Composite Rudders Take Shape for U.S. Navy

Although foreign navies have built fast patrol boats and ship deckhouses using composite materials, the U.S. Navy has been slow to embrace non-metallic construction materials. This is in spite of the fact that recent studies reveal that it costs the DoD between $10 billion and $20 billion each year to mitigate corrosion effects or try to prevent corrosion. The two major impediments to composites on navy ships are cost and performance in fires. However, surface combatant rudders differ from conventional shipboard structures on both counts. Being underwater, fire is not an issue. Given the complex shape of a rudder, they can be produced at less cost from molds with composites than conventional steel construction – especially if they're twisted.

Ship rudders located behind large propellers experience a flow stream that varies in "angle of attack" from top to bottom. To better align the entire rudder with the water flowing by it, U.S. Navy hydrodynamics engineers have developed a rudder shape that conforms to this stream by "twisting" outboard in the middle. The goal is to delay the onset of cavitation-induced corrosion/erosion damage. However, this shape is even more costly to build out of steel. Structural Composites in Melbourne, FL is currently building hybrid steel/composite rudders for a destroyer to validate construction methods and survivability. The project is building on our experience building composite minesweeper rudders over a decade ago. The Composite Twisted Rudder (CTR) is slated to be installed on a DDG-51 class destroyer next spring.

The reason we're using a hybrid steel and composite structure is because we need to be able to fit these to existing rudder stocks via a high-strength steel hub casting. Our major design challenge was to then transmit very high bending loads from the composite skin to the interior steel structure. The "interface" challenge is a common theme for large, dynamic composite structures and we are attempting a cost effective solution by maximizing the interface area and use of a high elongation adhesive to mitigate shock loads. Figure 1 shows the steel structure within the composite shell.

Fabrication Procedure

We first start with a hub casting made from HY-80 steel that weighs about 7,000 pounds. Only a few foundries in the country can cast with this high-strength material that the navy uses. A grillage made from machined HY-80 plate is then welded to the hub. The grillage has vertical flanges that interface with the composite structure. Meanwhile, female molds were built over a plug that was cut on a numerically-controlled router. Spacer skins the thickness of the rudder skin laminate were layed-up in the molds to allow us to build the core with expandable, medium-density polyurethane foam. The core is not really structural, but instead serves to support the E-glass preform that will be wrapped around it. Before the foam is blown in place, a labyrinth of PVC resin distribution tubes is installed in the rudder.

The composite skin is not as highly stressed as the internal metal structure so we opted to use an E-glass/vinyl ester laminate that has performed well in previous navy shock tests. The skin is built up from unidirectional material to create a quasi-isotropic laminate, with a good portion of the material running up and down to resist span-wise bending. Prior to wrapping the glass, the foam core is “excavated” in the area around the vertical steel fins. Layers of glass in increasing widths are laid in place over Trevira that has been bonded to the steel with Plexus MA310 until they are flush with the foam core surface. Here a layer of Colbond’s EnkaFusion infusion media is placed over the entire rudder surface. Then, a minimum of 25 layers of 18 oz. E-glass is tightly wrapped around the foam core.

All of the rudder construction happens with it upside down to keep the center of gravity low and so we can infuse from the high volume region up to the tapered rudder tip. Once all the glass is wrapped around the foam core, the molds are bolted around it, compressing the preform to a thickness that corresponds to the desired fiber content. Next, it’s time to test the mold flange gaskets with a vacuum check. Since we will be using a vacuum-assisted resin infusion process, any leaks in the mold would make it difficult to maintain a vacuum and would introduce air bubbles (voids) into the laminate. As with all parts produced using resin infusion methods, the actual “wet-out” process takes only a matter of hours, corresponding to the working time of the resin system used.

Although the shape of the CTR helps mitigate damaging cavitation bubbles on the surface, we still expect to see this effect. Therefore, we intend to cast a resilient elastomer (Versalink P-1000 from Air Products) around the CTR using the same molds used to build the rudder. We had intended to co-infuse the surface treatment with the outer reinforcement layers of the CTR to improve the bond strength of the surface treatment but were pleasantly surprised to achieve excellent results just by casting the material to a finished laminate. One nice feature of the Versalink is that it is clear, allowing us to inspect the laminate after vigorous mechanical testing. Figure 2 shows a schematic of the manufacturing process.

Design Challenges

Rudders on ships face the same structural design challenge that we see with airplane wings and windmill blades. All are foil shapes that we’d like to keep thin for efficiency, but develop high bending loads at the base that must be resisted with an efficient structure. For ship rudders, there is also a significant torque load generated from steering the vessel. We have been assisted in the design process by the Naval Surface Warfare Center, Carderock Division in Bethesda, MD (NSWCCD). They have been doing extensive finite element analysis of concepts developed jointly by Structural Composites and our subcontractor building the metal assembly, Maritime Applied Physics Corporation, of Baltimore, MD.

The CTR is designed to resist the estimated maximum hydrodynamic loads that it will experience over the life of the ship with appropriate safety factors. It also must be able to resist shock loads that it would experience if an underwater blast were to occur next to the ship. Structural Composites worked with Lockheed Martin over ten years ago on a hybrid metal/composite rudder for mine countermeasure ships, but the loads were significantly less because the rudders were smaller and the ships run slower. However, that effort did provide some insight on the best way to transmit loads from the composite shell to the internal metallic structure.

After several design iterations, we settled on a concept that utilizes a built-up I-beam attached to the aft side of our hub casting to help resist bending loads. Aft of this, a series of horizontal fins help absorb torsion and bending loads across the rudder profile. Vertical steel flanges then serve as the interface point to the composite. The skin laminate is built with unidirectional material to avoid transmitting loads across seams. Fiber in the vertical direction resists bending loads while fore-and-aft fibers handle the torsional loads. In the unsupported areas below and in front of the metal structure, composite "shear ties" made with double-bias reinforcement serve to link the rudder skins to create I-beam looking structures. Remember, we do not want to rely on the cast polyurethane foam core to resist shear loads.

Testing

If anyone reading this article plans to build composite structures for our navy, and I hope many will, please be prepared to do a lot of testing and validation. Culturally, the U.S. Navy is the most conservative branch in our military, geared to protecting floating billion dollar assets. This approach has led to an impressive safety record and protecting our sailors must be of paramount concern for anyone building ship systems. The navy is very familiar with how metal structures behave. The high-strength steel that we used is also used in submarine construction, where the consequences of failure are unimaginable. Compare this to the testing we see for aerospace structures. However, for surface ships we are looking at tons of structure that must be produced with an increasing focus on cost.

In order to develop "design allowables" for our skin laminate, we underwent an extensive series of coupon testing, using both dry and "wet-conditioned" test specimens. Procedures outlined in the newly-developed American Bureau of Shipping Naval Vessel Rules cite MIL-HDBK 17A statistical analysis for B-basis values. This procedure requires a minimum of six test samples from three unique test laminates and produces a test value designed to reflect variations within the manufacturing process. On top of the B-basis test value, a "knockdown" factor to account for the fatigue environment that the part will see must be applied. Therefore, it may not be uncommon to end up with design allowable values that are 1/3 of typical test values.

We next validated the steel/composite interface joint by testing a full-scale section of the joint, as shown in Figure 3. Some of these tests were stopped when we reached loads an order of magnitude greater than required. This testing compared favorably with Fracture Toughness models developed by NSWCCD. We also conducted numerous small-scale tests of surface treatments to ensure we don't get "hydro-peeling" of the coating.

As rigorous as the structural analysis has been for this program, navy personnel responsible for ship survivability mandated that we test a completed full-scale rudder, both statically and when subjected to underwater explosion. To apply the designed static load to the rudder, we are using a water bladder that will exert a uniform load across the face of the rudder, as shown in Figure 4. It doesn't take much water pressure applied over the 150 square foot face of the rudder to produce massive loads at the base.

To shock test the CTR, it will be mounted under a barge at Hi-Test Laboratories in Arvonia, VA. A series of explosions will then be detonated near the barge as it floats in a quarry. Needless to say, the response of the structure to this intense transient load is very difficult to predict analytically, but we do hope to compare the measured response to modeling being done by NSWCCD. The CTR will be examined using modal analysis and ultrasonic evaluation techniques during the testing program to determine if any damage has occured.

The ultimate test of the CTR concept will come after a set of rudders is installed on a destroyer for evaluation at sea over a two-year period. We have a unique challenge of fitting the CTRs to rudder stocks while our ship is in dry dock. Our contention that we can produce a rudder with increased survivability at half the cost of the current steel design will be borne out only after actual service in the fleet. Incidentally, the composite rudders installed ten years ago on the mine countermeasure ship have been performing well, requiring zero maintenance.

Funding

It is nearly impossible to introduce revolutionary concepts to the fleet, especially on what are called “legacy” platforms, i.e. ships already in service. This project started with two congressional earmarks (pork, as detractors like to call it). The first one was secured by Bath Iron Works, who enjoys substantial clout with the delegation from Maine. The second earmark we secured on our own by lobbying our Florida delegation based on the merits of the program. I’m not sure that could be repeated now in today’s political climate. However, the bulk of the funding for the project was competitively secured via the Defense Acquisition Challenge (DAC) Program, which was “established to provide opportunities for the increased introduction of innovative and cost-saving technology or products into existing Department of Defense acquisition programs,” according to their web site.

Our award was much larger than they typically allot for individual programs and it took us a few years of trying to impress upon them the potential for cost savings and increased survivability. Even so, the DDG-51 program was not very interested in back-fitting CTRs within their fleet, so we approached the Program Office for the U.S. Navy future surface combatant, now called DDG-1000. This ship is a revolutionary concept designed to have a composite deckhouse and a composite, shaped rudder. They were thrilled to have the chance to validate composite rudder technology while in the design stage of their ship.

It really is not easy for anyone except the major defense contractors to work through the extensive requirements for ship systems within our navy. With composites, the bar is always raised because naval engineers don’t have much history working with the material. When survivability was the primary driver for selection of ship construction materials over a century ago, our navy (and more importantly, the country’s supporting industrial infrastructure) made the switch from wood to steel. We hope the CTR project will help create opportunities for other innovative uses of composites to support our nation's warfighters.

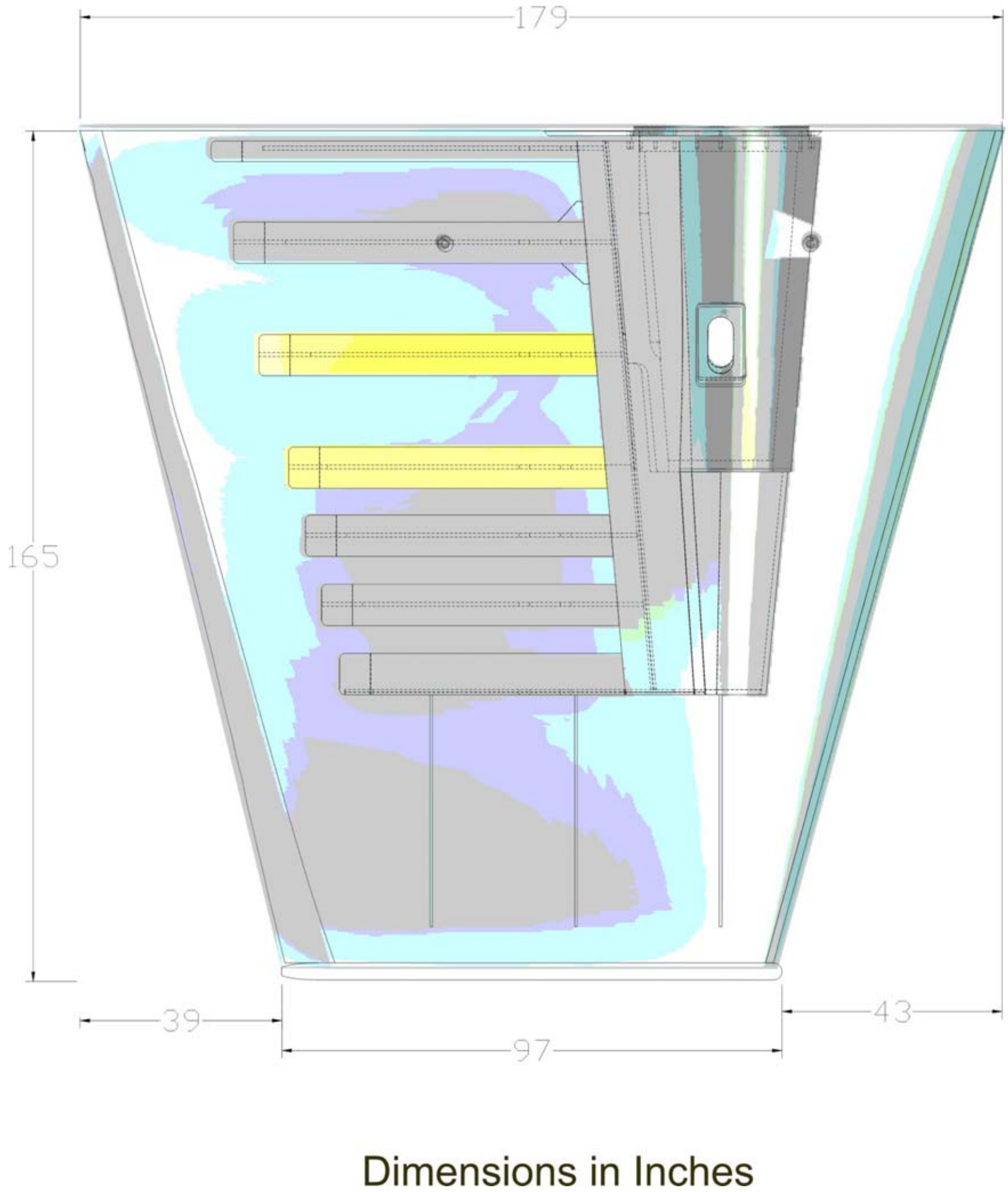

Figure 1. Schematic of Composite Twisted Rudder Structure

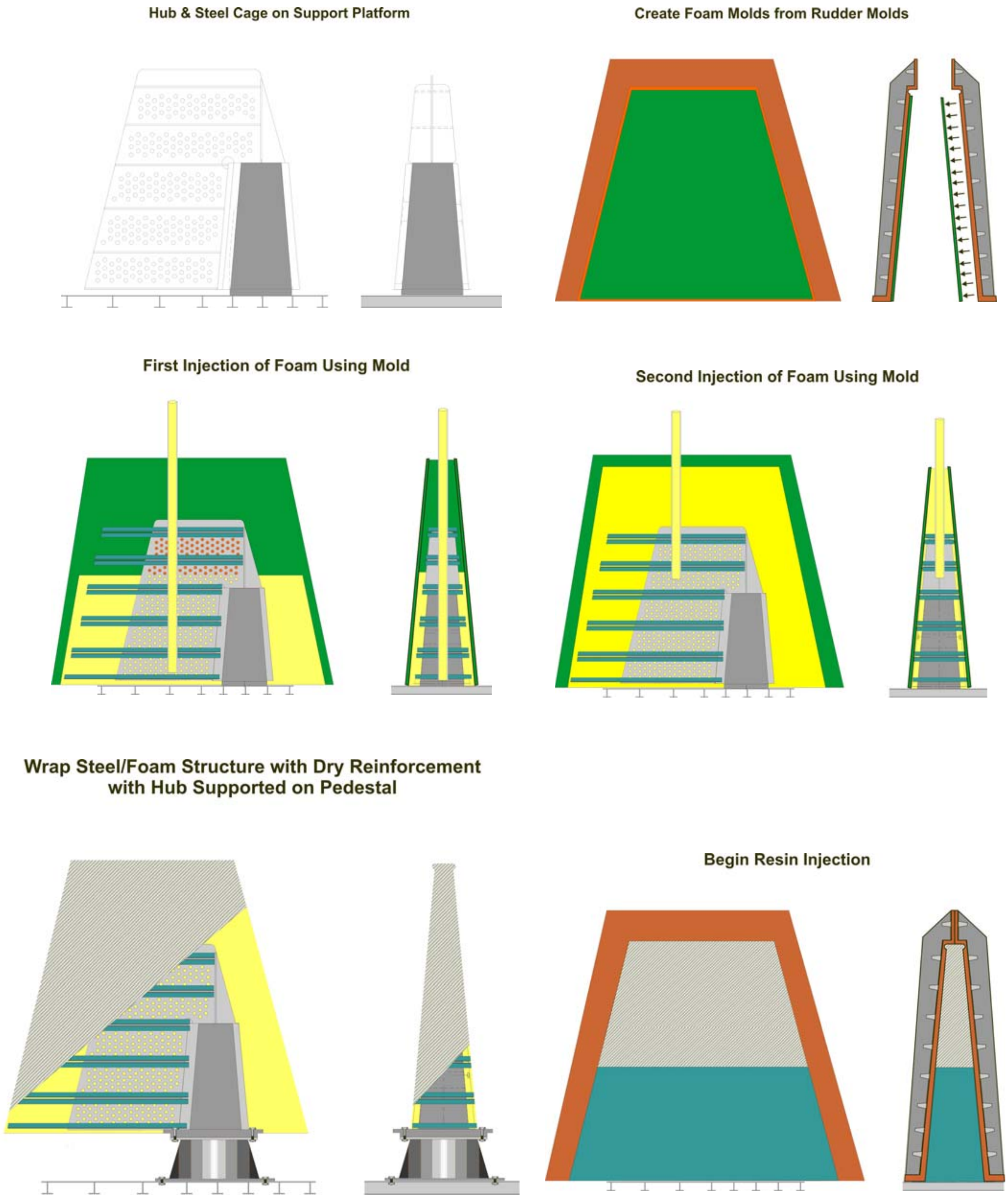

Figure 2. Schematic of Composite Twisted Rudder Manufacturing Process

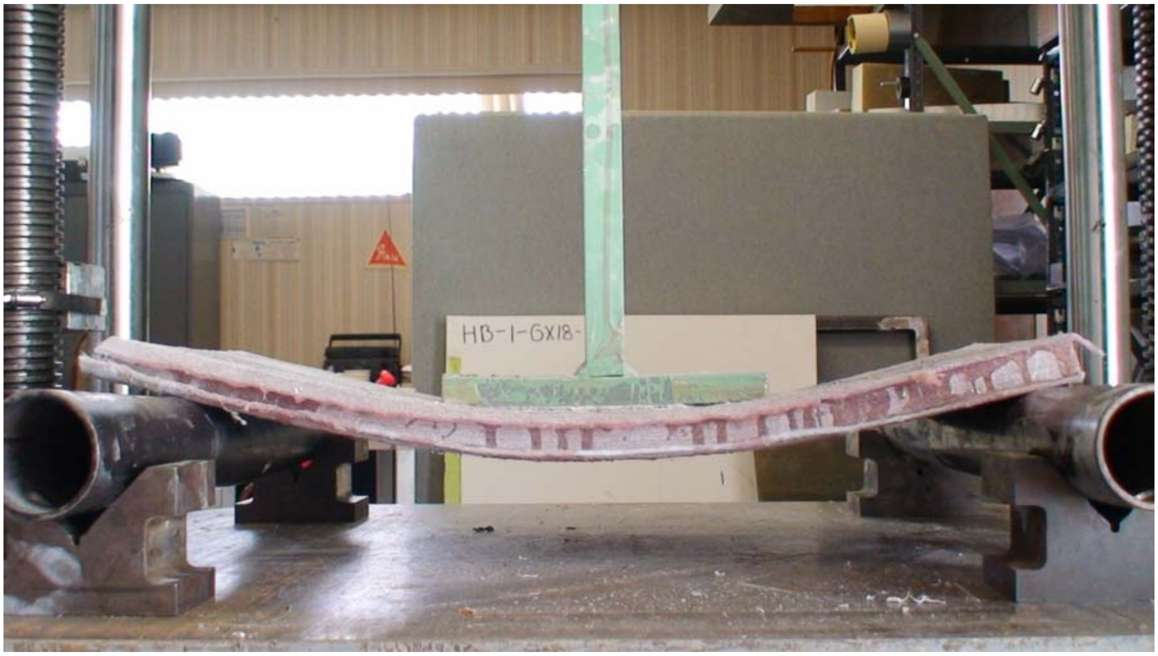

Figure 3. Structural Testing of Steel/Composite Interface Joint

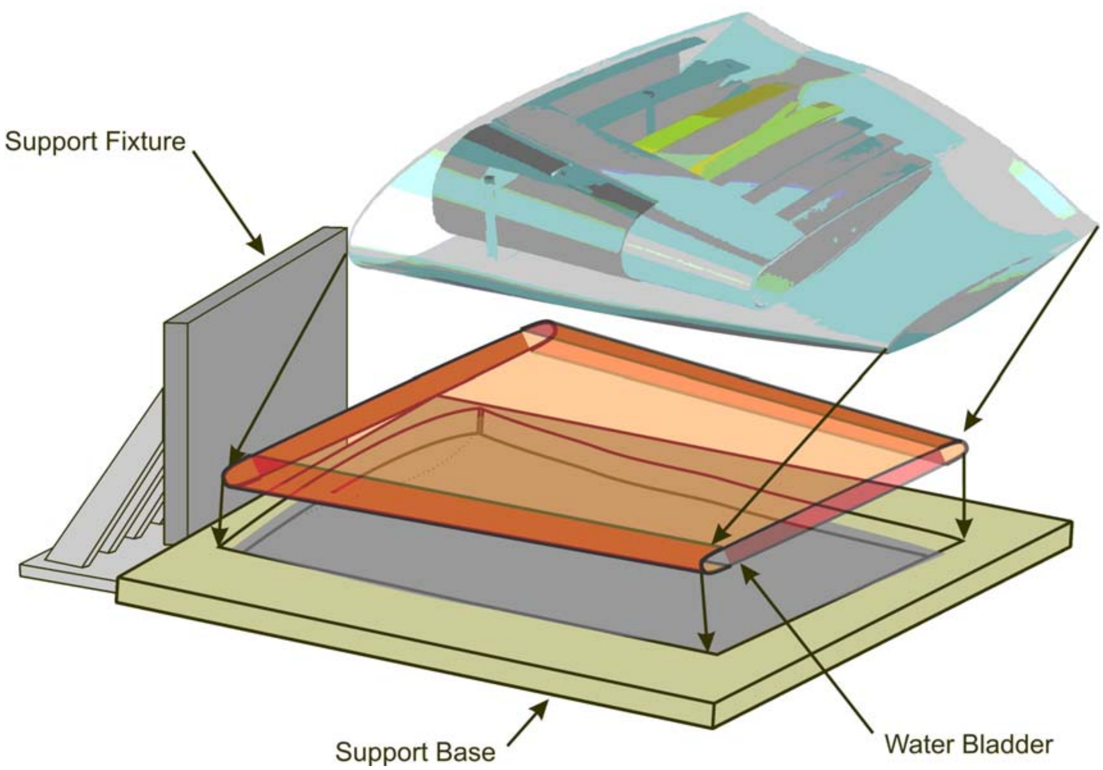

Figure 4. Plan for Full-Scale Static Testing