Using the CESE Immersed Boundary FSI Solver to Simulate the FSI of the Front Portion of a Turbofan, including Damage

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Abstract

In this paper, we demonstrate use of the LS-DYNA®. Conservation Element/Solution Element (CESE)[1] solver doing fluid-structure interaction (FSI) calculations employing its immersed boundary FSI method[2,3]. The fan rig used is a portion of the fan blade-off rig test for a generic fan rig model. The model is available through the LS-DYNA. Aerospace Working Group (AWG) at http://awg.lstc.com. In this model, programmed failure of some of the structural elements is set up in one blade near the fan hub. Two cycles of operation are analyzed with and without FSI, and then the failure situations will be demonstrated with and without FSI active.

Introduction

For many years, experimental testing has been used to study the safety issues surrounding blade-off events in jet engines. Simulation for the structural-only aspects of this problem has also been done for many years, including using LS-DYNA. One of the reasons for the creation of the generic fan rig model of the Aerospace Working Group (AWG) has been to study such problems, especially with the advanced structural material models in LS-DYNA. And a portion of that model is used in the studies reported here. It should be emphasized that this partial model in no sense represents anything real, or in actual use in industry.

It may be that the structural-only modeling of engine damage events may reveal most of the modeling issues that the design engineer needs to take into account. However, simulations of in-flight operation of such blade-off events require that the high-speed airflow involved be taken into account as well. Likely, this is also necessary to account for the FSI effects on mechanical parts that are more fragile. Thus, we have developed the capability to simulate fluid-structure interaction (FSI) using the CESE compressible flow solver. In addition, in order to deal with the blade-off event and the subsequent damage to the engine and aircraft, we have added a material erosion capability to this solver. This tool then allows us to deal with scenarios where secondary breakup of structural parts occurs as a result of the initial part failure.

A number of simulation runs have been done to assess these new capabilities. First, in order to confirm that the results we get with our FSI simulation are reasonable, we do a comparison between the operation of the fan without any loading due to a high-speed airflow and the same configuration with the airflow load taken into account. The next step is to add the programmed failure that the AWG has introduced into their model and do the same with our modified version of their model. This is run first with no FSI due to an airflow. Then a long-time simulation is run performing FSI due to the airflow.

The results obtained here have to be viewed as preliminary. While the CESE mesh used here is under-resolved, the calculation is nevertheless expensive. Moreover, the material erosion that occurs due to structural impacts causes tearing and other break up to occur in some regions of the structural assembly, and each time step where this occurs requires a complex adjustment to the contact interface between the compressible air region and the structural parts. That is, material erosion increases the expense of the computation quite a bit.

So, while the results here are essentially a demonstration of feasibility, it is clearly necessary to develop more accurate and more efficient mechanisms for these types of calculations. Ongoing work in these areas will be discussed in the concluding paragraphs.

Fan Blade-Off Rig Test

This example is derived from the Fan Blade-Off Rig Test for a Generic Fan Rig Model that is available at http://awg.lstc.com, the LS-DYNA Aerospace Working Group. The test setup is originally due to Kivanc Sengoz (GWU, NCAC), Steve Kan (GMU, CCSA) and Chip Queitzsch (FAA). The subset of the problem for use in these FSI studies with the CESE IBM solver is shown in Fig. 1, including the initial very coarse Eulerian fluid mesh made up of 36,750 elements.

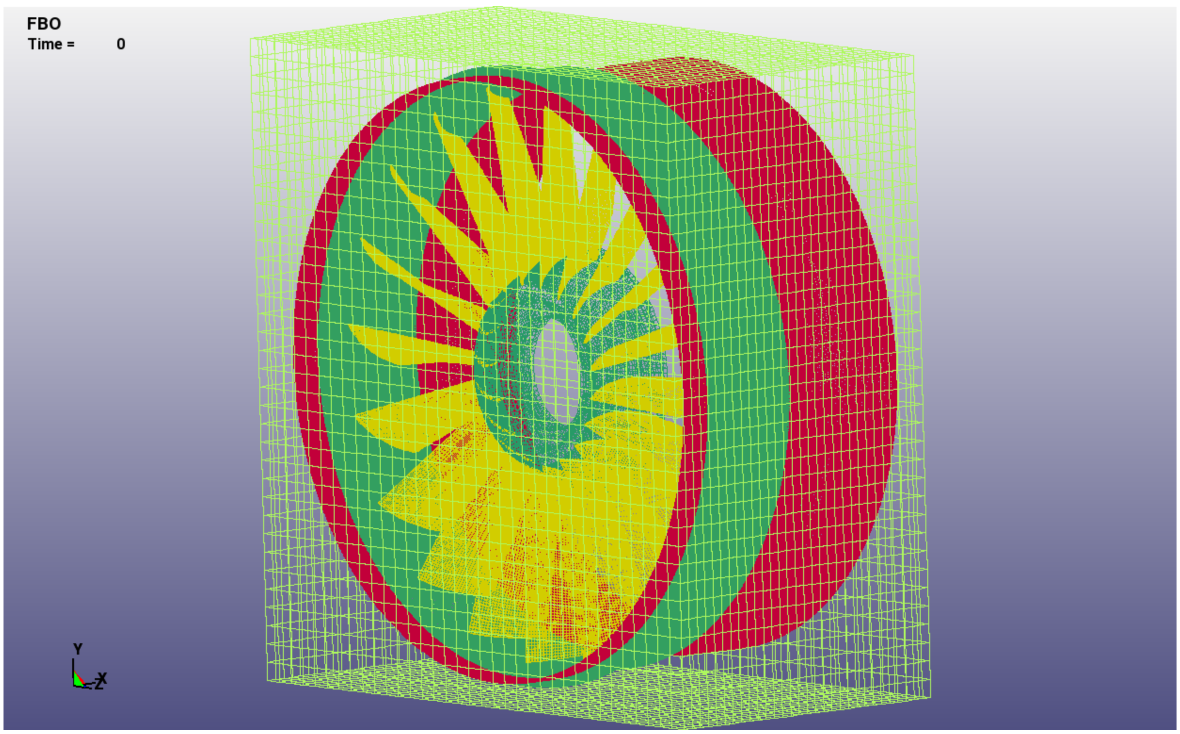
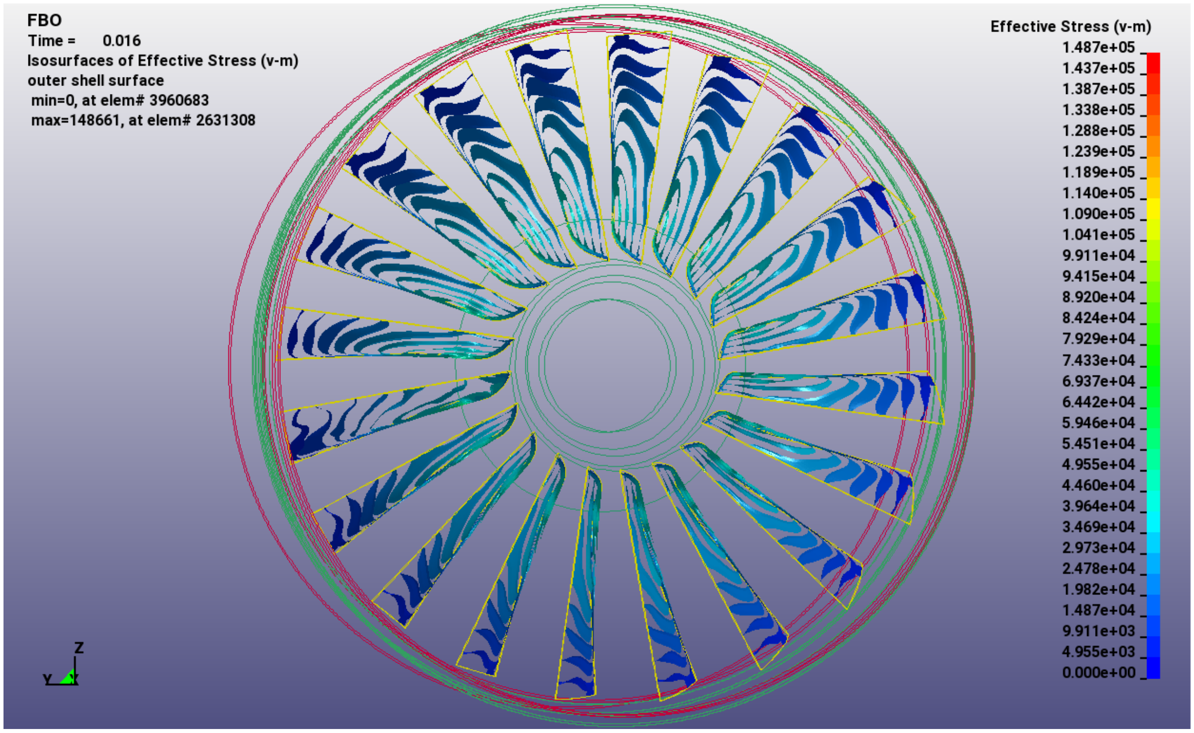
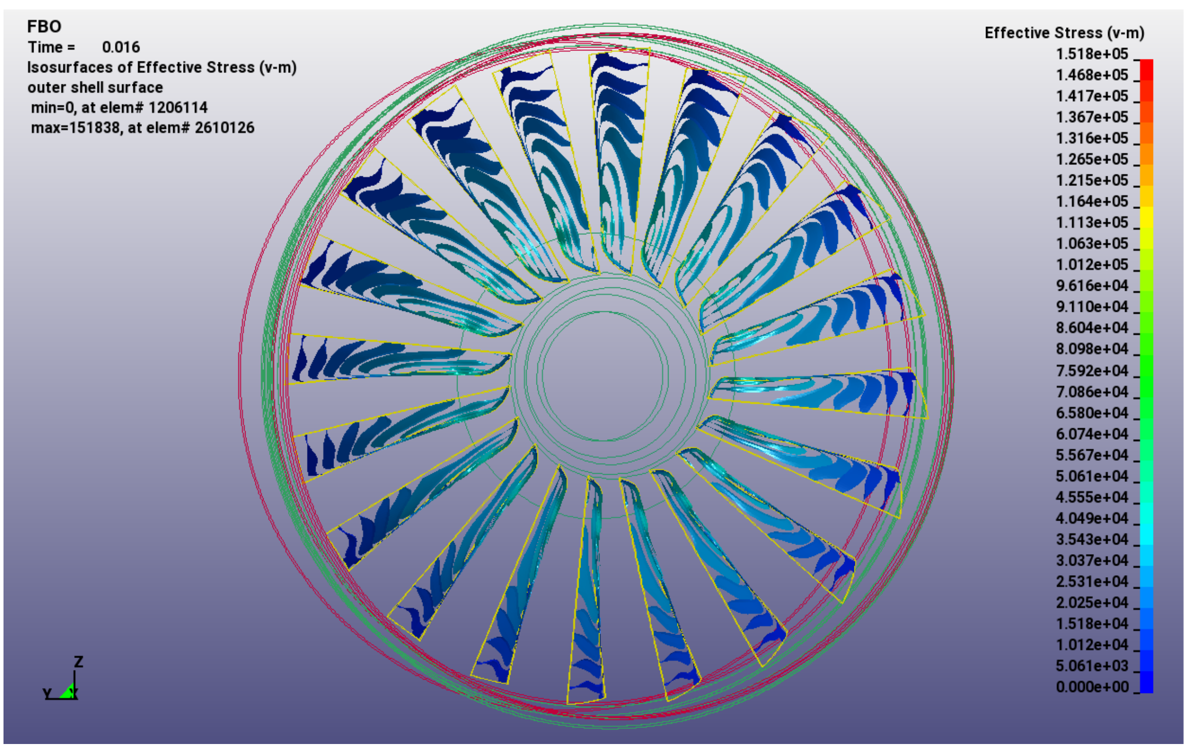


Figure 1 Initial Structural parts and the CESE FSI mesh

Next, we ran these subset models first without FSI, and then with FSI to get an idea of how the stresses in the fan would change due to the FSI loading. For this evaluation, each model was run for two full rotations of the fan blade assembly. In Figure 2, it can be seen that there are only small differences between the two cases, with about a 2% difference in the maximum effective stress.



(a)



(b)

Figure 2 Isocontours of effective stress: (a) with no FSI loading, and (b) with FSI loading.

For the blade-off simulations, we switched to a mesh more closely conforming to the containment parts of our model, and it has a total of 318240 elements. The fluid mesh along with the structural parts are shown in Figure 3.

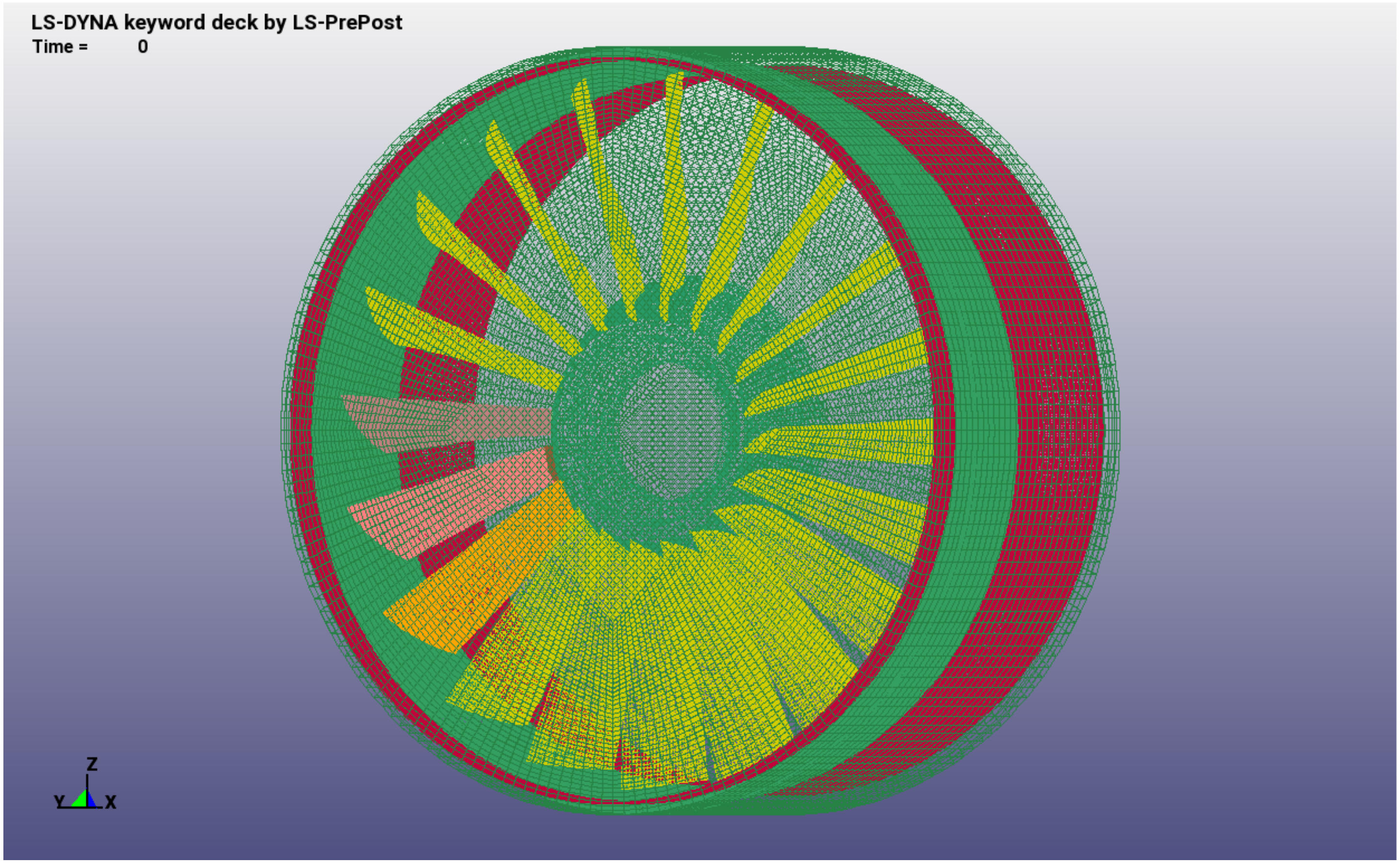


Figure 3. Higher-resolution fluid mesh with the structural parts visible.

The blade-off event is implemented in LS-DYNA via programmed failure, meaning that the mechanism that actually causes the blade to break off of the assembly is replaced by an artificial eroding of a layer of elements in the blade near the hub. At a time shortly after this material erosion has occurred, the displacements of the structural nodes are displayed in Figure 4.

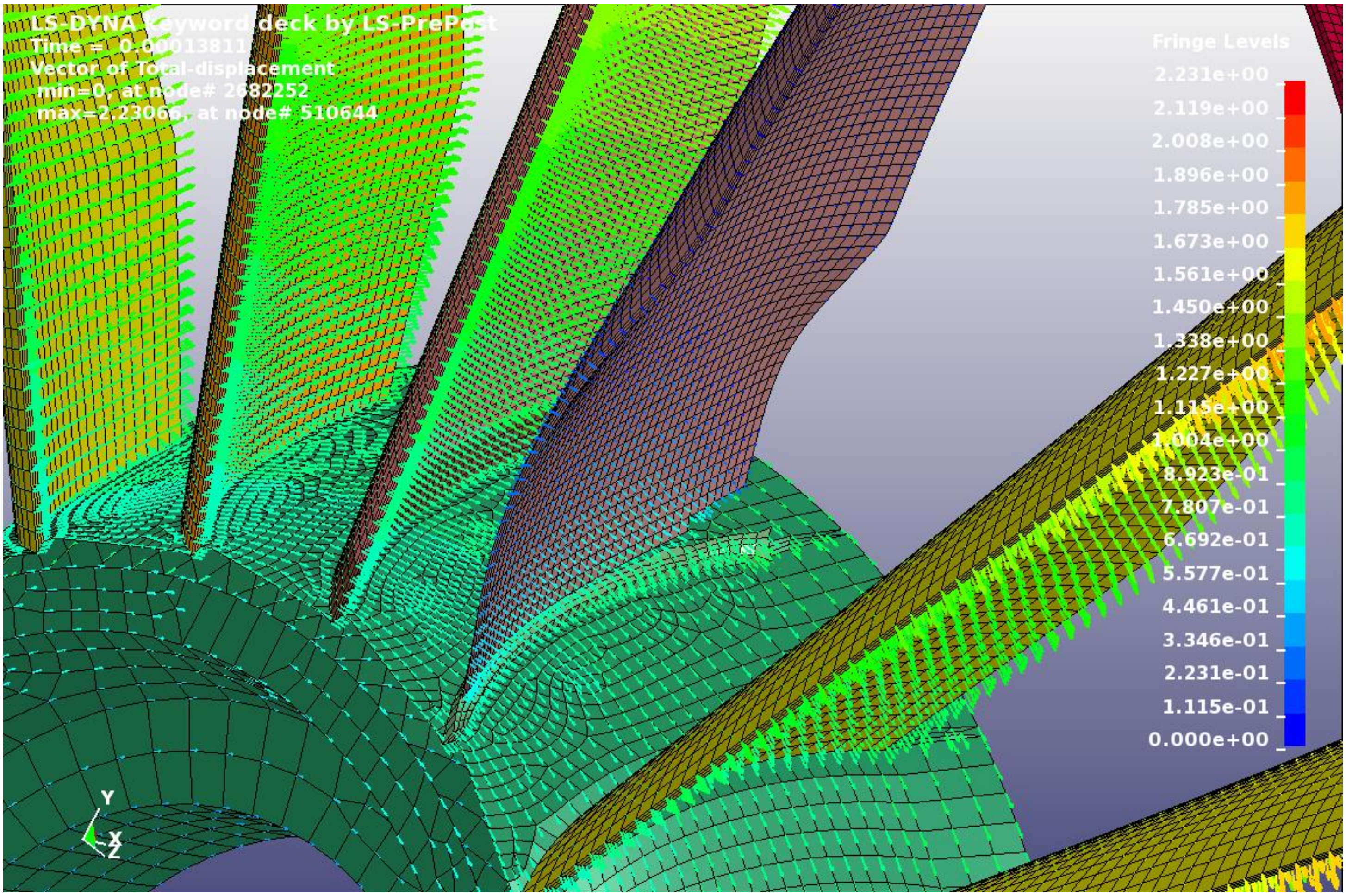


Figure 4. Structural node displacements for the fan assembly in the region of the blade off event that occurred just previous to the time shown here. The blade that is colored purple is the one that has broken off of the hub.

In Figure 5, the displacements of the surface nodes is visible for the upper section fan blades, and air pressure isocontours are shown in the bottom section of the fluid mesh. Note that the broken-off blade lies on the left side of the figure, just touching the top of the pressure isocontours.

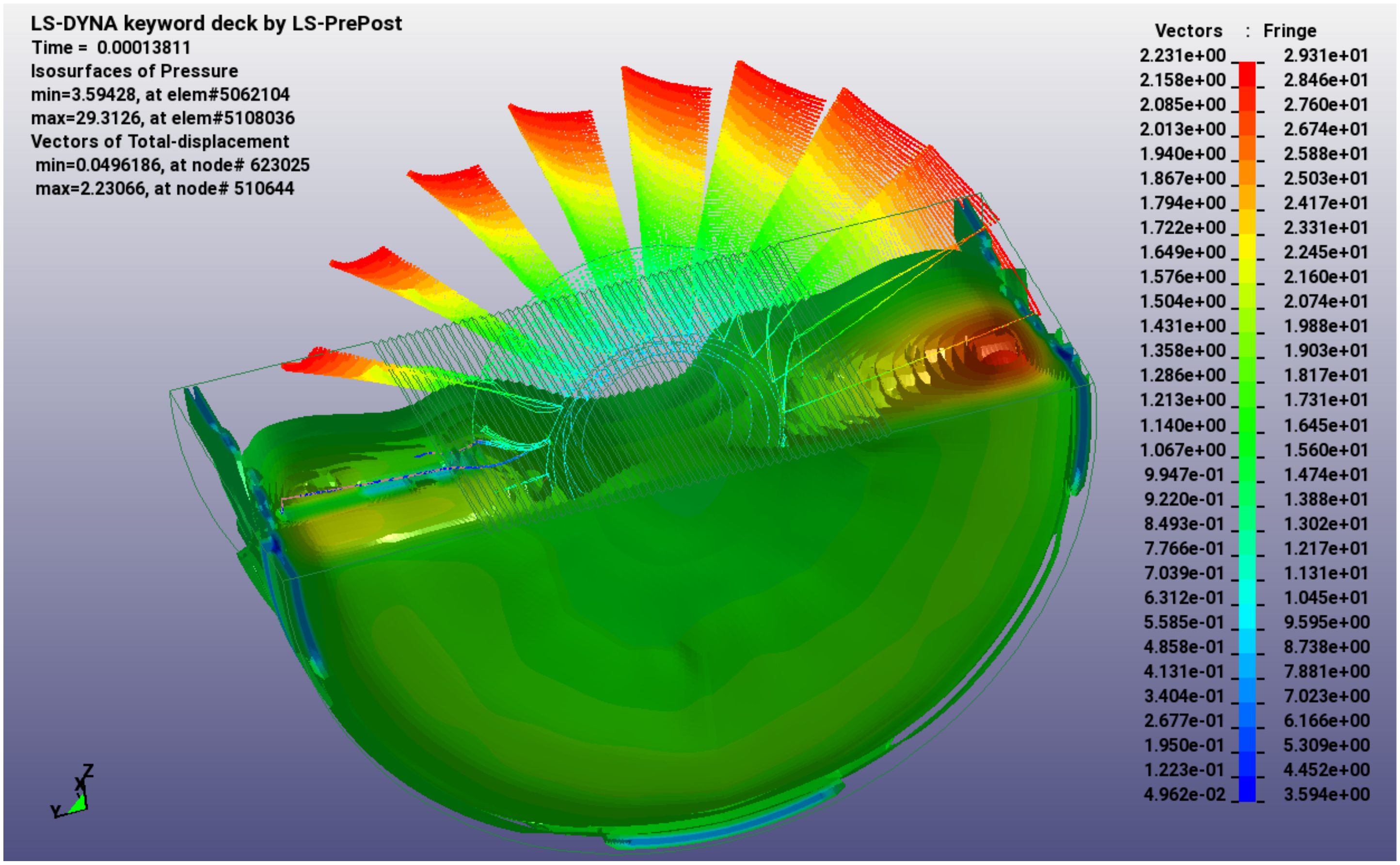


Figure 5. Structural node displacements for half of the fan assembly including the detached blade (adjacent to the pressure contours on the left side of the figure). Air pressure isocontours are shown for the lower portion of the fluid mesh.

Further on in the simulation, the released blade hits the adjacent blade that is rotating into it. This first impact of the released blade on another structure is shown in Figure 6. And thus, begins a sequence of events where blades are damaged to the point that some break off and then impact the containment parts. Some of the blades curl up from the impact, while others begin to tear holes in the containment parts. Subsequent damage details are visible in Figures 7-11.

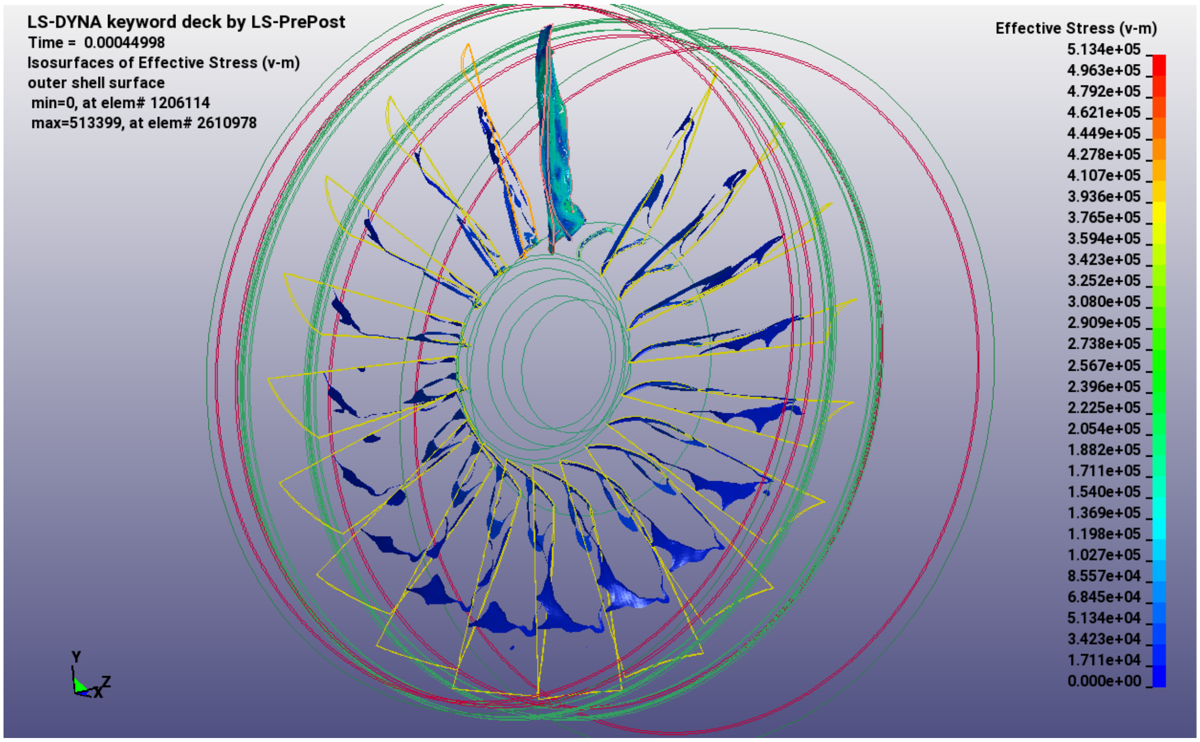


Figure 6. Effective stress isocontours at the time the released blade has initial contact with the neighboring blade.

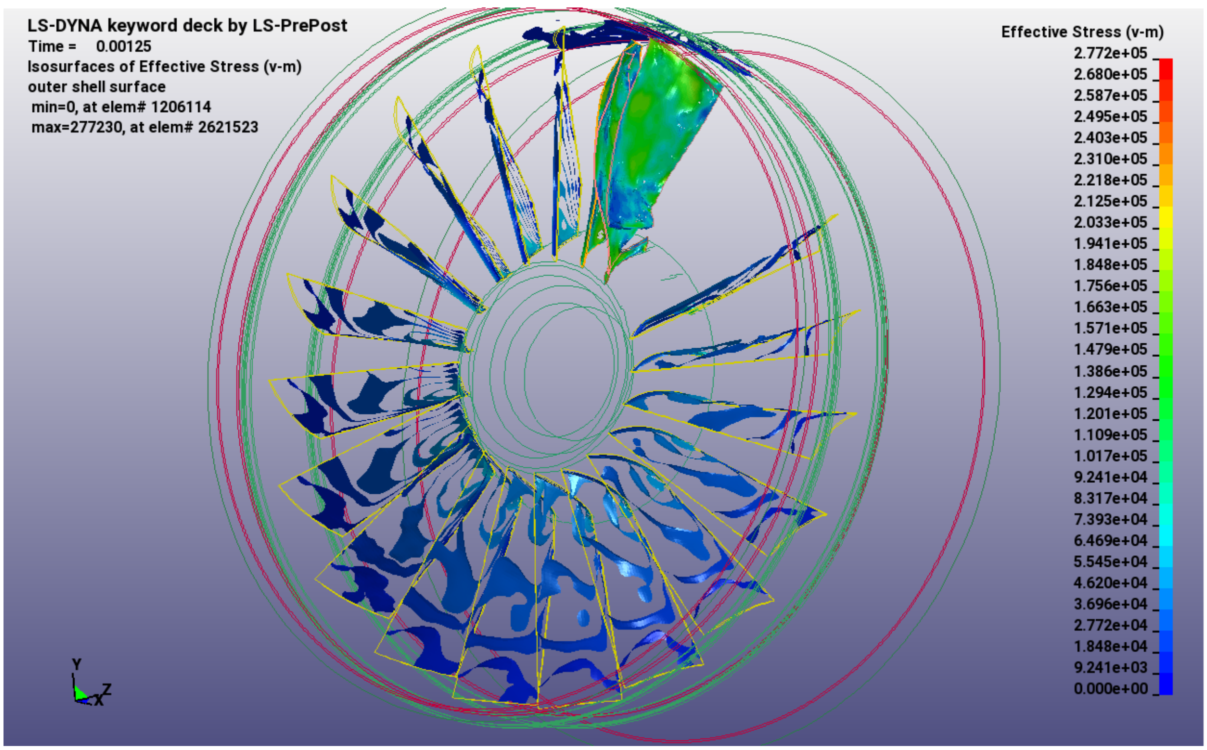


Figure 7. Initial impact of the released blade with a containment part.

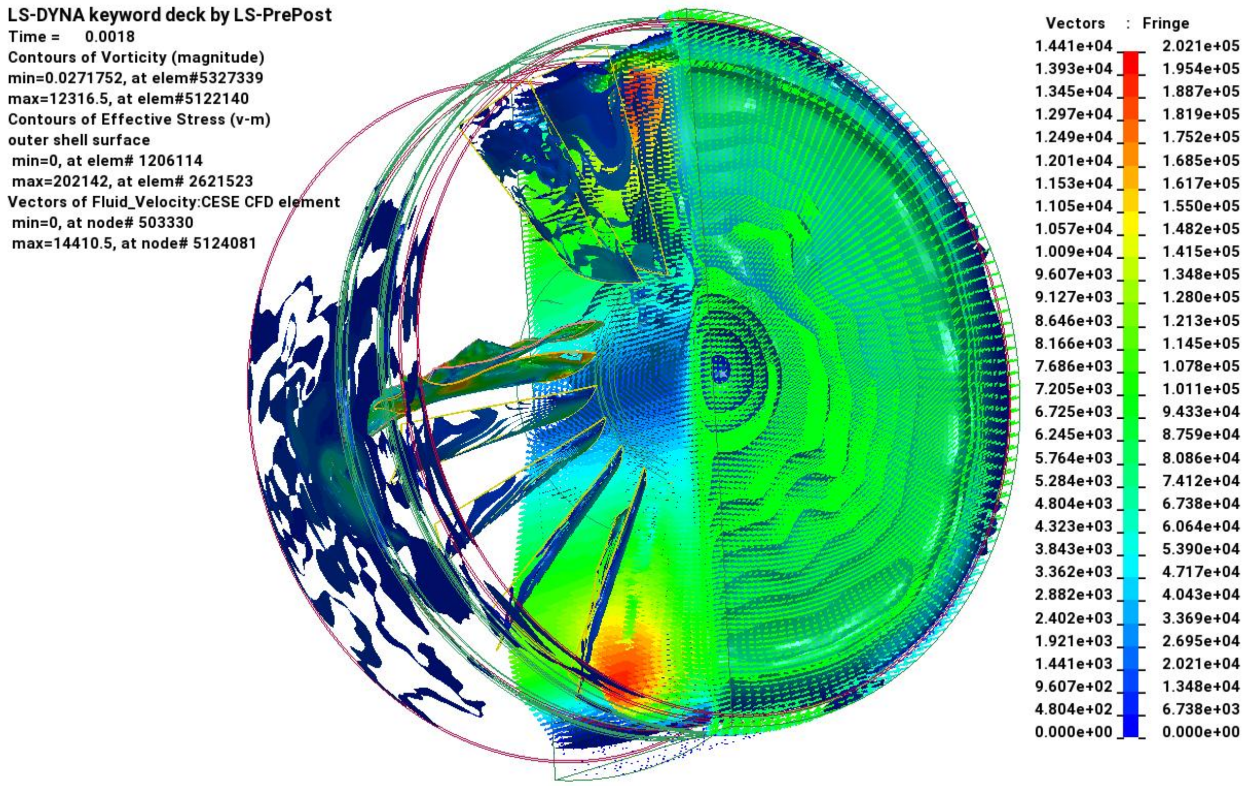


Figure 8. Still early interaction of the released blade with other structures. In addition to isocontours of the effective stress, also shown in this figure are isocontours of the fluid vorticity and fluid velocity vectors of half of the flow field

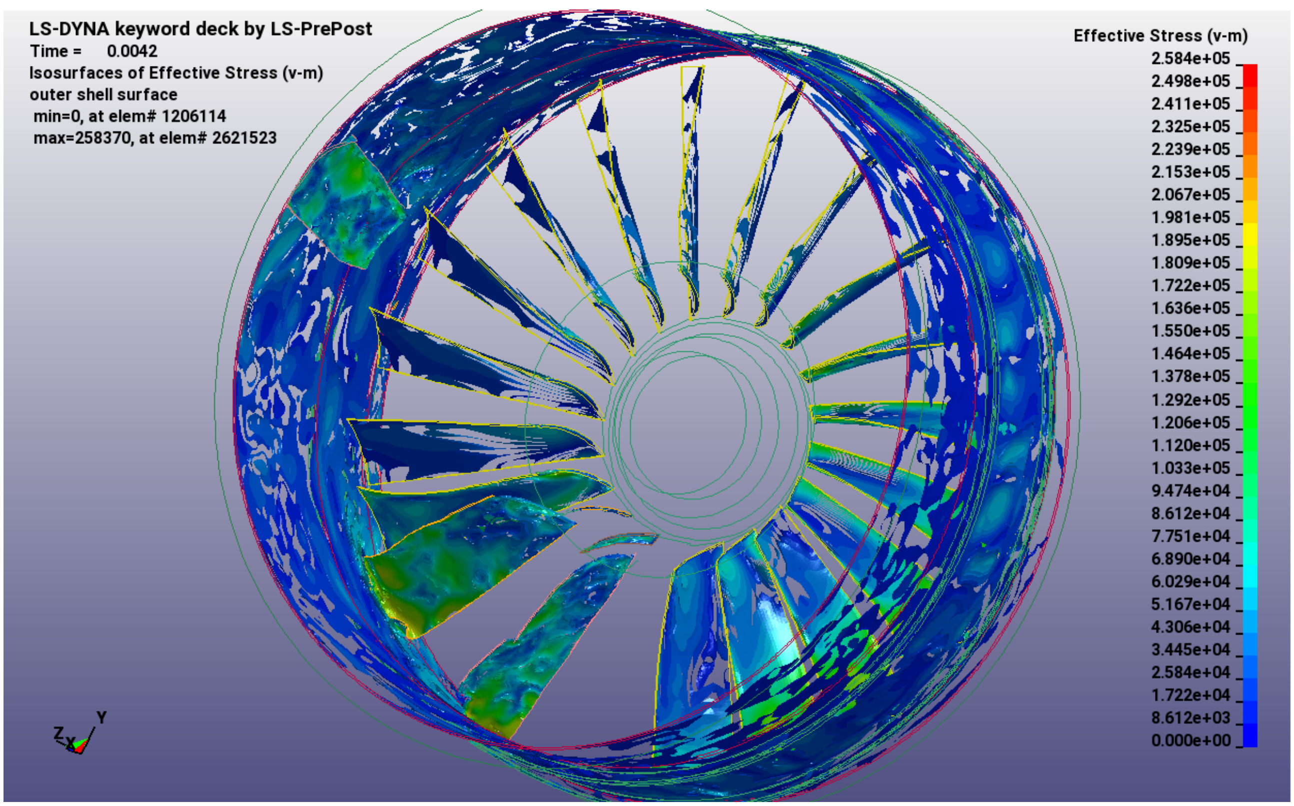


Figure 9. Adjacent blades (to the initially released blade) begin impact with the containment parts.

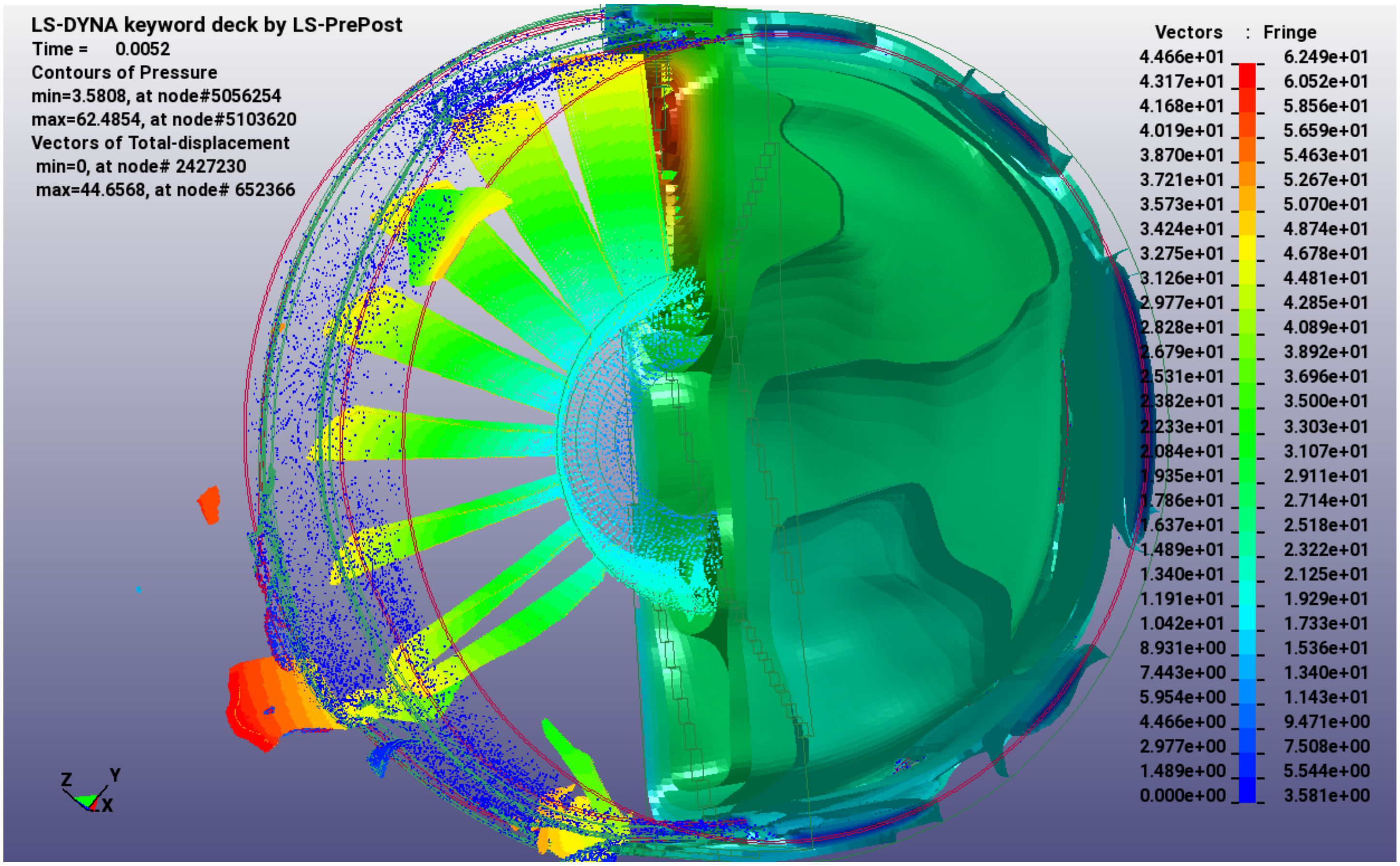


Figure 10. Fluid pressure isocontours and structural surface node displacements are shown at a time where multiple blades have penetrated the containment parts and have caused a number of fragments to be generated. Obviously, many structural element failures have occurred in the process. Each such event entails an expensive recalculation of the fluid-structure contact interface.

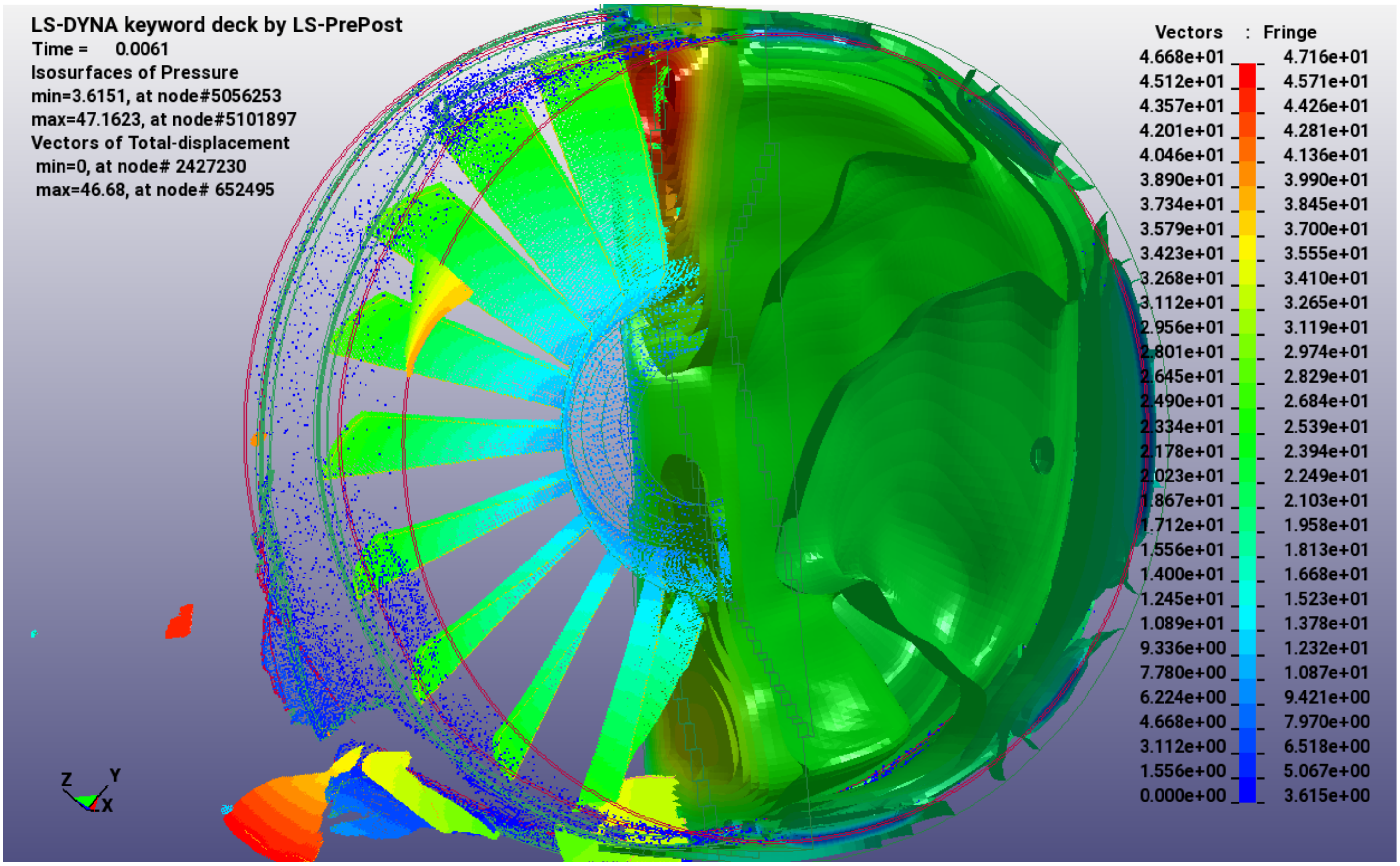


Figure 11. Fluid pressure isocontours and structural surface node displacements are shown at a time where one entire blade has broken through the containment parts laterally, and thus exited the fluid mesh (FSI no longer takes place for structural parts or elements that have exited the fluid mesh). Also, note that the initial blade that was released is in the process of exiting the rear of the assembly (and thus the fluid mesh domain as well). It can be noted that there are clear non-uniformities in the fluid pressure field where there are blades missing. Compare this with the much more uniform pressure contours in Figure 5.

Summary

In this presentation, we report a recent development of the immersed boundary FSI capability with the Conservation Element/Solution Element (CESE) compressible flow solver in LS-DYNA and its use in studying a highly simplified scenario of a blade-off event.

As noted in the introduction, these IBM FSI calculations with material erosion are expensive. In order to address these issues, and to improve the CESE accuracy with and without FSI, a new solver technology has been developed. This new method is known as the dual CESE method since it solves alternately for the state variables at the mesh element centers and then at the mesh nodes (using the dual mesh). This new technology is discussed in another paper in this conference. But for completeness, it should be pointed out here that this new method is more accurate and robust that the CESE method used in this study. Moreover, it has the ability to deal with better quality meshes (that include pyramid elements). The feature that it is missing at this point is the structural material erosion coupling. This is work currently in progress.

References

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