Crash Prediction for Marine Engine Systems Presented at the 2008 Abaqus Users' Conference

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Abstract: *Mercury Marine outboards, engines, and drives are designed to withstand indoor impact testing (called "logstrike") that simulates a collision with an underwater object. This test is comprised of an outboard or sterndrive device mounted on a mock boat that collides with a simulated log.*

Many parts are designed with the arduous logstrike test in mind. However, it is difficult to approximate the loads each part experiences during logstrike because of the complex and dynamic nature of the event. For this reason Mercury Marine R&D created a project to develop a capability for predicting the motion and loads of a logstrike event. A staged approach consisting of progressively sophisticated Abaqus/Explicit numerical simulations, validated by physical testing, was used to work towards successful simulation of the full logstrike event. This newly developed method is beginning to support product development programs and assist Mercury Marine engineers in designing components with more knowledge about the loads they must withstand. The method also enables the evaluation of designs without the need for physical parts. This provides the opportunity for better product integrity with reduced design time.

Keywords: *Crashworthiness, Design of Experiments, Experimental Verification, Impact, and Marine Engines.*

1. Introduction

What happens when you are boating and hit a submerged object? Mercury Marine has dealt with this question for a long time and designs its engines and drives with this reality in mind. Impact with a submerged object can produce severe loadings in many of the parts of the outboard or stern drive. Product validation testing for this requirement used to be done on the water by having a boat with a driver run over a log. A fence was installed on the boat to protect the driver. Part recovery was difficult for large parts, as they would need to be tethered. Small parts would be lost if they became detached. Weather and seasons were issues affecting when testing could be done. Waves in the water, the height of the boat in the water, and the contact of the boat hull with the log all made it difficult to strike the log in a repeatable fashion. Instrumentation was difficult as the boat was in motion and away from shore. Log to log variation was also an issue due to differences in grain structure and water saturation.

Overall, this was a good method to validate Mercury Marine products against underwater impact. However, there were still a number of things that could be improved to help with safety, repeatability, convenience, weather limitations, instrumentation and observation, part recovery, and even the time and cost of testing. In the mid 1980's an indoor test was created that improved many of these issues. The indoor test is called "logstrike" and is comprised of an outboard or sterndrive mounted on a mock boat that collides with a simulated log. The apparatus that includes the mock boat and simulated log is collectively called the logstrike machine. High-speed video and instrumentation are now common. Trim rod loads are recorded using a calibrated strain gauge on the side of the trim rod. A rotometer is attached to the tilt tube to measure the rotation of the outboard during the event. There are numerous options for additional instrumentation.

1.1 Motivation for simulation

In order to perform a logstrike test, it is necessary to have physical parts to test. Because of this, logstrike testing happens late in the design process and any failures on logstrike have large negative effect; this includes the need for additional design iterations, the cost of tooling and a new die, and possibly missing start of production dates. It would be helpful to predict early in the design process whether or not parts will pass logstrike, allowing the logstrike test to act solely as a final validation of the product. For this reason Mercury Marine R&D created a project to develop a capability for predicting the motion and loads of a logstrike event. The Crash Prediction Project utilized Abaqus/Explicit to numerically simulate the logstrike event in order to comprehend the motion and forces throughout the system. *All simulations herein will use Abaqus/Explicit as the solver.*

1.2 Development plan

The Crash Prediction Project used a staged approach to ensure successful simulation of the logstrike event. Each stage consisted of the following steps:

- Design and build experiment
- Physical testing
- Build FEA model
- Simulation
- Results comparison (physical test vs. computer simulation)

Each stage was designed to provide insight into the dynamics that occur during logstrike testing. The tests were designed to include instrumentation to provide quantitative data about key metrics for comparison to the FEA results. High-speed video was also used to record each experiment and to provide qualitative visual data. The project was divided into four stages of increasing complexity as follows:

1. Pendulum impact
2. Simple outboard with stiff leg on logstrike test rig

3. Simple outboard with prototype leg and variable power head mass on logstrike test rig

4. Full logstrike test (prototype outboard on logstrike test rig)

2. Stage One

A simple pendulum was designed for Stage One to validate Mercury's in-house capability to simulate impact events using Abaqus software. The Stage One test also served to calibrate the material model that is used for one of the key impact materials, "Material-A," in the simulated log used for logstrike testing.

Figure 1 shows the Stage One impact pendulum in its initial configuration (left) and just prior to impact (right). The apparatus consists of a base fixture that supports a pivot rod connected to one end of a solid rectangular beam that is attached to a prototype gear case at its other end. The two L-shaped supports near the bottom of the base fixture support a rectangular impact plate made of "Material-A." The plate thickness was chosen so that large strains would be observed in the test to help validate the nonlinear material model. A release mechanism keeps the pendulum locked in its initial horizontal position and can be triggered to allow the pendulum to swing downward under gravity until it rotates approximately 90º, at which point the gear case impacts the "Material-A" plate and begins decelerating. High-speed video was taken for the test, and a rotometer was connected at the pivot point to measure the rotational time history.

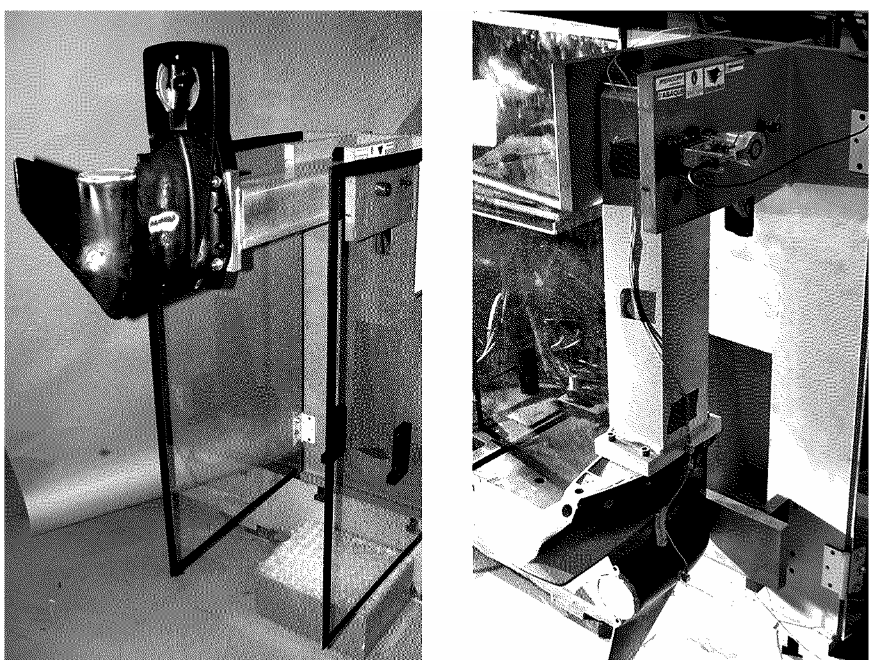

Figure 1. The Stage One impact pendulum locked in its initial position (left) and just prior to impact (right).

Because the gear case material is substantially stiffer than the impact plate, the Stage One simulation uses a rigid body surface mesh to represent the gear case. The surface elements do not exactly represent the entire mass of the gear case, so an additional point mass and inertia are placed at the Center of Gravity of the gear case and coupled to its reference point. The pendulum arm is modeled with beam elements. It is attached at the bottom to the gear case reference point, and at the top to a hinge connector element (which had one node fixed in space). The L-shaped supports are also included as rigid bodies and fixed in space, and the impact plate is placed on these supports with a negligible offset. The impact plate is modeled with C3D8R elements with enhanced hourglass control and a nonlinear material model.

The initial state of the simulation is set to just before impact, when the pendulum arm is approximately vertical. All of the moving nodes are given an initial rotational velocity that was determined by a hand calculation and verified during the testing. The simulation has gravity turned on and general contact is used to calculate the interaction between the gear case and the impact plate (with one set of contact properties), and between the impact plate and the L-shaped supports (with another set of contact properties).

As expected, the simulation results match the test results very well for this simple impact problem. Figure 2 shows the post-test deformed shape of the impact plate compared to the simulated deformation. The peak simulated deflection of the impact plate is within the scatter of the peak deflection measured from the test. Figure 3 shows that the time-varying angular position of the pendulum due to impact was also simulated within the scatter of the measured test results.

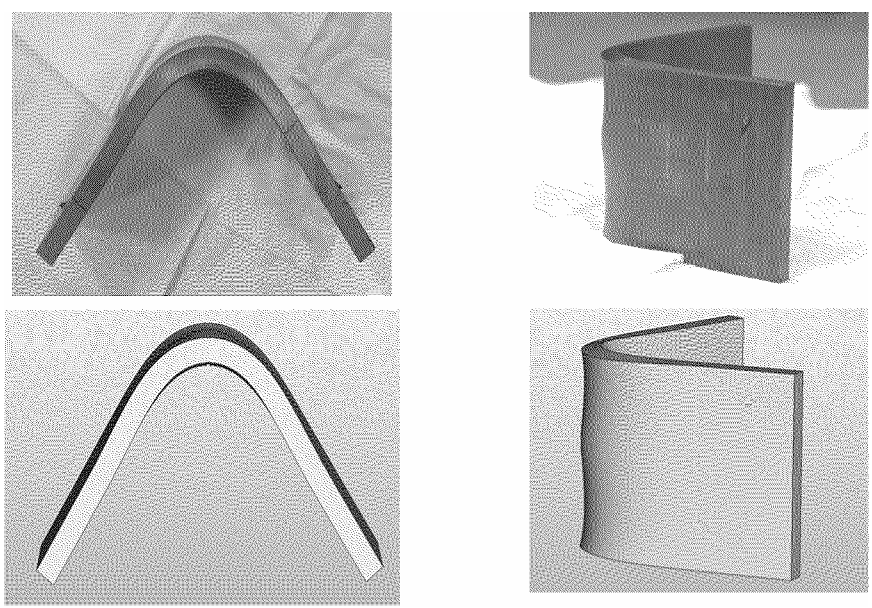

Figure 2. Comparison of Stage One deformed impact plates from test (top) versus simulation (bottom).

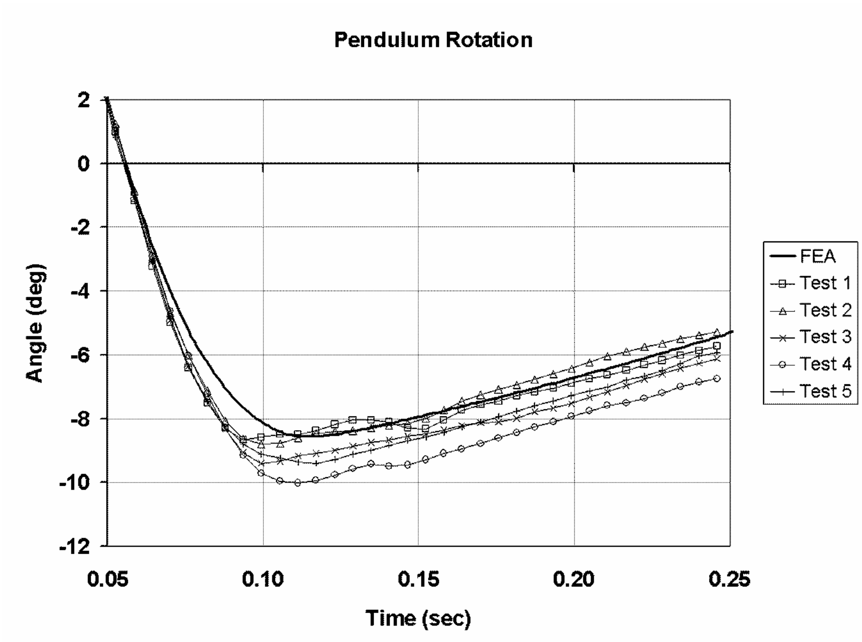

Figure 3. Comparison of the rotational time history measured from Stage One testing (solid lines) versus the response from simulation (dashed line).

3. Stage Two

Stage Two testing increased the complexity of the impact by using the logstrike machine. In order to isolate the response of the machine, a simplified outboard was designed that had the approximate mass, rotational inertia, and total size of an outboard engine. The Stage Two outboard was also designed to be very strong so that it could be used repeatedly without failure. Figure 4 shows this pseudo-outboard with a stout surrogate midsection and a prototype cowl, pan, gear case, trim rod, tilt tube, and transom bracket connected to the mock boat for logstrike testing. It should be noted that there is no power head under the cowl.

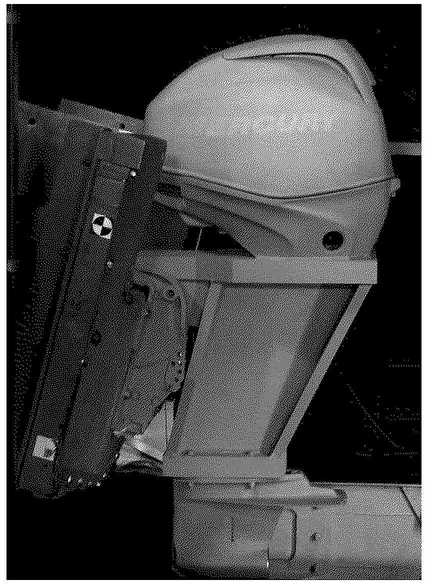

Figure 4. The Stage Two pseudo-outboard.

The primary metrics for this stage are rotation about the tilt tube, force in the trim rod, change in velocity during the impact, and peak acceleration at the gear case (fore-aft and vertical). Instrumentation was used to capture this data from the tests for comparison to output from the simulation, and high-speed video was captured for visual analysis. Testing was conducted at several impact velocities in order to determine its effect on the output.

The Stage Two simulation includes the initial attempt at a computational model of the logstrike machine. The pseudo-outboard is modeled with C3D8R elements for the midsection and shell elements (S4R and S3) are used for the gear case and the cowl. The pan and the transom bracket are discretized with tetrahedra and subsequently converted to rigid bodies. The trim rod is modeled with a connector element that is assigned appropriate behavior. Hinge connectors are used at pivot locations and coupling and tie constraints are used to assemble the components. The cowl latches are simulated with a connector that releases at a specified overload.

The initial state for each simulation is set for just prior to impact, and all moving bodies are given an initial velocity equal to the impact velocity. Gravity is turned on and general contact is used to calculate the impact between the outboard and the simulated log. Figure 5 shows a frame from the high-speed video of the test and the corresponding frame from the simulation.

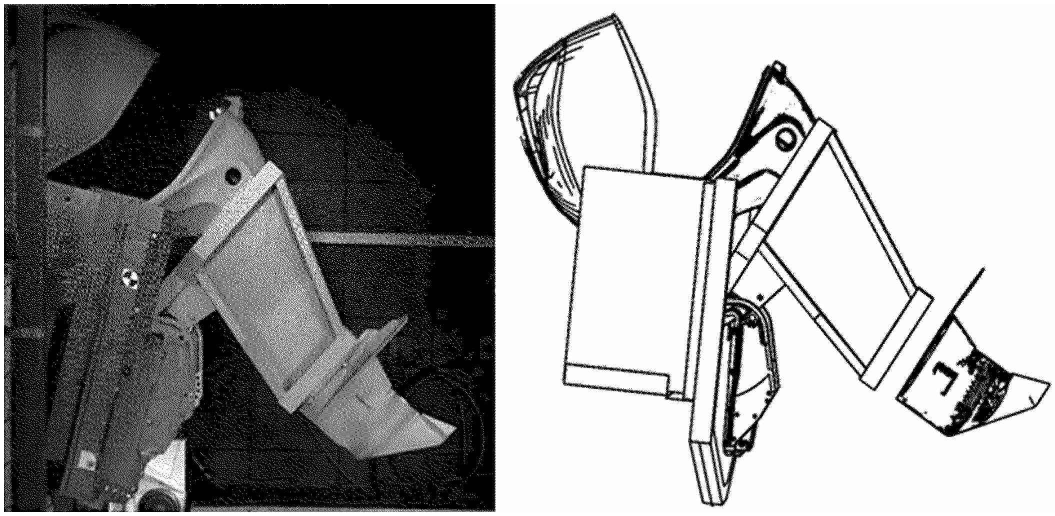

Figure 5. Comparison of high-speed video from Stage Two testing versus output from simulation.

Initial comparisons between test and simulation were encouraging because the qualitative measures were close and the trends with respect to changing impact velocity were correct. Most quantitative measures matched within a factor of two (some much closer), but this was larger than desired. Therefore, a calibration effort ensued.

3.1 Stage Two Design of Experiments

The nature of the logstrike machine made it challenging to determine exactly what set of input parameters to use in the simulation. These inputs include material properties, geometric sizes, masses, and interaction behavior between components. The goal of the calibration effort was to come up with a set of inputs to the model of the *logstrike machine* that caused the response of the *Stage Two outboard* to most closely match the measured data from testing. The calibrated set of logstrike machine input could then be used for all subsequent logstrike simulation, regardless of what outboard is used in the simulation.

Design of Experiments (DOE) was identified as a tool to guide this calibration effort. The candidate set of parameters was larger than practical (but still miniscule compared to the thousands of inputs to the FE model), so a set of prescreening simulations was run to rank the effect of each of the candidate inputs on a list of key output metrics. From the results of the prescreening, a reduced set of parameters were identified to use in a Central Composite Design to create response surfaces that were then used to optimize the selection of the *logstrike machine* inputs to best match the key metrics from testing the *Stage Two outboard*. The optimized set of inputs was then used in simulations to determine the accuracy of the calibrated model.

Figure 6 shows the improvements from the calibration. The peak vertical gear case acceleration is the only metric that is not under 25% after the calibration, but it still experienced substantial improvement. It should also be noted that the "original" errors shown in Figure 6 are from simulations using the baseline impact velocity, whereas the "calibrated" errors are shown over a range of impact velocities (baseline, minus 5 mph, and plus 5 mph).

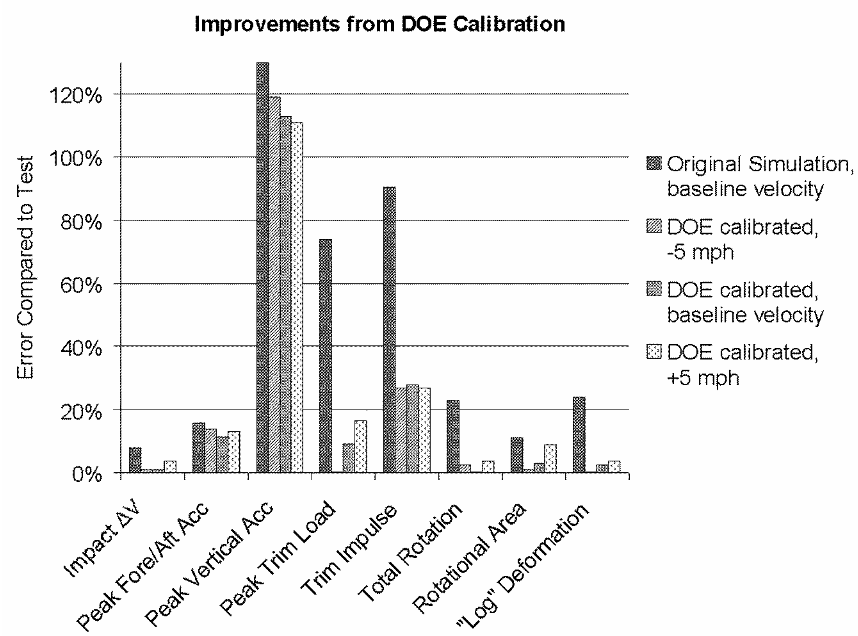

Figure 6. Error between test measurement and simulation results, before and after DOE calibration.

4. Stage Three

Stage Three testing was designed to investigate how a simplified flexible outboard responds to logstrike. Figure 7 shows the Stage Three pseudo-outboard with a prototype drive shaft housing (DSH), gear case, trim rod, tilt tube, and transom bracket. The large box on top of the DSH acts as a surrogate power head, and it can be tested in three configurations to investigate the effect of power head mass on the response of the outboard.

1. Low inertia (no weights inside the box)
2. Medium inertia (two weights inside the box)
3. High inertia (four weights inside the box)

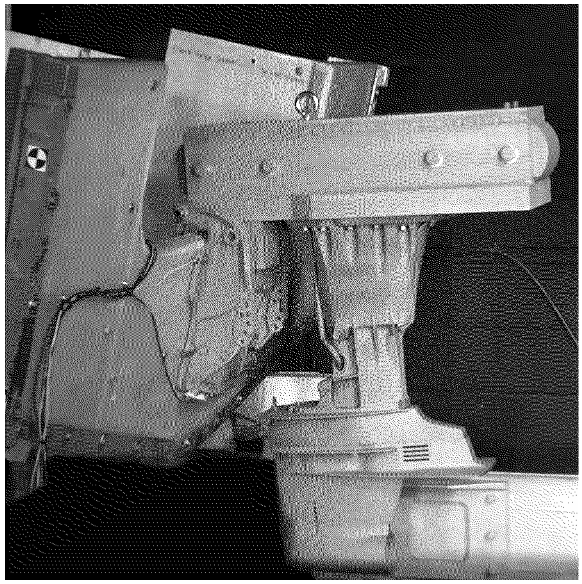

Figure 7. The Stage Three pseudo-outboard.

The simulations for Stage Three use the calibrated logstrike model from Stage Two. The stout Stage Two pseudo-outboard is swapped for a model of the Stage Three pseudo-outboard, which uses shell elements (S4R with limited use of S3) for the DSH and the gear case. The adjustable "power head" is modeled with C3D8R elements and point masses are used for the weights to adjust the model to the medium and high inertia settings. The transom bracket, trim rod, and tilt tube remain the same as in Stage Two.

The Stage Three testing was conducted at a variety of speeds for each configuration to determine the speed at which the DSH fails. Figure 8 shows test failure velocities along with predicted failure velocities from simulation. Equivalent plastic strain (PEEQ) was used to evaluate failure in the DSH and a 5-mph band was used for uncertainty of failure in the simulation.

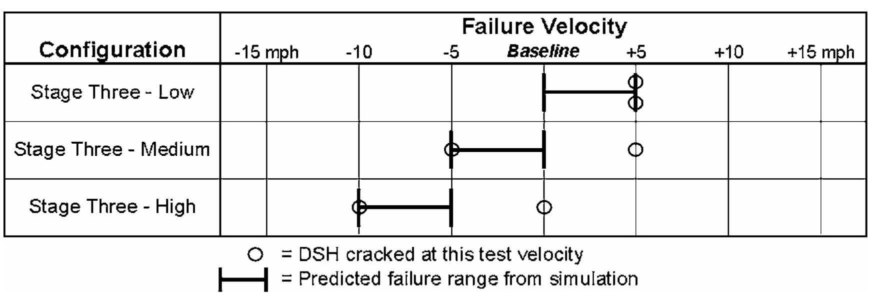

Figure 8. Failure velocity for Stage Three testing.

Two crack initiation points were identified during the testing: one near the mid-height of the DSH, and the other at the joint between the DSH and the power head. The Stage Three tests failed roughly half the time at the mid-height location (more for the low and medium inertia setup), and the other half at the upper location (more for the high inertia setup). There was no strong correlation between failure velocity and which crack location would be activated. Figure 9 shows the two types of cracks along with a contour of equivalent plastic strain from the simulation identifying the mid-height crack. The mid-height crack was identified as the failure point in all simulations, but the upper location is also predicted to have high strain values. The advantage of simulation is that the mid-height crack location can be strengthened in the model and subsequent simulation will identify the upper crack location for overload without noticeable increase in failure velocity. The upper location can then be strengthened as well and simulation can show an increase in failure velocity before the next failure location is activated.

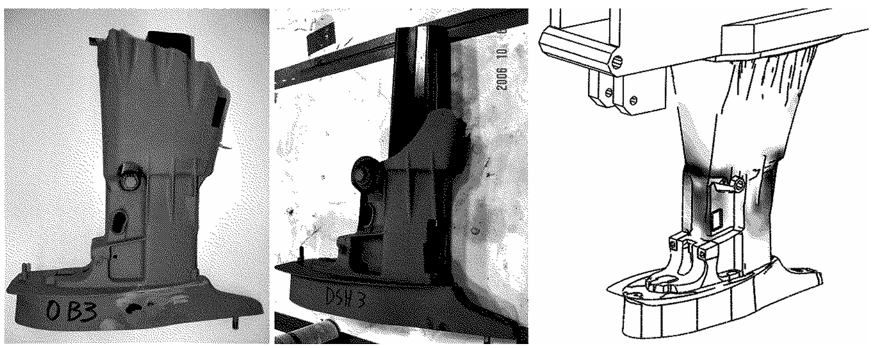

Figure 9. DSH crack locations from Stage Three testing: upper (left), mid-height (center), equivalent plastic strain from simulation (right).

5. Stage Four – Full Outboard

The testing for Stage Four was a logstrike test of a prototype full outboard. *Please note that the overloading shown in this section occurs on tests being performed at velocities exceeding the logstrike product validation requirement.* Other than higher test velocities, the only difference between the Stage Four testing and a standard logstrike test is additional instrumentation to help validate the simulations.

The full outboard simulation again uses the calibrated logstrike model from Stage Two, and now attaches to it a model of a complete outboard. Components along the primary load path are meshed for good quality stress resolution; this includes the gear case, drive shaft housing, transom assembly, the steering assembly, and the mount system. The cowl and chaps are meshed with shell elements for stiffness and mass contribution only. The adapter plate and power head are discretized to capture mass distribution but are converted to rigid bodies since they are stiff members not along the primary load path.

The Stage Four simulations identified excessive plastic strain in the lower steering yoke as the lowest velocity failure mode. The lower steering yoke sits at the bottom of the steering tube that runs through the transom assembly just forward of the drive shaft housing, shown in Figure 10-A. The steering tube is also identified to have large deformation and possible material failure.

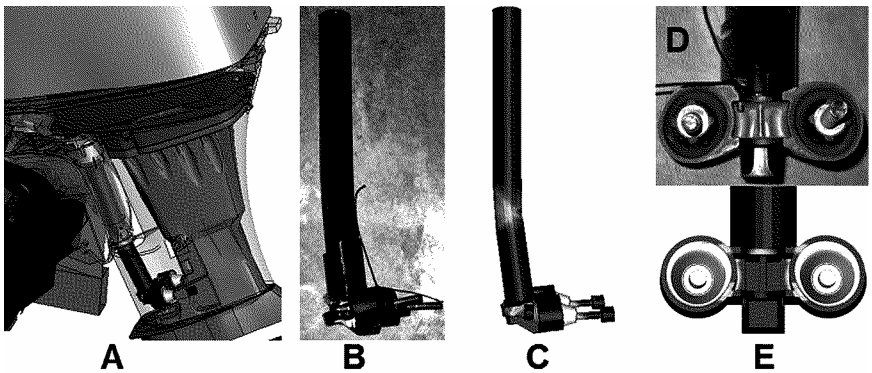

Figure 10. Steering tube, lower yoke, and lower mounts shown during the simulation (A), after logstrike testing (B, D), and simulation with contours of equivalent plastic strain (C, E)

The physical logstrike tests showed that the swivel tube did indeed experience severe deformation (Figure 10-B). It also showed that the lower yoke eyelets were permanently deformed during the test (Figure 10-D).

Impact velocity for these failures was under-predicted by approximately 10-mph. It is conservative to under-predict the impact velocity for failure so that the risk of a false-positive simulation is reduced. Simulations can be performed to determine the effect of component or material variation on the impact velocity for logstrike failure.

6. Conclusion

A staged approach was used to develop a simulation capability for the Mercury Marine logstrike test. Each stage consisted of progressively more complicated experiments and simulations, and the simulations were validated by the physical test results. The culmination of these stages was a simulation of a full outboard logstrike test, which predicted the failure location observed in the full outboard logstrike test. This demonstrates a capability to begin supporting product development programs and assist Mercury Marine engineers design components with more knowledge about the logstrike loads they must withstand. The method also enables the evaluation of designs without the need for physical parts. This provides the opportunity for better product integrity with reduced design time.

7. Acknowledgement

The author would like to thank Mercury Marine and its Research and Development Organization for their support of the Crash Prediction Project.