

# **A Forensic Investigation Of The Breakup And Sinking Of The Great Lakes Iron Ore Carrier *Edmund Fitzgerald*, November 10th 1975, Using Modern Naval Architecture Tools And Techniques**

**Sean Kery, CSC Advanced Marine Center, Washington, DC  
Ben Fisher, SAFE Boats International, Bremerton, Washington**

## **Abstract:**

The breakup and sinking of the *Edmund Fitzgerald* in November of 1975, with the loss of 29 souls, has garnered wide and enduring public interest. It has been the topic of a popular song as well as a number of television documentaries that have espoused a range of scenarios ranging from the plausible to the highly unlikely.

The focus of this paper is to develop numerical modeling methodology to investigate the breakup of a ship in heavy seas. The *Edmund Fitzgerald* provides an example that is useful in developing these tools that can then be generalized to investigate other vessels.

This paper will begin with a summary of the history of the vessel and the factual events leading up to her sinking. Next a detailed weights accounting and hydrostatic analysis that establishes the condition of the ship will be presented. The wreck lies on the bottom in two major pieces and as a confused debris field representing the middle 200 feet of the ship. An analysis of the strength of the hull girder in the locations corresponding to the established damage is presented. Several different linear and non-linear seakeeping programs have been used to study the vessels motions at various times over the voyage. These results include time histories of green water on deck as well as the primary loads on the hull girder due to wave induced stresses.

Based upon these new and state of art analyses, a new plausible scenario will be presented that takes all of the known facts into account.



**Figure 1: Photograph of Great Lakes Bulk Carrier *Edmund Fitzgerald* Intact**

Any successful modeling of this tragic sinking must produce results that are consistent with the physical evidence found on the wreckage.

**Background:**

The *Edmund Fitzgerald* was not the first, nor probably the last bulk carrier to break up and sink in heavy seas in a November gale on the Great Lakes. The *Carl D. Bradley* in 1958, and the *Daniel J. Morrell* in 1966 also broke up and sank to name a few.

The *Edmund Fitzgerald* was the first to have a song about it top the Billboard charts. Gordon Lightfoot’s poetic words and haunting guitar riffs on “The Wreck of the *Edmund Fitzgerald*” resonate with anyone who has experienced a storm at sea.

**Relevant Features of the Vessels Construction:**

The *Edmund Fitzgerald* was 729 feet long, with a beam of 75 feet and a depth of 39 feet. At 13632 gross tons, she was propelled by a 7500-hp steam turbine. The *Fitzgerald* was built in 1958 using a combination of riveting and welding, by the Great Lakes Engineering Works, River Rouge, Michigan. Seventeen at the time of her sinking is a relatively young age for Lakers where some are still active close to the 100 year mark. The riveted shear strake extended 15-3/8 inches above the weather deck, and the two vents leading into each ballast tank were 8 inches in diameter and ended 18 inches above that same weather deck. There were two similar vents 30 inches tall leading to the tunnels on each end. The tunnels were used by the crew to travel from one end of the ship to the other in bad weather.



Figure 2: Typical 30 inch Tall Deck Vent Leading into the Tunnels. Source Bob Wasalawski

Figure 3 shows the general layout of the ship. The ballast tanks were watertight compartments connected to pumps in the stern via pipes with intakes near the centerline. Note in the midship section that the main cargo hold has no watertight compartmentation. Also note that the funnel like cross section of the cargo hold concentrated the weight of the heavy iron ore towards the center.

Riveted ships built with thousands of rivets often have a few failed rivets that leave a hole open to the water outside. It is pure conjecture that the Fitzgerald was leaking before she left port but it would not be abnormal. A 1 inch hole located tens of feet below the waterline lets in hundreds of gallons per hour, but bilge pumps should be able to handle it under normal circumstances.

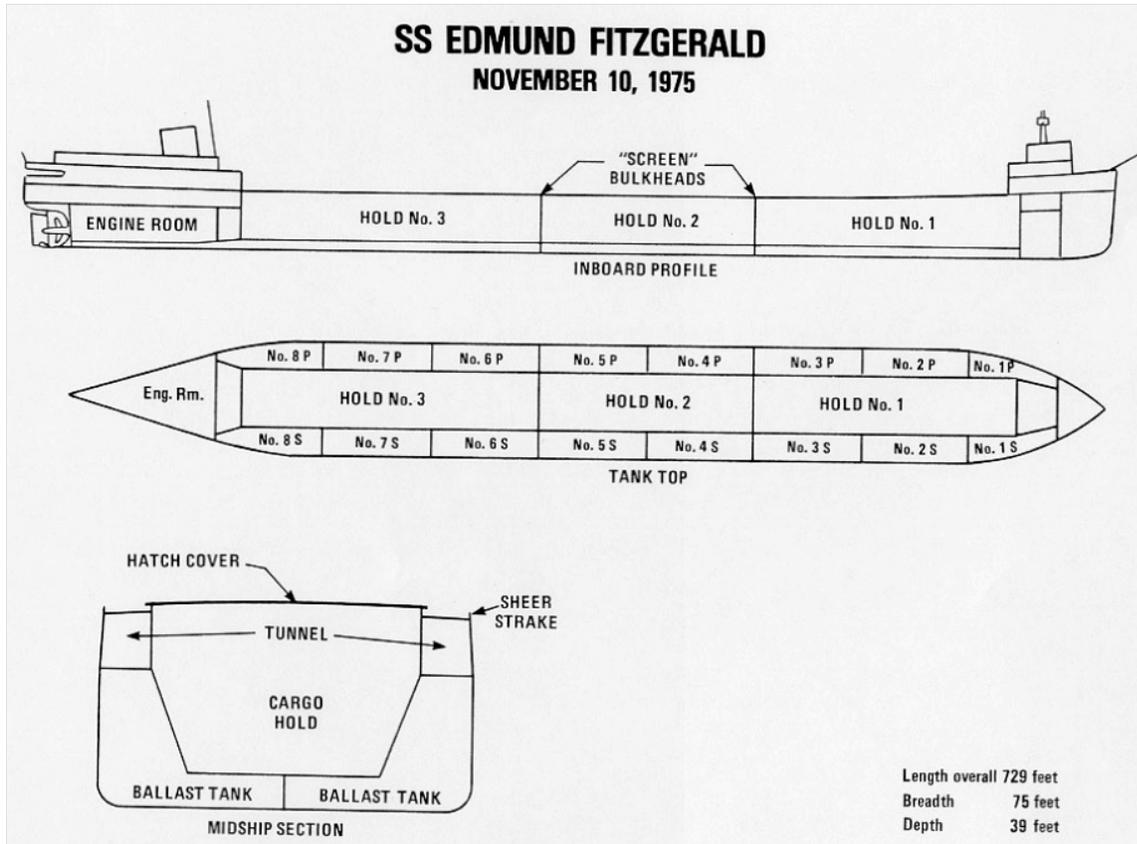
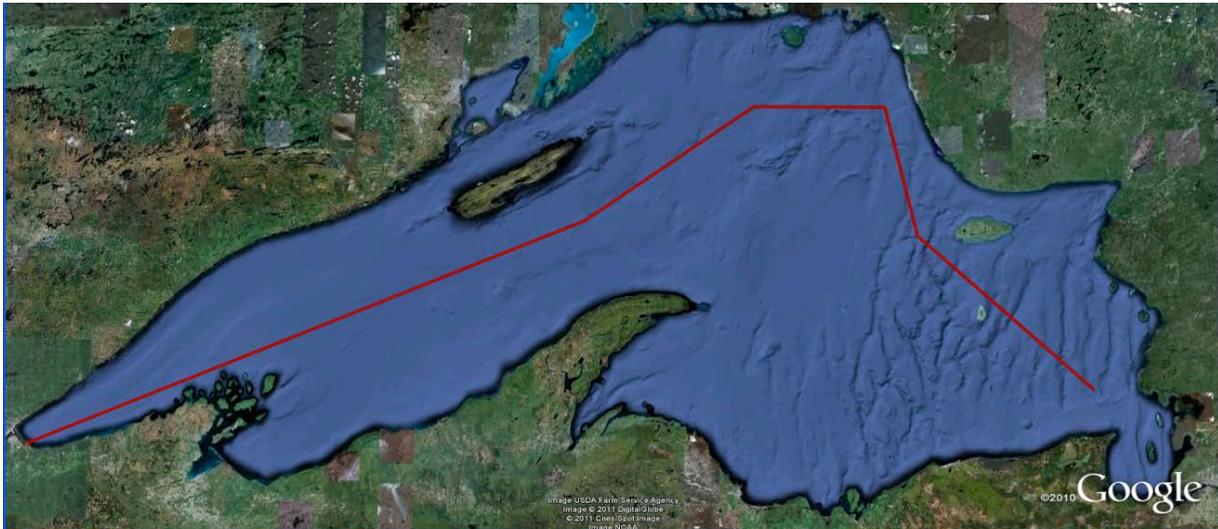


Figure 3: Simplified General Arrangement Sketch of the Edmund Fitzgerald

## FINAL VOYAGE

The *Edmund Fitzgerald* departed the port of Superior, Wisconsin, in the early afternoon of November 9, 1975, under the command of veteran captain Earnest J McSorley. She was loaded with 26,116 long tons of taconite pellets. She was downbound for Zug Island, near Detroit. Near Two Harbors, Minnesota she encountered another Iron Ore Carrier, the *Arthur M. Anderson*, captained by Jesse "Bernie" Cooper, also downbound. Around 0200 November 10 the two captains conferred by radio about the weather forecasts, which predicted storm conditions, and agreed that the best course of action would be to travel together along the northern route, hugging the Canadian shore, rather than proceeding along the normal shipping lanes, which hug the north shore of Michigan's Upper Peninsula. The probable trackline of the *Fitzgerald* is shown in Figure 4.



**Figure 4 Probable Course of S.S. Edmund Fitzgerald, November 9–10, 1975**Source: B. Fisher, Developed from Ramsay (2009)

The first part of the trip was relatively uneventful as the developing storm approached Lake Superior. Seas began building throughout the morning of November 10, and at around 1445 it started snowing, causing the crew of the *Anderson* to lose visual contact with the *Edmund Fitzgerald*.

At around 1530 on November 10, McSorley radioed Cooper to inform him that the *Fitzgerald* had taken damage and “had a list”. The ship had lost two of the deck vents used as ventilation for the ballast tanks and under-deck tunnel, and also had lost a section of the “fence rail” that was a wire rope handrail that ran along both sides of the weather or spar deck. The cause and additional extent of this damage remains unknown, along with the exact location of the vessel when the damage occurred. The *Anderson* asked the *Fitzgerald* if the pumps were going and the reply was “Yes both of them”. This indicates that water was already coming in somewhere, although how much and where remain unknown. That the pumps were going also suggests that the list was not so bad that the water was prevented from reaching the pump intake plumbing on the centerline.

McSorley radioed Cooper again at 1610 and informed him that, in addition to the damage already sustained, both of the *Fitzgerald*'s radars were no longer operational; he asked Cooper if he would provide navigational assistance. Between 1700 and 1730, the *Fitzgerald* had a radio conversation with Captain Woodard, pilot aboard the saltwater vessel *Avafors*, which was upbound near Whitefish Point. During this conversation McSorley informed Woodard that he had developed a, “bad list,” that his radar was not working, and that he was taking heavy seas over his deck. McSorley spoke to someone aboard the *Fitzgerald* while the mike was still open and the *Avafors* heard him say, “Don’t allow nobody on deck” followed by some conversation concerning a vent that was not understood aboard the *Avafors*. (NTSB Report 1978)

The last radio contact with the *Fitzgerald* occurred at 1910. At the end of the radio conversation, which was between the *Anderson* and the *Fitzgerald*, the mate on the *Anderson* asked how

McSorley was making out with his problems. McSorley's response, and the last contact from the *Fitzgerald*, was "We're holding our own."

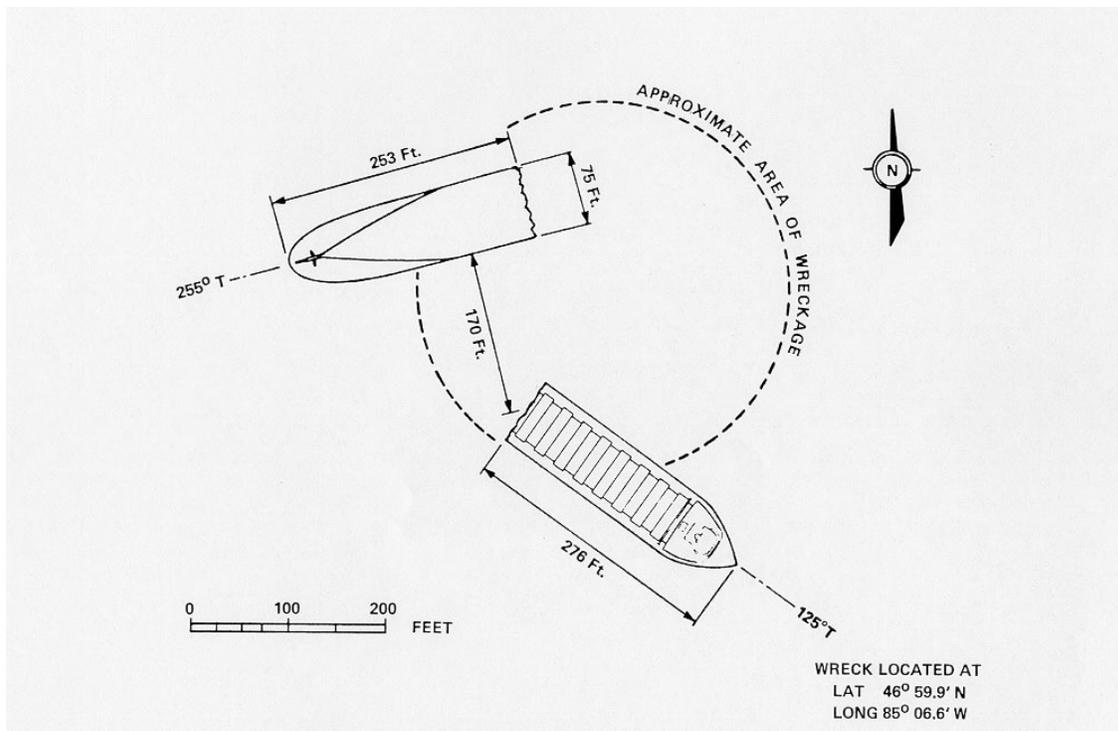
### **Search Operations**

Around 1920 the *Anderson*'s radar was checked, but there was no "blip" where the *Fitzgerald* should have been. Visibility had improved greatly by this time, and lights on the Canadian shoreline could be seen 20 miles away, in addition to the lights of the upbound vessels of which the *Fitzgerald* had been informed. However, the *Fitzgerald*'s lights, which should have been closer, were not visible. Finally, repeated attempts to contact the ship by radio were unsuccessful. Captain Cooper immediately called the Coast Guard station at Sault Ste. Marie, Michigan, and informed them of the suspected loss of the ship.

The Coast Guard launched an extensive search-and-recovery effort, even asking freighters in the area either to come about or to alter course to search the last known position of the *Fitzgerald*. No evidence of the ship or her crew was discovered until early November 11. The morning light revealed a large oil slick and one half of one of the ship's two lifeboats. The entirety of the second lifeboat, mangled by the sinking action, as well as inflatable rafts, life jackets, life rings, a sounding board, and various other pieces of debris were recovered or found washed up on the Canadian shore in the days following the by-then confirmed sinking. The search was called off officially on November 13. None of the crew was found (Department of Transportation, 39–46).

### **Wreck Site Survey**

On November 14, 1975, an aircraft fitted with a magnetic-anomaly detection unit discovered the probable location of the wreck, and the buoy tender *Woodrush* immediately followed with a side scan-sonar survey of the location, which indicated the presence of two large objects on the lake floor. In May of 1976 the buoy tender *Woodrush*, equipped with the Navy ROV CURV III, conducted an underwater survey of the objects discovered. The first dive identified the objects as the *Fitzgerald*'s wreckage and discovered that the stern was upside-down on the lake bottom. The next 11 dives revealed the nature of the wreck: the ship lies in two major pieces on the bottom, with large amounts of debris between the sections. The stern section is in good condition but is upside-down. The bow section is lying nearly perpendicular to the stern but is upright with a 15 degree list to port. Approximately 200 feet of the ship lies in pieces scattered throughout the debris field, along with the cargo of iron ore, which is distributed over the area of the wreckage. There is extensive damage to the bow section of the wreck, indicating a very-rapid sinking that involved a violent impact of the bow section with the lake bottom. The Coast Guard found that most of the hatch covers for the visible hatches were not secured to the combings, with some showing signs of collapse. Most of the clamps that secured the hatch covers to the combings were found undamaged. Additionally, no evidence of grounding damage was found on the exposed underbody of the stern section (Department of Transportation, 51–55). Coast Guard drawings of the wreck site and the two major sections are shown in Figures 5–8.



**Figure 5: Layout of *Edmund Fitzgerald* Wreckage Source: National Transportation Safety Board (1978)**

**Review of the damage recorded on the wreckage:**

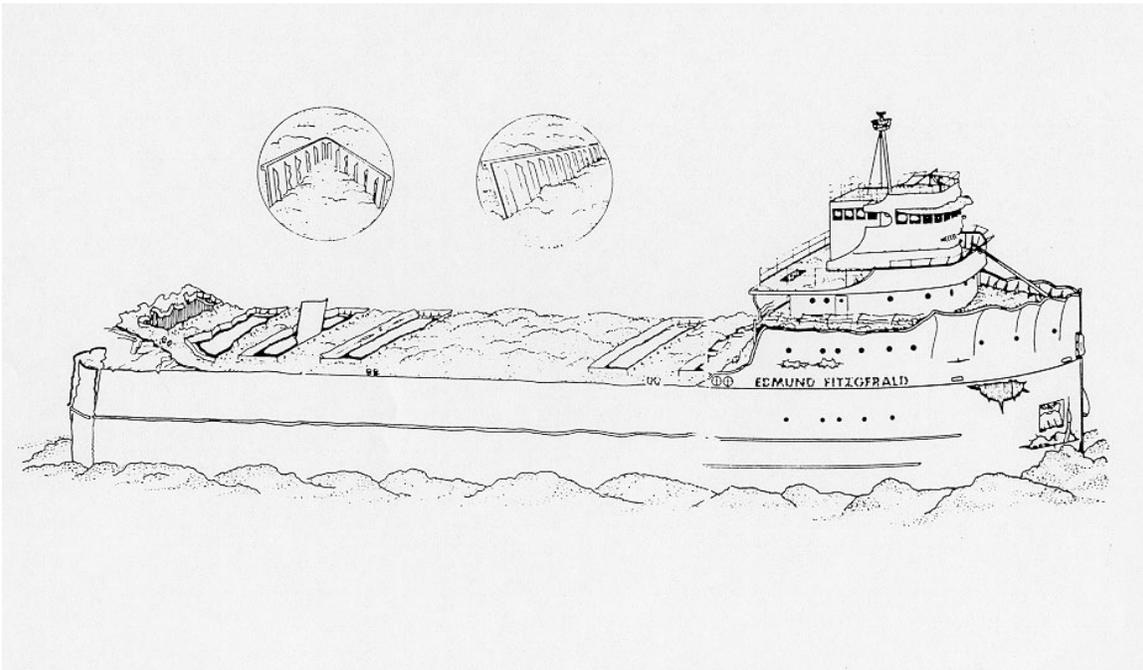
A representative number of the ship's original drawings were located at Bowling Green State University in Bowling Green, Ohio. These were used in concert with the Coast Guard reports and discussions with several people (Detweiller, 2010, Wasalaski, 2011) who have taken part in some of the several official visits to the wreckage to try to pinpoint the damage and figure out the likely order of the failure cascade. The radio messages from Captain McSorley and the condition of the wreckage, speaks of a succession of failures that eventually added up to the final sinking.

The number one and number two hatch covers located directly behind the forward house are punched down inside the hold. The sun visor surrounding the top of the pilot house is mangled and severely bent downwards. The radar antenna located on the top of the forward house is broken. Figure 6. The fracture pattern is consistent with a large volume of wind-blown green water crashing down on it. Given the snowstorm, high winds and fresh water spray, the radar antenna and much of the superstructure could have been encased in ice. Severe icing would provide additional area for the green water to act on.



**Figure 6:**

All but two of the rectangular windows on the back of the forward house have their glass blown inwards.



**Figure 7: Bow Section of Edmund Fitzgerald Wreck Source: National Transportation Board (1978)**

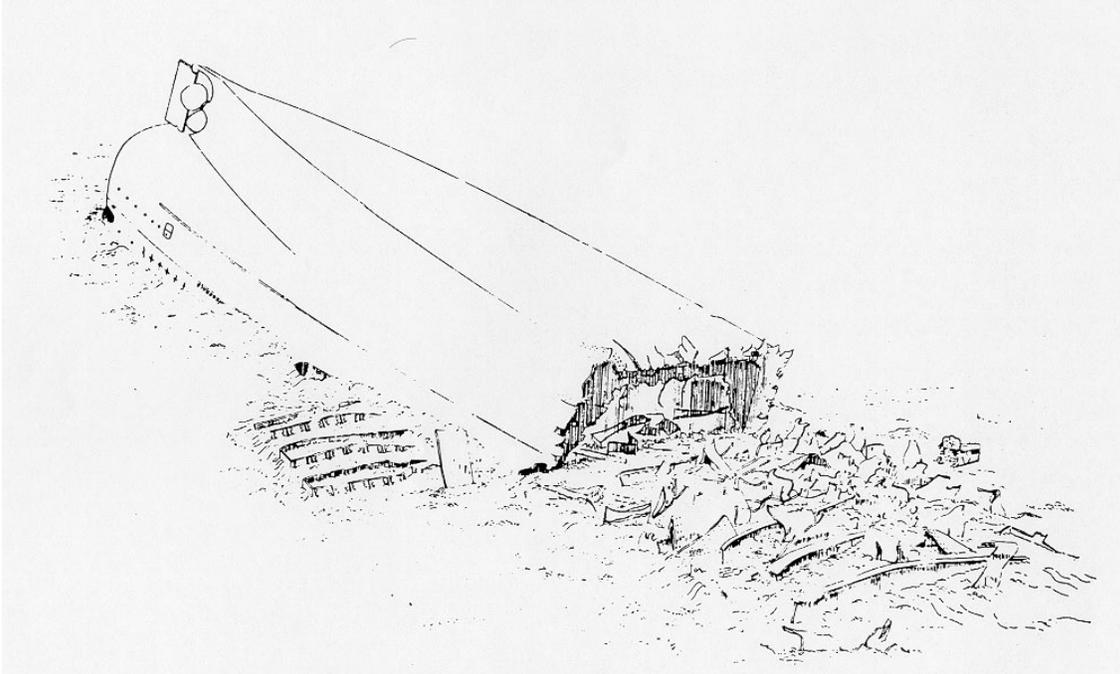


**Figure 8: Broken Rectangular Windows on Back of Forward House Source Bob Waslawski**

There is damage on the forward bow which is consistent with a possible hydrostatic implosion of a watertight compartment as the bow section descended in the water column. Much of the main deck is covered in a thick layer of taconite pellets. This indicates that the bow section reached the bottom before the cloud of taconite pellets that fell out of the various sections of the hold rained down around and on top of it.

There is no coating of taconite pellets on top of the largely intact stern which suggests that it may have floated for some minutes before sinking or that it may have contained enough trapped air inside watertight compartments to achieve a relatively slow terminal velocity compared to the taconite pellets.

The Vessel was last inspected by ABS and the US Coast Guard on October 31<sup>st</sup>, 1975, just 10 days before her sinking. Four minor structural defects were noted around the number 13, 15, 16 and 21<sup>st</sup> (aft most) hatch covers. They were scheduled to be welded up after this trip while the ship was laid up for the winter. The NTSB report attributes these to cargo handling, but some of them may also have been due to fatigue from the ship working in a normal seaway and the right angle hatch corners would have contributed a large stress concentration factor at the hatch corners.



**Figure 9: Stern section of Edmund Fitzgerald Wreck Source: National Transportation Safety Board (1978)**

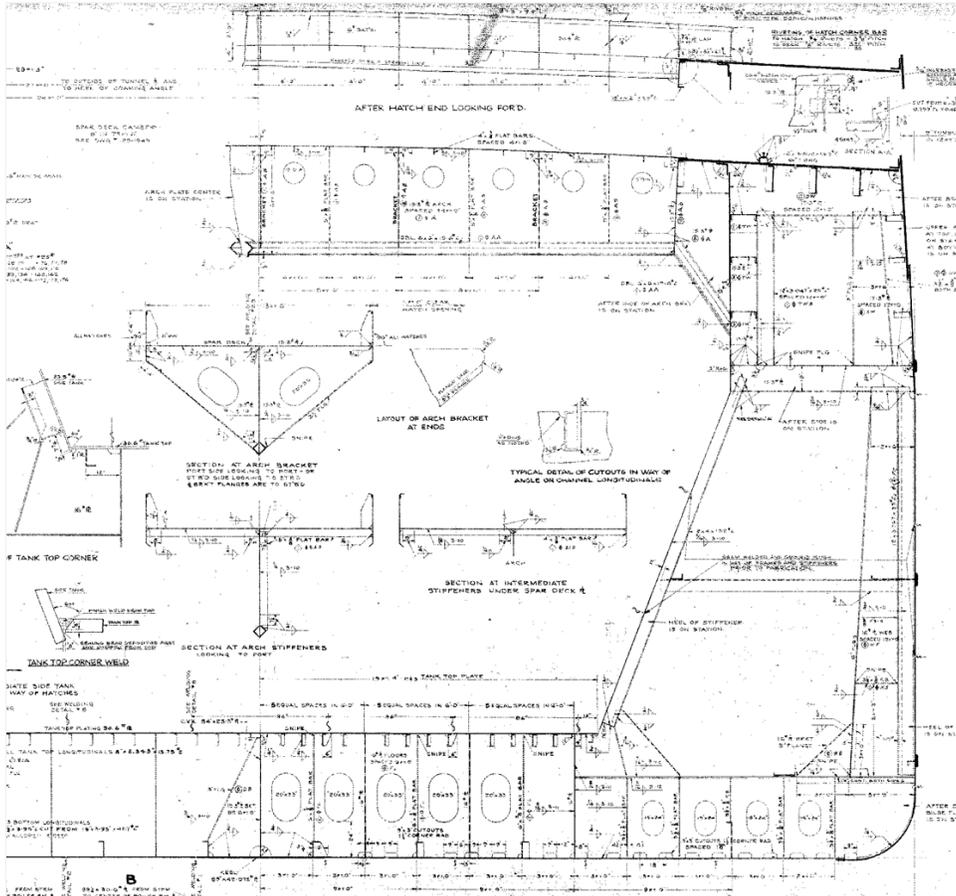
A number of sources have claimed that the *Fitzgerald* was damaged by running over a “6 fathom shoal”. There is no sign of grounding damage to the exposed stern section, which would be deepest in the water under normal conditions. She left the dock with final drafts of 27 feet, 2 inches forward and 27 feet, 6 inches aft. (NTSB 1978) Note that 6 fathoms is 36 feet, so the *Fitzgerald* would have passed over a “6 fathom shoal” with 8-1/2 feet to spare. A new more precise hydrographic survey of the area traversed by the *Fitzgerald* found that the 6 fathom shoal did not actually exist, but was rather an error on the earlier charts. The Coast Guard report and associated documents prove that there was no shoal water within 3 miles of the track of the *Fitzgerald* and therefore no damage due to grounding. However the popular media continues to push the discredited grounding theory.

### **Summary Description of the Analyses Performed:**

The analyses progressed over a number of years and include many different parts that combine to build a fairly comprehensive picture of the events.

- A careful analysis of the cargo loading by George Edwards showed how the cargo of taconite pellets would have had to be loaded to provide the draft readings recorded in the NTSB report.
- Edwards presented findings at the SNAME Annual Meeting in 2009 that showed that the ballast tank mushroom vents could act as a siphon to drain water trapped behind the 15 3/8 inch tall shear strake, down into the ballast tanks.
- Ben Fisher used Edwards analysis and drawing copies purchased from Bowling Green State University to develop a more detailed weights budget for the total vessel. This included all of the big weight items such as engines, boilers,

winch, cargo etc. The roll and pitch gyradii were developed from this information.



**Figure 10: Midships Section Drawing, (Similar to the *Fitzgerald* but may be from Sistership the *Arthur B. Homer*)**

- Fisher also studied the hull girder design and developed the maximum design bending loads.
- Fisher also provided a progressive flooding analysis based on the most probable damage and failure cascade.
- Kery developed the storm conditions, ships location, heading and damage condition from a variety of sources.
- The CG and Gyraadi were used by Kery to build hydrodynamic models of the vessel operating in waves in WASIM and in Orcaflex.
  - WASIM was used to develop both linear frequency domain RAOs and in a non-linear model to produce time series motions including primary loads and green water on deck.
  - The Orcaflex model used RAOs developed in WASIM to produce time series simulations where the waves and ship motions could be visualized.
  - The Primary loads were compared to Fisher’s strength model and the wave induced bending moment was compared to the hull girder section

modulus to determine probabilities of low cycle high stress fatigue versus over stress fracture.

- Both Edwards and Kery independently calculated the terminal velocity of taconite pellets, and estimated the time it would take to reach bottom in 530 feet of fresh water. This is useful in estimating the time from the ship breaking up on the surface and the bow reaching the bottom fast enough that the taconite pellets could land on top of it as observed on the wreck site.

### Reconstructing a Killer Storm

The first step was to establish a timeline of storm and vessel conditions. This supported the seakeeping and progressive damage and flooding analyses by providing the significant wave height, modal period wave direction, and ship flooding condition as the voyage developed.

The timeline was developed using several sources of information. The first was a weather hindcast for the storm developed by the National Weather Service in 1998. This paper detailed the wind and subsequent wave conditions over the life of the storm. These data were then confirmed using the USCG and NTSB accident reports, both of which detailed weather observations reported by both the *Fitzgerald* and the *Anderson*.

The vessel speed and heading was determined using the USCG or NTSB accident reports. This information was used to determine the wave direction relative to the ship. The vessel's condition (intact or listing) was also taken from the accident reports. Finally, data from a hydrostatic analysis of each vessel condition, including displacement, center of gravity, trim, list, and radii of gyration, were recorded on the timeline. This allowed for initial conditions to be established for any desired seakeeping run. The final stage of the timeline also provided the initial conditions of the progressive flooding model developed for this analysis. The development of the hydrostatic analyses is outlined in the next section. Table 1 below shows the conditions that were analyzed.

**Table 1: Storm and Vessel Timeline**

| <b>Time<br/>Nov.<br/>10</b> | <b>Wind<br/>Speed</b> | <b>Wind.<br/>Dir.</b> | <b>Wave<br/>Dir.</b> | <b>H<sub>1/3</sub></b> | <b>Fitz<br/>Course</b> | <b>Rel. Wave<br/>Dir.</b> | <b>Fitz<br/>Speed</b> |
|-----------------------------|-----------------------|-----------------------|----------------------|------------------------|------------------------|---------------------------|-----------------------|
| <b>(EST)</b>                | <b>kts</b>            | <b>Deg T</b>          |                      | <b>m</b>               | <b>deg T</b>           | <b>Deg</b>                | <b>kts</b>            |
| <b>0700</b>                 | <b>35</b>             | <b>050</b>            | <b>NE</b>            | <b>3</b>               | <b>060</b>             | <b>190</b>                | <b>14.2</b>           |
| <b>1430</b>                 | <b>30</b>             | <b>315</b>            | <b>NW</b>            | <b>5</b>               | <b>144</b>             | <b>009</b>                | <b>11.4</b>           |
| <b>1600</b>                 | <b>39</b>             | <b>304</b>            | <b>NW</b>            | <b>6</b>               | <b>139</b>             | <b>015</b>                | <b>10.3</b>           |
| <b>1910</b>                 | <b>50</b>             | <b>300</b>            | <b>WNW</b>           | <b>7</b>               | <b>139</b>             | <b>019</b>                | <b>10.3</b>           |

The Great Lakes typically freeze over in the winter so the NOAA / NDBC wave and weather buoys are recovered and stored on land from early November until ice out in the spring to prevent them from being destroyed. As a result, there is little or no high quality wave data available for the area in which the *Edmund Fitzgerald* went down, in the right season of the year. Four sources of information were used to estimate the storm conditions as closely as possible.

**Table 2: Significant Wave height vs Modal Period in Lake Superior (Pore 1970)**

| Period<br>Seconds              | Wave Height in Meters |             |             | Lake Superior, All data 1960 through 1969 |             |             |            |            |            |           |           |           |          |          |          |          | Count | Percent      |            |
|--------------------------------|-----------------------|-------------|-------------|---|-------------|-------------|------------|------------|------------|-----------|-----------|-----------|----------|----------|----------|----------|-------|--------------|------------|
|                                | 0                     | 0.5         | 1           | 1.5                                       | 2           | 2.5         | 3          | 3.5        | 4          | 4.5       | 5         | 5.5       | 6        | 6.5      | >6.5     |          |       |              |            |
| <= 5                           | Count                 | 1288        | 3122        | 3147                                      | 1531        | 371         | 169        | 78         | 31         | 10        | 1         | 4         |          |          |          | 2        | 9754  | 46.00497     |            |
|                                | percent               | 7.395       | 17.926      | 18.070                                    | 8.791       | 2.130       | 0.970      | 0.448      | 0.178      | 0.057     | 0.006     | 0.023     |          |          |          | 0.011    |       |              |            |
| 6                              | Count                 | 8           | 187         | 726                                       | 868         | 330         | 159        | 94         | 45         | 13        | 7         | 3         | 1        |          |          |          | 2441  | 14.01585     |            |
|                                | percent               | 0.046       | 1.074       | 4.169                                     | 4.984       | 1.895       | 0.913      | 0.540      | 0.258      | 0.075     | 0.040     | 0.017     | 0.006    | 0.000    | 0.000    | 0.000    |       |              |            |
| 8                              | Count                 | 1           | 24          | 145                                       | 260         | 177         | 99         | 54         | 20         | 12        | 10        | 2         |          |          |          | 2        | 1     | 807          | 4.63367    |
|                                | percent               | 0.006       | 0.138       | 0.833                                     | 1.493       | 1.016       | 0.468      | 0.310      | 0.114      | 0.069     | 0.057     | 0.011     | 0.000    | 0.000    | 0.011    | 0.006    |       |              |            |
| 10                             | Count                 | 2           | 12          | 43  | 83          | 53          | 53         | 33         | 19         | 10        | 4         | 1         | 1        | 2        |          |          |       | 316          | 1.814424   |
|                                | percent               | 0.011       | 0.069       | 0.247                                     | 0.477       | 0.304       | 0.304      | 0.189      | 0.109      | 0.057     | 0.023     | 0.006     | 0.006    | 0.011    | 0.000    | 0.000    |       |              |            |
| 12                             | Count                 | 3           | 5           | 11  | 21          | 34          | 23         | 11         | 11         | 2         | 1         |           | 1        | 1        |          |          |       | 124          | 0.711989   |
|                                | percent               | 0.017       | 0.029       | 0.063                                     | 0.121       | 0.195       | 0.132      | 0.063      | 0.063      | 0.011     | 0.006     | 0.000     | 0.006    | 0.006    | 0.000    | 0.000    |       |              |            |
| 14                             | Count                 | 0           | 8           | 4   | 8           | 7           | 19         | 2          | 8          | 3         | 5         |           |          |          |          |          |       | 65           | 0.37322    |
|                                | percent               | 0.000       | 0.046       | 0.023                                     | 0.046       | 0.040       | 0.109      | 0.011      | 0.046      | 0.017     | 0.029     | 0.000     | 0.000    | 0.000    | 0.006    | 0.000    |       |              |            |
| 16                             | Count                 | 0           | 3           | 6   | 3           | 2           | 6          | 4          | 3          | 2         | 1         |           |          |          |          |          |       | 30           | 0.172255   |
|                                | percent               | 0.000       | 0.017       | 0.034                                     | 0.017       | 0.011       | 0.034      | 0.023      | 0.017      | 0.011     | 0.006     | 0.000     | 0.000    | 0.000    | 0.000    | 0.000    |       |              |            |
| 18                             | Count                 | 0           | 1           | 1   | 1           | 3           | 1          | 1          | 1          |           |           |           |          |          |          |          |       | 7            | 0.040193   |
|                                | percent               | 0.000       | 0.000       | 0.000                                     | 0.006       | 0.006       | 0.017      | 0.006      | 0.006      | 0.000     | 0.000     | 0.000     | 0.000    | 0.000    | 0.000    | 0.000    |       |              |            |
| 20                             | Count                 | 1           | 2           | 5   |             |             |            | 1          |            | 2         |           |           |          |          |          |          |       | 11           | 0.06316    |
|                                | percent               | 0.006       | 0.011       | 0.029                                     | 0.000       | 0.000       | 0.000      | 0.006      | 0.000      | 0.011     | 0.000     | 0.000     | 0.000    | 0.000    | 0.000    | 0.000    |       |              |            |
| >21                            | Count                 | 11          | 6           | 9   | 3           |             |            |            |            |           |           |           |          |          |          |          |       | 29           | 0.166514   |
|                                | percent               | 0.063       | 0.034       | 0.052                                     | 0.017       | 0.000       | 0.000      | 0.000      | 0.000      | 0.000     | 0.000     | 0.000     | 0.000    | 0.000    | 0.000    | 0.000    |       |              |            |
| Calm or<br>Period not recorded | Count                 | 2212        | 477         | 605                                       | 315         | 118         | 54         | 32         | 11         | 4         | 2         | 1         | 1        |          |          |          |       | 3832         | 22.00276   |
|                                | percent               | 12.701      | 2.739       | 3.474                                     | 1.809       | 0.678       | 0.310      | 0.184      | 0.063      | 0.023     | 0.011     | 0.006     | 0.006    | 0.000    | 0.000    | 0.000    |       |              |            |
| <b>Total</b>                   | Count                 | <b>3526</b> | <b>3846</b> | <b>4701</b>                               | <b>3093</b> | <b>1093</b> | <b>585</b> | <b>309</b> | <b>150</b> | <b>56</b> | <b>33</b> | <b>11</b> | <b>4</b> | <b>3</b> | <b>3</b> | <b>3</b> |       | <b>17416</b> | <b>100</b> |
|                                | percent               | 20.24575    | 22.08314    | 26.99242                                  | 17.75953    | 6.275838    | 3.35898    | 1.774231   | 0.861277   | 0.321543  | 0.189481  | 0.06316   | 0.022967 | 0.017226 | 0.017226 | 0.017226 |       |              |            |

Pore 1970 published a compilation of significant wave height and modal period data from Ship observations from 1960 through 1969. The table for all of Lake Superior for all year long (table 2) shows 12 storms with waves higher than 5 meters in this 9 year period. These sorts of ship observations are biased by weather routing and underreporting of severe wave conditions because the crew neglects to make notes when it gets really rough.

Hultquist, Dutter & Schwab 2006, from the NOAA National Weather Service recreated the storm using modern modeling tools and the isobars and winds recorded during the storm at various locations around the Lake on land. They predict a significant wave height of 7.9 meters but offered no guidance on the modal period. Pores table shows that the worst storms had a modal period of around 8 seconds.

Ochi 2003 describes the rise of waves from severe storms such as the tropical storm force winds estimated at 50 to 80 miles per hour that raised the *Fitzgerald* Storm. The waves are typically rising and are well below the fully developed condition for that wind speed. This forces steep waves and shorter periods than if the seas were fully developed.

Walden & Hoffman show spectra taken near Deer Park on Lake Superior in 24 foot significant wave height. The modal period in this storm was on the order of 7.5 seconds.

Based upon these references and the fetch limited basin and rapid rise of this storm, the WASIM analyses focused on 7.5 to 9 second modal periods at a 7.9 meter significant wave height and a JONSWOP type wave spectrum. The JONSWOP spectrum was developed for the North Sea which is a similar fetch limited basin with steeper than

normal waves. By the time the *Fitzgerald* and the *Anderson* make their turn southward the waves and winds were coming from about 20 degrees off the following sea condition.

### **Assumptions Made to Support the Analyses**

Several assumptions were necessary to support analysis of the sinking of the *Edmund Fitzgerald*.

1. The Analysis was made in the Full Load Departure Condition assuming the fuel used at the time of sinking was inconsequential to the overall weight distribution.
2. The reported list was to starboard.
  - The wind and wave directions as the ship passed Caribou Island were from the northwest, meaning that any debris in the water striking the ship would most likely have hit the starboard side.
  - Captain McSorley mentioned that two vents had been lost or damaged. There is at least one damaged vent on the bow section of the wreck, located on the starboard side near hatches 4 and 5. This is very possibly one of the vents to which McSorley had referred.
  - The rudder on the wreck is offset slightly to port as would be necessary to steer a straight course with a starboard list. Rudder angles on wrecks can be misleading as the direction may have changed in the course of the sinking due to unknown reasons.
3. Two ballast tanks were assumed to have been flooded, since two slowly-filling ballast tanks would have resulted in a “list” at 1530 and a “bad list” at 1730. The two tanks selected were Ballast Tanks 2 and 3 on the starboard side of the vessel. These tanks were chosen because of their proximity to the damaged vent, which is near the boundary between these two tanks.
4. Assume that the permeability of taconite is 0.60, and that the permeability of hold space not occupied by taconite is 0.95. These values are based on U.S. Code of Federal Regulations (CFR) Title 46, Subchapter S, Part 172, Subpart H: Special Rules Pertaining to Great Lakes Dry Bulk Cargo Vessels.
5. The sinking began with the collapse of the Number one and possibly number two hatch covers just aft of the forward house. There are two reasons for assuming the collapse of this particular hatch cover.
  - The waves were boarding the vessel from the stern starboard quarter, advancing down the length of the spar deck, and striking the forward deckhouse. This caused a piling effect as the waves reflected from the deckhouse. The piling effect occurred primarily over the number 1 hatch cover right behind the forward house and to a lesser extent the number 2 hatch cover. The hatch covers were designed to withstand up to four feet of hydrostatic water head without buckling; however, this piling effect could have doubled or tripled the rated hydrostatic loading even without taking into effect dynamic events such as wave breaking. This indicates a high probability of hatch-cover collapse.

- The number 1 & 2 hatch covers were found within the hull of the bow section of the wreck. The hatch cover shows signs of exterior buckling, and the state of the hatch combing indicates hatch-cover buckling.

### **Weight Distributions**

The weights analysis began with the longitudinal weight distribution, followed by the transverse and vertical weights analyses. These were necessary to determine the actual CG and the roll and pitch gyradii of the vessel to support the loading and seakeeping analyses. The cargo longitudinal weight distribution developed by Edwards was refined and analyzed by the General Hydrostatics (GHS) computer model.

The determination of the radius of gyration in roll, (aka roll gyradius) requires both the lateral and the vertical locations of the significant weight items to be developed.

The new distribution was based on a weight distribution for the Great Lakes steamer *Arthur B. Homer*, which was a near-identical sister to the *Edmund Fitzgerald*. However, the weight distribution available was tabulated for the *Homer* after she had been lengthened by 96 feet. Therefore, the distribution was corrected to represent the vessel in the as-built condition, to match the *Fitzgerald*.

There were two steps involved in this process. The first step was to correct the LCG of each of the weight items to match the vessel's original length. Since the weight item LCG's were measured from the vessel's stern, each value for LCG aft of amidships remained the same, and values of LCG forward of amidships were reduced by 96 feet.

The second step was to correct the total weight of continuous-weight items within the vessel's parallel midbody, where the lengthening had occurred. These continuous-weight items included structure and piping. The result of these corrections is a weight distribution that is a fair representation of the *Fitzgerald*'s. This was verified by comparing the shapes of the original distribution with the corrected distribution.

The next step was to determine the TCG and VCG of each item from the GA drawing. The VCG of the cargo distribution was determined in a separate calculation by using the weight-per-volume of taconite specified in the NTSB accident report to determine the volume of cargo underneath each hatch opening. The next step was to match these volumes by multiplying the length of each section of cargo underneath a hatch by the cross-sectional area of the cargo distribution at that location.

Because the cross-sectional area of the cargo hold is height dependent, a table of heights within the hold, cross-sectional areas of the hold, centroids of area, and the second moments of area about their centroids was developed. This table was used to determine the height of the cargo pile in each section of the hold. The process was checked by multiplying the total calculated cargo volume by the weight per volume of taconite and comparing with the known weight of the vessel's cargo. The comparison showed the process to be valid, as the cargo weight determined by the process differed by only 11 LT from the known cargo weight, an error of only 0.04%. The centroid of area that

corresponded to the determined height was taken to be the cargo pile VCG. The TCG of the cargo was assumed to fall on centerline.

### Calculation Of Radii Of Gyration Of The Vessel

The next step of the analysis was to determine the *Fitzgerald's* radii of gyration for the seakeeping analysis. The pitch and roll radii of gyration were calculated. The yaw radius of gyration was assumed to be the same as the pitch radius of gyration.

The pitch radius of gyration was calculated using the weight distribution developed by Edwards. This distribution includes discrete weights as well as a longitudinal distribution of the weight of hull steel and cargo.

The roll radius of gyration was calculated using the itemized weight distribution developed from documentation of the *Fitzgerald* and her sister ship *Arthur B. Homer*.

**Table 3: Intact Radii of Gyration Results**

|              | <b>Gyradius</b> | <b>%Length or Beam</b> |
|--------------|-----------------|------------------------|
| <b>Pitch</b> | <b>183.9 ft</b> | <b>25.9%</b>           |
| <b>Roll</b>  | <b>19.58 ft</b> | <b>26.1%</b>           |

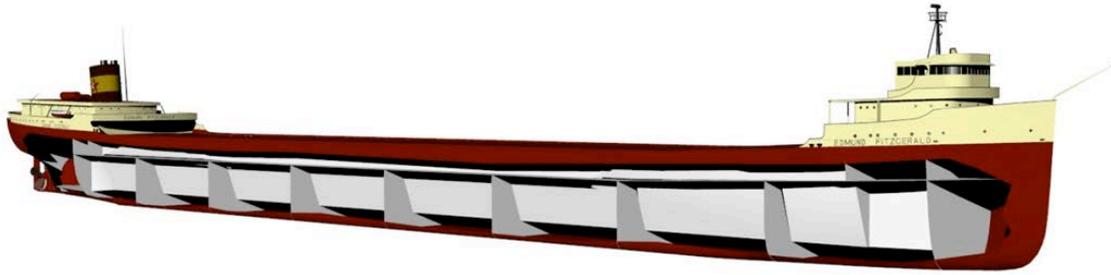
The value for the pitch radius of gyration was consistent with values for similarly-sized Great Lakes vessels. The value for the roll radius of gyration, however, seemed at first to be incorrect, as typical values for roll radii of gyration for ships range between 30% and 40% of beam. Careful checking confirmed that the smaller than usual roll gyradius is due to the funnel like shape of the cargo hold, concentrating most of the weight close to the centerline.

### Developing Hydrostatic Analyses

Once the weight distribution and vessel conditions had been established, they were used to develop the hydrostatic analyses. This process was broken into two stages. The first stage was to develop the internal geometry model of the vessel. The second stage was to perform the hydrostatic analysis of each condition.

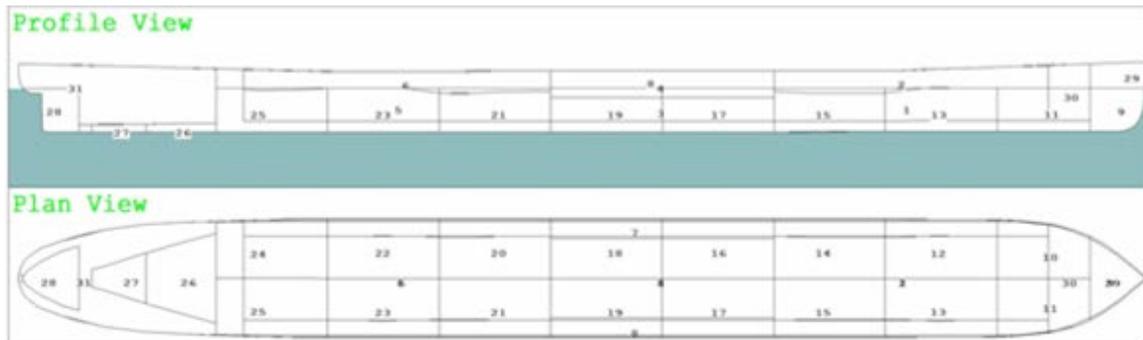
### Modeling Internal Geometry

The model of the hull and its internal geometry was developed based on copies of original drawings of the vessel acquired from Bowling Green University. The hull was developed based on the vessel body plan, and the internal watertight geometry was developed based on the vessel general arrangement drawing. The hull and subdivision model was first developed using Rhinoceros (Rhino), a three dimensional NURBS surface modeling program. This model was then imported into GHS. The Rhino model developed is shown in Figure 11.



**Figure 11: Rhino Model of Internal Geometry**

Figure 11 shows the arrangement of most of the internal geometry. Only watertight boundaries were modeled. At the forward end of the vessel is a forepeak tank with the forward windlass room above the forepeak. Aft of the forepeak, amidships, is the forward crew space with the forward end of the Number 1 ballast tank outboard. Aft of the forward crew spaces, amidships, is the cargo hold. Outboard of the cargo hold are eight L-shaped ballast tanks numbered from 1 at the forward end to 8 at the aft end. Above the ballast tanks outboard of the cargo hold is an under deck tunnel that provides access from the forward spaces to the aft end of the vessel. Aft of the cargo hold is the engine room. Below the engine room are double bottom ballast tanks 9 and 10. At the very aft end of the vessel is an aft peak tank. The corresponding GHS geometry model is shown in Figure 12.



**Figure 12: GHS Internal Geometry**

One of the difficult aspects of modeling the internal geometry was the cargo hold and its contents. The cargo hold of the vessel contained no watertight subdivision along its length; however, the hold was divided into three sections by way of two non-watertight screens. This allowed for variable loading of cargo, which presents a second problem—the cargo distribution of the vessel was not uniform over the length of the cargo hold, nor did it occupy the entire volume of the cargo hold. With these issues in mind, the cargo hold was modeled using six GHS tanks. Three were designated as cargo, and three represented the void spaces above the cargo. The GHS tanks were divided longitudinally at the locations of the screens. The permeability of the cargo was taken as 0.6, and the permeability of the void spaces was taken as 0.95.

### **Analyzing Timeline Conditions**

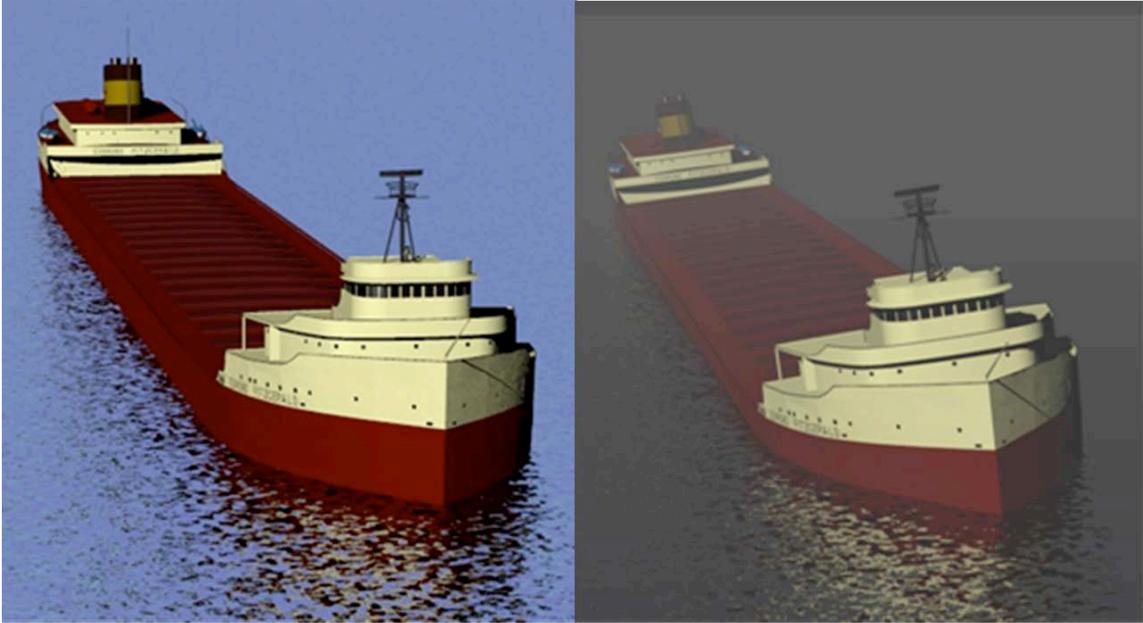
With the geometry developed, each vessel condition in the timeline was analyzed. For intact conditions, the full-load condition at departure was used. In addition to the intact

conditions, two damaged conditions were analyzed. The first was an intermediate condition that assumed a 4-degree list to starboard, representing the list experienced at 1530 and reported by Captain McSorley. To represent this condition in the hydrostatic analysis, Ballast Tanks 2 and 3 on the starboard side were assumed to be about 64% full. The flooding was modeled using the added weight assumption in order to obtain an intermediate stage of flooding. The second damaged condition represented the condition of the ship at 1910, just prior to her foundering. For this condition, ballast tanks 2 and 3 on the starboard side were filled to 100%, resulting in an approximately 7-degree list, which represents the “bad” list mentioned by McSorley at 1730. Beyond the lists each damaged condition resulted in a forward trim and a reduction in total freeboard. The results of the hydrostatic analysis for each condition are presented in Table 4 below.

**Table 4: Vessel Conditions Timeline**

| <b>Time</b>  | <b>Heel</b>   | <b>Trim</b>   | <b>Disp</b>   | <b>LCG</b>       | <b>TCG</b>     | <b>VCG</b>    | <b>K<sub>pitch</sub></b> | <b>K<sub>roll</sub></b> |
|--------------|---------------|---------------|---------------|------------------|----------------|---------------|--------------------------|-------------------------|
| <b>(EST)</b> | <b>deg +S</b> | <b>Deg +f</b> | <b>(LT)</b>   | <b>ft Aft FP</b> | <b>ft (+S)</b> | <b>ft ABL</b> | <b>ft</b>                | <b>ft</b>               |
| <b>0700</b>  | <b>0</b>      | <b>0</b>      | <b>34,987</b> | <b>342.41</b>    | <b>0</b>       | <b>19.5</b>   | <b>183.9</b>             | <b>19.58</b>            |
| <b>1430</b>  | <b>0</b>      | <b>0</b>      | <b>34,987</b> | <b>342.41</b>    | <b>0</b>       | <b>19.5</b>   | <b>183.9</b>             | <b>19.58</b>            |
| <b>1600</b>  | <b>4.05</b>   | <b>0.28</b>   | <b>36,373</b> | <b>335.75</b>    | <b>0.84</b>    | <b>18.96</b>  | <b>186.2</b>             | <b>19.80</b>            |
| <b>1910</b>  | <b>7.28</b>   | <b>0.58</b>   | <b>37,661</b> | <b>329.69</b>    | <b>1.53</b>    | <b>18.87</b>  | <b>187.4</b>             | <b>19.85</b>            |

The effect of the list on the vessel is best shown visually. Figure 12 is a comparison of the intact and damaged conditions in still water. Figure 15 is a representation of the initial condition for the progressive flooding, including the wave conditions present at the time hatch cover Number 1 presumably collapsed.



**Figure 13. Illustration of Intact and Damaged Conditions**



**Figure 14. Damaged Condition In Waves**

Figure 14 demonstrates the severity of the wave conditions present at the time of the sinking.

The most important step of the analysis was the development of a computer routine to model the progressive flooding of the vessel. The model was programmed in Microsoft Excel using Visual Basic for Applications (VBA). The GHSCom module for GHS allows GHS to communicate with other software that uses VBA or C++ program code. This interface ability allows other software packages to be used to develop inputs for GHS and to process outputs from GHS. With GHSCom, the number of available GHS commands is limited. For the purposes of this analysis, however, the available commands were sufficient.

### **Flooding Model**

The flooding model was developed as an iterative process. The model begins at time 0:00:00 with the initial conditions shown in figure 13. The hatch cover is assumed to have just collapsed. GHS is then called using GHSCom to solve the equilibrium condition of the vessel. Results for vessel draft, displacement, heel, and trim are output into an Excel spreadsheet. This data are then used to establish the static freeboard of the vessel at the Number 1 hatch using the relationship of depth – draft = freeboard. At this

point, wave height data developed from the WASIM seakeeping analysis are used to determine the instantaneous water head over the hatch cover, which in turn determines the water flow rate through the hatch, through

$$Q = CA\sqrt{2gH}, \quad (1)$$

where  $Q$  is the flow rate in cubic ft per second,  $C$  is a discharge coefficient, which was taken as 0.8 for a rectangular opening,  $A$  is the inflow area in square feet (the cargo hatches measure 11 feet by 48 feet),  $g$  is the local gravitational acceleration, and  $H$  is the water head over the hatch cover in feet, which varies depending on the static freeboard of the vessel and the instantaneous wave height. The volume of water entering the vessel was determined by multiplying the flow rate by the length of the time step, which for this analysis was one second.

The next step is to distribute the water added to the vessel throughout the cargo hold. This adds complications because of the nature of the cargo hold and cargo distribution. The hold is modeled as six separate watertight tanks, but in reality water would have been able to communicate freely among all of them. Therefore, a sequence needed to be established that as accurately as possible models the distribution of water throughout the hold. After some experimentation, a sequence was developed that provides the best accuracy in modeling flow through the hold and is as follows:

- 1) Cargo section 1 begins to fill, with 100% of the water added in the time step applied to section 1.
- 2) When cargo section 1 has reached 15% of volume, cargo section 2 begins to fill. At this point 20% of water added during the time step is applied to section 2, and 80% is applied to section 1. This represents the slower flow of water aft through the taconite pellets.
- 3) When cargo section 1 has reached 100% volume, 99% of water inflow is directed to section 2 and 1% of water inflow is directed to void section 1. This represents the overflowing of cargo section 1 directly into cargo section 2, with some water beginning to fill the void space above the cargo in section 1.
- 4) When cargo section 2 has reached 60% volume, 9% of water inflow is directed to cargo section 3, 90% of water inflow is directed into cargo section 2, and 1% of water inflow remains directed into void section 1. This stage represents water continuing to fill the cargo hold and moving aft. The high starting point of section 2 and the low inflow rate represent the slower filling of the aft sections as the vessel begins to trim forward more.
- 5) When cargo section 2 has reached 100%, 9% of water inflow remains directed to cargo section 3, 90% is directed into void section 2, and 1% of water inflow continues to be directed into void 1. This represents the overflowing of water from cargo sections 1 and 2 into void section 2.
- 6) When void section 2 has reached 50%, 9% of water inflow is directed into cargo section 3, 41% of water is directed into void section 2, and 50% of water inflow is directed into void section 1. This condition represents the water level in void section 2 meeting the water level in void section 1. At this point, flow is assumed

to add to each section equally, with water continuing to flow into cargo section 3. The sequence is discontinued after this point, because discrete experimentation within GHS has indicated that the vessel will founder before either of the void spaces has entirely filled.

In addition to modeling flow through the hold, when static freeboard becomes negative, water is assumed to downflood into the forward winch room through the hawse pipe, and into the forward accommodation spaces through non-watertight doors that provide access from the forward house to the spar deck of the vessel. Water inflow was calculated in a manner similar to flooding into the number 1 cargo hatch, with appropriate values for inflow area.

At the end of each iteration, the volumetric load of each tank is added to the GHS geometry model using GHSCoM. This loading condition is then taken as the new initial condition for which a new equilibrium is determined, and the process is repeated. The process continues until the depth of the bow is 530 feet or more below the surface, which is the depth of Lake Superior at the location of the wreck.

### **Hull Loading Analysis**

The final step of the analysis is to evaluate the combined effects of hull loading from progressive flooding and hull loading from waves as determined by the seakeeping analysis. This is accomplished in several stages. The first is to assess the as-built capacity of the hull girder by performing calculations from the ABS 1978 Rules for Building and Classing Bulk Carriers for Service on the Great Lakes. The second stage is to determine the hull loading from progressive flooding at each time step in the flooding model. The final stage is to combine the progressive flooding loading with the wave loading from the seakeeping model. In order to assess the initial structural capacity of the *Edmund Fitzgerald's* hull girder, calculations for maximum allowable stress, still-water bending moment, and dynamic bending moment were performed. The calculations performed are taken from Section 2 of the 1978 AS Rules for Building and Classing Bulk Carriers for Service on the Great Lakes. The dynamic bending moment is modeled as a combination of wave bending and springing bending moments.

The total design bending moment from the ABS 1978 calculations is 452,282 LT-ft. The ABS maximum allowable stress is 12 LT/in<sup>2</sup>; however, when the *Fitzgerald's* actual section modulus was used with the ABS bending moment, the resulting stress was 10.6 LT/in<sup>2</sup>. This indicates that the *Fitzgerald* was over 10% stronger than required by the 1978 ABS rules.

### **Hull Loading from Progressive Flooding**

The vertical bending moments from the progressive flooding of the vessel were determined using GHS's Longitudinal Strength (LS) module. Each different loading condition was input to GHS and analyzed using the LS module. Shear, bending moments, and hull deflection were tabulated at frame 75 (257.5 ft aft of the FP) and at frame 145 (467.5 ft aft of the FP). These locations were chosen to match the locations where bending moments had been measured in the seakeeping analysis. These locations are also in close proximity to the observed separation points on the wreck. The output

values of vertical shear and bending moment were then recorded into an Excel spreadsheet.

### **Combining Hull Loading from Flooding and Waves**

The first step was to select the WASIM hull loading data corresponding to the wave-height data used in the progressive flooding model. This, combined with the location at which shear and bending moments had been tabulated, ensured that the combined bending moments were summed at the same location and time. A very important aspect of the analysis was to ensure that the still-water bending values were not double-counted. Therefore, a separate WASIM run was performed to obtain the WASIM generated still-water bending values for the vessel. These still-water values were subtracted from the total hull loading values, leaving only the wave-induced loading. The next step was to record the WASIM-generated vertical shear forces and bending moments into the same spreadsheet as the flooding bending moments, matching the locations and times at which the forces and bending moments occurred. Then, the shear forces and moments induced by flooding and waves were summed to obtain the total shear forces and bending moments present at each time step during the sinking. Finally, the stresses present in the hull girder were calculated.

### **Vertical Bending Analysis**

The first step of analyzing the time series of hull loading was to develop the still water hull-loading progression from the flooding sequence. The maximum shear and bending moments resulting from flooding are presented in Table 5.

**Table 5. Hull Loading From Flooding**

| <b>Location</b>  | <b>Maximum Shear<br/>(LT)</b> | <b>Maximum Bending Moment<br/>(LT-ft)</b> |
|------------------|-------------------------------|---|
| <b>Frame 75</b>  | <b>-1737</b>                  | <b>90114.3 Sag</b>                        |
| <b>Frame 145</b> | <b>8398</b>                   | <b>160568.8 Sag</b>                       |

### **Modeling Ship Motions and Responses:**

The WASIM analyses of the *Edmund Fitzgerald* proceeded in several stages over a period of about 3 years. Initial runs made with typical values for roll and pitch gyradii and CG showed that it was feasible to calculate the green water pressures at the hatch covers. The exploratory runs were made with cut planes at the locations of the known breaks in the hull to develop the shear stresses and bending moments

### **Run Conditions:**

About 100 non-linear WASIM runs were made in all, corresponding to the 4 degree through 10 degree list conditions. Many of the early runs broached and capsized due to the severe seastate and following seas condition. While this is a plausible sinking scenario at some level, the fact that there was no mention of difficulty holding course in the radio traffic or reported by the *Anderson* in similar conditions makes this unlikely. The pseudo-physics based rudder model used in WASIM and the need to restrain the yaw with a system of springs, cast the accuracy of this broaching behavior into doubt.

Eventually the right combination of simulation controls was developed to keep the yaw within +/- 15 degrees of the nominal heading which seemed reasonable for near following seas in these extreme waves.

The actual speeds dialed in and the speeds made good were not recorded other than some widely spaced positions versus time so speeds of 8 and 10 knots were used in the WASIM model as increasing speed in high waves often degrades course keeping stability and increases hull stresses.

While the wave modal period of 7.5 to 9 seconds was indicated by the research, a small parametric study of wave periods from 7 to 12 seconds was performed and the greatest susceptibility to motions appears to be around 9 seconds so that was used in the remaining runs.

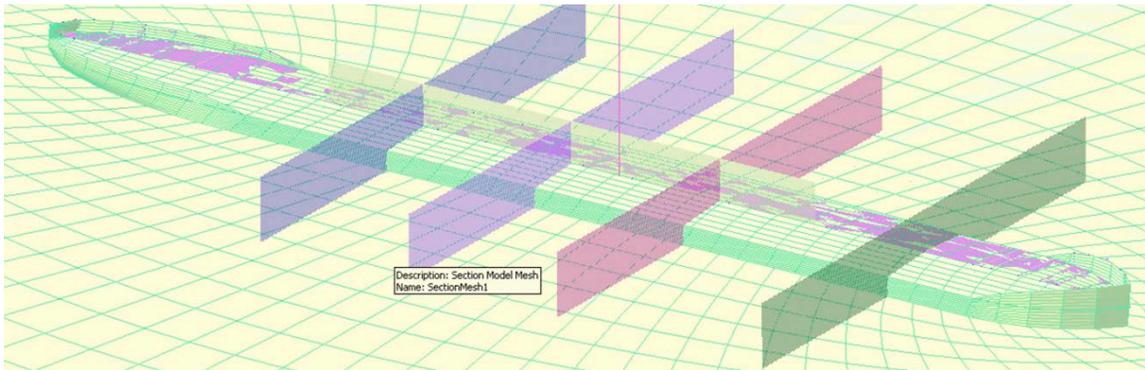


Figure 15: Initial Cut Planes at Locations of Hull Breaks

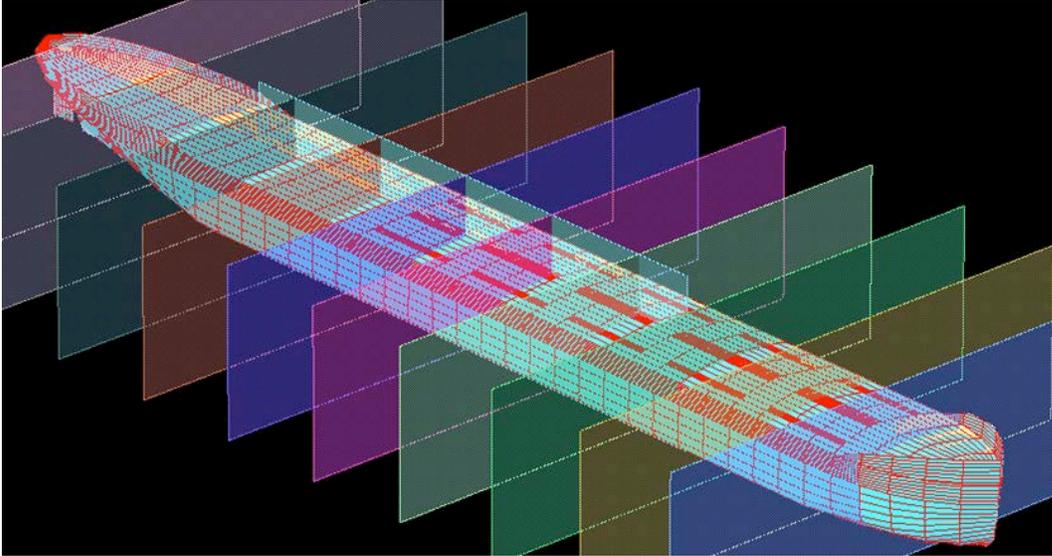
Table 6: Locations of Initial Cut Planes

| Cut Number |                          | Plane | Length from |         |
|------------|--------------------------|-------|-------------|---------|
|            |                          |       | AP meters   | AP feet |
| 1          | Aft Hull Failure         | YZ    | 77.1        | 253     |
| 2          | Middle of Failed Section | YZ    | 107.6       | 353     |
| 3          | Fwd Hull Failure         | YZ    | 138.1       | 453     |
| 4          | Number 1 Hatch Cover     | YZ    | 191.1       | 627     |

Later the cut planes were increased in number, figure 16, to show the distribution at ten locations along the entire hull girder. The eleventh location in table 7 is a XZ longitudinal + vertical plane, perpendicular to the other ten YZ Transverse + vertical plane cuts.

Figure 17 illustrates a typical 6 degree of freedom; wave induced force and moment diagram. There are the shear forces in the X,Y,Z directions and the moments about the X,Y,Z axes, where X is longitudinal, Y is transverse and Z is vertical. The origin is at the aft perpendicular, centerline, baseline.

The Matlab routine written to post process each time series automatically produces these minima and maxima curves. The minima and maxima curves can be misleading because they are built from the minima and the maxima in each time series at each location which do not necessarily occur at the same point in time.



**Figure 16: Cut Planes Used to Develop Wave Induced Hogging and Sagging Moments**

**Table 7: Locations of 10 Evenly Spaced Transverse + Vertical Cut Planes**

| Cut Number | Plane | Length from  |            |
|------------|-------|--------------|------------|
|            |       | AP<br>meters | AP<br>feet |
| 1          | YZ    | 202.0        | 662.7      |
| 2          | YZ    | 181.8        | 596.5      |
| 3          | YZ    | 161.6        | 530.2      |
| 4          | YZ    | 141.4        | 463.9      |
| 5          | YZ    | 121.2        | 397.6      |
| 6          | YZ    | 101.0        | 331.4      |
| 7          | YZ    | 80.8         | 265.1      |
| 8          | YZ    | 60.6         | 198.8      |
| 9          | YZ    | 40.4         | 132.5      |
| 10         | YZ    | 20.2         | 66.3       |
| 11         | XZ    | 101.0        | 331.4      |

Figure 18 shows the maximum vertical bending moment along the hull girder from all 14 runs made at 8 knots in 26 ft (7.9m) significant wave height at 9 seconds modal period in a JONSWOP spectrum. The orange and green horizontal lines correspond to the maximum design values at frames 75 and 145. Clearly the vertical bending stresses encountered exceed these design limit values by a large margin. The vertical red and blue lines represent the forward and aft hull fracture locations discovered in the wreck.

Figure 19 shows the  $F_y$  wave induced shear forces on the Hull girder in the same waves. In this case the limiting values do not appear on the graph as they are well outside the maximum range achieved.

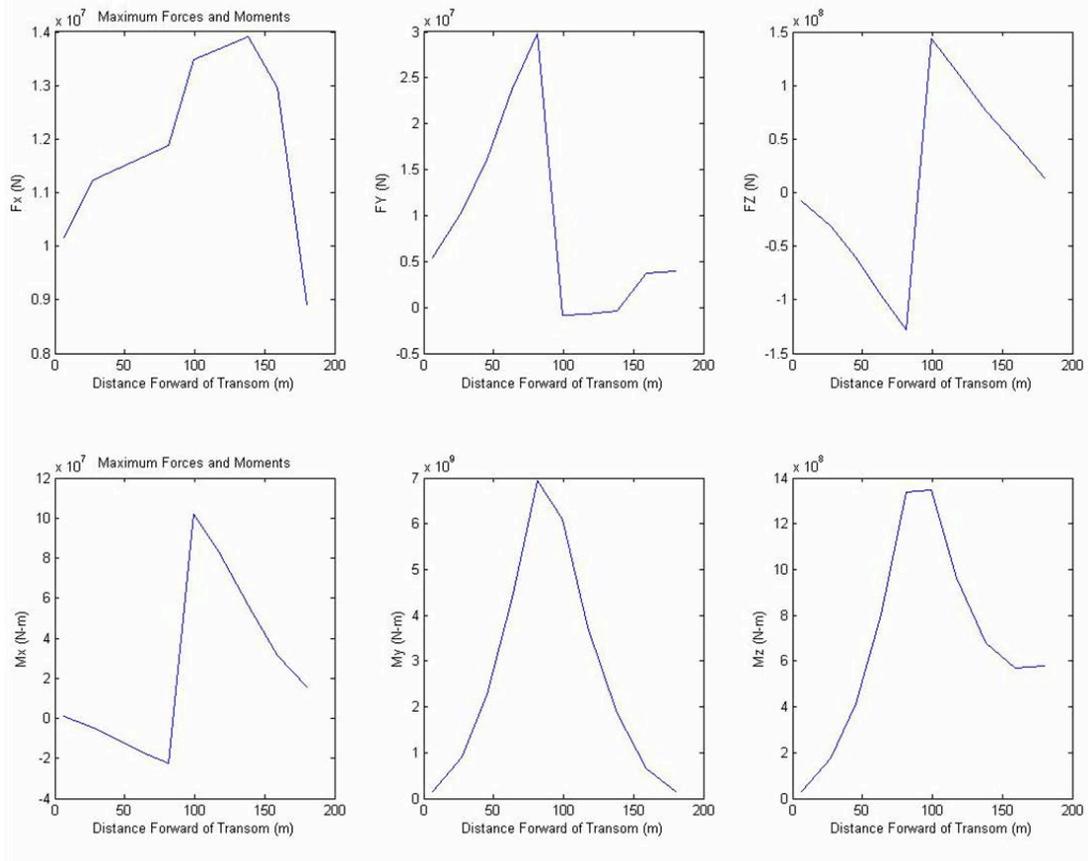


Figure 17: Maximum Shear Forces & Bending Moments in 6 DOF from Typical Run

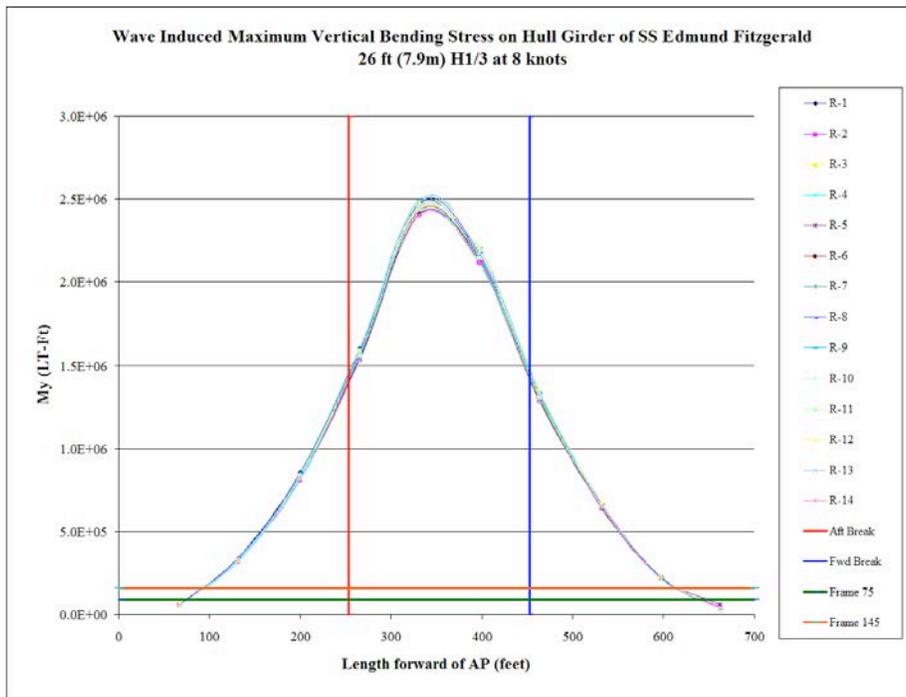
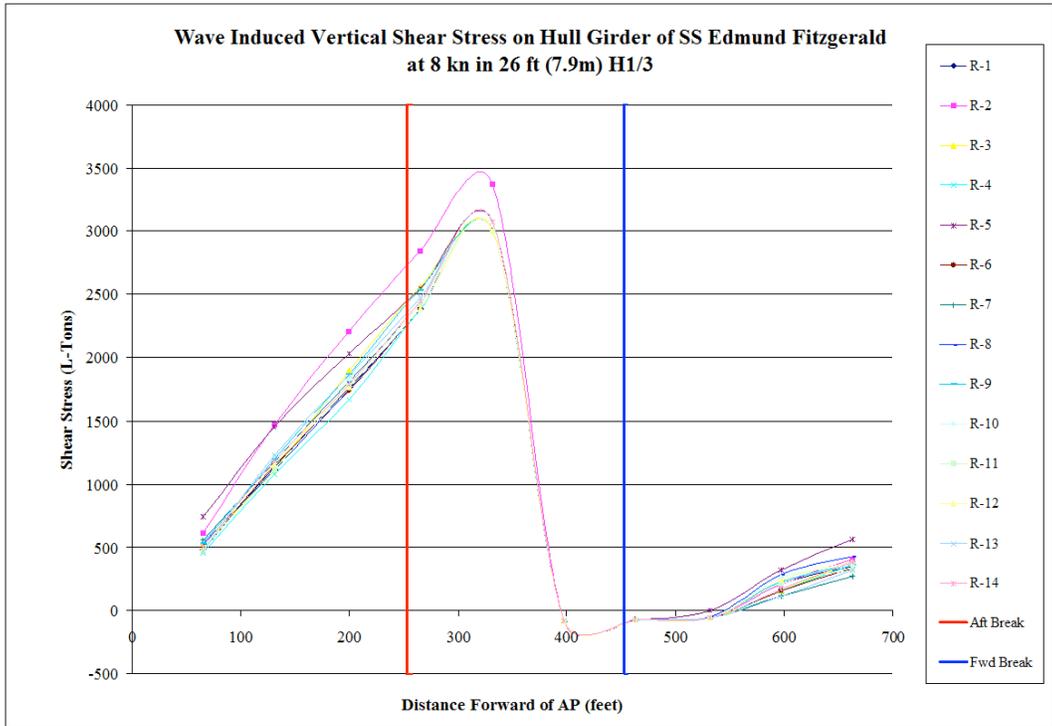


Figure 18: Maximum Wave Induced Vertical Bending Stress.

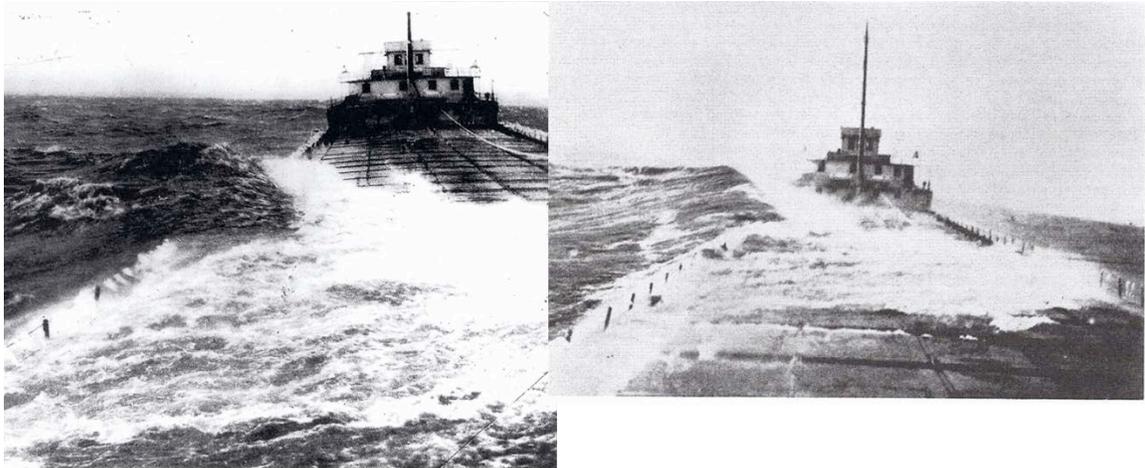


**Figure 19: Maximum Wave Induced Shear Stress.**

Figures 17, 18 and 19 all represent runs in the damage condition where the vessel is listing an average of 7.4 degrees to starboard and is trimming 18 inches (.5m) down by the bow.

Based upon this data, failure of the hull girder in bending amidships cannot be ruled out.

**Green Water on Deck:**



**Figure 20: Two Instances of Green Water on Deck of Great Lakes Iron Ore Carrier, (Unknown?)**

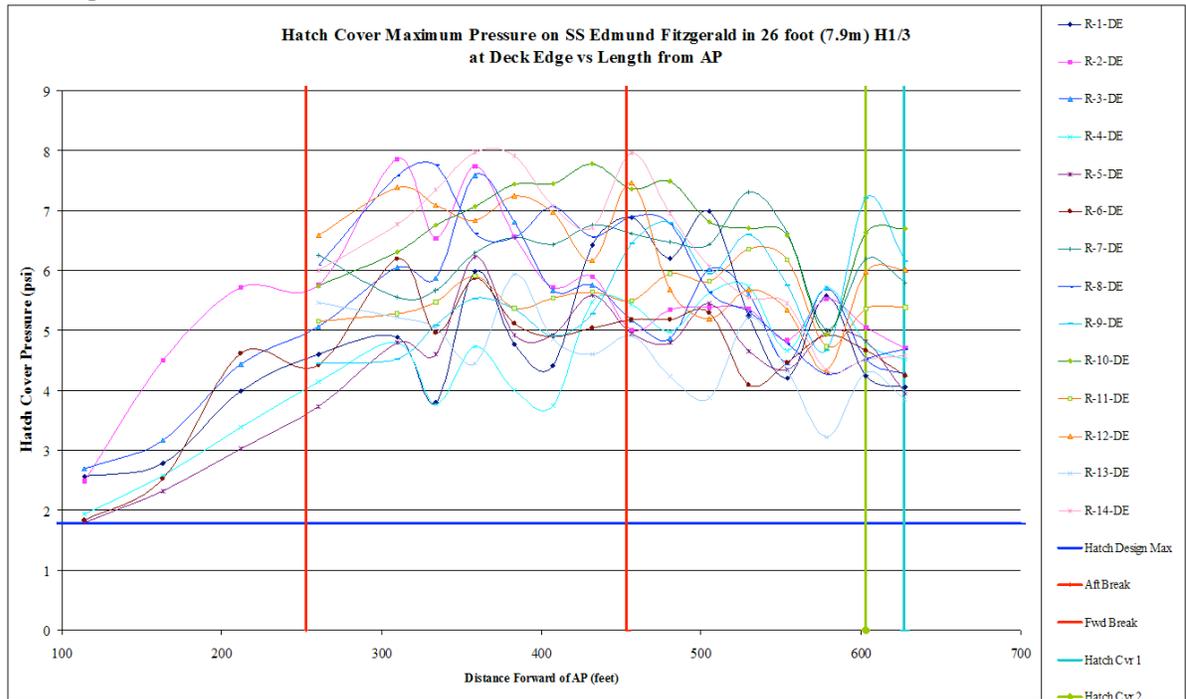
The unknown vessel in figure 20 survived the storm to get these pictures published whereas some others did not. The window configuration on the back of the forward house rules out the *Fitzgerald*. The first 19 hatch cover locations were modeled with a

pressure sensing panel adjacent to the centerline of the ship and with a corresponding one located at the deck edge.

These were analyzed in two ways.

- The locations in the .pres file include the hydrostatic head and the Froude-Krylov pressures for each panel selected for each time step.
- The locations in the .rel file is only the hydrostatic head component of the pressure over the panel location as if the ship were not there.

Neither of these is ideal but the development of a post processing algorithm that would make the wave correctly shoal as it boarded the complex ship deck and elevated hatch geometry is beyond the scope of what could be achieved with the time available. As valuable as such a model would be, extensive model testing would be necessary to develop and validate it.



**Figure 21: Maximum Hatch Cover Pressures in 7.9m waves at 8 knots**

The hatch cover design pressure was 4 ft of fresh water or about 1.8 psi

The vertical red line on the right is the location of the aft hull break. The vertical red line in the center-right is the forward hull break. The vertical blue line is the location of the number one hatch cover and the vertical green line is the number two hatch cover.

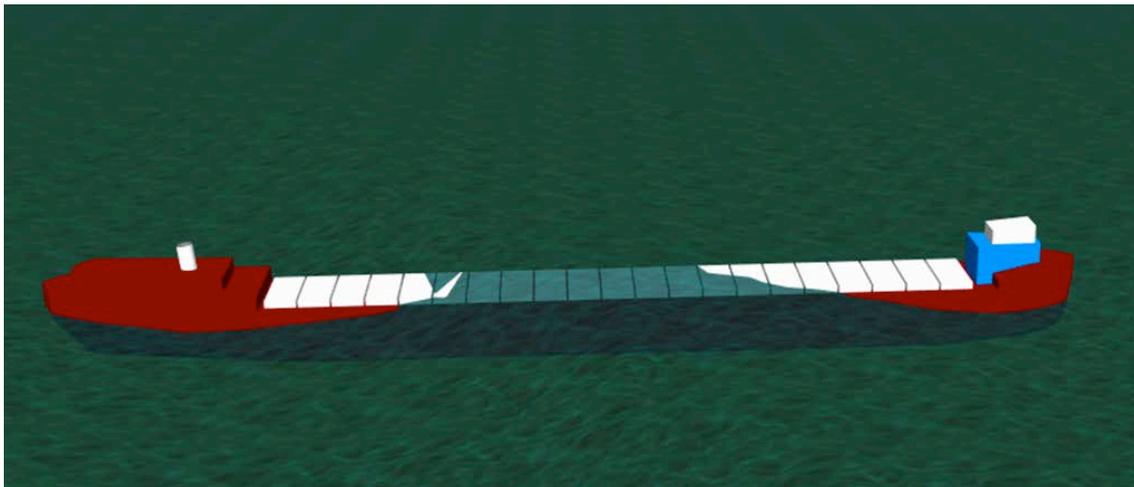
The data represents 14 different 40 minute runs where the only difference between them is the starting phase of the 200 unevenly spaced wave components making up a JONSWOP spectrum. Again these are the maxima from the entire time series in each of 14 cases and do not represent an instant in time.

It is fairly obvious that the maximum pressure was 3 to 4 times the design load of 1.78 pounds per square inch, over much of the ships length. The aft most hatch covers were sheltered by the stern house to some degree. The pressures shown represent the hydrostatic head pressures of the green water sweeping a smooth deck. In reality the local pressures would be much more chaotic.

When the waves reached the aft end of the forward house, they would attempt to reflect off it like harbor waves do off a sea wall with a localized doubling in height if the wall is high enough. This doubling in height as the wave reflected off the house right over the forward hatch covers suggests that this may have been causative in the hatch cover failure and eventual downflooding.

In the case of the *Edmund Fitzgerald* the forward house was probably not tall enough to provide for a complete reflection. Much of the water that splashed upwards backed by 50 mile per hour winds kept going until it crashed down, smashing down the sun visor on the front of the pilot house and tearing up the radar antennas. The wave slap from a breaking wave can exert thousands of pounds of force over an area the size of the rectangular windows on the back of the house, so it is not surprising that they were blown in.

The freezing temperatures, high winds and fresh water may have resulted in significant ice accumulation on the radar antennas and forward house which may have contributed to the damage by providing additional impact area.



**Figure 22: Orcaflex Visualization Model Showing Extent of Green Water on Deck**

The Orcaflex model was used to visualize the motions and the spread of green water on deck. Unfortunately the graphics don't show the wave steepness.

#### **Terminal Velocity of the Taconite Pellets:**

The terminal velocity of taconite pellets were determined analytically in 34 degree F fresh water. Based upon a dry weight of 116 to 130 pounds per cubic foot and a void fraction of 44%, the density of the individual pellets is 0.12 to 0.135 pounds per cubic inch. Based on the Reynolds Number and Hoerner 1965 Page 3-8 Figure 10, the drag coefficient is 0.47 for the range of sizes typical for taconite pellets.

A total time to reach the bottom 530 feet down is 2.5 to longer than 3.4 minutes. Pellets discharged in the upper 50 feet of the water column would meet wave particle velocities that exceed their terminal velocity. When this happens they can be trapped to move with the wave causing a few seconds pause before they get deep enough to get out of the

influence of the waves. The most wave affected pellets would likely be drifted some distance downwind before reaching the bottom creating a tail to the debris field.

**Table 8: Terminal Velocity of Taconite Pellets.**

| V ft/sec | 3/8" Dia | 1/2" Dia | 5/8" Dia |    | 3/8" Dia | 1/2" Dia | 5/8" Dia |
|----------|----------|----------|----------|----|----------|----------|----------|
| 1        | 1.7E+03  | 2.2E+03  | 2.8E+03  | Cd | 0.47     | 0.47     | 0.47     |
| 2        | 3.4E+03  | 4.5E+03  | 5.6E+03  | Cd | 0.47     | 0.47     | 0.47     |
| 3        | 5.1E+03  | 6.7E+03  | 8.4E+03  | Cd | 0.47     | 0.47     | 0.47     |

|                 |                     | 3/8" Dia | 1/2" Dia | 5/8" Dia |         |
|-----------------|---------------------|----------|----------|----------|---------|
| 116 pcf pellets | V Terminal          | 2.6      | 3.0      | 3.3      | ft/sec  |
| 130 pcf pellets | V Terminal          | 2.8      | 3.2      | 3.6      | ft/sec  |
|                 |                     | 9.53mm   | 12.7mm   | 15.88mm  |         |
| 116 pcf pellets | V Terminal          | 0.78     | 0.91     | 1.01     | m/sec   |
| 130 pcf pellets | V Terminal          | 0.85     | 0.98     | 1.10     | m/sec   |
| 116 pcf pellets | Time to fall 530 ft | 205.9    | 178.3    | 159.5    | Seconds |
| 116 pcf pellets | Time to fall 530 ft | 3.4      | 3.0      | 2.7      | Minutes |
| 130 pcf pellets | Time to fall 530 ft | 190.1    | 164.7    | 147.3    | Seconds |
| 130 pcf pellets | Time to fall 530 ft | 3.2      | 2.7      | 2.5      | Minutes |

In the top table the 9 values on the upper left are the Reynolds Numbers for the three sizes over the expected range of speeds. The drag coefficient proved to be insensitive over this range. Spheroids without dimples or laces do not sink straight but rather fall in a wobbly pattern due to the helical vortex shed behind them creating significant off vertical lift forces. The pellets would spread as they fell due to this and the difference in terminal velocity with size could lead to some size grading in the process as the larger heavier pellets fall faster than the smaller lighter ones.

The total settling time of several minutes and the lack of taconite pellets on the stern section suggests that the stern section remained afloat for several minutes or sank at a slower terminal velocity than the pellets.

## Results

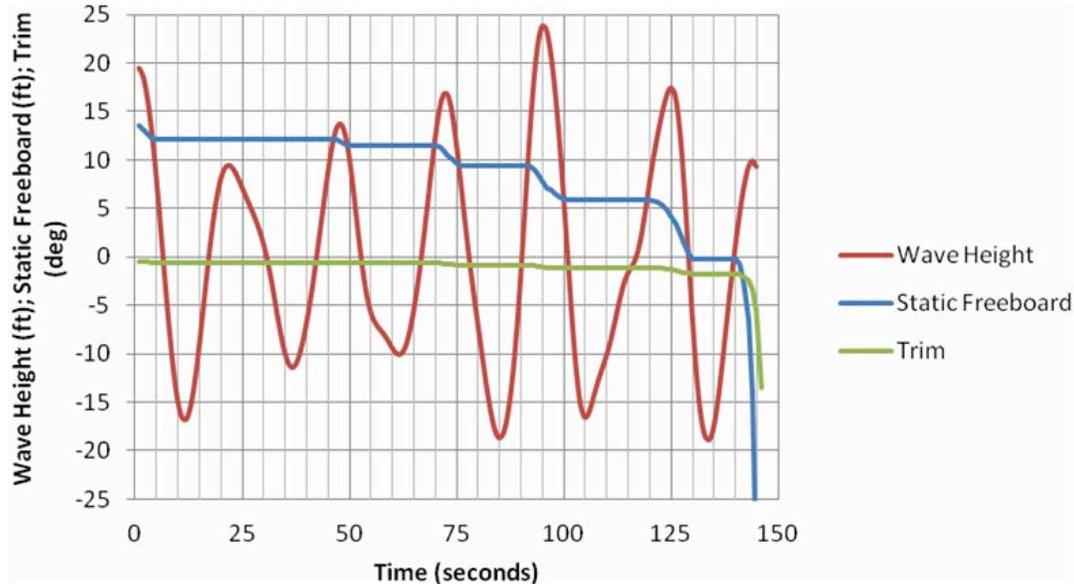
### Sinking Analysis (Preliminary)

The results presented in this section are preliminary. This analysis needs to be repeated for different realizations to evaluate how much the results vary from wave train to wave train. While every wave in this example lead to flooding through the hatch cover that will not be the case in every wave train.

The results of the progressive flooding model are summarized in the chart shown in Figure 23. In figure 23, the red line indicates the time history of wave height, the blue line is a time history of static freeboard, and the green line is a time history of vessel trim by the bow. Three very important results should be noted based on this graphical representation of the sinking process. The first is the time required for the vessel to sink. The progressive flooding analysis resulted in a hatch-collapse to bottom-impact time of approximately two minutes and twenty-seven seconds. This time is incredibly fast for a vessel the size of the *Fitzgerald*.

In addition to the rapid sinking time, the second result is the observed decrease in freeboard with each wave that exceeds the static freeboard level. The freeboard is seen to

fall in steps to zero as the vessel sinks. Once the freeboard effectively vanishes, the next wave causes the vessel to plunge.



**Figure 23: Summary of Progressive Flooding Model Results**

The third result is a similar trend in the trim of the vessel. Throughout the sinking process, there was no significant variation in vessel trim. The trim at time 0:00 was 0.58 degrees forward, and by time 2:24 it had only increased to 3.4 degrees by the bow. However, as can be seen in the plot, after 2:24, or 144 seconds, the vessel trim begins to drop dramatically, confirming the bow-down plunge indicated by the rapid loss of freeboard.

One of the limitations of the GHS analysis used was that water flow between compartments was not accounted for within GHS, leading to inaccurate modeling of the vessel condition during the late stages of the sinking. Namely, as the vessel plunged, the intermediate GHS equilibrium cases do not account for flow of water forward. This limitation actually adds a degree of conservatism to the results, since accurate modeling of water flow forward would lead to a more severe sinking condition.

**Summary of Possible / Probable Hull Failure Modes:**

The condition of the wreckage shows that the ship broke up near amidships sometime during the sinking process. This occurred with sufficient violence that the debris lost coherence as ships sections and did not remain attached to the bow or the stern.

- The bow and stern are completely separated on the bottom and the middle of the ship is shredded.

- The bow is upright and appears to have reached bottom first in under 2.5 minutes due to the heavy layer of taconite pellets on top of it. There is a dune of sediment where the port side dug in as the ship slid sideways to a stop.
- The damage on the bow is not consistent with a head on collision with the bottom as there is minimal crushing. The Stem bar is still straight.
- The damage to the reinforced plate bow bulwark is consistent with getting slammed repeatedly with the waves falling back down and forward pushed by high winds from astern as they crashed off the aft end of the pilot house.
- The stern is upside down and appears to have reached the bottom after the taconite pellets so sometime after about 3 minutes
- Figure 9 shows the stern on top of some of the structure of the midbody, again supporting the idea that it reached the bottom last.
- Figure 5 shows that the stern location is not far past the location of the bow, which shows that the propeller and strong following winds did not continue to push on it for very long after the bow sank. If they had the separation would be significantly larger.
- The analysis the final plunge covers a time period of only about six seconds; although this value is inaccurate because hydrodynamic drag on the vessel during the sinking process has not been accounted for, the speed with which the sinking occurred was still very rapid and clearly explains the lack of either distress calls or survivors from the accident.

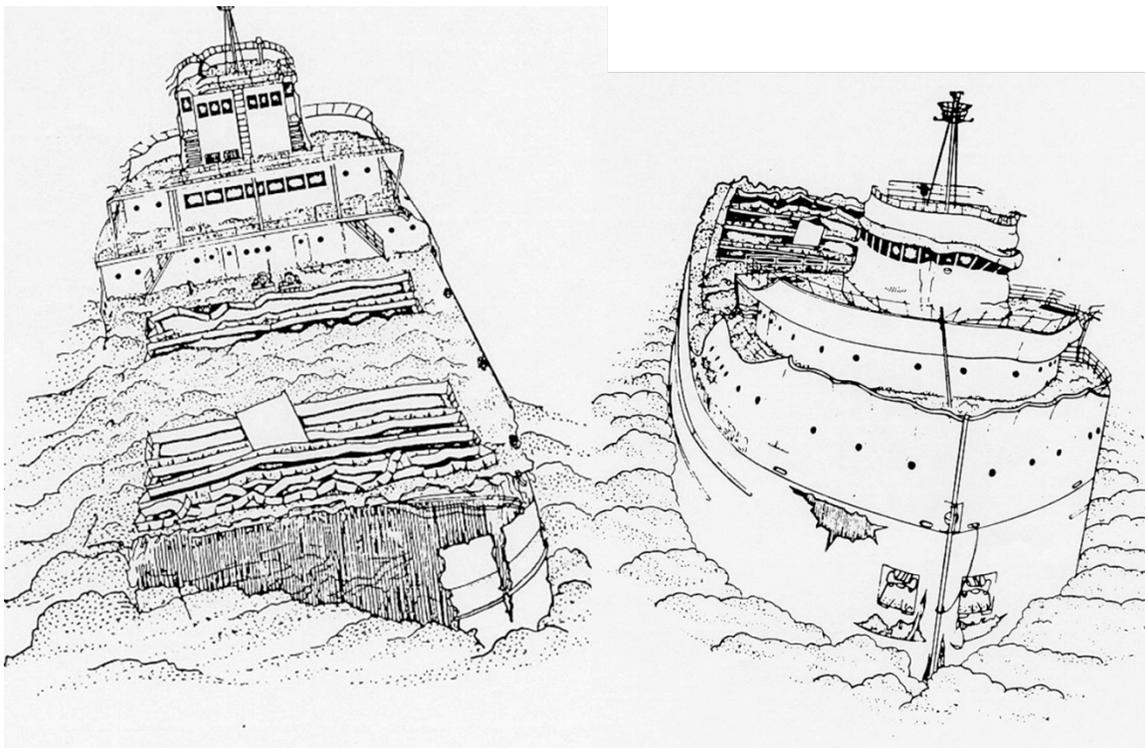


Figure 24; Views of Bow Section from Aft on Left and Forward on the Right. (USCG)

**Theory 1: Intact until the bow hit the bottom**

If one assumes that the vessel remained intact during the sinking process, at the point the bow collided with the bottom there would still be up to 200 feet of the vessel's stern remaining above the water. If the vessel did not break apart on the surface, the sudden dive of the ship and subsequent impact with the bottom would have been violent enough to cause the hull-girder collapse, but there would have been collision damage to the bow and the broken middle section would show a telescoping type of damage. It would have been unlikely in this case that the stern would completely detach and completely sever itself structurally from the crushed bow and mid section.

One of the least credible assertions made in the past is that the propeller kept turning after the bow hit the bottom and that thrust caused the damage. The propeller would be out of the water in a fluid with 1/700<sup>th</sup> the density so the thrust would be minimal and again the damage would be of a crushing or telescoping type that is not at all consistent with the evidence on the bottom.

### **Theory 2: Broach & Capsize Followed by Breakup and Sinking**

While this cannot be completely ruled out, the evidence does not support this as the likely failure mode. There are many other vessels of similar type including the *Anderson* who was only a few miles behind the *Fitzgerald*. Broaching is not reported as a common type of problem with these ships. There was no report of steering trouble reported by either vessel according to the NTSB and USCG reports.

### **Theory 3: Breakup on Surface, Midship Section First**

If the *Fitzgerald* had failed due to the hatch covers amidships getting blown in, and / or the hull girder breaking, then the condition of the two forward most hatch covers located just behind the pilot house remains unexplained.

### **Theory 4: Breakup On Surface, Failures Of First And Second Hatch Covers**

This scenario builds on a failure cascade that proceeds as follows:

- Some object, most likely a floating log is carried aboard the starboard side of the *Fitzgerald* by a boarding wave that breaks the lifeline wire and smashes off the two vents as described.
- The two ballast tanks begin to flood. This increases the mass forward such that the list begins and slowly increases. Instead of the hull girder responding normally, the increased mass forward and to starboard begins to cause the midsection and stern to respond more actively than the bow to the wave excitation.
- The list causes boarding waves to sequentially break windows on the back of the forward house, allowing water into the lower accommodation spaces and increasing the flooding forward.
  - These waves breaking against and reflecting off the house cause huge masses of green water to thunder down on the Pilot house and bow.
  - These large masses of solid green water break the radar antennas, and bend the sun visor and the bow sheet bulwark, downwards and forward as shown on the wreckage.

- A wave riding up the lower freeboard starboard side reflects off the forward house and blows in the forward two hatch covers and exacerbates the existing flooding.
- The mass of the forward part of the ship drops into the trough behind the damaging wave as the next crest lifts the center of the ship in an extreme hogging and sagging load condition which causes the failure of the hull girder amidships.
- This next wave boarding from starboard also pushes the center of the ship to port more than the heavy bow or the stern.
- The bow begins to accelerate downwards as the partially fractured hull girder continues to tear away from the stern section. The starboard side of the bow section tears away last producing the inward bend on the after starboard edge of the bow section. This provides a powerful wrenching motion to the starboard side of the stern section that pulls it over onto its starboard side in the course of it flooding and capsizing.

This allows the bow to reach bottom first, fluttering such that it strikes with the lower port side. Next the debris from the mid section rains down with the taconite cargo expelled from the midsection and stern close behind. The stern suddenly freed of the weight of the mid section and bow bobs back up as it continues to capsize and then sinks, arriving at the bottom last.

## **Conclusions:**

### **The Storm:**

The *Fitzgerald* storm type is a seldom occurring event that has claimed other vessels when the first severe winter storms of November come up before shipping on the lakes has stopped for the season. Trying for one more trip before the weather closes in has been a fatal mistake in these cases. They don't happen every year so normally the outcome is favorable. These rapidly intensifying storms occur other places than the Great Lakes region. The international Experiment in Rapidly Intensifying Cyclones in the Atlantic, (ERICA), Project of the late 1980's studied these storms that occur off the coast of New England (Kery 1990). A NOAA Weather Buoy involved in that experiment recorded the lowest Barometric Pressure ever recorded in the Northern Hemisphere during one of these "Bomb storms".

A 2 inch snow fall in Boston builds to Hurricane force by the time it gets to Georges Bank 90 miles to the East, with extreme dangerous conditions for the fishermen and mariners who are working or traversing those areas. Waves around 8 meters significant wave height are implicated in sinking the *Fitzgerald*. A bomb storm off New England often has a significant wave height of 12 to 14 meters.

### **The Event:**

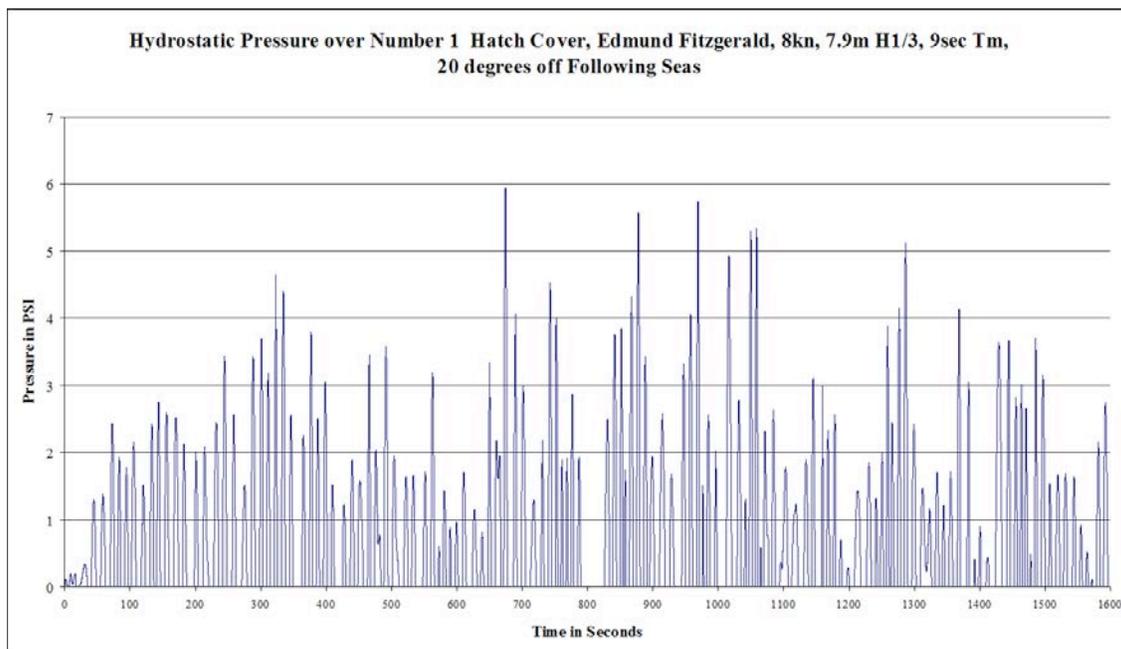
Of the many waves encountered in the course of this trip by both the *Arthur Anderson* and the *Edmund Fitzgerald*, most were not adequate to cause the sinking. The damage to the two vents began a failure cascade that took a while to reach a critical point just as the *Fitzgerald* reached the worst portion of the storm. The *Anderson* survived but the *Fitzgerald* did not.

### **The Failure Mode(s):**

The failure cascade as described in Theory four is consistent with all of the available damage. This is the only explanation put forward so far that is consistent with all of the evidence available. The damage to the wire rope rail and the two vents is documented but the proposed method (debris of some type coming aboard with a wave) is conjecture. This is not a necessary assumption but it is more plausible than assuming that the damage was done by the wave alone.

**The Modeling Effort:**

The sinking of *Edmund Fitzgerald* occurred because of the convergence of a number of seldom occurring events. November gales were a known risk, but they have not caused sinkings every year, but rather only once in a decade or so. The damage to the vents on the *Fitzgerald* that initiated the failure cascade, did not occur on the *Anderson* or the *Avafors* in that storm, nor was it a common occurrence on vessels in this trade. Waves large enough to produce the damage to the forward house only occur in a few waves out of hundreds. Figure 25 shows a typical green water on deck time history from part of a single run. The pressure only exceeds 5 psi about 6 times in about 128 wave encounters.



**Figure 25: Example of a Pressure Time Series over Number One Hatch Cover**

The maximum pressures of 10 psi over the forward hatch covers in figure 21 only occur in one out of the 14, 40 minute time series. As explained previously this pressure does not account for the reflection and approximate doubling when the wave hit the back of the house and went up it. However this does not change the fact that these are seldom occurring events at the threshold level of 26 ft (7.9m) significant wave height.

A series of four runs were made with a 26 ft (8.5m) significant wave height at 10 knots to investigate the sensitivity to the estimated extreme significant wave height. The maximum pressure over the number one hatch cover increased to 14.3 psi before

accounting for the reflection, which is almost 43% higher. In addition a larger number of waves reached higher pressures, indicating that the inception of hatch failure is strongly a function of the maximum significant wave height.

#### **Future Directions for Research:**

There are many areas where continued research can provide sharper focus on the foundering or breakup of vessels in extreme conditions.

- The addition of point masses to the WASIM model to represent various flooding conditions will lead to more credible hull primary shear and bending moments. This capability already exists but it has not been brought to bear on this problem yet due to time constraints in preparing this paper.
- The behavior of a boarding wave can be developed for a smooth deck as a Matlab post processing algorithm. Once this is working, it can be improved to include the effects of simple shapes or steps in the deck structure such as hatch covers.
- An Orcaflex model can be created that models the breakup and foundering including the pieces dissociating and landing on the bottom to provide a mathematical basis for theory number 4.

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