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DIRECT COMPARISON OF WIDE-AREA HULL DEFORMATION FROM DYNAMIC MEASUREMENT DURING BLAST VS. NUMERICAL SIMULATION

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ABSTRACT

Tools have been developed to compare the dynamic deformation of vehicle hulls as they undergo blast-testing with numerical simulations. These tools allow quantitative comparisons and measurements over a wide area of the hull surface, rather than point comparisons as have been performed in the past. The experimental measurements are performed with the Dynamic Deformation Instrumentation System (DDIS) that was developed for TARDEC. Numerical simulations of the test article attached to Southwest Research Institute's Landmine Test Fixture were performed with LS-DYNA using an empirical blast-loads model. The specific example highlighted in this paper is the deformation by blast testing of a hull component.

INTRODUCTION

The dynamic deformation of a vehicle hull during an explosive loading event is of considerable interest in understanding the potential harm that can come to the vehicle's occupants. Traditionally, this loading and early dynamic deformation have been hard to measure, as they occur in a violent environment on a time scale of less than 10 milliseconds. However, in the last few years, more robust cameras have been developed that can be protected to such an extent that they can be placed near the blast event. Simultaneously, developments in image-analysis software have permitted accurate deflections by way of digital image correlation (DIC). These developments allow the dynamic measurement of the interior surface of a vehicle hull undergoing blast loading. An important fact is that this measurement is dynamic (the example presented here has images recorded at every 125 microseconds) and it covers a wide area of the hull surface. It is not just limited to one point. The new data thus opens up a much larger realm of validation of and comparison with our computational solutions and development of our models. Now, instead of just comparing a pre-selected point's deformation, the deformation of the entire bottom of the hull can be compared with the numerical simulation result. Such a comparison allows a better understanding of the validity of the modeling approach and the accuracy of the blast loads, and a sense of how much confidence one can have when making a decision based on simulation results. This exciting new era of diagnostics combined with numerical work promises new insight and quantitative accuracy in our modeling of blast and other dynamic events related to survivability.

THE EXPERIMENTAL SETUP

In recent testing by Southwest Research Institute (SwRI) in support of TARDEC and the Concept Vehicle Prototype (CVP) program, explosive loading experiments were performed on various hull components. Two high-speed cameras, part of the Dynamic Deformation Instrumentation System (DDIS) developed by SwRI for TARDEC, were mounted on the top of SwRI's Landmine Test Fixture that holds 1.22 meter per side square test articles (Figures 1 and 2) [1]. Using the parallax in the cameras' optical paths, through Digital Image Correlation (using ARAMIS software), the dynamic deflection of the inside bottom of the hull during the explosive loading event was measured. LED lights illuminated a dot pattern that was applied to the upper surface of the inner hull; the DIC system used these, in conjunction with its calibration, to determine the physical location of the upper surface of the inner hull for each set of images that were taken during the test.

Figure 1: SwRI's Landmine Test Fixture holding a hull component above a soil pot. At the top of the test fixture is the superstructure holding dual offset high-resolution high-speed cameras.

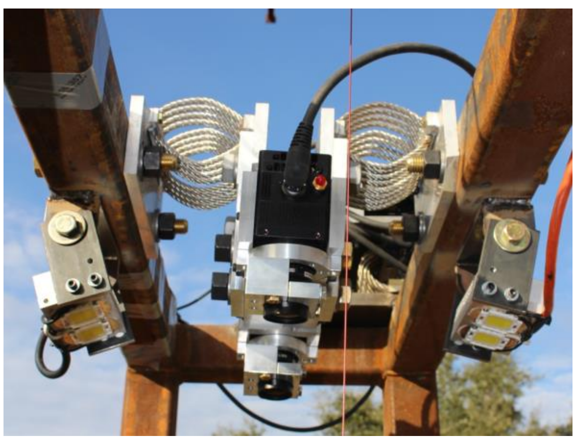

Figure 2: The dual cameras attached to shock isolators. LED lights are to either side. Also visible is the vertical cable of the string-pot gage, attached to the outer spider frame, that measures the fixture jump height.

AN EXAMPLE EXPERIMENT

During a test (Test #1, in this case), the cameras were run at 8,000 frames per second; thus, we were able to construct deflection/deformation plots every 125 microseconds. Fiducials were attached to the test fixture and were in the image to allow the removal of the camera motion, thus identifying the relative motion of the hull component to the test fixture and hence allowed a quantification of the dynamic deformation process. This collection of data over a wide area of the inner bottom of the hull provides the dynamic deformation of the hull. Given this deformation information, it is possible to determine, if a floor were hung above the hull, whether the hull will contact any part of the floor during such an explosive event, and to what extent. Figure 3 is one frame of a movie that was produced for each test. It shows the hull deformation during a blast event. This particular frame, at 4 milliseconds after the initial hull motion due to the blast (i.e., it is not 4 milliseconds from the explosive detonation), is taken at the time of maximum deformation. The upper left part of the image colors the amount of deformation of the hull bottom, with the most deformation (colored orange) occurring directly above the explosive charge. This image shows that we are seeing the upper hull surface that is observable through the circular hole in the top of the test fixture. The upper right part of the image shows the deformation of a cross section across the hull at that time (the cross-section location is indicated in the upper left figure by the vertical black line). The lower image shows the deflection of the center point (which happens to have the maximum deflection) versus time; the plot remains the same, but the vertical red-dashed line moves from left to right in accordance with the advancing movie. After reaching a maximum deflection of 20.5 cm at 4 milliseconds, the deformation decreases and will eventually end up at a post-test static value. This movie is extremely helpful in understanding what happened during the blast event as well as the times involved.

A second version of the film shows the actual shape of the hull rather than the amount of deformation. Figure 4 shows an initial image of the hull shape cross section and then a late-time image of the hull cross section. This movie is, for many, easier to understand as it displays the actual shape rather than the deformation.

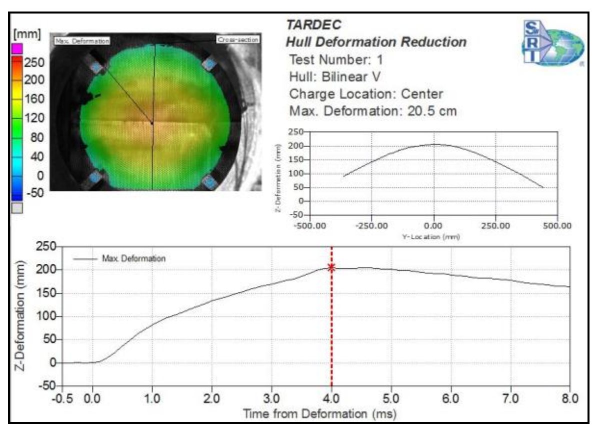

Figure 3: A frame at 4.0 milliseconds after initial hull motion from the movie showing the deformation of the hull as seen at the inner surface.

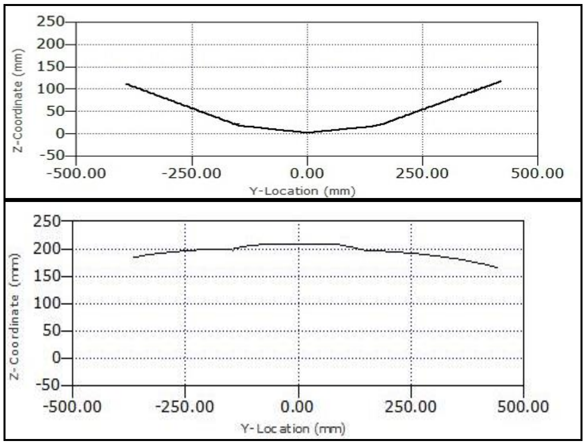

Figure 4: Initial and late-time hull shape cross sections.

Historically, dynamic deformation measurements were performed with pins (sometimes instrumented to obtain location vs. time; for example, see [2] where shorting pins were used to develop a displacement vs. time for a finite number of points during blast tests) or with foam crush gages. The final amount of deformation of the pins or crushing of the gages was used as a measure of the dynamic deformation of the material. However, with the DDIS system, we have a much greater capability in measuring deflection and deformation during the blast event. Also, with the DDIS, we take a post-test image to provide the final static shape of the deformed panel, which can also be compared to simulations; Figure 5 shows the final shape of this particular panel.

Figure 5: Post-test image of the deformed panel. The visible upper surface contains the black dot pattern for the DIC measurements on the white-painted inner hull surface.

PRE-TEST NUMERICAL PREDICTIONS

As part of preparing for the experimental program, pre-test numerical simulations were performed. In particular, a three-ring binder containing results of these pre-test predictions was on hand at the test site for review before and after each blast experiment. This allowed immediate comparisons of maximum deflection and jump height after each test, typically in less than one hour, and before the next test was performed.

The pre-test predictions were performed using LS-DYNA and a finite element model of the hull component test article panel and Landmine Test Fixture. The hull component was primarily modeled with quad shell elements. The blast loads were supplied with an empirical soil blast-loading model [3]. The finite element model was developed using tools developed for DARPA's Adaptive Vehicle Make program [4-5]. Figure 6 shows a cross section of the fixture with the deformed blast panel at the point of maximum deflection (which according to the computation is 21.7 cm). It should be noted, and can be seen by comparison with Figure 1, that a slight difference in experimental setup vs. the pre-test simulation is that there is a 90 degree rotation (from above) in the initial hull symmetry setup. The rotation was chosen at the site due to ground-based camera placement. There is also another difference in initial setup that will be described later in this paper.

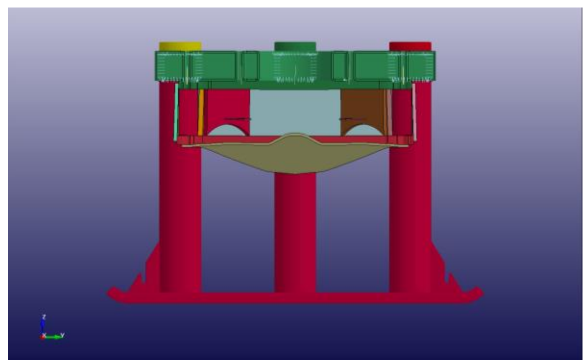

Figure 6: Pre-test numerical simulation cross section showing the maximum deformation of the panel.

In addition to the cross section of the maximum deformation, the three-ring binder contained dynamic deflection contours (Figure 7) and late-time "static" deflection contours. The numerical simulations are not carried out in time long enough for true final state, so the computational team uses its judgment in choosing an appropriate time to identify the static deflection based on the elastic oscillations in the hull structure after the plastic deformation is complete, usually carrying out two or three oscillation cycles and picking a median point. Also, the three-ring binder contained predictions of impulse imparted to the fixture and fixture jump height. In the experiments, these values were measured with string-pot gages, accelerometers mounted on the fixture, and high speed cameras that were on the ground at a safe distance.

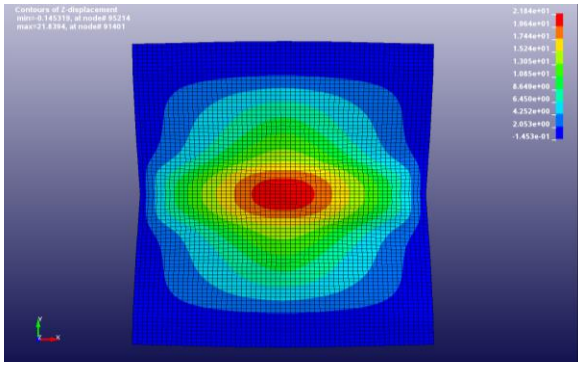

Figure 7: Dynamic deflection contours from the pre-test numerical simulation.

NEW COMPARISON TOOLS FOR COMPARING EXPERIMENTAL AND COMPUTATIONAL RESULTS

This dynamic experimental data was compared to pre-test predictions. The comparison was not only at the point of maximum deformation but also over nearly the entire bottom of the hull panel. Figure 8 compares the numerical simulation with LS-DYNA (in blue) and the measured dynamic deflection over the bottom of the hull as measured in the Landmine Test Fixture (in red). The times of comparison were based on maximum deformation for the simulation and experiment, respectively, and were not based on an absolute time. In addition to the three dimensional comparison, Figures 9 and 10 show cross sections: a centered front-to-back cross section and a centered side-to-side cross section. A visualization tool was developed that allows researchers to rotate these comparison images, and thus fully explore agreement or lack thereof. These tools also allow the production of movies showing the deformation vs. time of both the experiment and computation simultaneously displayed and overlaid.

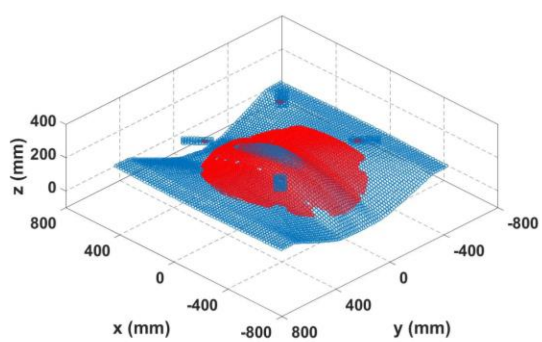

Figure 8: Comparison of pre-test numerical simulation (blue) with the experimentally measured (red) deflection at the maximum deflection for both.

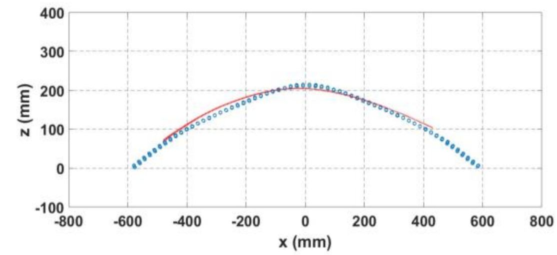

Figure 9: Front-to-back cross section comparing pre-test numerical simulation (blue) to experimental (red) deflection results.

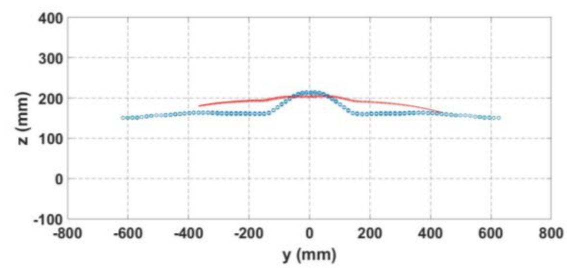

Figure 10: Side-to-side cross section comparing pre-test numerical simulation (blue) to experimental (red) deflection results.

In this specific experiment, the maximum deformation between test and pre-test simulation agrees very well (as was stated above, the experimental deflection was 20.5 cm and the computational deflection was 21.7 cm), and that agreement is clear from the cross sections. However, the ability to compare over the entire hull shows that the agreement is not uniform. This new comparative capability greatly expands our ability to see, quantify, and understand what is occurring in highly dynamic events. In particular, we are able to use these comparisons to plot the difference at these times of the deflections, which essentially correspond to the error in the pre-test numerical simulations. Figures 11 and 12 show the error at the maximum deformation time for each on different scales. The large error at the corner points is where fiducials enter the image: the DIC software has difficulty determining displacement near the edges of regions where there is a jump in displacement. The fiducials are mounted to the fixture and are located above the hull; hence near the edges of the fiducials the DIC software does not return good location values and so large errors appear in the comparison with the numerical simulation. Away from these fiducials, the plots show the difference between the computational and experimental results, thus providing a better understanding of how deformation is occurring.

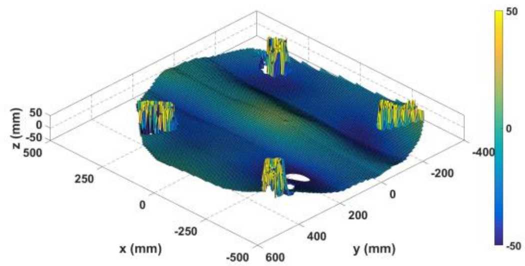

Figure 11: Difference (or error) between the pre-test numerical simulation and the experimental deflection.

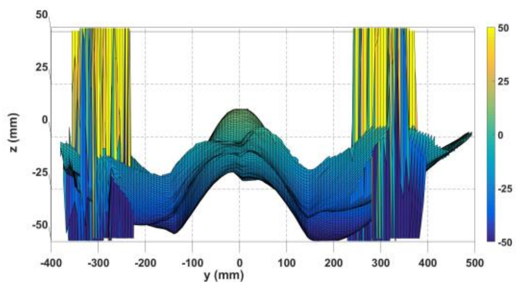

Figure 12: Another view of the deflection difference or error.

However, we have even more powerful comparison tools than this. Since we have the deflection history of arbitrary points on the inner surface of the hull, we can compare them to the pre-test numerical simulations. Figures 13, 14 and 15 show three such comparisons: the center point, halfway towards the corner, and a corner comparison (before the fiducial). The zero time in these curves is adjusted so the center point shows first hull motion at zero time (the times in the other frames are then determined by this initial zero time). The numerical simulations are again in blue and the experimental results are in red. By looking at the center point comparison (Figure 13), we can see that the numerical blast-loading algorithm is loading the plate more quickly than is occurring in the experiment. We see that the maximum deflection in the numerical simulation occurs at a correspondingly earlier time than the maximum deflection in the experiment. Moving away from the center, we see that the numerically predicted deflection decreases and becomes less than the experimentally observed deflection. However, it is still clear that the numerical blast loading occurs on a shorter time scale than the experiment.

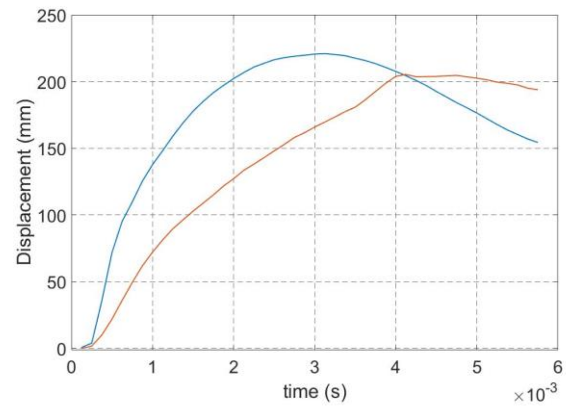

Figure 13: Centerpoint deflection history from pre-test numerical simulation (blue) and experiment (red).

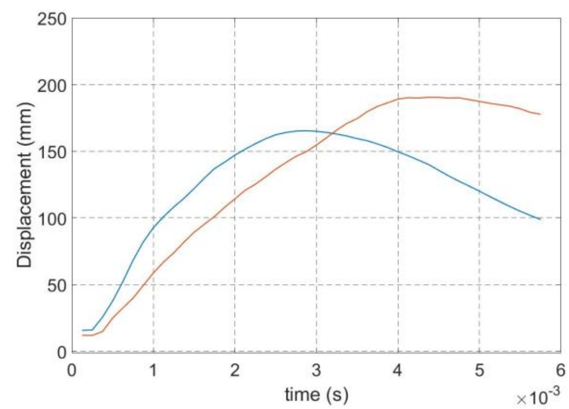

Figure 14: Midway point between center and corner deflection history from pre-test numerical simulation (blue) and experiment (red).

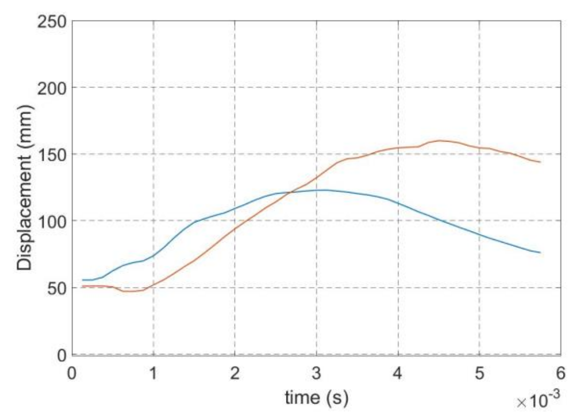

Figure 15: Near corner deflection history from pre-test numerical simulation (blue) and experiment (red).

BOLTING

It turns out there was a difference between the fixture/test article geometry computed in the pre-test numerical simulation and the geometry that was tested. The meshing tools had an auto-welding option that automatically welded together materials that were close together. When we performed the pre-test predictions, we used this option in our numerical simulations. Thus, the test hull component was welded onto the SwRI Landmine Test Fixture. However, in the actual experiment, the hull component was bolted onto the Landmine Test Fixture. We originally thought that the way this joint was modeled would have little effect on the numerical simulation vs. experiment comparison; however, in the experiments, some of the bolts broke. In particular, with five bolts along each side, front to back, on each side three of these bolts broke (Figures 16 and 5; so 6 of 10 bolts broke, leaving only 4 corner bolts holding). It was assumed these bolts were breaking at later time and had minimal influence on deflection, but these tools provided us the opportunity to explore this effect.

Figure 16: Post-test photograph with corner bolt still holding but showing where three bolts along the edge had failed (with the opposite corner still holding), thus allowing the hull edge to permanently deform.

Post-test LS-DYNA computations were performed where now the welds at the connection of the hull component to the Landmine Test Fixture were removed, and bolts were placed within the bolt holes. The bolts were modeled as beam elements which could fail. The strength of the bolts was adjusted to achieve the bolting failure pattern observed in the experiment, so these are clearly post-test numerical simulations. Unfortunately, we were not able to observe when the bolts had broken in our ground-mounted high-speed camera images (which were positioned to measure other things as well as being increasingly obscured by soil as the event progressed), and thus all that could be matched were the bolts that failed and those that did not, not the time of failure.

The bolts failed relatively early in these new numerical simulations of the blast event, and so the new attachment method did affect the maximum deflection and deformed shape. Thus, the effect of the bolts, in the post-test simulations, was not strictly late time. Figure 17 shows a comparison of the entire hull surface, and Figures 18 and 19 show cross sections. Here the maximum deflection of the simulation is larger than before: it is 23.7 cm vs. the 21.7 cm previously computed, an increase of nearly 10%. The "hump" in the middle of the numerical simulation is less than before in the side-to-side cross section, but in the front-to-back cross section we see a more peaked deformation at the center. Finally, Figure 20 shows the deflection vs. time. We see that at early time the deflections of the pre-test numerical simulation and post-test bolted numerical simulation exactly agree, but then they diverge at around 2 milliseconds.

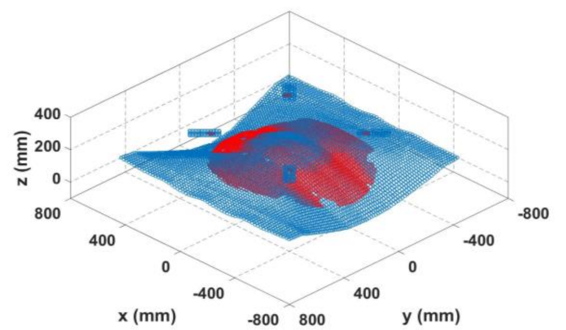

Figure 17: Comparison of post-test bolted numerical simulation (blue) with the experimentally measured (red) deflection at the maximum deflection for both.

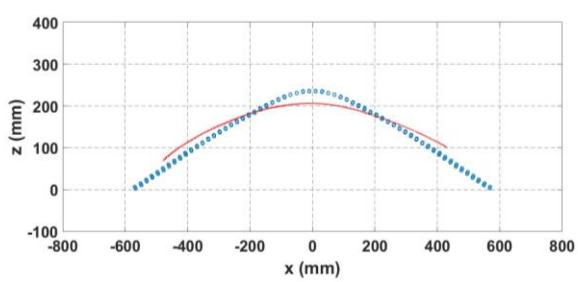

Figure 18: Front-to-back cross section comparing post-test bolted numerical simulation (blue) to experimental (red) deflection results.

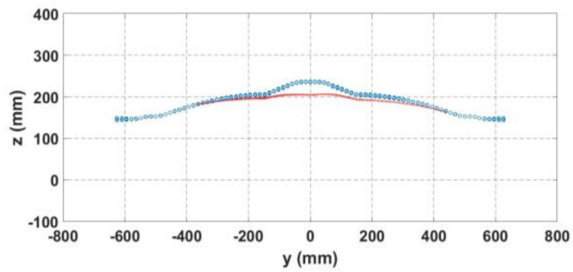

Figure 19: Side-to-side cross section comparing numerical post-test bolted simulation (blue) to experimental (red) deflection results.

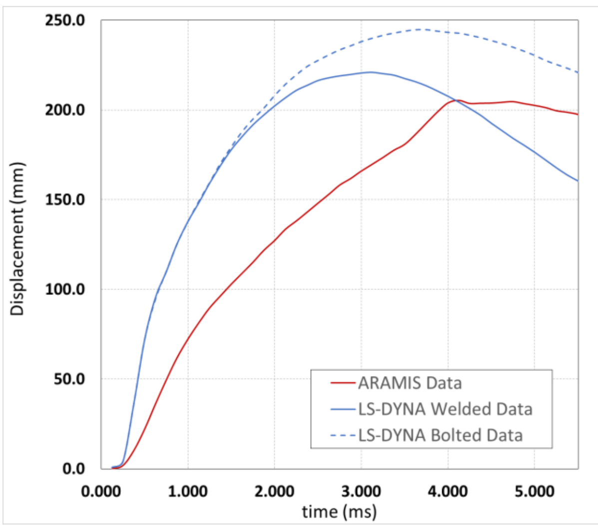

Figure 20: Centerpoint deflection history from pre-test numerical simulation (solid blue), post-test bolted numerical simulation (dashed blue), and experiment (red).

CONCLUSION

We have presented new tools that assist in the understanding of dynamic deformation of the blast loading of hulls. Tools that have been developed also allow rapid comparison with numerical simulations including pre-test predictions which assist in validating tools. These comparison tools can, in the future, be used to improve our modeling of the blast event on structures by rapidly providing wide spread motion comparisons while computational codes, material constitutive models, and blast loading algorithms are developed, verified, and validated.

ACKNOWLEDGMENTS

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