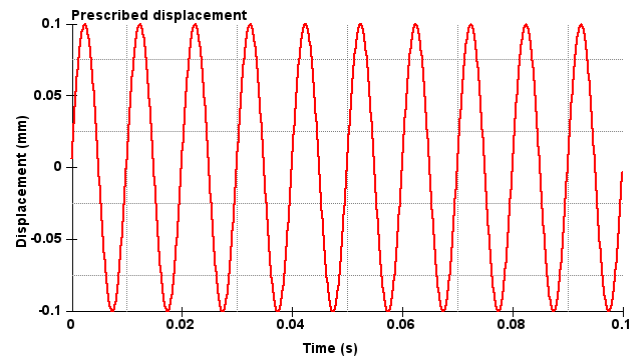
Figure7. A L-BEAM constrained to a bottom plate

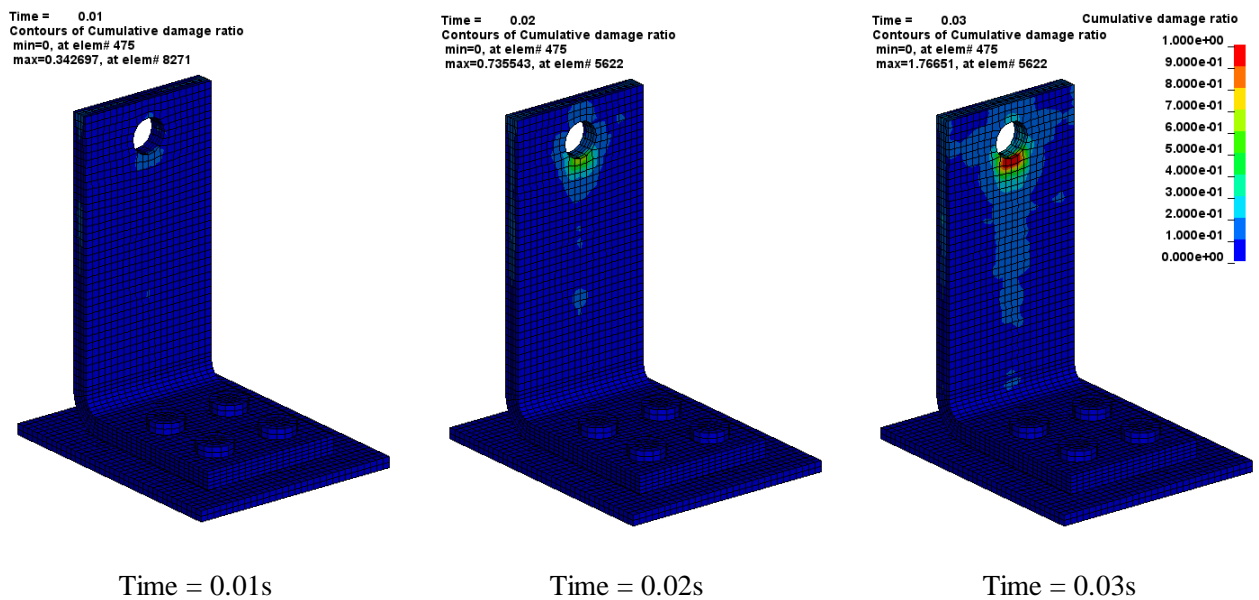Figure8. Prescribed harmonic displacement on the hole

| Time = 0.01s | Time = 0.02s | Time = 0.03s |

Figure9. Cumulative damage ratio at different time points

3.2 Fatigue failure simulation

A new keyword ***FATIGUE_FAILURE** was implemented to introduce a mechanism to model the failure of elements due to fatigue. With this keyword, user can define a threshold cumulative damage ratio (the default value is 1.0) and all the elements with cumulative damage ratio larger or equal to this value can be removed from the structure for subsequent simulation. For increased safety factor, the threshold cumulative damage ratio can be defined as a number smaller than 1.0.

This is a simple way to show the local failure of structures due to fatigue, and it provides an opportunity to study the effect of local fatigue failure on the overall behavior of structures in a long term. An approximate fatigue crack propagation trajectory can be obtained by this approach.

A more accurate simulation of the fatigue crack propagation can be achieved by using the approach by fracture mechanics, or using the cohesive zone modelling.

The max cumulative damage ratio at time 0.03 second is 1.76651 (see Figure9). It is obvious that several elements have failed (including element 5622, which exhibits the max cumulative damage ratio 1.76651). With ***FATIGUE_FAILURE** and **IFAILURE**= 1 and **DRATIO**=1.0, LS-DYNA automatically removes those elements whose cumulative damage ratio ≥ 1.0 from the structure. The remaining elements and their cumulative damage ratio fringe plot are shown in Figure10. Then the cumulative damage ratio of the remaining elements continues to grow with the loading. Figure11 shows the cumulative damage ratio at 0.04 second. One can see that the cumulative damage ratio of several other elements goes beyond 1.0 at 0.04 second (e.g. element 5587), and this results in failure of those elements too. Those failed elements are removed too, as shown in Figure 12. It is expected that with the loading cycles going on, more and more elements will have cumulative damage ratio ≥ 1.0 and will fail and be removed from the structure. Figure13 shows the keyword setting for modelling fatigue damage evolution and fatigue failure.
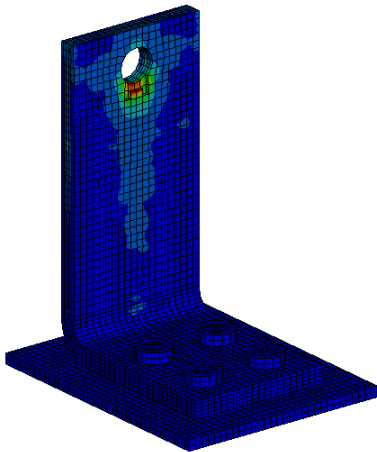
Figure10. Cumulative damage ratio at 0.03s (failed elements are removed)
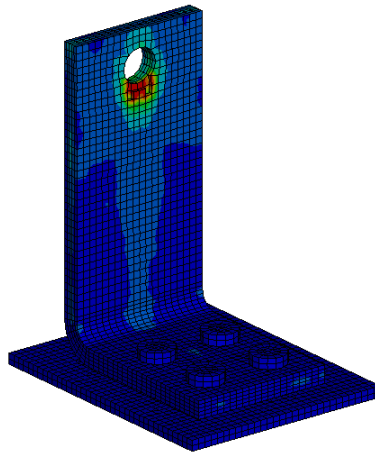
Figure11. Cumulative damage ratio at 0.04s

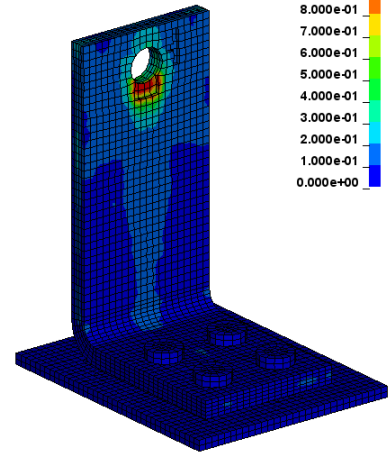Figure12. Cumulative damage ratio at 0.04s (failed element are removed)

```
*FATIGUE_ELOUT
$#      pid     ptype
$
$#       dt
$
$#   strsn      index     restrt     texpos
         0          0
$
*DATABASE_D3FTG
$#  binary        dt
         1     1.E-02
*FATIGUE_FAILURE
$#ifailure    dratio
         1         1.
*DATABASE_ELOUT
     1.E-05          2
```

Figure13. Keyword setting for modelling fatigue damage evolution and fatigue failure.

4 Multiaxial fatigue analysis

Many mechanical components experience multiaxial cyclic loadings during their service life. Compared with the uniaxial fatigue problem, the multiaxial fatigue problem is more complex due to the complex stress / strain states and loading histories. Stress / strain state is always three dimensional.

Three multiaxial fatigue methods are provided in LS-DYNA time domain fatigue analysis. Figure14 shows keyword setting for modelling multiaxial fatigue.

- A scalar index (e.g. Von-Mises stress, 1st 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
```

Figure14. Keyword setting for modelling multiaxial fatigue

Figure15 and 16 show the cumulative damage ratio of a simple plate with different multiaxial approaches. One can see that the damage ratio is 1.2655 with MAXIAL=0 and the damage ratio is 1.3045 with MAXIAL=2.
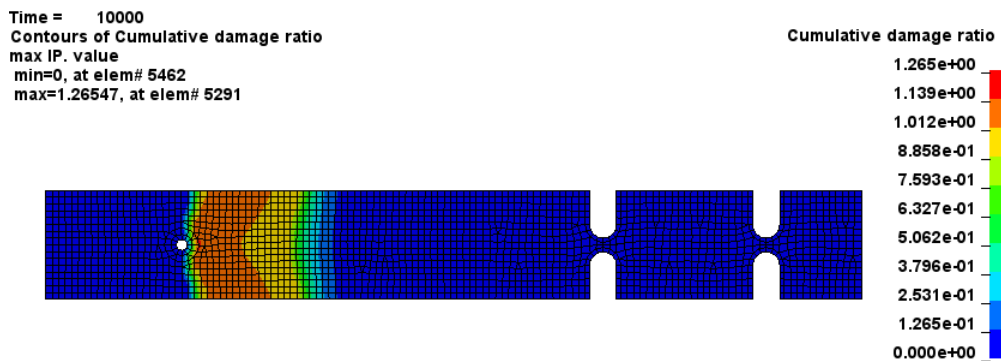

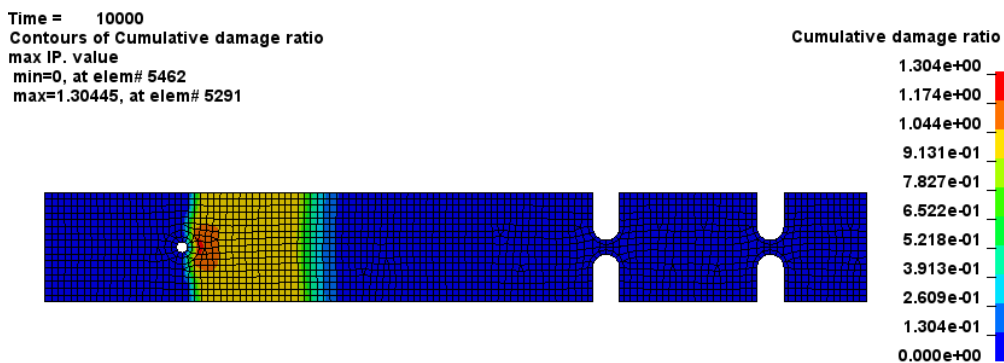Figure15. Cumulative damage ratio for MAXIAL=0

Figure16. Cumulative damage ratio for MAXIAL=2

5 Fatigue summation

This keyword reads in existing fatigue databases defined by ***INITIAL_FATIGUE_DAMAGE_RATIO** and sum up the damage ratio results from them to obtain the final cumulative damage ratio. The final cumulative damage ratio results are dumped to a new d3ftg database. The Figure17 and 18 show a comparison of a simple plate cumulative damage ratio with and without damage from transient preload. One can see that the damage ratio is 0.3440 from fatigue load and the damage ratio is 0.3443 from fatigue load plus transient preload.
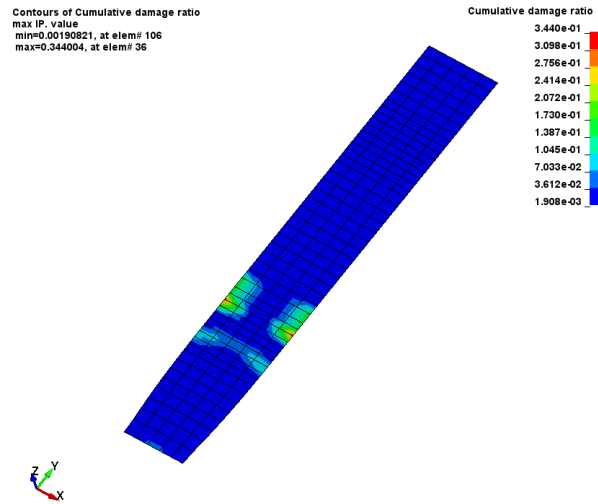

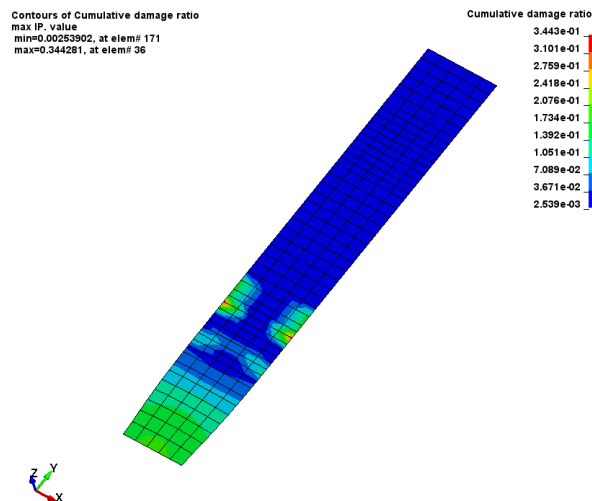Figure17. Damage ratio from fatigue load

Figure17. Cumulative damage ratio from transient preload + fatigue load

6 Summary

This paper reviews recent updates in time domain fatigue analysis in LS-DYNA, and introduces several new keywords and options for running these features. These new options and enhancements enable users to solve more comprehensive problems in NVH and durability analysis.