The Breakup of *Titanic*

A Progress Report from the

Marine Forensics Panel (SD-7)

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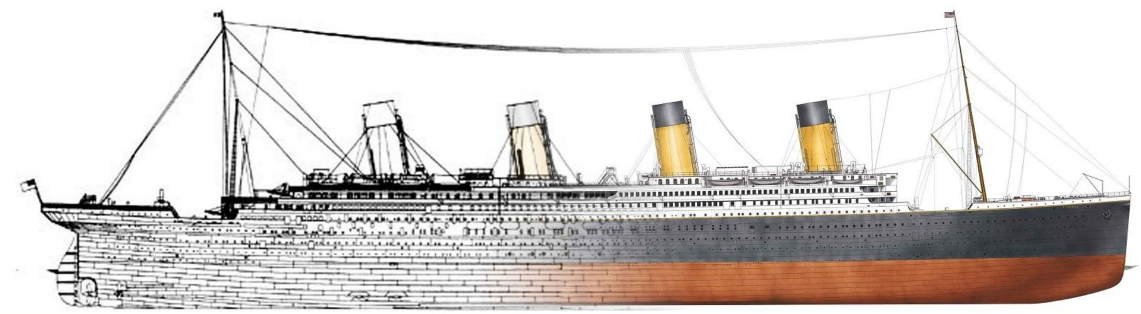

Photo courtesy of Robert Hahn, Titanic Research and Modeling Association

ABSTRACT

RMS Titanic collided with an ice berg and sank on the morning of April 15th, 1912. Testimony at hearings on both sides of the Atlantic included conflicting stories of the ship breaking in two or sinking whole. The discovery of the wreck in 1985 confirmed that the ship did break near the surface. Recent evidence and analysis indicates that the initial point of hull failure was at or near the double bottom and the ship effectively broke bottom-up.

KEY WORDS: Titanic; keel; break-up

INTRODUCTION:

Since the discovery of the wreck of *RMS Titanic* in 1985, there have been many attempts to explain how the ship broke apart. Armed with new evidence from the wreck site and a more mature understanding of early 20th Century hull design, we have developed a new reconstruction of the breakup. This reconstruction reconciles engineering analysis, survivor testimony, and physical evidence from the wreck site to a greater degree than any previous reconstruction.

THE BREAKUP AND ENGINEERING ANALYSIS:

In 2005, an expedition sponsored by the History Channel surveyed two pieces of the *Titanic*'s bottom. These pieces, coming primarily from beneath Boiler Rooms #1 and #2, lie upside down on the ocean floor, some distance from either the bow or the stern section of the wreck. While this was not the first expedition to locate or photograph these pieces, the 2005 expedition's photographs of these pieces led the Panel to revisit its analysis of the *Titanic*'s breakup. While the analysis is not yet complete, the Panel's work to date has led to the development of a new – and significantly altered - reconstruction of the breakup.

Previous investigations carried out over the years by members of the Panel provided necessary data for our investigation.

Bedford & Hackett[1] determined the loads on the ship for a number of flooding conditions. Arthur Sandiford (in reference [2]) developed shear and bending moment diagrams for a selected flooding condition. Sandiford also developed a simplified midship section, reproduced in Garzke and Woodward [3].

The starting point for this investigation is the flooding condition which Sandiford labeled "C-7". This is the most severe flooding condition for which calculations are available - it is not necessarily the condition in which the breakup began.

Panel member George Edwards, on re-examinination of Sandiford's diagrams for this flooding condition, found it necessary to revise them. The revised shear diagram is shown in Figure 1. The sign convention for the shear diagram is the opposite of Sandiford's, and distances are measured from the forward perpendicular rather than the aft, but the numerical values agree quite closely with his. Most of the revisions were in the moment diagram, shown in Figure 2.

The revised moment calculations give a maximum bending moment of approximately 1.71 million ton – feet, or 4.1 x 10^{10} inch – pounds. This maximum occurred inside Boiler Room #2, and is much smaller than the moments originally calculated by Sandiford. (This value occurs at a point between the two highest moments shown in Figure 2.)

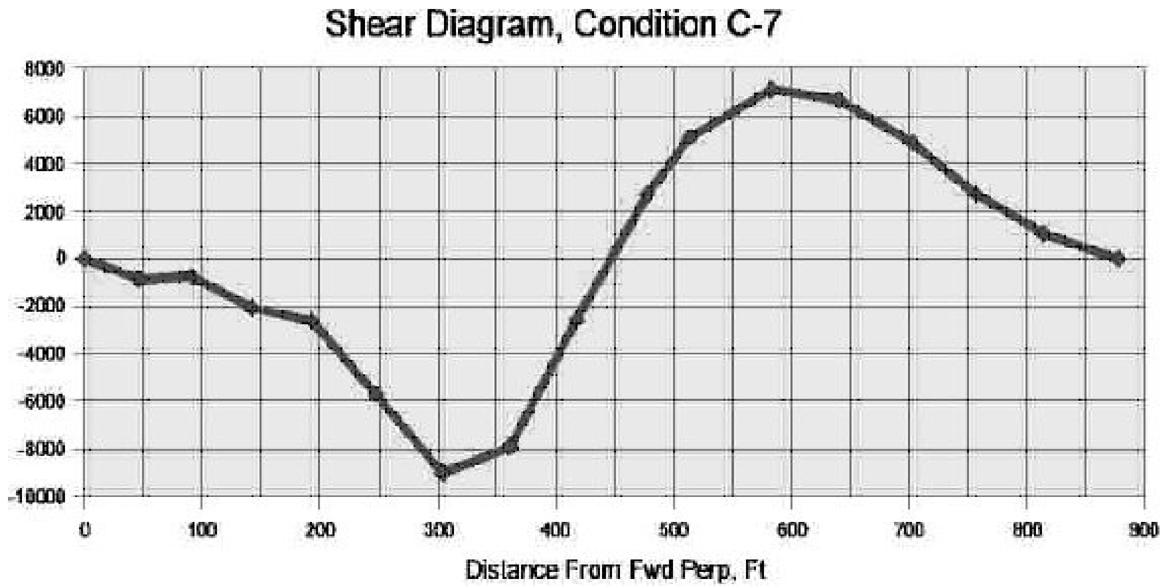

Figure 1 – Shear diagram for condition C-7

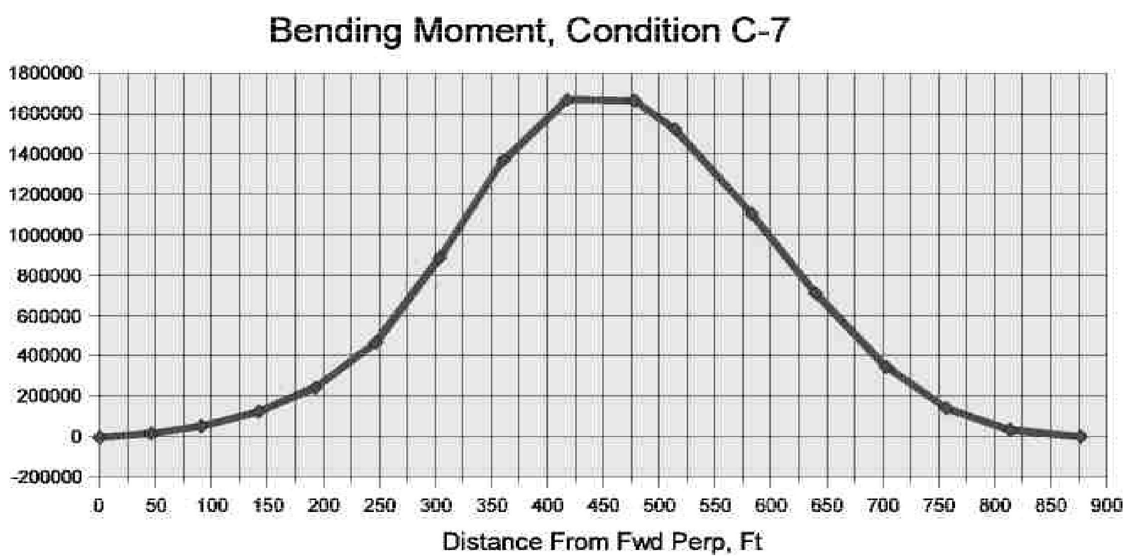

Figure 2 – Bending Moment for condition C-7

In addition to the center vertical keel (or keelson), the ship had four longitudinal girders which carried hull girder stresses and formed tank boundaries. Additional longitudinal members were fitted between the ribs, but they had lightening holes, and were not meant to carry hull girder stresses. Sandiford counted only the four longitudinal girders as part of the midship section. Since the additional longitudinal members could be expected to carry compressive loads better than tensile loads, and since the bottom structure was loaded in compression at the time of the breakup, we modified Sandiford's cross section to include all of the longitudinal members in the double bottom, and simplified it somewhat, as shown in figure 3.

The neutral axis (shown dashed) is 398 inches above the keel. The upper section modulus is 1.86 x 10^6 inches^3, while the lower section modulus is 2.23 x 10^6 inches^3. For the calculated bending moment, the hull girder stresses are approximately 22 ksi (tensile) at the uppermost strength deck (B Deck), and 18.4 ksi (compressive) at the keel.

We used these stress values as the starting point for our investigations. As noted earlier, this does not necessarily imply that they were the maximum stress levels reached before the breakup began. Whatever the actual stress value may have been, the compressive stress at the keel was roughly 83 percent of the tensile stress at the strength deck.

However, knowing where the stress was greatest is not sufficient. A failure will occur whenever the stress exceeds the strength – and there was a significant difference in strength between these two locations. The landings (longitudinal seams) in the bottom structure were only double riveted. The butts (lateral or vertical seams) were triple riveted in the tank top, and quadruple riveted in the bottom plating. In reference [4], we see that double riveted joints, even when made with steel rivets, have a joint efficiency of only 28 percent based on "gross" area. For triple riveting, this efficiency increases to 42 percent, and for quadruple riveting, it increases to 56 percent. If the plate UTS was about 63 ksi (as assumed in reference [4]), we could expect rivet failures to begin at average plate stresses of 18 ksi (for double riveting), 27 ksi (for triple riveting), or 35 ksi (for quadruple riveting).

This would not pose a problem in a ship whose bottom plates were connected by true butt joints, since compressive stresses could be transmitted by direct contact between the ends of the plates. However, the forward and aft ("butt") ends of *Titanic*'s plates were joined with lap joints (called "butt laps"), so the hull girder stress is transferred from plate to plate only by shear in the rivets.

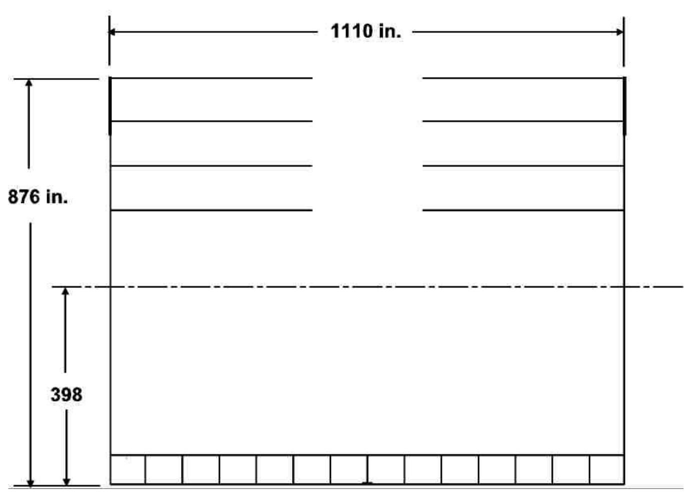

Figure 3 - Neutral axis of Titanic

(For more detailed information about the design and construction of RMS *Titanic* and other early 20th Century liners, see reference [3]. For further information on riveted joint design, also see reference [4].)

Near the strength deck, on the other hand, the side shell strakes were made up of a double thickness of one-inch plate, with octagonal "triple plates" to bridge the gaps between adjacent plates. The two layers of plate were heavily riveted together, so as to approximate, as nearly as possible, the strength of a continuous strake of 2 – inch steel plate. The "Big Piece[1]", recovered from the wreck site by the 1998 expedition, came from one of these strakes. The failures at the forward and aft ends of the "Big Piece" were primarily in the plates, not at the joints, so we can say that the joint efficiency was as close to 100 percent as any riveted structure could ever achieve.

So, if we compare stress to strength, we see that stresses at the keel were equal to 83 percent of the stress at the strength deck, but the joints in the bottom structure had only 42 to 56 percent of the strength of the side shell plates. While it is somewhat of an oversimplification to consider the strength of individual joints rather than the strength of an entire structure, this difference in strength prompted a more detailed investigation of the bottom structure, in an effort to identify at least one potential failure mode.

The photographs returned by the 2005 expedition show a roughly three-foot long portion of the keel, at the aft end of the aft piece, bent in an "S" shape. There is also a portion of the keel, bent in the opposite direction, at the aft end of the forward piece. Buckling calculations indicate that, given the presence of transverse frames every 36 inches, the keel could not have buckled in the conventional sense. However, the authors note that there was a sloping transition of the tank top plating between the 76 – inch depth of the double bottom under the engines and the 63 – inch depth elsewhere in the ship. This asymmetrical transition might have led to the development of stresses that would cause a bending failure in the keel.

The available drawings conflict with regard to the starting and ending points of the transition. An inboard profile of the ship, first published in *Engineering*, vol. 90, 1910, and reproduced in Reference [3], shows a gradual transition, extending from one frame space (3 feet) aft of the Reciprocating Engine Room's forward bulkhead to roughly 2 frames (or 6 feet) forward of that bulkhead. This would place the forward end of the transition inside Boiler Room No. 1, quite close to the location where the keel bent.

Halpern (see Reference [5]) showed the watertight boundary between tanks at Frame 29, but the watertight bulkhead (above the level of the tank top) at Frame 30. Halpern showed the tank top at its full 76 - inch depth from Frame 29 aft. Based on the most detailed plans available, the forward end of the transition was placed at Frame 25, inside Boiler Room No. 1.

There was another significant transition in this part of the bottom structure. Additional longitudinal girders were provided to support the two reciprocating engines, and extended forward one frame space beyond the forward bulkhead of the Reciprocating Engine Room. These additional longitudinal girders just ended at that point. They were apparently not intended to carry hull girder stresses, but in reality, they undoubtedly did carry their share of those stresses.

A finite element model of a portion of the double bottom was made to investigate the behavior of this structure. In this model, the tank top sloped from 76 inches above the bottom at Frame 29 to 63 inches at Frame 25. (A number of computer runs with other configurations revealed that changes in the starting and ending points of the slope had relatively little effect on the behavior of the model.) The model is shown in Figure 4, embedded in a sketch (not to scale) showing the location of the model within the ship.

The model was made using ALGOR finite element software. Brick elements were used for the bar keel; plate elements were used for the remainder of the structure. A thickness of 0.75 inch was used for the tank top plates. A thickness of one inch was used for all other plates, except that the thickness was increased to two inches near the joint between the tank top plating and the center vertical keel, where the actual connection was reinforced with longitudinal angle irons.

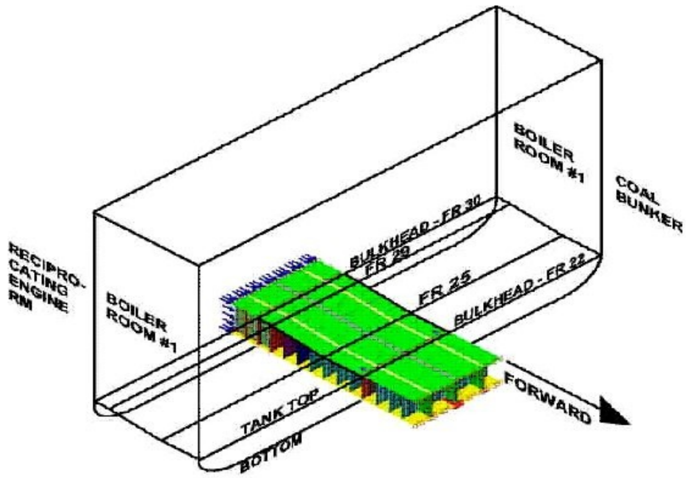

Figure 4 - Keel section model

The large (aft) end of the model was extended two frame spaces (6 feet) aft of the bulkhead between Boiler Room No. 1 and the Reciprocating Engine Room. The extension of the model into the Engine Room is only meant to improve the reliability of the portion of the model under Boiler Room No. 1 – it is not meant to model events inside the Reciprocating Engine Room.

The forward end of the model coincides with the watertight bulkhead at Frame 18. A "bunker bulkhead" at Frame 22 was also modeled. The total length of the model is 42 feet, and the width is approximately 20 feet. Transverse frames are spaced three feet apart in our model, as they were in the actual ship.

The forward end of the model is fully fixed. The nodes at the aft end are constrained against translation in the vertical and athwartships directions; the top and side nodes at the Engine Room bulkhead and bunker bulkhead are also constrained in this way.

The compressive forces due to hull bending are distributed along the structural members at the aft end. Hull shear forces are not included, since most of the shear would be taken in the side shell, not in the keel. Nodal loads were calculated for a stress of 18 ksi at the aft end of Boiler Room No. 1.

There was a row of three manholes, with variable spacing, on either side of the keel. The model included one of these manholes on either side of the keel, shifted about one foot toward the keel to keep it away from the edge of the model, where stress levels might not be as realistic as in the center.

While the loads were calculated to produce a stress of 18 ksi in the after portion of the model, the stress farther forward was found to be about 20 ksi, since the cross section is smaller than at the point where the loads were applied.

The analysis was first run with the manholes open. The results showed that the stresses to either side of each manhole were roughly double the average stress, as would be expected from a stress raiser of this type. But, noting that the manholes were each cut into a single plate, so that no joints were involved, and noting that the manholes appeared to be too far apart for a failure at one manhole to propagate across the breadth of the ship, they were not analyzed further.

To increase the visibility of other stress raisers, the manholes were filled in with steel plate, and the analysis was run again. The resulting stresses and displacements are shown in figure 5. (To make the results easier to interpret, the structure aft of the engine room bulkhead has been removed from the display. Displacements are magnified 200x.)

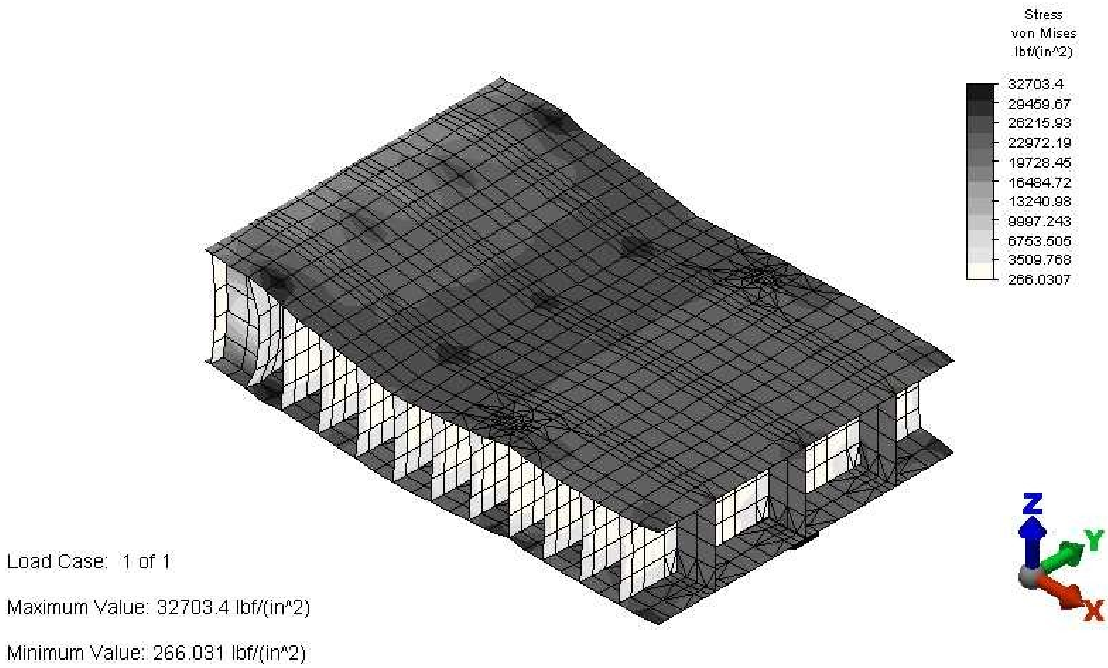

Figure 5 - Stresses at the keel transition

The average stress in the tank top and bottom plating is about 20 ksi. This is somewhat higher than the 18 ksi for which the nodal loads were calculated, largely because the original loads were calculated before the decision was made to include the extra longitudinal members under the engines.

There are a number of "hot spots" visible in the tank top plating. Some of these "hot spots" coincide with the endpoints of the "extra" longitudinal girders that make up the foundations for the reciprocating engines. The maximum stresses there are calculated to be about 32 ksi, or roughly 60 percent above the average stress in the bottom structure. For an 18 ksi nominal stress, the stress at the hot spots would be just under 29 ksi.

There are also "hot spots" of roughly the same magnitude in the tank top plating at the forward end of the transition, at the connections to the longitudinal girders.

There is substantial vertical deflection of the keel, even though there are no vertical loads on the model.

The stresses reported here are Von Mises equivalents. Additional computer runs were made to confirm that the principal and Von Mises stresses agree quite closely, as we would expect in a situation where the loads are essentially purely compressive.

The actual stress needed to cause a failure would depend on the detail design of the structure, as well as on the quality of the materials, etc. However, the calculated stress of 29 ksi at the "hot spots" is large enough to make the triple riveted joints in the tank top plating a good candidate for the initial failure – if not at the moment when the ship reached this particular flooding condition, then soon afterward. A slightly higher stress would be needed to initiate a failure in the bottom plating, which was quadruple riveted.

The primary focus has so far been on the possibility of failure initiation at riveted joints. However, the possibility of other types of failure cannot be ignored. The yield strength of the steel (generally expected to be 30 ksi, perhaps a bit more) is not much greater than the stresses at the "hot spots" - and a number of assumptions were made that would bias these stress estimates downward. Most importantly, all of the transverse and longitudinal members were treated as solid. In reality, as noted earlier, many of the members had lightening holes. Also, even though the keel itself would not buckle, the possibility of a buckling failure in the plates could not be ruled out. A number of additional finite element runs were therefore made to study these effects.

It was not possible to use the same model for these studies, due to an accumulation of geometry problems. An older, simpler model, which did not include the extra longitudinals under the engines, was used. As this study was only intended to be preliminary, existing element boundaries were used to define the edges of the lightening holes. Even with these approximations, useful results were obtained.

It was found that the applied loads would have to be multiplied by a factor of about 3 to produce buckling of the entire structure. This essentially rules out buckling as the initial failure mode. Buckling would only occur if some other kind of failure happened first, reducing the strength of the remaining structure.

The pattern of "hot spots" was not substantially different when lightening holes were included. The "hot spots" still occurred above each longitudinal member at the point where the transition in double bottom depth ended. The stress at these "hot spots" was found to be about 40 percent higher than the average stress. Figure 6, in which displacements are multiplied 250 times, shows the stresses and displacements.

In this image, the average stress was somewhat lower than the nominal 18 ksi, since the loads on the lightened longitudinal members had to be decreased to avoid unrealistic deflections. The lightened members were found to be able to carry just under half as much hull girder stress as their solid counterparts. If the other stresses are adjusted to correspond to an 18 ksi average plate stress, the stress at the "hot spots" is found to be about 25 ksi.

From these studies, it can be seen that the lightening holes do have some effect on the load carrying ability of the structure. For the model used in this study, correcting the section properties to account for the effects of the lightening holes would increase the stress in the bottom structure by about 7 percent.

Since the purpose of this study was to identify potential causes of an initial failure, rather than to produce hard numerical results, this difference was not considered great enough to invalidate the results obtained from models without lightening holes. However, it does appear that the lightening holes should be included in the analysis whenever modeling time and processing power permit.

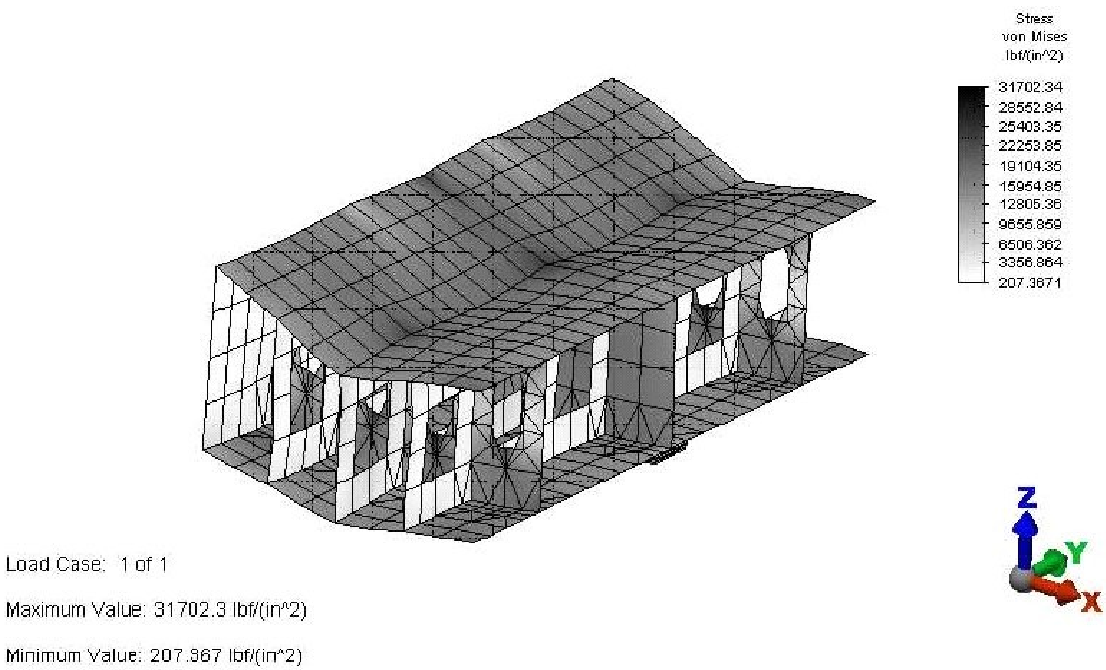

Figure 6 - Keel displacements

Summing up, the finite element studies uncovered three possible points where the breakup could have begun – the manholes aft of Frame 22, the change in slope at Frame 25, or the endings of the "extra" longitudinal girders at Frame 29. Of the three candidates, the manholes aft of Frame 22 appear to be the least likely. The change in slope at Frame 25 - which coincides with the break between the two double bottom pieces - appears to be the most likely candidate.

Once a likely starting point for the failure was identified, it had to be determined whether the failure could have progressed, in a manner consistent with survivor testimony and the physical condition of the wreck, until the ship broke completely in two. The most likely sequence is as follows:

1) At the start of this reconstruction, the ship is in its flooded condition, at least comparable to the C-7 condition mentioned previously. Bending stresses produce compressive loads in the tank top plates, bottom plates, and the side shell below the neutral axis, while deck and shell plates above the neutral axis are loaded in tension. As these forces and moments increase, a failure - most likely in the bottom plating, as discussed above - occurs just forward of the reciprocating engine room (i.e., in that part of the bottom structure which separated from the ship), probably at Frame 25, as discussed above.

2) Since there is a "hot spot" at each longitudinal, the failure of the bottom structure rapidly propagates across the full breadth of the ship. The failure progresses around the turn of the bilge, as far as a double riveted "landing" (longitudinal seam) in the side shell, which then fails over about 60 to 70 feet of the ship's length. (Landings higher up in the ship were triple riveted.) This effectively separates these portions of the bottom structure from the rest of the ship.

Because the side shell plates low in the ship, near the tank top, are farthest from the neutral axis, they fail before the structural members above the neutral axis. As the failure progresses upward, the neutral axis continues to move higher, eventually reaching a point between B and C Decks. Since these decks are reinforced by very strongly riveted strakes of doubled shell plating, one or both of these decks are the last to remain intact. This sequence is shown in Figure 7.

3) The condition of the ship at the start of the breakup is shown (in an approximate way - trim angle and waterline location are NOT to scale) in Figure 8. Once the bottom sections are separated, the weakened hull can no longer resist the applied moment, so a structural hinge forms in the uppermost strakes and the associated deck(s). Whether by coincidence or because the superstructure provided a small amount of additional strength, the upper end of the failure is at or near the aft expansion joint in the superstructure. As the hull bends, the stern of the ship comes back down into the water. As more of the stern section gets support from buoyancy forces, the hogging moment on the hull is relieved, so the failure ceases to spread. The uppermost strength decks and side shell plates remain intact. This leaves the ship in the condition shown in Figure 9.

This is as far as the available data can take us. To continue the reconstruction beyond this point, it is necessary to rely on engineering judgment, survivor testimony, and the physical condition of the wreck.

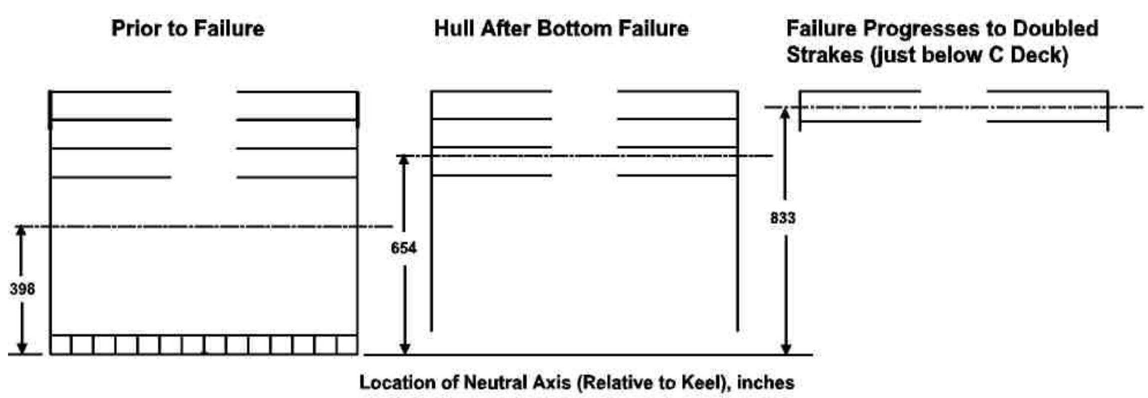

Figure 7 - Stresses and neutral axis location in the cross section

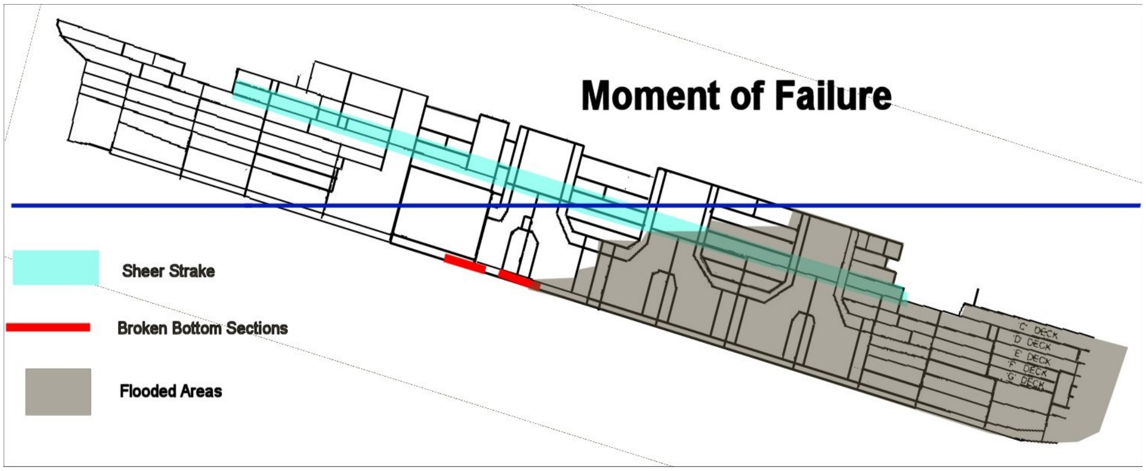

Figure 8 – Moment of Initial failure

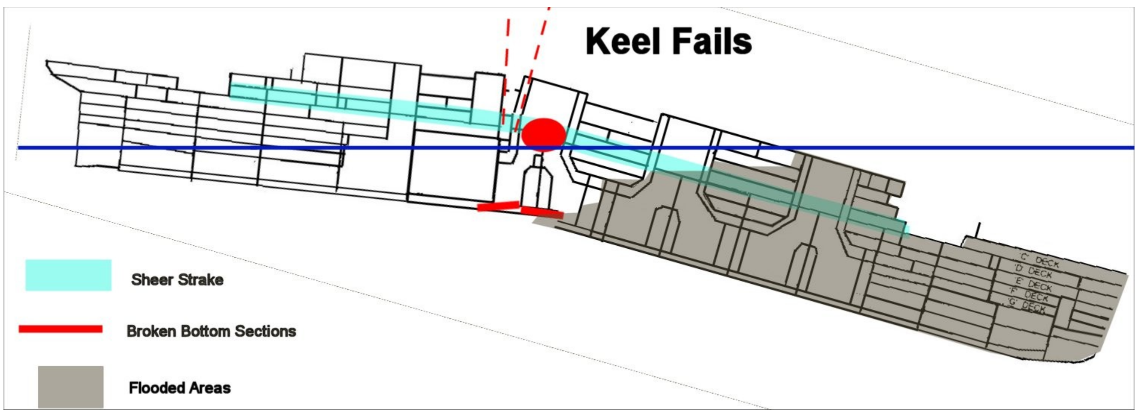

Figure 9 - Initial failure of the double bottom

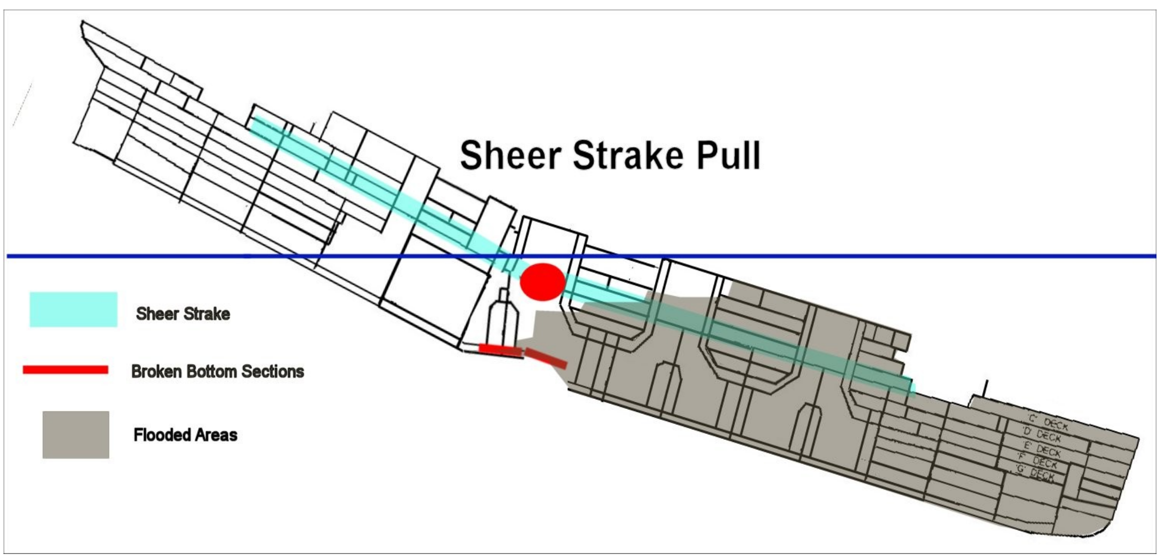

Figure 10 - The bow section pulls downward on the stern section

4) As the bow section continues to flood, it is probable that it pulls the forward end of the stern section down, as shown in figure 10. The bending moment on the remaining connections between the bow and stern sections is now reversed. Between this point in the sinking process and the time when the ship reaches the ocean floor, two things have to occur:

- The last connections between the bow and stern sections have to be broken
- The stern section has to take on enough water to continue to sink, even without the weight of the flooded bow section pulling it down.

In this reconstruction, it is quite possible for the stern section to rise to a relatively steep angle, while the bow section remains at a relatively shallow trim angle. It is not possible to estimate, with the data available, the maximum possible angle that the stern may have achieved.

PASSENGER TESTIMONY

While survivor testimony is often inconsistent or contradictory, it is worth noting that the picture of the sinking presented in this paper can be reconciled with many survivor statements - perhaps to a greater extent than any other reconstruction. This is especially true when we consider the vantage point from which each survivor watched the ship go down.

For example, survivor Elmer Z. Taylor, a mechanical engineer who witnessed the breakup from Lifeboat #5, off the starboard side, said (see Reference [3]):

“The cracking sound, quite audible a quarter of a mile away, was due, in my opinion, to tearing of the ship's plates apart, or that part of the hull below the expansion joints, thus breaking the back at a point almost midway the length of the ship.”

This description of the ship, afloat but with her back "broken," is entirely consistent with the condition depicted in Figure 9.

Pitman, watching from essentially the same vantage point, speaks of four explosions after the ship disappeared. (US p168). Peuchen, off to port in Lifeboat #6, describes three explosions just before the lights went out and no explosions after (US p200-2). Pitman and Peuchen directly contradict one other but have clarity as to the number of explosions.

Osman describes the ship breaking up and objects sliding forward from the stern and coal being coughed up the funnels with black smoke and steam. (US p.253). This supports that the break-up explosions occurred on the surface. He was in close proximity to the wreck and mentioned no underwater explosions. His descriptions were vivid for otherwise being in the dark.

Buley, who eventually joined Fifth Officer Lowe in Lifeboat #14 off the port side, states *Titanic* tipped to the after funnel, broke in two, and the stern righted itself and floated 5 minutes. (US p.268-9.) He places the roar on the surface. He stated he clearly saw the outline of the stern from 200 yards.

Steward Crowe about a mile away was less clear about times. His testimony was lucid that the ship broke and the stern settled. (US p.277). His testimony seems to associate the explosions with the stern starting its final plunge.

Alexander Littlejohn was in lifeboat 13, a half mile off to starboard. "We watched her like this for some time, and then suddenly she gave a plunge forward and all the lights went out. "Her stern went right up in the air. There were two or three explosions and it appeared to that the stern part came down again and righted itself.”

Greaser Ranger, in Lifeboat #4 off the port side, describe a break at the surface, the stern briefly rights, then sinks. Quartermaster Bright gives a similar account.

Chief Baker Joughin told the British inquiry that while he was still on board the Titanic, he heard a noise that sounded like parts of the ship buckling. He experienced some motions of the ship that are roughly consistent with Figure 9. He also speaks of the ship taking on a pronounced list. This would indicate that the breakup was not symmetrical.

Joughin's testimony is strong evidence in favor of a bottom - up failure of the hull. It would be difficult to imagine him failing to notice a top - down failure.

A bottom up failure would also explain why the engineering department suffered the most deaths percentagewise. The central command post for the engineers' activity was the Reciprocating Engine Room. A bottom up failure in this area of the ship meant that this space would have instantly flooded after the double bottoms broke free of the ship.

Second Officer Lightoller, who testified that the ship went under with her decks intact, was on overturned Collapsible B, much farther forward than most of the other survivors, and may not have had a clear view of the ship's final moments.

Some of the survivor accounts appear to describe additional motions of the stern section, beyond that shown in our reconstruction. It is for this reason that our reconstruction was not continued beyond the condition shown in Figure 10.

PHYSICAL EVIDENCE

It will also be seen that the physical condition of the wreck can be better accounted for by this reconstruction than by any other theory advanced to date.

In particular, the uppermost strakes of shell plating, with pieces of the strength deck attached, project farther aft than any other elements of the bow section of the wreck, suggesting that the uppermost shell strakes and the associated decks were among the last – if not THE last – elements to fail. The portions of the hull and deckhouse that might have interfered with the flexing of the ship are either missing or collapsed. So, while we cannot prove that this reconstruction is accurate, we have yet to see any physical evidence that cannot be reconciled with it.

The Bow section

The bow section appears today deeply imbedded in the mud at the stem and sits nearly flat on the keel at the No. 2 boiler room. A bend in the ship of upwards of 10 degrees appears in the area of the forward well deck below the bridge area. The forward bow is also skewed a few degrees to port at the same area. As the descent of the bow has been studied in other related papers, it will not be further discussed here.

A second bend in the hull appears directly under the forward expansion joint. This is significant to discussion of possible actions around the aft expansion joint during the break-up. While Titanic was still on the surface, the expansion joint opened enough with the downward bend of the bow to cause funnel stays to snap, causing the No. 1 funnel to fall forward. On impact with the bottom, the ship apparently bent briefly upward to cause the two sides of the officers quarters to slam together. The aft side of the officer's quarters bulkhead shows compression rippling. After impact on the bottom, the expansion joint reopened as the rear of the bow section settled flat.

The tear area at the rear of the bow exhibits several forms of damage. On the portside, the lower shell plate suffered a long somewhat diagonal tear through the overlapping shell plates. The sheer strake composed of the Y & Z strakes appear intact and appeared to be still connected to the stength deck (B-deck). The weight of B-deck sagging down into the collapsed lower decks pulled the sheer strake inward, twisting out the lower sections of shell plate to form a "canopy" that hung out from the side of the hull. Portions of the X strake through the 1st class dinning saloon farther forward showed that some of the sections between the large double port holes area had popped out.

On the starboard side, the shell plate bows outward from the fallen decks. Once again, the sheer strake appeared to have remained connected to B-deck, forming a "swoop" to A & B decks from side to side.

Two similarities between the two sides of the tear area are that the sheer strake maintained its integrity with the strength deck and the shell plate is separated from all lower decks going roughly 75 feet forward from the tear. The shell plate also shows a consistently vertical tear from the tank top to the sheer strake on both sides. The lateral tears to all interior decks follow a largely veritical path through the boiler uptake for No. 3 funnel. Just forward of the tear around the Grand Staircase, alternating decks have partially collapsed. The structural pillars on C & E-decks are bent and skewed, thereby reducing the orignal spacing between the decks.

In recent years, the sheer strake and strenth deck appear to have separated, altering the shape of the tear area from the configuration seen in the 1985 and 1986 explorations.

The Stern Section

The stern section has often been called a “chaotic mess” or “junkyard” when compared to the bow section. There are a large number of identifiable features on the stern that permit damage patterns to be assessed.

In general, the stern can be divided horozontally along D-deck. The watertight bulkheads running up for the tank-top to D-deck provide the bulk of structural integrity that remained after the implosion/explosion process.

Above D-deck, living areas were supported by a system of small steel pillars spaced 6-9 feet apart that were integrated into the wood walls and lighter superstructure steel work. These pillars allowed the upper decks to totter in various directions as the integrity of the decks with the shell plate failed. The 1986 explorations showed some spacing between the upper decks remained in random pockets on the forward half of stern, providing the illusion there was some height to the forward upper stern. All of these spaces appear to have collapsed in recent years and all upper decks are largely lying flat in a pile covering D-deck.

Dividing the stern vertically in half up the watertight bulkhead between the Dynamo compartment and the No. 5 Cargo compartment, other diferences between the fore and aft halves of the stern are apparent. On the forward half of the stern, the shell plate is separated from the keel for a full 175 feet going back from the forward tear. While that section of shell plate is still attached on the portside at the strength deck, it is entirely missing on the starboard side. The debris on the starboard side is mainly an assortment of smaller debris from various parts of the ship. Another consistency with the bow is that the shell plating separated from the interior decks at some point in the process over the entire area with the possible exception of the sheer strake on the portside in the area of the First Class restaurant on B-deck. In addition, a portion of the sheer strake extends forward above a diagonal tear in the lower shell plate similar to what was observed in the area of the “canopy” on the portside of the bow. Portions of B and C-decks also appear extended forward to shoud the portside of the reciprocating steam engine.

The area aft of the Dynamo compartment shows damage more consistent with implosions. The aft well deck and parts of D and E-decks appear pushed downward. The sides of the hull bend outward and down from the tanktop.

Common Damage Patterns

In early construction photos of *Olympic* and *Titanic*, the dominant features before plating began are the frames, composed of the nine-inch ribs and beams. These were channel beams and were space on three-foot centers through the center of the ship and had progressively closer spacing near the stem and stern. After plating however, the decks and shell plates had significantly more riveting to the beams and ribs respectively, such that the decks and shell plating were integral units. The connections between the decks and shell plates consisted of brackets separated by the width of a frame and the height between decks.

In numerous places over the bow and stern sections, it appears that where movement of the shell plate relative to the decks took place, these connection brackets failed. Separation of the decks and shell plates occurs over the entire stern forward of the No. 6 hold (aft most hold) and on the bow from the no. 2 funnel going aft to the tear. In all of these areas, the shell plate or the decks appear as contiguous units but there is rarely any connection to a deck except for the strength deck.

Additionally, in the bend areas of the bow under the well deck, under the expansion joint, and at a large vertical tear in the portside under the No. 1 funnel, the shell plate appears bent or broken in continuous sections that have popped off the underlying decks. The vertical tear below the No. 1 funnel also does not extend upwards into the Y and Z sheer strakes, but does run the full height from the tank top though the overlapping shell plates.

The Center Sections

Analysis alone would not have been conclusive enough to support this reconstruction. Recent photographs of two double bottom pieces, which lie on the ocean floor some distance from the hull,

Figure 11 – S-shaped bend in keel bar

provided the additional evidence needed to confirm the suspicions which our analyses has raised. One photograph clearly shows the bar keel bent into an "S" shape, consistent with bending under a large compressive load (Our calculations indicate that a straightforward buckling failure is unlikely, but a slight misalignment would produce a large enough bending moment to cause the failure.) This photographic evidence strongly supports the hypothesis that the failure began at or near the bottom.

We did not obtain permission to reproduce images from the 2005 expedition. However, that expedition was not the first to locate or to photograph the double bottom pieces. An earlier expedition had returned a photograph (see Figure 11) showing the S - shaped bend in the keel. However, the significance of that image was not realized at that time.

PREVIOUS THEORIES

It has long been believed that *Titanic* broke downward from the aft expansion joint and this was depicted in James Cameron's "*Titanic*" of 1997. This theory was reenforced by a Finite Element Analysis simulation done in 1996. Initial models of the ship showed the expected pull and compression stresses expected but no "hot spots". Later refinements added to the model included the expansion joints. These were modeled as a U-shaped cut in the hull based on an elevation plan of *Olympic* and *Titanic*. Other, more definitive plans of *Titanic*'s expansion joints, were not available to the modelers at that time. The result showed a decisive "hot spot" around the base of the expansion joint in the model and the obvious conclusion was that a break in the ship would likely have occurred there.

What the stress model did not account for was that the superstructure was well isolated from the stresses imposed on the structural hull by an Atlantic seaway. Construction details shown on plans found subsequent to the stress simulation show that the superstructure plates and ribbing were literally tacked onto the top edges of the sheer strake and were deliberately non-integral to the structural hull to reduce the ability of the structural hull to conduct any stresses to the superstructure. The simulation model did not include this and treated the entire hull upto the A-deck overhang as a uniform surface. As a result, the simulation model converted the expansion joint from being a stress relief device for the superstructure into a stress producer in the structural hull.

The lay of the wreck is not consistent with a break aft of the #3 funnel at the expansion joint. If it required the weight of the stern out of water to produce enough energy to break the ship vertically at the expansion joint, then where did the additional energy come from to produce a second knife-like break forward of the #3 funnel? Did the keel pull the stern under? The double bottom alone, once bent, could not do what the entire structure of the ship could not do. The stern would likely have broken off cleanly and floated longer.

The combination of the identified flaws in the simulation model and the condition of the wreck largely invalidate the theory of a top-down break at the expansion joint.

ROLE OF THE EXPANSION JOINTS

The analysis in this paper concludes that the expansion joints did play a role in the break-up, but it was opposite of the conclusion reached from the earlier Finite Element Stress Analysis simulation.

Rather than the ship breaking at the expansion joint on the strength deck through the sheer strake and downward, the exansion joint allowed the ship to flex slightly at those points and stresses at the keel provided the points of failure.

The superstructure of a ship is deliberately designed to **not** interact meaningfully with the structural hull. The three decks of superstructure on *Titanic* did provide a modest amount of additional stiffening in the overall cross-section of the ship. The expansion joints then represent a sudden decrease in the cross-section of the ship for the one frame at which they occur. This also represents a slight dip in the neutral axis directly above a discontinuity in the double bottom. At that point, the double hull tapers upward to include heavier bracing to support the recipricating engines. In the extreme bending situation that *Titanic* experienced, the expansion joints provided a hinge point at which compression stresses at the keel were slightly magnified. Evidence of keel compression and hull deformation is seen on the bow section radiating down from the expansion joint. The anaysis presented here indicates a similar effect may occurred at the aft expansion joint.

FUTURE DIRECTIONS

Of course, this isn't the whole story. Much remains to be worked out:

- While the analysis shown in this paper illustrating that the failure could have begun in the bottom structure, and three candidates for the initial failure were identified, the authors still cannot be certain of exactly where the initial failure occurred, or what the stress level was at the time of that failure.

Extending the finite element model across the full breadth of the ship, and extending it to encompass the entire engine room as well as all of Boiler Room #1, may make it possible to determine, with a greater degree of confidence, where the failure originated. The model would be further enhanced by including elements of the engines themselves, since the aftermost break runs through the engine foundations, and portions of the engines were found in the debris field.

- It is not possible to determine the maximum angle to which the stern section may have attained before going down. Previously calculated limits on the trim angle were meant to apply to the ship as a whole. If the bow section submerged before the stern section began to rise out of the water, then the stern could have assumed almost any conceivable trim angle, while the bow could have remained at a relatively shallower trim angle.

- Some stern compartments beyond the Reciprocating Engine Room may have flooded gradually, but survivor testimony and the condition of the wreck suggest that some compartments imploded as they were pulled below their crush depth[2]. The decks and sides of the stern section also suffered extensive damage which has not yet been explained. Details of the processes by which this damage occurred remain to be developed.

- The failure mechanism by which the "Big Piece" separated from the rest of the wreck remains to be identified. It is difficult to envision any single stress condition that could have produced the failures we see in this portion of the hull, but it is conceivable that the failures on the various edges of this piece could have been produced at different times, by different loads, while this portion of the hull acted as a structural hinge joining the bow and stern sections. The deck and/or side shell plating on one side of the ship may have failed before the other - this would account for the absence of a mirror image of the "Big Piece" on the other side of the hull. Also, a connection between the bow and stern on only one side may have generated a moment tending to rotate the stern as it sinks, possibly accounting for its present orientation on the ocean floor.

- A more extensive reconstruction of survivor testimony, taking into consideration the vantage point from which each survivor saw the sinking, may permit a more complete reconciliation of the testimony of each survivor with the overall sequence of events.

CONCLUSIONS

As *Titanic* tipped about 15-17 degrees during the final plunge on the morning of April 15th, 1912, a failure occurred either at the keel or in the keelson bracing flanking the tank top. Either way, both failed and the ship began a catastropic break-up sequence that separated the ship into two main sections at or very near the surface. The physical and forensic evidence points directly to a bottom-up failure in the hull girder. Analysis of the current condition of the wreck and the ship's construction indicates that the top two sheer strakes (Y and Z strakes) likely broke last following a widespread pattern of structural failures in the lower hull and decks.

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FOOTNOTES

1The "Big Piece," a 22-tons section of Titanic's side plate comes from a portion of the ship several feet forward of the second expansion joint and centered around the sheer strake.

2Red cork appeared on the water surface shortly after the stern disappeared. Cork was used as an insulating material in the refrigeration spaces that were located in the stern section.