Investigating the Loss of *H.L. Hunley*

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Recent archeological investigations of the civil war submarine H.L. Hunley have changed our understanding of how the vessel conducted its final attack on the U.S.S. Housatonic. Previously, the submarine was thought to have used a standoff charge against its target, but it is now clear that the charge was bolted to the end of a short spar projecting from the submarine. This means that the submarine would have been in close proximity to the weapon when it exploded. A multi-part investigation is being conducted with the goal of determining if this reduced standoff distance could explain the mysterious loss of the vessel in the minutes or hours after the attack. Here, the results of a bottom-up naval architectural analysis and numerical simulations of the final attack weapon effects are reported. Together, the results provide new insight to the vessel's stability characteristics, propulsion, and dynamic loading environment during the attack. Additionally, a discussion of possible loss scenarios, informed by both calculation results and inspections of vessel's hull, is presented. While the story of what happened to H.L. Hunley that night remains shrouded in mystery after this work, several important new research questions emerge.

KEY WORDS: Forensic Investigations; Underwater Explosions; Historical Naval Architecture; Submarine; *H.L. Hunley*

INTRODUCTION

On February 17, 1864, the human-powered Confederate submarine *H.L. Hunley* attacked the USS *Housatonic*, a Federal sloop-of-war participating in the blockade of Charleston, South Carolina. The explosion resulting from *Hunley's* torpedo sank the 1240-ton ship in a matter of minutes and secured *Hunley*'s place in history as the first submarine to sink an enemy combatant. Although its attack on USS *Housatonic* was successful, the submarine and all hands were lost at sea in unknown circumstances. The lack of clear evidence as to what occurred to *Hunley* during and immediately after this legendary attack has led to various theories about the sequence of events during and after the attack. However, the exact cause of the loss of *Hunley* remains a mystery. This work uses both conventional naval architecture and high-fidelity weapon effects simulations in an effort to shed light on the loss of the submarine. While these calculations continue to be refined as more evidence is uncovered, the current effort aims to provide the community with an update on the progress so far and the new research questions raised by this work.

H.L. Hunley, seen in Figure 1, was the third in a series of three submarines developed by an ad-hoc group of private citizen-inventors and was named after its sponsor and co-designer Horace Lawson Hunley, The first two submarines of this series, *Pioneer* and *American Diver,* saw use as test vehicles but did engage in combat. The final submarine, *Hunley*, incorporated all of the lessons from the previous two designs and was surprisingly refined in its design. A crew of eight operated the vessel— seven crew members used their arms to turn a large central crankshaft that rotated a propeller at the stern of the vessel. The captain of the vessel, stationed in the forward hatch tower, was responsible for operating the ballast valves, primitive dive planes, and a conventional rudder. *Hunley*'s original operational concept was to dive under a target vessel and attack using a towed mine. However, utilizing a spar torpedo, or explosive charge affixed to a long spar at the bow of the vessel, was a deemed to be a more reliable attack method (Stephenson 2016).

Hunley, fabricated in Mobile, Alabama, arrived in Charleston, South Carolina not long after its fabrication to assist with breaking the Union blockade. Operational testing saw both success and tragedy with two separate deadly sinking incidents but also several successful test missions. An initial attempt at attacking the Union fleet in and around Charleston was unsuccessful, possibly owing to poor weather.

Figure 1. *H.L. Hunley* submarine at the Warren Lasch Conservation Center, Charleston, SC.

On February 17th, *Hunley* left at sunset from its dock for its final mission to attack the naval blockade of Charleston Harbor. Amidst calm seas, having selected the anchored *USS Housatonic* as its target, *Hunley* approached. Lookouts on *Housatonic* spotted the submarine in close proximity to the vessel at 20:40 and, determining that *Hunley* was a threat, the crew opened fire with small arms. Although *Housatonic* attempted to escape, having slipped its anchor chain, it was unable to get underway in time. At roughly 21:00, *Hunley* managed to drive its charge into *Housatonic* just aft of the mizzenmast of the vessel as illustrated in Figure 2. The resulting explosion was catastrophic to the wooden vessel and *Housatonic* sank to the bottom within minutes. Due to the shallow water resulting in *Housatonic*'s masts and rigging remaining above water, causalities were limited to five deaths. *Hunley* was semi-submersed during the attack— the crew had orders not to dive because of the inherent risks in doing so. As such, the attack configuration very much resembled that used by the Confederacy's semi-submersible David boats despite *Hunley* retaining its full capacity to submerge (Littlefield, 2015). For further details on the attack configuration, see Scafuri et al. (2014)

What happened next to *Hunley* is a mystery. The vessel did not return to its dock as expected and the location of its loss was not clear. As none of the crew survived the final mission, the vessel's condition, configuration, and intended escape plans on the final mission remain unknown. Fortunately, in 1995, marine explorers located *Hunley's* wreck off the coast of Charleston about 1000 feet further out to sea from the known wreck of *USS Housatonic*, with both roughly aligned with the prevailing tidal current, as shown in Figure 3. Murphy et al. (1999) and Conlin et al. (2005) give comprehensive overviews of the *in-situ* examination of both wrecks. In 2000, the submarine was raised from the sea-bottom and moved to a specially prepared tank facility at the Warren Lasch Conservation Center (WLCC) in North Charleston, SC. Since arriving at WLCC, *Hunley* has undergone an extensive archaeological and conservation effort that has yielding numerous findings and provided insight into the submarine's operation and final attack.

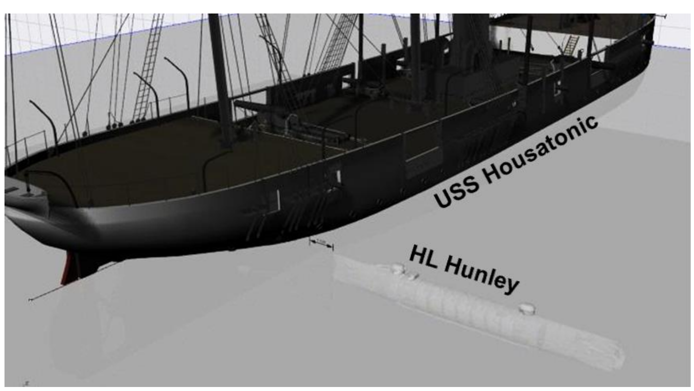

Figure 2. Approximate attack configuration. Credit: Michael Scafuri, Courtesy: WLCC & Friends of the Hunley.

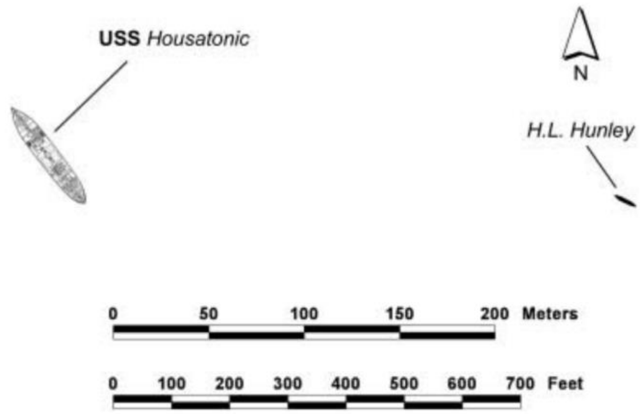

Figure 3. Final wreck locations – After Conlin and Russell (2006)

One of the most critical findings made by WLCC has been the discovery of a spar with a copper sleeve indicating a fixed spar torpedo weapons system. Until this finding, most descriptions of the attack assumed that *Hunley* utilized a line-operated detachable spar torpedo system whereby the explosion was initiated from a distance. In contrast, a fixed system consisting of an explosive charge permanently affixed to a spar would result in *Hunley* being separated from the explosive charge only by the length of the spar. This would have generated a far more severe loading environment for *Hunley* and its crew than the detachable system. The largest spar torpedo, Singer's Torpedo, shown in Figure 4, consisted of approximately 135-pounds of black powder and a spar length of approximately 16 feet in length, along with a line-operated fuse.

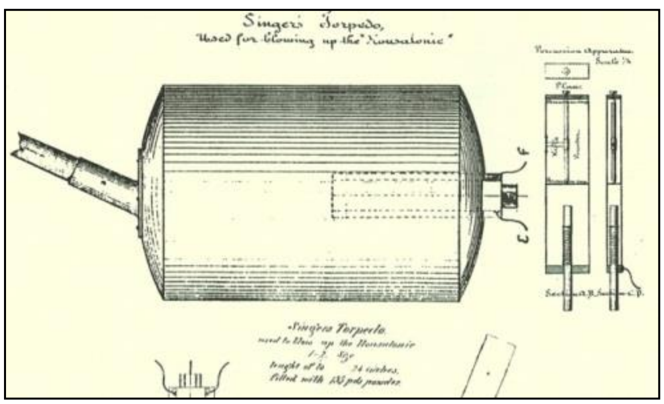

Figure 4. Period drawing of Singer's Torpedo indicating the size of the explosive charge (Gillmore). Note the text at the top of the drawing which reads "Used for blowing up the Housatonic".

The more severe effects of the explosive loading on *Hunley* makes the location of *Hunley's* wreck even more puzzling as the two facts put together indicate that the explosion was not immediately fatal to *Hunley*. However, it is clear that *Hunley* remained nearby or was disabled in some fashion as it did not make significant progress to return to shore. To help bound the possible scenarios both a bottom-up naval architecture analysis and a weapons effects analysis were performed. The naval architectural analysis, which consists of two distinct portions, examines basic naval architectural aspects including weight, stability, and powering as well as post-attack drift and flooding scenarios through digital replica of the vessel. The weapons effects analysis examines the transient response of *Hunley* and its crew to the underwater explosion loads generated by the explosion using high-fidelity computational mechanics tools. Performing these calculations required performing full-scale testing of relevant explosive charges and the development of an appropriate numerical model of the explosion process.

NAVAL ARCHITECTURE ANALYSIS

Given the amount of uncertainty surrounding the vessel's final mission, a bottom-up technical analysis was commissioned alongside ongoing archeological investigation of *Hunley*'s wreck. The goal of this approach was twofold. First, it was desired to see if the current understanding of the vessel, based on limited historical records and interpretation of the artifacts found, was consistent with what would be plausible from a physics-based model. Second, a naval architecture model of the vessel could help answer what-if scenario questions regarding the vessel's capabilities, and the crew's options during the final mission.

Preparation of a Hydrostatics Model

Developing an estimate of the lines plans of the vessel was central to the ability to investigate the vessel as a submarine or semi-submersible. After recovery, WLCC performed laser and structured light geospatial scans of both the exterior and much of the interior of the vessel. Geometrical surface models were developed using this scan data which consisting of 3D point data. The vessel consists of three main regions, a bow and stern section connected with a large mid-body. The mid-body is essentially a prismatic oval manufactured by expanding a circular pressure vessel into an ovoid using an expansion strake at the joint between the two semi-cylindrical halves. The bow and stern region both taper down roughly linearly and symmetrically to a vertical stem and sternpost on the vessel's centerline. A large casting is used to form the end of the bow and stern, with shaped plate connecting this casting to the mid-body. Internal floating ring-frames were included in the design and appear to have been pressure fit. At the time of the laser scan, the majority of the vessel was covered in concretion, a mixture of shells, marine growth and products of corrosion that forms on the outside of submerged structures. The laser and structured light scan included this concretion. Using least-squares fitting between the point clouds as well as engineering judgment, an approximate molded line was determined along the length of the vessel.

The vessel is also heavily appended. Two hatch towers for crew access sit on top of the vessel, each is roughly cylindrical. These doubled as command centers for the crew, with small portholes cut so that the vessel could see its surroundings when surfaced. Aft of the first hatch is a snorkel box, which housed rotatable snorkel tubes for exchanging air while submerged. Additionally, there is a box keel comprised of both fixed and detachable ballast weights, forward dive planes, and a propeller, rudder, and propeller shroud at the stern. Finally, the lower part of the spar and estimate of the torpedo charge were added to the model. The dimensions of each of these items was either measured or in the case of damaged or incomplete artifacts, estimated, and added to the model.

While the vessel's fairly complex propulsion, ballast pumping, and control systems were investigated in detail for the weight analysis, for hydrostatics the interior was simplified. The vessel features two large ballast tanks in the bow and stern regions. Each was formed by a partial bulkhead at the forward and aft ends of the central crew compartment, and could be flooded with seawater. Interestingly, the vessel only used partial bulkheads with a gap between the bulkhead top and the hull for these ballast tanks. This allows free communication of air throughout the vessel, but also raises the potential for ballast water to spill out of the tank if the tank is overfilled or if the vessel is significantly disturbed. The two ballast tanks and their spill points were included in the hydrostatics model, as well as the central crew compartment. The final model was assembled in the Rhino3D surface modeling program, and then exported via the Orca3D plug in to the GHS hydrostatics package. Rendering of both the Rhino3D model and the GHS model are shown in Figure 5 and Figure 6.

Lightship and Mission Weight Estimation

Estimating the lightship weight of the vessel, as well as the final mission weight of the vessel is critical to understanding how the crew could have operated the vessel. Ballast tank filling, spillage, and overall vessel stability are all related to the lightships and operating weights. A bottom-up weight estimating approach was taken, based around a 1-digit Navy Enhanced Ship Work Breakdown Structure (ESWBS) classification. The largest component of the vessel's weight is the hull structure. Current measurements of the existing wrought iron hull plates in areas with minimal corrosion were used to estimate the average as-built thickness of the vessel. At the time this work was done, the vessel was only partially de-concreted, which limited the number of measurement locations that could be used. However, a reasonable estimate of 0.29 inches was obtained, contrasting with a reported design thickness of 3/8". The density of wrought iron also varied piece-to-piece, and average density of 481 lb/ft^3 was used. Hatches, dive planes, and the external keel ballast, all cast iron, were all included in the overall hull structures category. Propulsion and outfitting weights were also considered part of the permanent lightship of the vessel. These weights were among the most difficult to estimate. Some components had been identified and preserved, for these exact weights were used. Many components had either deteriorated, or in case of the propulsion gearing, remain covered in concretion in the hull of the vessel. Weights were estimated for such components. Propulsion and outfitting represented 0.45 LT and 0.11 LT of weight respectively.

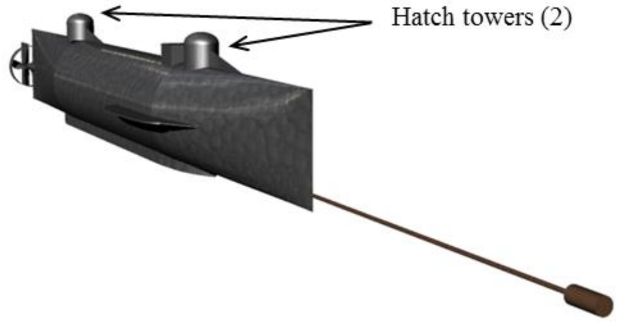

Figure 5. Rhino3D model of the vessel

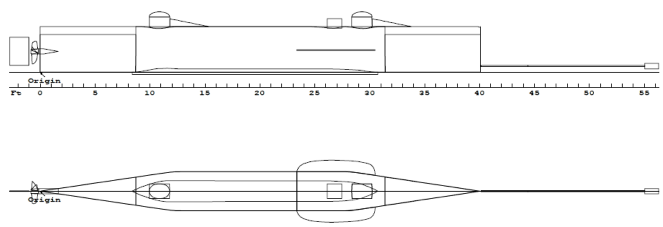

Figure 6. GHS model of the vessel. The estimated operational draft is between the top of the hull and half-way up the hatch towers.

It is not known if the designers carried out any rudimentary displacement calculations, or if the vessel's final configuration was arrived at through trial and error. If trial and error was used, the weight discussed above would represent the first condition that the vessel could have been floated out to see where it sat in the water. Creative System's General Hydrostatics (GHS) package was used to investigate if the vessel would have been stable if floated at this point in construction. With a total displacement of 5.62 LT, this model shows that the submarine would indeed float upright, with a slight stern trim and a noticeable 3.25 degree list to starboard, owing to the asymmetric propulsion arrangement. Upright transverse GM is 0.23 feet, which is certainly small but would indicate that the vessel would remain upright if floated in this condition.

In addition to the permanent hull structure, the vessel was ballasted through the use of different size pig iron blocks. All of these blocks had been removed from the submarine during the archeological work, cleaned, and weighed. The pig iron ballast blocks can be divided into three major categories. The first category is several large ballast blocks that were placed in the bottom of both the forward and after ballast tanks. While they were not permanently attached to the hull, it appears that these blocks were more or less treated as stationary masses. Likewise, in the main crew compartment, different size pig iron blocks were laid at the bottom. The second category of ballast is the larger, heavier (>70 lbf) blocks from this location. Owing to their weight, it is unlikely that they were frequently moved. The third and final group of ballast blocks is the smaller blocks in the main compartment. These blocks, which all weighed less than 70 lbf, could have been adjusted by the crew to bring the boat into balance when fully loaded. Altogether, all three types of ballast represent 2.27 LT of additional weight.

The last weights to consider were the variable mission weights. Mission weights comprise the black powder charge and spar – a weight of 0.09LT with the charge, and 0.03LT after the charge was used were estimated for this weight. Additionally, the crew weight was estimated based upon the remains recovered. Individual crew members ranged from 131.0 lbf to 171.5lbf, with an all-up crew weight of 0.57 LT. Using GHS, the vessel was further simulated. A pier-side condition was investigated with the spar torpedo attached and all large ballast blocks placed in the vessel. This resulted in a total displacement of 7.11 LT with an upright GMT of 0.45 Ft. Then, the loading of the crew and small ballast blocks was simulated, one crew member at a time. During this process, the vessel's GMT varies only slightly from the pier-side condition, and then increases to 0.62 ft when the final smaller ballast blocks are all placed on the bottom shell. Trim remains reasonable throughout.

Finally, GHS was used to iteratively flood the fore and aft ballast tanks to bring the vessel to the final attack condition reported in the historical literature. The ballast tanks each have a useable volume of just over 31 cubic feet. Filling the forward ballast tank to 75% of its capacity, and the aft ballast tank to 45% of its capacity bring the vessel to an even-keel condition with both hatches and the snorkel box fully exposed and the upper crown of the hull just dry. These filling levels leave some space between the fluid and the top of the partial bulkhead, and also indicate that even with small errors in the weight estimate, the vessel would be ballast-able to the reported attack configuration. In this position the GMT is 0.70ft. The longitudinal GM is also reduced notably in this condition, down to 7.2ft from values between 20-40ft in the previous load cases. A table of the estimated weight components for this deck-awash condition is presented in Table 1. For this calculation, the origin is the stern frame on the baseline, X is positive forward, Y is positive to starboard, and Z is positive up. This agrees very well with period accounts regarding the waterline.

Table 1: Final Weight Estimate at Departure, Deck Awash. Origin is the stern frame on the baseline, X is positive forward, Y is positive to starboard, Z is positive up

Group	Title	Weight (LT)	X (ft)	Y (ft)	Z (ft)
1	Hull Structure	5.06	20.04	0.00	1.48
2	Propulsion Plant	0.45	11.20	0.09	1.88
6	Outfitting Systems	0.11	19.50	0.12	1.77
7	Armament	0.09	52.82	0.00	0.00
F	Loads, Departure	3.92	20.95	-0.06	1.00
	Total	**9.63**	**20.30**	**-0.02**	**1.29**

Adding an additional 5% filling to the forward and aft ballast tanks brings the waterline up onto the hatches and snorkel box. This condition closely matches the description given by William Alexander (1902) of the vessel's loading condition. However, this description was published nearly 40 years after William Alexander had last been with the vessel, and he was not on the crew list for the final mission. In this position, the GMT is similar at 0.71ft but the GML is further decreased to 1.6ft. One feature of this reduced GML is that the vessel is likely to trim 2-3 degrees by the stern when the charge explodes and is removed from the weight estimate. As the spar-rigged torpedo was a recent modification, it was never tested through explosion before the final mission, it is not clear if the crew would be aware of this behavior.

The weight analysis, while requiring some estimation for items that either decomposed or were not yet de-concreted, largely replicates our understanding of the vessel from historical sources. The vessel floats upright, with positive stability, in all considered load cases. While the vessel is certainly tender at the lightest and deepest drafts, an iterative approach to ballasting and refining the operation of the vessel seems plausible. The vessel could operate in the semi-submerged mode described with reasonable ballast tank fillings. Of course, the vessel was originally designed to be fully submerged. While operating as a submarine was not investigated in this project, it is clear that the vessel has adequate ballast capacity and stability to fully submerge. Indeed, this enters into the actual loss of vessel as there is very little reserve buoyancy left in the semi-submerged mode. A net water inflow of only 50 gallons would overwhelm the remaining reserve buoyancy available in the hatch covers and snorkel box. This indicates that the vessel would be very susceptible to any sort of flooding, especially if the crew were unready to operate in a fully submerged mode.

Resistance and Propulsion Modeling

A key limitation of *Hunley*'s operation is the reliance on human power to propel the vessel. Given the distances involved, the presence of a substantial tidal current, and the relatively low speed of the vessel, it is clear that propulsion concerns would have been central to the operation of the submarine. William Alexander, a former crew member, noted that the submarine could not always fight the tide around Charleston (Alexander, 1902). At the time of analysis, most parts of the propulsions systems had not been fully cleaned of the concretion, so much of the following analysis must be regarded as preliminary and approximate. Historical records indicate that the vessel could obtain a top speed of roughly 3-5 knots, though the basis for such estimates is unclear. To try to corroborate these estimates, a rough resistance and propulsion estimate was made for the vessel. The vessel's resistance was calculated as a submarine, ignoring wave drag, assuming *Hunley* would have tried to flee the scene of the attack submerged. The drag in the attack position would likely be higher owing to the hatch towers projecting through the water, as well as wave drag terms. Using the approximate method given in *Introduction to Naval Architecture* (Gillmer and Johnson, 1982), the drag of the vessel was estimated as:

$$R_T = 0.5\rho V^2((C_v + C_a)S + 1.8C_vS_a \quad (1)$$

Where the viscosity coefficient was taken as:

$$C_v = C_F\left(1 + 0.5\left(\frac{D}{L}\right) + 3\left(\frac{D}{L}\right)^3\right) \quad (2)$$

The coefficient of friction, C_F,was taken from the 1957 ITTC friction line (Lewis 1988) in this approximation assuming salt water, and other values are given in Table 2. Again, this calculation must be viewed as approximate as the submarine is not perfectly cylindrical, Reynold's numbers are lower than modern submarines, and the actual value of hull roughness given the wrought iron hull plates and rivets is not known.

Table 2: Resistance model assumptions

Symbol	**Description**	**Value Used**
L	Submarine length	40 ft
D	Submarine diameter	3.75 ft
S	Wetted surface area	612 ft^2
S_a	Append surface area	140 ft^2
C_a	Correlation allowance	0.0001

The propeller was entirely covered in concretion at the time of the analysis, and all three blades have lost portions of their surface through either corrosion or erosion. Thus, blade profiles and exact blade contours were not available. Given this situation, the laser scan data was used to estimate the intact propeller configuration, and a propeller model from the Wageningen B-Series (Lewis 1988) was used. This will most likely over-estimate the propeller efficiency, given the roughly 100 years of propeller development between the date of *Hunley*'s construction and the B-Series. The propeller diameter was estimated at 31.6 inches, with a P/D ratio of 0.776 and an expanded area ratio (EAR) of 0.29. Assuming wake factor and thrust factors equal to 0.1, it was possible to develop curves of both human propulsion power required, and the equivalent crankshaft RPM required to move the vessel through the water. These curves are given in Figure 7 and Figure 8. In Figure 7, a rough estimate of the available power per person using only upper arms was added at 0.067 horsepower per person. As the exact cranking position of the crew remains unclear, this too must be regarded as an estimate. This line was drawn for both all seven members cranking, and a five member cranking case, as the cranking crew members would also have to attend to any bilge pumping or aft ballast tank adjustments required. Thus, if the vessel was damaged or being re-configured, not all seven crew members would be able to crank

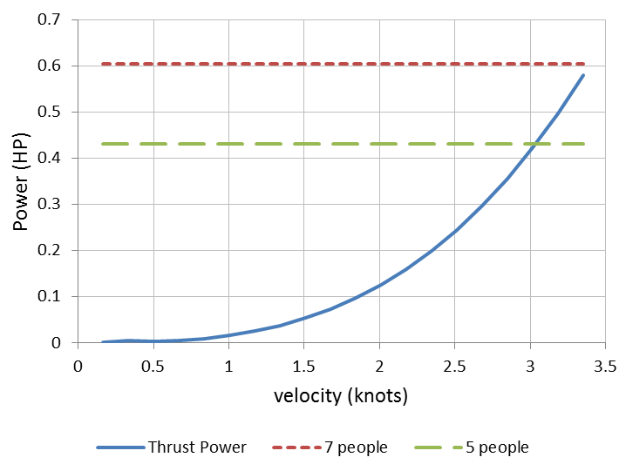

Figure 7. Estimated propulsion power required

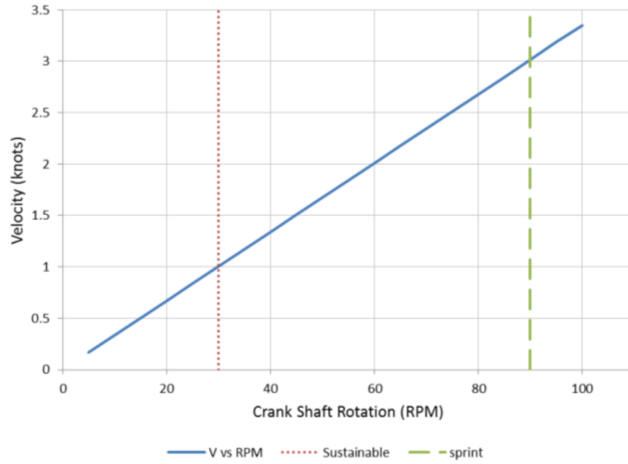

Figure 8. Estimated crankshaft RPM at crew stations vs. speed

Figure 7 and Figure 8 are again surprisingly close to the historical records given the approximate nature of the analysis. The vessel appears to have enough power to sprint slightly above 3 knots when fully submerged. However, such a speed requires rotating the crankshaft in excess of 90 RPM, which approaches the upper limit of human capability. It is unlikely that rotation rates in excess of 90 RPM could be sustained for a long period of time, however, the vessel can still move at speeds of 1-2 knots between 30-60 RPM. This speed range ties in with the Alexander recollection that the vessel had to time the tidal currents carefully, as the vessel could not fight a large current for a long period of time (Alexander, 1902). Finally, it must be reiterated that this analysis is approximate and preliminary – when the propulsion systems is fully preserved, more accurate information on the gearing, propeller profile and pitch, and internal crank arrangements are likely to surface that could allow a more precise estimate to be made.

WEAPON EFFECTS ANALYSIS

Weapons effects analysis of *Hunley*'s engagement with USS *Housatonic* requires using a high-fidelity computational mechanics approach in order to capture the complex interactions of the underwater explosion (UNDEX) with both vessels. This analysis presented herein was performed using the DYSMAS software code. DYSMAS consists of an Eulerian inviscid shock-physics code developed by the US Navy, DYSMAS/FD, and a Lagrangian explicit dynamics Finite Element code developed by Lawrence Livermore National Laboratory, Paradyn. The two codes are coupled together utilizing a fully deformable boundary mesh on which pressures and motions are exchanged between both domains thus accurately capturing Fluid-Structure Interaction (FSI) effects.

In order to capture the response of *Hunley's* crew to the UNDEX-induced structural motions, separate simulations using a numerical model of an automotive crash "dummy" or Anthropomorphic Test Device (ATD) are utilized using the LS/DYNA code. The details of the various aspects of this analysis is as well as an overview of the results are provided below.

Structural Modeling Procedure

A detailed Finite Element Model (FEM) of *Hunley* was developed from laser and structured light scans. This was accomplished by taking transverse and longitudinal slices of the scan point cloud data and smoothing the position of point data in order to form regular surfaces. Smoothing was necessary due to the concreted and non-smooth nature of the hull. Direct thickness measurements of the hull were made to provide plating thickness in the different regions of the hull and non-structural mass was included in the FEM to account for the ballast blocks that were present so that the total weight matched the bottom-up weight estimate that was developed. The model was meshed using a mesh size of approximately 4 cm and consists of 32,000 shell and 12,000 solid elements. *USS Housatonic* was modeled using geometry provided by WLCC and developed from a sister ship of *USS* Housatonic. Since the goal of the calculations was to examine *Hunley's* response rather to determine the damage development in the target ship, *Housatonic*'s structure was modeled as rigid shells. A view of the FEM and scan data from which the FEM was prepared are shown in Figure 9.

Hunley's wrought iron plating and hatch tower and end cap iron castings were modeled using separate elastic-perfectly plastic material models. The yield stress was determined from period data collected by Beardslee (1879) and Kirkaldy (1862). It is readily observed that wrought iron of this period is quite strong (typical yield 30-40 ksi) and ductile (typical elongations 15-30%) although quality control was very poor and poor distribution of slag could result in very weak or brittle material. The reader is referred to Bowman and Piskorowski (2004) for a distillation of the data provided by these historical works along with more recent test data on historical iron samples.

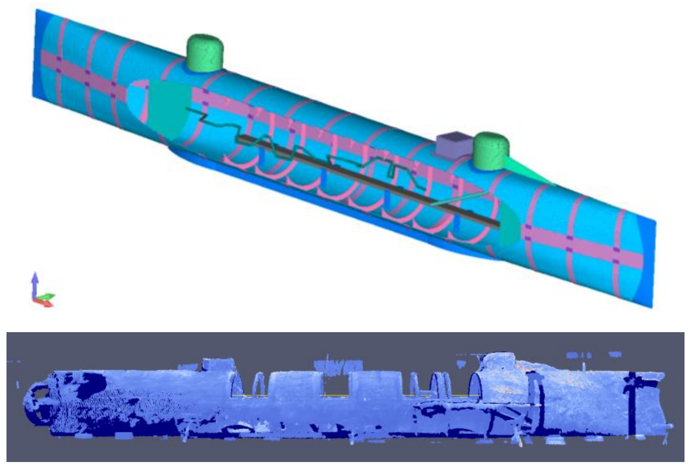

Figure 9. Cutaway view of HL *Hunley* FEM (Top) and overlaid laser and structured light scans (Bottom).

Fluid Modeling Procedure

Simulations utilized a large fluid domain of approximately 230x230x95 feet (70x70x29 meters) to capture the zone in which the UNDEX phenomena of pressure wave propagation and explosion-generated bubble phenomena occur. The free surface and air above the free surface was included to capture the full nature of the loading environment. In the zone where the bubble expands and contracts, the fluid grid size was 0.787 in (2 cm). The grid size was graded away from this region to ensure an efficient computational domain. A Tillotson Equation of State (EOS) (Tillotson, 1962) with a pressure cutoff to capture cavitation was used to model water and a Gamma-Law EOS to model air. Black powder behavior was captured using a non-ideal Jones Wilkins Lee (JWL) EOS for which the details are provided below. Boundary conditions consisted of a rigid reflecting boundary condition on the bottom surface to capture pressure-wave reflections of the sea bottom. A fully reflecting bottom condition was selected to provide a worst-case scenario for reflected pressure waves.

The computational domain for the fluid grid consisted of approximately 350M fluid cells sized at 1.6 inches (4.0 cm) in the refined region of interest. The calculations were run in a parallel manner across 256 cores on an IBM Dataplex High Performance Computer (HPC), Kilrain, located at Stennis Space Center and operated under the DoD High Performance Computer Modernization Program (HPCMP). The calculations took approximately 60 hours to run.

Black Powder Overview

As a propellant that does not detonate but rather deflagrates, or violently burns, the explosive behavior of black powder differs greatly from typical detonable underwater explosives. As opposed to detonation that occurs in a near instantaneous manner, deflagrations are relatively slow. Although bulk quantities of confined black powder do explode and generate high-pressure reaction products, the time scale on which this occurs is an order of magnitude slower. Additionally, as a granular material that burns on an individual particle surface area, the rate of production of the explosive products is pressure and grain-size dependent. For further details about black powder including data on the pressure dependence on the rate of reaction, the reader is reference to an extensive overview prepared by Sasse (1985).

The UNDEX behavior of bulk quantities of black powder is minimally documented; the only work that provides pressure records of a black powder UNDEX event are those published by Hilliar (1919). Furthermore, no documentation of the explosively generated gas bubble was located despite the criticality of this phenomenon in determining the effects of UNDEX on structural response. Furthermore, Hilliar utilized large hexagonal grains and was limited in the ability to collect detailed pressure records. Therefore, testing of representative explosive charges was determined to be necessary.

Black Powder UNDEX Testing and EOS Development

UNDEX testing of black powder was at the Underwater Test Facility (UTF) located at Aberdeen Test Center (ATC) in Aberdeen, MD to examine its behavior as an underwater explosive. Six representative full size explosive charges were prepared utilizing period rifle grade (FFg) black powder as seen in Figure 10. Testing was performed using one of two test geometries: a “Demonstration” configuration in which the charge axis was horizontal and at a depth matching that of the attack and a 50-foot depth “Characterization” configuration suitable for development of an EOS for numerical modeling. Both PVC and sheet aluminum charge casings were tested; it was determined that the role of case confinement was minimal. Therefore, all “Characterization” tests were conducted using PVC cases. Instrumentation consisted of an array of underwater pressure transducers to collect pressure records. The “Characterization” configuration also included a vertical array of pressure transducers from which to infer the bubble period.

Furthermore, piezo-electric transducers, or piezo-pins, placed along the length of the charge casing, provided estimates of burn-wave velocities.

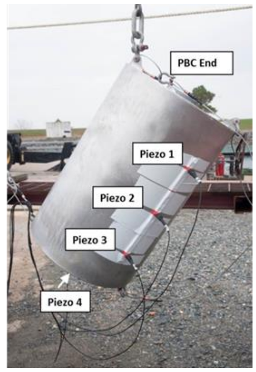

Figure 10. Explosive test charge with piezo-pins identified.

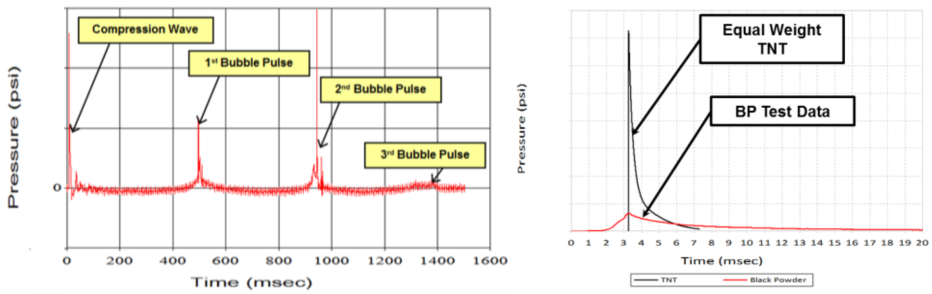

Figure 11. Typical "Characterization" configuration pressure record and comparison to equal-weight of TNT. Note pressure levels are redacted due to security concerns.

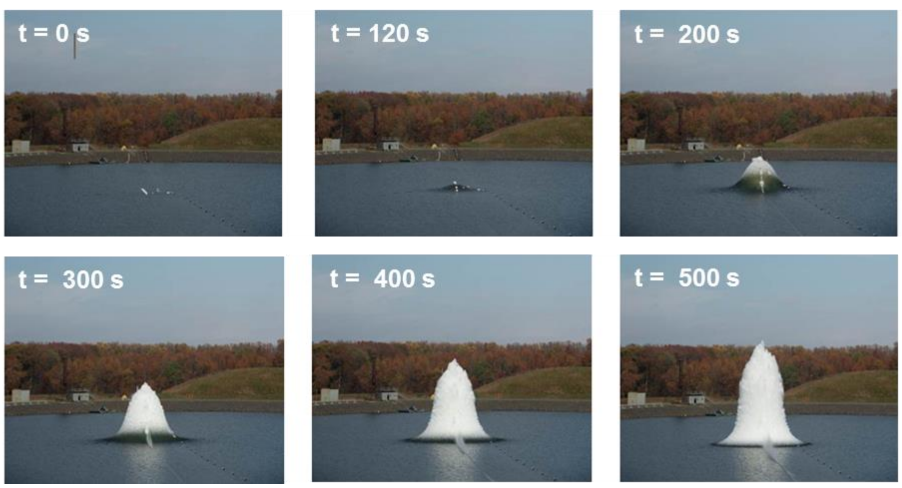

Figure 12. Plume generated by "Demonstration" test mimicking Hunley's attack.

Figure 11 presents a typical pressure record illustrating the initial compression wave and the subsequent pressure disturbances emanating from the pulsating gas bubble. A direct comparison of pressure traces generated by equal weights of TNT, a common reference high explosive, and black powder at the same standoff distance reveals that the black powder pressure trace exhibits a finite rise time, lower peak pressure level compared to TNT but a much longer decay. Hunley's torpedo would have generated a water plume virtually identical to that shown in Figure 12. The explosion did not result in bulk cavitation was the plume remained intact until approximately 150 ms due to this lack of cavitation.

Numerical simulations captured the explosive output of black powder utilizing a Jones-Wilkins-Lee (JWL) EOS with programmed burn and late-time energy release. The equation of state relating pressure p to density ρ is given by:

$$p = A\left(1 - \frac{\omega\rho}{R_1\rho_0}\right)e^{-R_1\frac{\rho_0}{\rho}} + B\left(1 - \frac{\omega\rho}{R_2\rho_0}\right)e^{-R_2\frac{\rho_0}{\rho}} + \omega\rho e \qquad (3)$$

CHEETAH thermochemical calculation software (Fried and Souers, 1995), developed by LLNL, was used to derive coefficients for the JWL EOS. The moving flame front, captured using programmed burn, has a velocity taken directly from piezo-pin data collected during the experimental effort. The relatively slow energy deposition of the burning black powder grains was captured using a pressure dependent rate equation for the evolution of burned volume fraction:

$$\frac{df_b}{dt} = A\left(1 - f_b\right)^m\left(\frac{p}{p_{ref}}\right)^n \qquad (4)$$

Here, f_b represents the fraction of explosive that is burned and the coefficients A, m, and n are tuned to experimental data and are limited in applicability to the grain size tested. The DYSMAS software manual (NSWCIHEODTD, 2016) contains full details on the implementation of this model.

Numerical simulations of both test configurations reveal that the model tuning is able to capture the relevant pressure wave characteristics including the slow rise time and long decay time as seen in Figure 13. Furthermore, the bubble period is within 3% of recorded test data. This indicates that both the rate and total energy delivery of the explosion are physically correct.

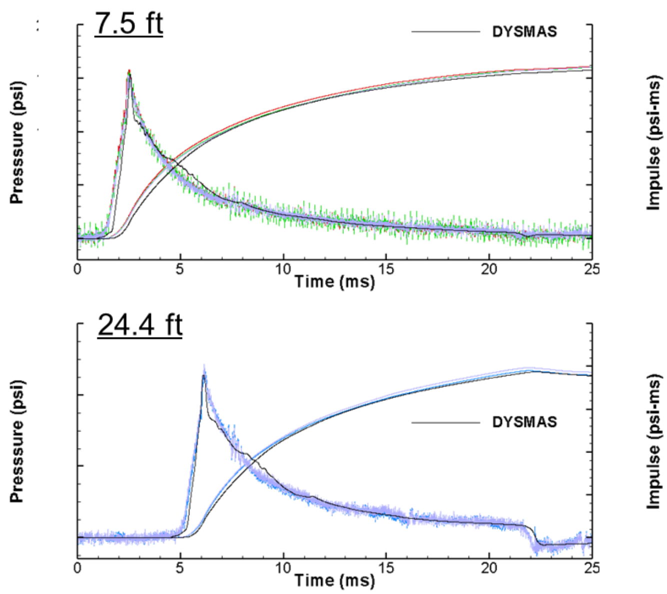

Figure 13. Correlation of pressure and impulse of numerical simulations performed with black powder EOS and experimental data. Note pressure levels are redacted due to security concerns.

Crew Modeling

Crew injury modeling was performed using the Hybrid III 50th Percentile Male (H350) ATD. The H350 ATD is suitable for assessing the probability of injury that results from accelerative loadings and represents a male weighing 171 lbs and 5'9" tall. It was determined by Hirsch (1963) that the lacerations, concussions, leg/knee and back strains or fractures are the most common shipboard injuries resulting from such motions and the H350 is capable of capturing the relevant back and leg injury modes as well as head injury occurring from head accelerations. The H350 is not able to capture lacerations nor is the modeling procedure sufficiently refined to capture head trauma resulting from causes other than global motions and impact with primary structure or the central crankshaft. Fortunately, the H350 is a close surrogate for the average size and weight of *Hunley*'s crew as evidenced by the human remains recovered from the vessel.

Since an ATD FEM is not currently available in DYSMAS, ATD simulations were performed in the LS-DYNA Finite Element code, a well-established tool for performing such calculations. Inputs to the ATD simulations consisted of structural motions extracted directly from the fully-coupled DYSMAS simulations of the engagement. Seven crew members were included in the calculation and resulted in a model size of 3.1M elements (430k elements per ATD). Calculations were run on 96 CPU's and took approximately 60 hours to run. The ATD's were positioned in *Hunley* as shown in Figure 14.

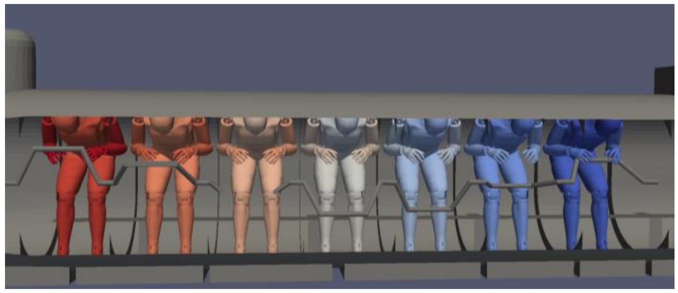

Figure 14. ATD positioning representing *Hunley's* crew, cutaway view.

Results

Calculations of *Hunley*'s engagement with *Housatonic* reveal that the torpedo was devastating and overmatching to *Housatonic* while transmitting relatively low levels of loading to *Hunley*. First, pressure waves emanating from the explosion propagate and reflect off both *Housatonic*'s hull and the sea-bottom as seen in contours of pressure shown in Figure 15. Interestingly, due to the small presented area of the bow, *Hunley* experiences pressure loading primarily from the bottom-reflected wave rather than the first wave emanating directly from the explosion. Both pressure waves are of relatively low severity, consistent with the previously discussed differences between black powder and TNT when used in a weapon. These pressures would have resulted in purely elastic deformation of *Hunley's* structure.

Later in time, an expanding and contracting bubble of initially high-pressure explosive reaction products occurs. The bubble reaches its peak size at approximately 240ms, subsequently contracts, and finally collapses into a high-velocity bubble jet or water column that is known to have devastating effects upon impact. Figure 16 shows the overall expansion and jetting process and Figure 17 shows a detail of the jet immediately before impact. *Hunley* is seen to react to these loads by deforming vertically in a rigid-body pitching fashion in which the bow of the vessel rapidly rises while the stern remains almost stationary until later in time. The bow the of vessel reaches a maximum velocity of 9.5 ft/s (2.9 m/s) at 96 ms resulting in an average acceleration of 3.1 g's.

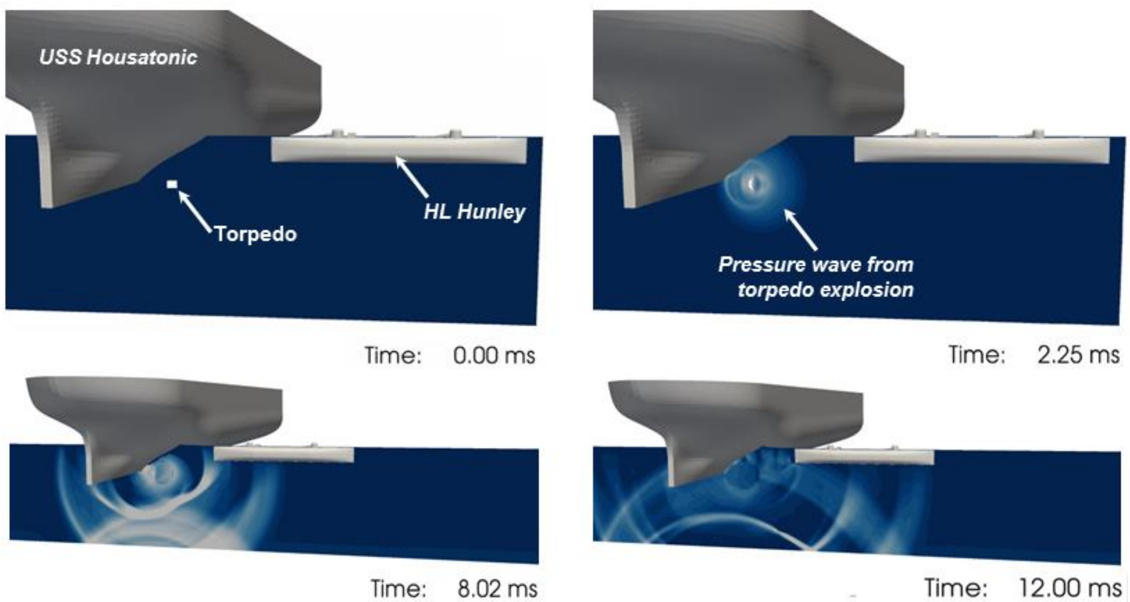

Figure 15. Contours of pressure illustrating the emanating pressure wave and bottom reflection wave from the explosion.

ATD simulations were utilized to study the effect of these pitching and heaving motions on the crew. Figure 18 illustrates the initial position of the crew and the kinematic position at the point of maximum excursion. It is observed that the crew is thrust downward due to the vertical motion of the submarine and that several of the crewmembers impact the central crankshaft. However, the imparted motions are quite benign in nature and the relevant injury metrics do not indicate a probability of injury. This is consistent with Hirsh's experimentally based observation (1963) that a 10 ft/s peak change in velocity would have to occur at over 15 g's to cause the onset of injury for a seated crewmember. Work by WLCC has indicated that the explosion did not result in freshly broken bones, consistent with this finding. Therefore, accelerative injury to the crewmembers was not the immediate cause of *Hunley*'s demise. At present, the current modeling procedure is unable to predict hearing loss or noise-induced disorientation from the blast.

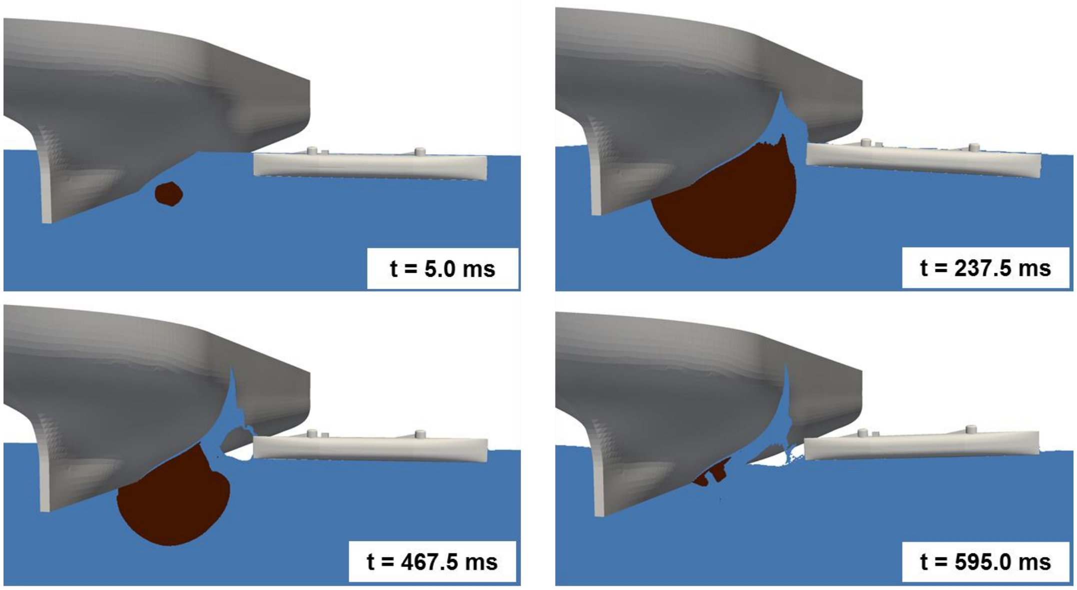

Figure 16. Contours of density in the fluid. Dark red regions indicate regions consisting of black powder explosion products. These results indicate that the explosive charge produced a large bubble which then collapsed into a high-velocity jet against the *Housatonic's* hull. This jet would have been overmatching for *Housatonic's* hull and resulted in a large hole leading to sinking.

Figure 17. Close up view illustrating the bubble jetting effect. The bubble jet is a high velocity water column that imparts a severe local loading on the hull of *USS Housatonic*.

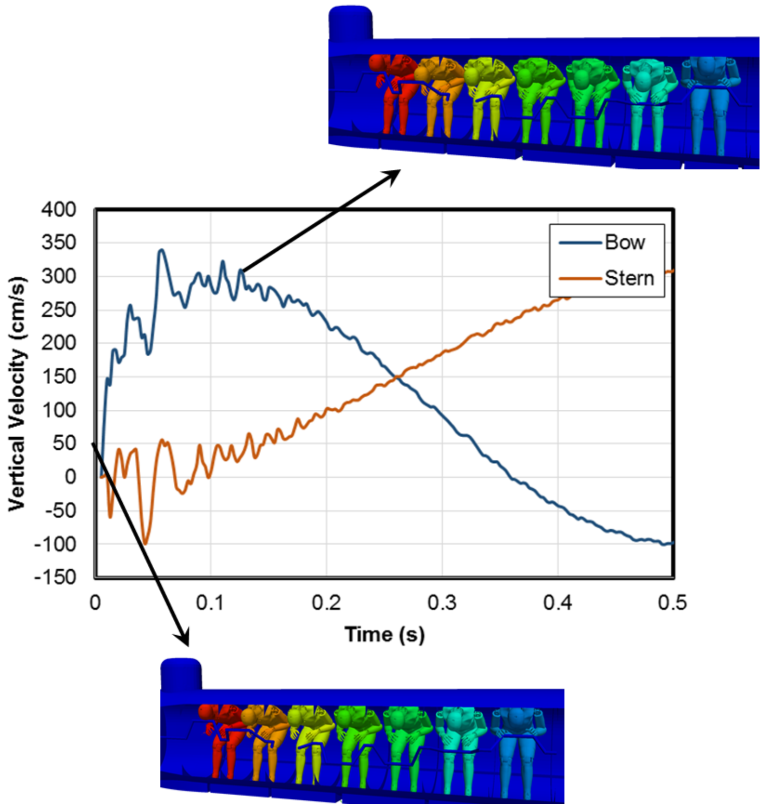

Figure 18. Hull motions and effect on crew. The crewmembers' heads are seen to pitch down from the vertical motions imparted by the explosion.

LOSS SCENARIOS POST ATTACK

While the efforts described above address the stability and propulsion characteristics of *Hunley* and the response of the submarine and its crew in the first seconds after the attack, the mystery of what happened after remains. Numerous possible loss scenarios have been proposed in the literature. For example, William Alexander (1902) proposed that the vessel became stuck in *Housatonic's* wreckage and was unable to escape. However, the location of the wreck makes it clear that *Hunley* was clear of *Housatonic* when it finally sank. One eyewitness on *Housatonic* noted that a he had observed a light some 50 minutes after the attack. It has been suggested that this was a signal *Hunley* had planned to give to indicate it was returning.

A recent archeological discovery also may have played a role in the loss of the vessel. The forward ballast tank fill line appears to have fractured at the connection to the hull (Stephenson 2016). This ballast line appears to have fractured at a bolted connection, with the pipe slipping down until it hit one of the bolt heads, exposing a crescent-shaped region for flooding. An image of this connection is shown in Figure 19. The role this fracture could have played in the loss of the submarine was selected for investigation in this project. However, this selection should not be interpreted as precluding other, unrelated or compounding, loss scenarios. Possible damage to the submarine from small arms fire as well as the crew's ability to manage their oxygen supply after the attack are also under consideration, and may have played a role in the final loss of the vessel. As the following section will indicate, the role of the ballast fill line is complex, and a does not provide a clear-cut explanation for the loss of the submarine.

Flooding and Drifting Scenarios

As discussed previously, when ballasted down to the semi-submerged attack position, *Hunley* has very little reserve buoyancy— only the hatch towers and snorkel box project above the upper crown of the hull. Calculations indicated that somewhere between 50-75 gallons, or 430-640 pounds of additional weight need to be added to the vessel for it to fully submerge, depending on the final attack waterline. Additionally, *Hunley* was located approximately 1000 feet from the attack site. Given the close proximity of the vessel to the explosion of the black powder charge, one possible scenario is that the ballast fill line fractured during the attack. It is possible that the crew were disabled or disoriented by the explosion and that the vessel drifted to its final sinking location while slowly filling with water. If the crew were not disabled, it is also certainly possible that they propelled the vessel to its sinking location.

Figure 19. Fractured forward ballast fill line at thru-hull connection, looking inboard.

Experimental Modeling of the Failed Connection

A key question is how fast the broken pipe flange would allow water into the submarine. Handbook calculations and CFD analysis indicated that the flooding rate would be high, but not out of the question to allow a sink-and-drift scenario to take place. Given the complexity of the joint, as well as its small size (the thru-hull opening is 1.5” in diameter), it was decided to experimentally test the fitting to approximate the flow rate. Additive manufacturing, or 3-D printing, was used to make a replica of the damaged area out of ABS plastic. The geometry of the curved outer surface of the hull of the submarine was taken from the laser scan data, and field measurements and photographs of the ballast fill line were used re-create its position, wall thickness, and length. The fill line was modelled up to the control valve just inboard of the hull surface. This valve was found in the closed position, and was represented in the model by simply closing the end of the fill pipe at the appropriate position. A mounting frame was then added around the curved hull surface, and some additional material was added between the pipe and the hull surface below the fracture to increase the strength of the model. Figure 20 and Figure 21 show a rendering of the model and a photo of the experimental setup, respectively.

Experiments using the ballast pipe connection replica were conducted by placing the connection in a variable-pressure water chamber and measuring the rate of discharge via the crescent-shaped opening. These results are shown in Figure 22. The break in the data points near 20 inches of external water depth was a result of switching from pure hydrostatic head to a combination of hydrostatic head and applied air pressure to simulate deeper depths owing to the geometry of the available pressure chamber. The external water depth of the ballast fill line in the decks awash condition is roughly 19.5”. The test results indicate that the water would start flowing in at a rate of 22-23 gallons per minute and would be flowing faster than 30 gallons per minute when the submarine become fully submerged. Assuming all hatches and the snorkel box were closed, there would be a buildup of internal air pressure as the vessel flooded. However, as the volume of the water required to sink the vessel (75 gallons) is small compared to the volume of air in the hull, this term was neglected for the simulation. The flowrate indicates that the submarine would have a maximum of three minutes before fully submerging from its semi-submersed state barring corrective efforts to stem the flow of water. These experimental flow rates fell between the CFD (slightly lower flooding rate) and handbook estimated (slightly higher flooding rates) values.

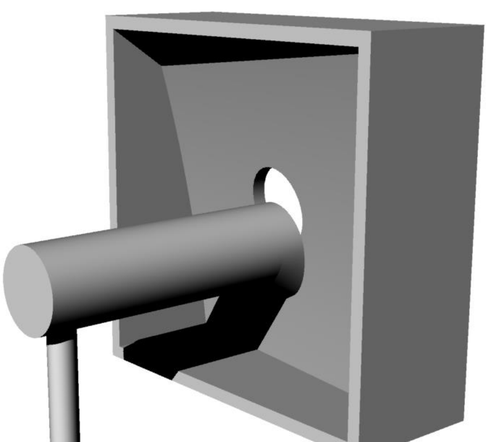

Figure 20. 3-D printed fracture ballast fill line

Figure 21. Fracture ballast fill line replica mounted in variable-pressure water chamber

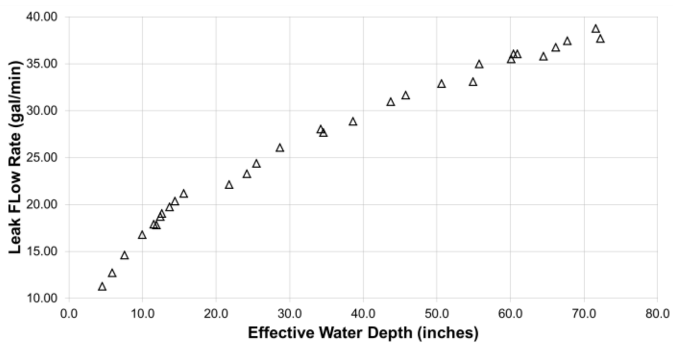

Figure 22. Flowrate vs. external water depth through the broken ballast water fill line replica

Drifting Timeline

Using the estimated flooding rate, the drift rate of the submarine was estimated. On February 17th, 1864, the switch to ebb tide occurred at 1611 as measured at Fort Sumter at the mouth of Charleston's harbor; the maximum offshore current would occur just after 20:00 that night. This ties in well with *Hunley* leaving on the ebb tide so that the current would help the crew reach the blockade vessels offshore. Based on current tidal tables, the switch to flood tide would not occur until 23:21, well after the attack window. Tidal velocities were estimated from NOAA data as approaching 1.4 knots at peak velocity and would have decreased to approximately 1 knot after the attack took place. An important caveat to this estimate is that the entrance to Charleston harbor was reconstructed with large jetties in 1877 and the current patterns in 1864 are likely to be different from present day currents. Based on the 1000 foot distance between the two wrecks, it would take 10-13 minutes to drift this distance depending on the assumption on how fast the current reduces and the exact time of the attack. This is not compatible with the sinking timeline from the flooding estimate, which indicates that only 3 minutes are needed to submerge the vessel. The vessel would have to sink about 25 feet down in the water column after it departed the surface, however, this process would not make up for the current large time difference. If the crew was not incapacitated, they could attempt to stem the water inflow which would lead to additional time. However, there is no evidence of attempts to release the keel ballast blocks – possible from within the submarine – or escape from the vessel. Both of these would also be logical actions to take if the crew was alert and attempting to control the damage.

DISCUSSION

The discovery that the *Hunley's* weapon was operated in a short standoff mode via a fixed spar has changed the understanding of how the *Hunley's* final attack took place. While the idea that explosion-induced damage from the attack crippled the submarine seems attractive, the analysis carried out in this work does not lead to a smoking gun – indeed it perhaps leads to even more questions. In particular, it is erroneous to compare the explosion effects on *Hunley* with a modern naval weapon of similar size due to the characteristic behavior of black powder as an underwater explosive.

The initial naval architecture analysis of the vessel seems to largely track the historical record. It is reasonable to assume the vessel was initially constructed and ballasted in an iterative fashion; the vessel's final mission description fits well with the found artifacts. Based on the estimated weight, it is clear the vessel could have operated in both submarine and semi-submerged modes with reasonable ballast tank filling levels and stability. The vessel's longitudinal stability does become smaller as the vessel approaches the fully submerged condition, which would lead to the potential for large trim angles if upset. However, there is no evidence that the stability ever became critical to the safety of the vessel. Additionally, the rough resistance and propulsion model outlined again tracks well with historical data – the submarine could hit top speeds in the region of 3 knots, but for long distance transits was probably constrained to speeds near 1 knot. Such capabilities line up with the estimated speed of the final attack on the *Housatonic*, as well as Alexander's recollection that the vessel needed to plan its missions around the tidal currents. Finally, as expected, *Hunley* has very little reserve buoyancy in the reported attack position. Thus, situations which result in flooding into the vessel could become fatal very quickly.

The weapon effect analysis is also largely consistent with the historical record. *Hunley*'s torpedo was clearly strong enough to fatally damage *Housatonic* via a bubble jetting effect. Yet, owing to the long duration, low intensity pressure-pulse characteristics, the loading on the submarine was relatively slow and benign. This pressure loading and subsequent bubble-driven fluid flows would have resulted in a heaving-type motions that would not damage *Hunley*'s hull. The finite element model showed elastic stresses, which matches up with the lack of visible damage on the recovered vessel. Furthermore, the crew analysis indicates a low chance of significant human injury from the accelerations experienced during the weapon event.

The discovery of the broken ballast fill line during preservation provides a mechanism to allow flooding water to enter the vessel. While the weapon effect finite element model was too coarse to directly model the stresses in this connection, given the overall flexibility of the hull, a failure in this relatively stiff pipe run is logical. However, when experimentally tested, it is clear that the rate of water flow through this fractured connection is too high to support an unpowered drift to the vessel's final sinking location. Rough estimates of tidal current velocities indicate 10-13 minutes would be required to drift to the sinking location, while the flow through the pipe would cause the vessel to sink below the surface in less than 3 minutes.

To cover the 1000 feet in the roughly 3 minute sinking time, the submarine would have to be moving at 3.3 knots. Assuming the tidal current is supplying part of this velocity, it would be feasible for the submarine to have driven itself to the final sinking location. However, such a scenario does not match other historical evidence. Assuming the crew was able to crank the submarine, why would they choose this course of action over stemming the inflow of water or de-ballasting the submarine? Additionally, such a rapid loss scenario does not match the reported pyrotechnic signal 50 minutes after the attack. It is also possible that the pipe did not initially break in the final position it was found in. If the initial break was a smaller fracture, and the pipe further displaced as the submarine flooded and settled to the bottom, the initial flooding rate would be slower. It seems unlikely that the pipe shifted during the recovery of the submarine as the broken pipe was concreted into its found position, so any change in the pipe position would need to have occurred soon after the vessel was lost.

Thus, based on the analysis conducted to date, a simple clear-cut explanation of the loss of the *Hunley* from human incapacitation and the failed ballast line resulting from the explosion of the *Hunley's* own weapon is lacking. The weapon effects are not severe enough, and the flooding rate from the ballast fill line is too fast to make a neat story. There are several other theories that have been advanced on why the vessel was lost, including flooding through a damaged hatch tower, or that the crew simply mis-calculated their oxygen capacity and died while waiting for the tide to turn on the bottom of the seafloor. At the moment, none of these theories matches all the historical data in a simple fashion.

FUTURE WORK

Further understanding of *Hunley*'s operation and final engagement continues to be a priority. Topics of future research will include the impact of crew movement on stability that may have resulted in an unstable trim state as well as the effect of explosion noise and blunt trauma on the crew.

In addition to investigating the loss of the vessel, a clearer understanding of how the vessel operated is also worth pursuing. Understanding the vessel's technical limits may help in hypothesizing how the crew may have approached the post-attack situation. One key area of uncertainty is the ability of the vessel to move against the tidal current. Closely related to this is the vessel's endurance underwater, which would primarily be limited by the need to have sufficient oxygen for the crew to be able to continue to operate the propeller crank and vessel controls. An improved understanding of the vessel's resistance and propulsion is critical to both areas. As part of a student Master's thesis at Michigan, a 1/3 scale model of the *Hunley* has been built and is currently in testing to better understand the vessel's resistance. Ongoing work on de-concreting the vessel at the WLCC is expected to further our understanding of the vessel's propeller shape, as well as the internal propulsion gearing and other arrangements. Hopefully, in the near future, a better understanding of the power required to propel the vessel, and range and endurance available to the crew on the night of February 17th will emerge.

CONCLUSION

To examine the impact of the explosion of the *Hunley's* own weapon would have had on the vessel and its crew, a three-part analysis was carried out. First, a bottom-up naval architecture analysis of *Hunley's* loading condition, stability, and propulsive characteristics were made. This approach used standard naval architecture techniques coupled with the extensive data available from the archeological investigation of the vessel and physical testing of black powder explosions. Then, the moment of the attack was simulated using the DYSMAS software code to solve the coupled fluid-structure interaction problem governing the deflagration of black powder charge and the impact on both the target vessel and *Hunley*. These simulations were conducted using explosive modeling that has been developed from full-scale tests of a replica torpedo. Using ATD's, the impact of weapon on the *Hunley's* crew was estimated. Finally, a broken ballast fill line was examined to see if weapon-induced damage to this system could explain the loss of the vessel. Given the historical nature of the investigation, and the lack of complete information in many areas, the results here should be treated as preliminary and subjected to future refinement.

While the analysis did not lead to a clear and simple story regarding *Hunley*'s loss, several important conclusions can be drawn from this work. First, the historical record on how the vessel operated was shown to be plausible when simulated with modern hydrostatics and propulsion calculations. While these calculations, especially those related to propulsion, could be refined as more archeological data is available, the current understanding of the vessel appears consistent with a first-principles simulation of the vessel's construction, loading, and final mission. Secondly, the weapons effects analysis indicates that both the overall loading, and the potential for accelerative human injury, is low. Unlike a modern high explosive, the black powder used in *Hunley's* weapon generates a low magnitude, long-duration impulsive load. This event would have been more than sufficient to overwhelm the structure of the target vessel, the *Housatonic*, but would not have resulted in high structural stresses or accelerative loading to *Hunley* and its crew. Finally, the discovery of the broken fill line does not lead to a clear-cut loss scenario either. Via experimental testing, the flow rate through this fractured connection would be too high to support an unpowered drift of the vessel to its final resting place based on estimated tidal currents. A powered sprint to the final wreck site is possible, but hard to explain in light of other options available to the crew. Through the research reported in this project, an improved understanding of the vessel and the experience of the final attack is now possible. Despite this improved understanding, the mystery of what caused the vessel's final loss remains.

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