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Failure Analysis of Texas Tower No. 4

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ABSTRACT

The Texas Towers were a series of platforms installed off the U.S. East coast in the 1950's to support early warning radar facilities. Texas Tower No. 4 (TT4) was installed in a water depth of 185 feet in 1957. At this time, TT4 was heralded as an 'engineering marvel', a major innovative ocean engineering accomplishment. However, problems in the structural integrity of the platform developed after the installation. In spite of vigorous efforts trying to save the platform, TT4 failed during a storm in January 1961 with the loss of the lives of all 28 personnel that were onboard at the time. This was one of the famous incidents during the early age of Ocean Engineering. In 2000, a study was undertaken by the authors together with the American Bureau of Shipping who pooled their resources of information and insights into platform behavior and experience to revisit the failure of TT4. The objective of this study was to see if with modern ocean engineering technology (storm forces, structure capacities), the details of failure of the structure could lead to a better understanding of behavior of current platforms where there is a paucity of actual failure. This paper summarizes the results from this study and the associated study of human and organizational factors in the life-cycle of what was, at the time, an innovative deepwater structure.

INTRODUCTION

The Texas Towers were a series of platforms installed off the U.S. East coast in the 1950's to accommodate early warning radar facilities. Texas Tower 4 (TT4) was installed in a water depth of 185 feet in 1957. At this time, TT4 was heralded as an 'engineering marvel'; a major innovative ocean engineering accomplishment. But, shortly after it was installed, unusual motions and sounds were reported by personnel onboard the platform. Studies were commissioned to measure and analyze the dynamic motions. The second author was a graduate student at this time and assisted with the analysis of the motions of TT4 conducted by Brewer Engineering Laboratories[6].

Studies of the dynamics indicated that bracing and joints were not as effective in stabilizing the platform as had been anticipated during the design of the platform. Pinned joints and some damaged braces were identified as likely responsible for the excessive motions. Underwater inspections later confirmed these results and supplemental bracing was installed in an attempt to stabilize and strengthen the platform. In September 1960, a hurricane further damaged the platform; fracturing underwater braces and joints. In December 1960, the decision was made to evacuate TT4 for repair, but before this could be done the platform was hit by a winter storm in January 1961 and collapsed into the sea with the loss of the lives of all personnel onboard.

Subsequent to the failure, extensive underwater surveys identified many of the factors that were responsible for the failure of TT4. These were presented into a Congressional Committee hearing evidence investigating the collapse[1,2,3]. The second author was again involved in a study of the failure; this time as a platform design engineer for Shell Oil Company. The story that emerged from this study was a lesson in the dangers of engineering innovation and hubris, and organizational malfunctions. While the platform failed directly due to the loads developed by a storm, the elements that were responsible for the failure were deeply rooted in Human and Organizational Factors (HOF).

The objective of this study in early 2000 was to see if with modern ocean engineering technology (storm forces, structure capacities), the details of failure could lead to a better understanding of behavior of current platforms where there is a paucity of actual failure. This paper summarizes the results from this study and the associated study of HOF in the engineering design of this innovative deepwater structure.

DESIGN AND CONSTRUCTION OF TT4

Texas Towers, so-called because of their resemblance to oil drilling platforms in the Gulf of Mexico in 1950's, were huge manned platforms designed to serve as radar stations (Fig. 1). Five towers were originally planned to be built off the Atlantic coast, extending radar coverage seaward. Only three were eventually built: TT2, TT3 and TT4.

The feasibility of installing radar platforms, similar to oil-drilling rigs employed in the Gulf of Mexico, was first studied by the Lincoln Laboratory at Massachusetts Institute of Technology in 1952. Lincoln Laboratory concluded that a cluster of such Texas Towers might serve air defense purposes if erected about 100 miles off the northeastern coast of the Atlantic seaboard. Being fixed installations, Texas Towers could accommodate heavy duty, long-range radar units like those used on land, instead of lighter and shorter range sets used aboard picket vessels.

Air Defense Command agreed with Lincoln Laboratory's recommendation that five Texas Towers be built. Lincoln Laboratory selected five sites for positioning the radar platforms that stretched from south of Nova Scotia to offshore New Jersey. TT4 was the southern most location in 185 feet of water and 84 miles southeast of New York City. In 1953, U.S. Air Force (USAF) authorized construction of Texas Tower No. 2, 3 and 4.

Located in a site where the water depth was about three times that at the sites of TT2 and TT3, TT4 had a completely different 'innovative' design and construction procedure. TT4 had three large diameter (12.5 ft) vertical steel legs interconnected with three tiers of horizontal K-bracing underwater (Fig. 2). Installation of TT4 was based on a self-floating tripod substructure that would be towed to location, upended and attached to the seafloor with large caisson footings, which would provide significant foundation fixity given the site's soil profile. A self-floating deck would be towed to location, maneuvered into the legs, attached to them and then the deck would be raised to the top of the legs where it would be permanently attached to the legs. Another thing unusual about TT4 was the use of pin connections in the underwater bracing system. This decision, made by the design engineers, was based on the grounds that the pin connection would eliminate secondary bending stresses because of its lesser rigidity.

The U.S. Navy was responsible for design and construction of the towers. Under the supervision of the Navy Bureau of Yards and Docks, TT4 was designed by the engineering firms Moran, Proctor, Mueser and Rutledge of New York City, and Anderson-Nichols and Company of Boston. It is noteworthy that none of these design firms had any significant ocean engineering experience. They were very experienced civil structural and geotechnical engineering firms. Construction contract for TT4 was awarded to J. Rich Steers, Inc. of New York City in collaboration with Morrison-Knudsen, Inc., of Boise, Idaho. This construction team was very experienced in heavy civil construction, but had no significant ocean construction experience. The finish of installation of TT4 on July 8, 1957 was widely regarded as an engineering triumph at that time; this was an innovative deepwater structure that involved significant extensions of the existing technology. After an inspection, the USAF accepted the tower from the Navy and the contractors and became the final user and responsible for the maintenance of the tower.

DETERIORATION AND FINAL COLLAPSE OF TT4

The Navy, design companies and construction contractors were proud of their engineering achievements when the tower was transferred to Air Force. However, only 3 years later, 14 Air Force personnel and 14 civilians lost their lives when TT4 fell into the ocean on January 15, 1961.

The aftermath investigations showed that defects, deficiencies and inadequacies inherent in the design and construction procedure sealed the fate of TT4 from the very beginning. TT4 was a tremendous 21-million-dollar (1957 value) project that went wrong[1,2,3].

In the process of towing TT4 to site in June-July 1957 (Fig. 3), two diagonal braces, vital to the structural integrity of this huge tripod, were lost in a storm. The contractors, design engineers and the Navy Bureau of Yards and Docks decided to improvise repairs, replacing the lost diagonals at sea rather than return to shore for complete repairs. Consequently, the original design strength was not restored, even though the contractors and engineers thought that the repairs were effective. Later developments demonstrated that the tower structure was actually in a weakened condition due to this improper repair from the very beginning.

From the time it was erected, notable motion of the structure became the rule rather than the exception for Texas Tower 4. Alerted by this structural degradation, the Navy, requested by the Air Force, conducted underwater inspections of TT4's jacket structures in late 1958, resulting in the discovery that certain collar connection bolts, which hold the pin connections to the replaced diagonals, either had sheared or worn loose. The problem was aggravated because the defective portion weakened, not only in its immediate area, but also shifted considerable stress onto non-defective members. From late 1958 to May 1959, with at least six interruptions due to storms, the contractor finished repairs that stabilized the platform's motion for several months. Four successive storms struck in the winter of 1959-1960, bringing back the motion again. Table 1 summarizes the history of storms that affected TT4 from August 1958 through January 15, 1961[3,4].

In early 1960, another underwater team was sent down to inspect the structure and found certain pin connections damaged beyond repair. Then a set of above-water X-bracing was manufactured and installed in August 1960 (Fig. 4). According to the contractors and design engineers, original design strength was restored to TT4; it could withstand winds up to 125 miles per hour and breaking waves up to 35 feet high[1,2]. Hardly a month later, however, Hurricane Donna (September 12, 1960) whirled in with conditions and forces exceeding the design specifications: 132 mile per hour winds (gust) and breaking waves exceeding 50-foot height. TT4, without evacuation of all personnel (no time for evacuation because of the fast advance of the hurricane), survived Hurricane Donna, but not without first shaking and rocking a great deal from the impact of the hurricane and suffered heavy structural damage. A part of TT4's superstructure was destroyed; worst of all, underwater braces were fractured. Further examination of above and below-water components resulted in a decision to undertake extensive repairs in the spring of 1961. February 1, 1961 was established as the date for complete evacuation of TT4.

Meantime, a maintenance crew of 28 personnel (14 USAF and 14 contractor repair personnel) were stationed aboard to perform certain repair work. In December 1960, one winter storm struck TT4, causing more damages to all the above and below water bracing on the AB side so that panels of braces between Leg A and B were effectively not functional. Then on 14 and 15 January 1961, TT4 was again caught in a winter storm that battered the tower with winds up to 85 miles per hour and waves up to 40 feet high. The final moments came at about 19:20 PM the night of January 15, when one of its three legs failed; the remaining two thereupon also collapsed, and the platform, with all hands aboard, sank to the ocean's floor (Fig. 5).

INVESTIGATIONS AFTER THE INCIDENT

As there were no survivors from the incident and the failure investigation didn't reveal the exact failure path in the structure. How TT4 failed remained a question to the present time[1,2]. Congressional and Air Force investigations of the structure failure concluded that there were many possible failure scenarios[2,3]. Still, the Congressional hearing after the collapse of TT4 made some general conclusions about why this tragedy happened. Besides pointing the human and organizational malfunction in judgment leaving personnel on board at risk in winter storms, the congressional hearing report also summarized several technical factors leading to TT4's final collapse.

Firstly, the design criteria for environmental loading were not sufficient[1,2,3]. The Navy Bureau of Yards and Docks working in cooperation with the Woods Hole Oceanographic Institute (WHOI) and the structure design engineers determined the design criteria of environmental loads based on the 20-year accumulation of wind and wave charts of WHOI. Three design load cases and one towing operation load case were specified (Table 2). The design engineers' report indicated:

> *"Under hurricane conditions with high wind velocities, it is not probable that waves over 40 feet will occur. It is, however, definitely possible under these high wind conditions that the waves will be unstable and will be breaking due to wind forces and independent of bottom drag conditions."*

Understandably, these criteria definitely can not be considered adequate from the modern engineering perspective. These criteria were even regarded low by the investigating engineers at the time[1,2,3]. The wave hindcast predictions at the time were not as accurate as what we use today. Also, engineers' knowledge about the formulation of the wave forces on offshore structures was still limited at that time.

To experienced ocean engineers and mariners now, the design conditions in Table 2 were clearly inadequate both in selection of the storm criteria (20 years vs. 100 years that would now be considered appropriate), and in the physical estimate of wave heights, where a much higher number would now be picked for that region. The storm, wind, and wave force calculation procedures specified by WHOI were similarly inadequate also somewhat less than used in current thinking. The drag and inertia coefficients were based on results from laboratory tests on 'smooth' element (with drag coefficient C_d = 0.4, and inertia coefficient C_m = 1.5)[5]. These values are considerably lower than today's current values (0.65 and 1.6 respectively)[15]. This led to important underestimates in the environmental loading to which the tower would be exposed during its anticipated 20-year life in the Atlantic Ocean. Hurricane Donna (September 12, 1960) definitely exceeded these design criteria. It was a category 4 hurricane with a gust wind speed of about 132 mph and a wave height greater than 50 ft at the TT4 site. Also, there is no indication in the available documents that dynamic effects, which is an essential part of the standard modern design practice, were considered in the design of TT4 at the time. But what happened later proved that dynamics developed from the loose pin connections on TT4 played a major in its collapse.

Secondly, there were important and unanticipated changes to the original design[1]. During fabrication of TT4, the construction contractors requested several changes that deviated from the original design due to manufacture difficulties. The structure could not be built as envisioned by the designers[1,2,3]. The design engineers and the Navy's Bureau of Yards and Docks approved these changes. Such changes had several major consequences that later proved to be the source of structural problems for TT4:

In permitting the substitution of the original temporary construction platform with the permanent deck platform, it meant that the permanent platform would be jacked up above the water before legs had been embedded into the ocean floor and before any concrete stiffening had been placed in the legs.

Without the legs first being embedded, there was insufficient draft above the upper panels of bracing (at –5 feet) to float the deck platform (with a draft of about 11 feet) into position between them. For this reason, the upper panels of bracing had to be folded down in the initial stages of construction to be connected later underwater.

In order to fold down the upper panel of braces, an increase in the tolerance between the pins and sockets into which they were to be inserted was granted. Difficulty in fabrication of the pinned joints had required an increase in tolerance from 1/64 inch to 1/16 inch. For the upper panels of bracing this was further increased to 1/8 inch. What happened later showed that this decision initiated a chain reaction that directly contributed to the structural deterioration of TT4.

Other unexpected changes were: the water depth was actually found to be 185 feet instead of 180 feet as thought at the time of marking the spot by buoy; and the tide was 3.5 ft instead of 1 ft. These facts led to reduction of foundation footing depth from 20 ft to 18 ft and platform elevation from 67 ft to 66.5 ft.

Thirdly, there was mishandling of data due to limited knowledge in the installation procedure[1,2,3]. The patented Cuss method (by Mr. Theodore Cuss, who was the chief designer of TT4) of erecting offshore structures was used to install TT4. The method of lashing the folded braces had insufficient strength to resist the environmental loading. The tie-down calculation did not lead to a design that can stand the environmental loads and secured the braces in position during towing.

The template (consisting of three legs and their permanent and temporary bracing) and the permanent deck platform, were towed separately to sea from Portland Harbor on June 28, 1957. The template was floated in a horizontal position resting on the A-B side. A storm that didn't exceed the criteria for the towing operation occurred at the site, which delayed the upending process. After the storm, it was discovered that the two folded diagonals in the upper panel of braces on the AB side (frames between Legs A and B) had broken loose from their lashings and were damaged. During the upending process, these diagonals sheared off at their connecting pin plates and were lost. On-site repair was decided to replace the lost braces, which failed to restore the structure's design strength. Considering what happened later, this was a grave engineering mishap for TT4.

Fourthly, initial damage repairs were not successful[1,2,3]. The design changes, inadequate tie-down design and underestimate of environmental loads mentioned above were the direct reasons for loss of two diagonal braces during the towing and upending operation. The decision to repair this damage by replacing the diagonals at sea was made jointly by the Navy officers, contractors and design engineers. To do these improvised repairs at sea, the design engineer designed a collar connection encircling legs A and B as a means to secure the replacement diagonals to the legs. Dardelet bolts having a serrated shank were inserted through the collars into the legs to keep the collars from moving vertically along the legs. This design placed too much reliance upon underwater diver-repairmen working under adverse conditions. The Dardelet bolts, viewed by some as nothing more than a temporary device, were considered a construction deficiency[1,2]. The above fact was stated in the Congressional hearing report. It is understandable that the designers, contractors and Navy officers were under pressure to avoid delay of installation. The decision to make improvised repair on site is a typical human and organization error in decision making.

The three legs were also damaged during installation when the deck platform was towed into the position between the three legs. A sea swell of 3 feet in height caused the deck to dent the three legs, the indentations being an average of 10 feet high, 6-8 feet wide, and about 10-12 inches deep. The final position of these dents was about 10 feet underwater after embedment of the footings. Steel reinforcement was applied at the dents to strengthen the legs. After these repairs, the tower still moved violently when Air Force accepted it in 1957. The tower was actually in a weakened condition, as the original structure design strength had not been restored.

Fifthly, the continuing repairs could not keep up with the accumulation of damage due to inherent design deficiencies.[1,2,3,4] The larger tolerance in pin sockets introduced during fabrication and installation allowed movement of pins in the sockets. This movement under constant wave load kept wearing off the pin joints thus the structural integrity of TT4 deteriorated gradually. With the loose pins, the natural period of the structure became longer thus subject it to further impacts from dynamic effects and accelerated the damage by secondary impact stress during the motion. The Navy, designers and contractors recognized this deterioration due to dynamics and tried hard to restore TT4's strength by constant repair. But their effects could not keep up with the pace of structure strength degradation. Eventually some pin connections were found damaged beyond repair by environmental loads.

By summer of 1958, Air Force personnel on board reported considerable movement of the tower with frequencies of 15-18 cycles per minute (cpm), although in relatively calm sea with the maximum wind speed and wave height were about 30 knots and 15 feet respectively[3,4]. The frequency of the horizontal oscillations gave some clues as to the stiffness of the tower (design frequency was 37 to 46 cpm). The analysis engineers led to the conclusion that the upper tier of bracing on the A-B side was not functioning. It would take 2 to 3 inches deflection of the platform to fill the gap in the loose pins and bring the diagonals into action. In late 1958 and early 1959, these loose pin connections were repaired and the Dardelet bolts were replaced by T-bolts to fix the loose collars. According to the design engineers, it was estimated that, if the tower leg steel were stressed to the yield point, the tower could stand a 125mph wind combined with 36 ft non-breaking wave or an 87 mph wind with a 67 ft wave[1,2]. It was said that this repair reduced the tower movement to a lesser magnitude than at any time since the installation[3].

However, within less than one year, the motion of the platform became excessive again[6]. This time, divers reported the pin connections had loosened from 1/8-inch tolerance to as much as 1 inch in some cases. These loose pins and worn connections became a cause of considerable concern to the design engineers who thought no remedy could be proposed to remedy this design deficiency. This led to the installation of above-water X-bracing, which was called by Col. DeLong (an expert in offshore engineering at the time who got involved in the construction and design of self elevating offshore drilling rigs) during the congressional hearings "a desperate move to save TT4". The X-bracing was installed in the area producing maximum resistance to the passage of waves (from 9 ft above water to 59 ft above water), thus causing additional wave force. But the effect of the bracing in strengthening the structure was questionable.

One month after the installation of X-bracing, Hurricane Donna caused extensive damage to the structure of TT4. These included cracks and fractures in the X-bracing, one broken diagonal connection in the top tier of bracing, two torn-loose diagonals in the middle tier, all on A-B side. At that time, no qualified person could or would assess the true damage caused by Donna in terms of remaining tower strength, or what the tower might withstand in terms of wind and waves. Before any really effective repairs were done, one more storm in December 1960 hit TT4, breaking one more diagonal connection in the lowest tier of bracing on the A-B side. By this time, the whole bracing system on A-B side was ineffective. The design engineer was unable to give any estimate of the remaining strength of the tower. The storm on January 15, 1961 destroyed TT4 while it was in a very weakened condition.

Sixth, use of pin connections on TT4 was an innovative 'solution' to a technical analysis problem[1-4]. According to the design engineers, the decision to use pin connections was based on the grounds that the pin connections would eliminate secondary bending stresses. Due to limited knowledge at the time, there were no feasible means to analyze the structure to determine the magnitude of the secondary stresses in the joints. This was conventional practice in design of bridges (The design firm was very good in bridge designs). Among all the design decisions, use of pin connections on TT4 was very controversial during the initial design stage. Some engineers (including Col. Delong) voiced very strong objections to the use of pin connections on the basis of the fact that "the sea never gets tired", its constant random motion would only serve to cause wear of the pin connections. In addition, designers of the fixed platforms in the Gulf of Mexico used fully welded connections at that time to eliminate this problem; in most cases they used 'extra steel' to assure that the secondary stresses could be carried without overstressing the joints.

The increase of fabrication tolerance between the pin and its socket made the pinned connections ineffective; the loose pins caused secondary impact stress in the connections and the connections wore quickly. This wear reached such an extent that very large platform deflections were needed to make the diagonals functional. For small deflections, the diagonals moved back and forth in the loose pin connections without any contribution to the structure strength. The effective stiffness of the tower was reduced significantly from that originally anticipated in the design. The accelerating accumulation of wear of these pin connections was a major factor causing the deterioration of TT4 strength.

DATA COLLECTION

As there were no survivors and the aftermath inspection didn't reveal the exact failure mechanism in the structure, the failure investigation during the congressional hearing did not lead to any decisive conclusions on exactly how the structure had failed[1,3]. The purpose of this study was to see if based on the application of the latest technology on storm wind, wave, and current forces and on the ultimate limit state performance characteristics of the structure if an accurate hindcast could be developed to explain how the structure failed.

The first task of this study was a collection of structural and environmental data related to TT4[4-11]. An extensive survey was conducted to gather as much related information on TT4 as possible. This information included: structure design information including configuration, material properties and design conditions and forces; construction information; structure damage and repairs before the final failure, information on the storms that affected TT4 including environmental parameters, loading characteristics, and structure motion characteristics.

The major sources of technical data for this project were: "Design and Construction Report on the Texas Towers Offshore Radar Platform" by the Navy, design engineering and contractor firms (referred to as Design Report in the later chapters of report)[5]; "Final Report – Motion Analysis of Texas Tower No. 4" by Brewer Engineering Laboratories (referred to as Motion Study Report later in this report)[6]; and congressional hearing reports[1-3]. In addition, personal documents from members of Texas Tower Association (TTA)[11] and scuba clubs in New York and New Jersey[12]; National Ocean and Atmospheric Administration (NOAA) oceanographic database; and Mariners' Weather Log were obtained[7-10]. The TTA was particularly helpful in providing many documents and discussions that filled in missing parts of the information required to perform this hindcast study[4-11].

STRUCTURAL INFORMATION

TT4's original configuration is shown in Fig. 2[5]. The substructure is an equilateral triangular platform (distance between each leg center is 155 ft, the length of each side of the triangle deck is about 187 ft). The platform topside weighed between 5500 and 6000 tons with all equipment onboard[5]. The jacket and footings, comprised of legs, K-bracing and footing caissons, add an additional 1800 tons to the total weight. As installed, the A-B side of the tower was on a bearing of N. 26 degrees E.

The lower deck elevation of TT4 was 66.5 ft above water. This 66.5 ft elevation would provide clearance for a 92 to 96-ft high storm wave and associated surge, which is much larger than any wave that was experienced during the service life. The height of the lower hull was 20 ft. The height of the upper hull was 15 ft. The heights of the two lower radar domes were 35 ft. The height of the base for the center radar dome was 28 ft and the diameters of radar domes were 53 ft.

The legs of TT4 were steel tubes 13/16-inch thick, with an outer diameter of 12.5 ft. A concentric 8-ft diameter tube extended from the top of the legs to 50 ft below the surface of the water. It was between these two tubes that stiffening concrete was poured to provide greater rigidity. The lower part of the leg was used as ballast tanks during installation and fuel tanks after installation, so it was not reinforced with concrete. This section is the weak part of the leg, which broke near the footings during the fatal storm, according to the investigating divers. As to the deck and leg connection, vertical deck loads were transferred by 8 K-braces bolted to the legs just above the lower deck. The legs were also laterally welded to the lower and upper decks. This leg to hull connection was strong.

The pin-connected K-bracing systems of TT4 were installed below water at depths of 25 ft, 75 ft, and 125 ft, the horizontal braces being affixed to the legs at those levels with the diagonal braces extending from the midpoint of each down to the legs and next lower horizontal brace.[5] The diameter and thickness of the primary horizontals and diagonals in the upper tier of bracing were 2.5 ft and 1 in, respectively. The inner secondary horizontals have a diameter of 2 ft. The horizontals and diagonals in the middle and lower tiers of bracing have the same diameters as those in the upper tiers but the wall thickness of these braces is 0.75 in. After Hurricane Donna, above-water X-bracing with the same cross-section parameters was added between +9 ft and +5ft.

The concrete footings beneath each leg were 25 ft diameter, that were sunk and embedded into the ocean floor to a depth of 18 ft. The seabed was uniform very compact / dense sand. The design of these footings was proved sufficient. During the inspection after the collapse of TT4, divers found the footings intact, without any evidence indicating movement, scour or failure[1,2,4].

The underwater observations of the wreck after the incident revealed that leg A broke at approximately the bottom of the concrete filling in the leg (50 ft depth)[1,2,4]. The other legs (B and C) broke at the bottom of the lower deck. Just above the footings, Leg A and C fractured, while Leg B bent without tearing. Braces were all torn loose or broken, the platform rotated slightly counter-clockwise, and moved ultimately 200 yards to the southwest. These findings and limited divers' reports gave no significant evidence to determine the failure mode or to support a positive cause of failure.

Several sources provided useful information about the structure conditions of TT4 on January 15 before it collapsed. The known damage on the A-B side as of January 15 were: cracks in above water X-bracing, a broken diagonal in the upper tier of the underwater bracing, a fractured horizontal brace in the second tier, a broken diagonal in the lowest tier and loose pin connections in the first and second tiers[1,2,4]. The communication between the tower and the shore base indicates that it was "likely" a repaired horizontal brace in the second tier failed at 10:30 am on January 15. Thus the bracing system between the Legs A and B might be ineffective over the full height of the jacket structure. After that, the tower "was gyrating" in excess of 2 ft. At 17:45, the commander on board inspected the above-water X-bracing and reported 20-in crack in the X-bracing vertical plates[3,4].

ENVIRONMENTAL INFORMATION

A list of storms and hurricanes that affected the TT4 site during 1958-1961 is summarized in Table 2.[1,4] While there does not exist any eyewitness reports of the conditions at TT4 that caused its failure, there are other sources that provided relatively accurate environmental data[4,6-10]. The aircraft carrier Wasp that was summoned to evacuate the tower and was rushing to TT4 reported several series of unusually big waves between 18:00-19:30 when it was 18.5 miles from TT4. Other sources of environmental data include reports from the supply ship AKL-17 (11.5 miles from TT4), communications between TT4 and people onshore at about 19:15, and weather and sea forecast reports from nearby Air Force bases. At about 1920-30, TT4 collapsed suddenly. It disappeared from the radar screen of AKL-17. Based on all the information available, it was concluded that the maximum prevailing weather at that time consisted of sustained winds of approximately 65 knots and waves of 35 to 40 feet. The wave period was reported to be approximately 10 seconds and surface current speeds in the range of 2 to 4 feet per second were reported by the ships in the area.

The water depth at the site of TT4 is 185 ft. The location was called by the design engineers "unnamed shoal offshore New York". The soils at the sea floor were uniform very compact /dense sands. The marine growth in that area, based on the divers' inspection, had a thickness of 1 to 3 inches in the range of 0 to –90 ft[4]. According to the design and construction reports, the current on site was up to 6 ft per sec and had an approximately constant profile from mean sea level to the sea floor. The astronomical and meteorological tide/surge was up to 5 ft. Hurricane Donna imposed heavy damage on TT4, which contributed to its ultimate collapse. Environmental data of Donna was also collected to calibrate and analyze the damage conditions prior to the storm that caused TT4's collapse.

Failure Analyses

Two computer programs were used to perform the structure analyses of TT4: TOPCAT[12,13] and EDP[14]. TOPCAT is an ultimate limit state - limit equilibrium structure analysis program. EDP is an advanced finite element analysis program. Both of these offshore structure analytical tools have extensive verification and calibration pedigrees that have addressed both storm loading and structure – foundation capacities.

Environmental Load Calculation

Two load cases were analyzed in detail: the fatal winter storm on January 15, 1961 and Hurricane Donna. The environmental parameters for these two storms are summarized in Table 3. Both TOPCAT and EDP were used to calculate the wave-current loads on TT4. Results from each program were compared to verify the validity of the analyses. Wind forces were calculated by TOPCAT. Environmental load calculations were also calibrated by comparison between the results from these modern analysis tools and the original calculations by TT4's design engineers.

Aerodynamic forces

Sustained wind speeds were used to compute the global wind loads. Gust velocities were used for the calculation of individual structural elements. TOPCAT prediction of wind force for the design load case (125 mph wind + 35 ft wave) was verified against the calculations by TT4's design engineers. The results agreed within 6%.

Hydrodynamic forces

In TOPCAT, standard values of wave force coefficients C_d and C_m suggested by API guidelines[15] for tubular structure members were used. The EDP analysis model used modified values of C_d and C_m; C_d and C_m are functions of marine growth, Keulegan-Carpenter Number and Reynolds Number[14,15]. Wave-current forces obtained by TOPCAT and EDP were within 9 %.

An interesting finding from the storm load analyses was that based on using the same environmental parameters, modern analysis software, such as TOPCAT and EDP, predict slightly smaller wind loading than the original calculation by the TT4's designers, but larger wave-current loads (by about 6-10%). TT4's designers might underestimate the environmental force due to the limited knowledge at the time, but their results were not very far away from the ones obtained by modern recipe.

TOPCAT Analyses

TOPCAT model was used to estimate the ultimate capacities of TT4 in the worst damage scenario – all bracing systems on the A-B side not functioning. In this scenario, with the wave and wind load direction parallel to A-B side, TOPCAT predicted that the K-bracing systems on the other two sides would fail when TT4 is loaded by the fatal storm In this worst damage condition, TT4's jacket was reduced to unbraced portals. This portal structure could not stand the storm loading and the legs totally failed, thus causing the collapse of the platform.

Hurricane Donna Cases

Two load cases of Donna (end-on and broadside loading) were studied using TOPCAT. The diagonal and horizontal braces were predicted not to fail, which is consistent with the inspection after Donna. The braces were strong structural members themselves. According to structural analysis by TOPCAT, these braces have high compression and tension ultimate strength (in the range from 1600 kips to 2800 kips). Analysis results from EDP program confirmed this conclusion. The maximum material utilization in API code check of these braces obtained by EDP never reached 1.0, even for the worst damage cases studied

On the other hand, extensive fractures were reported by divers at the pin connection details. TOPCAT can only model weld tubular joints for conventional offshore platforms. It does not have the ability to model the failure mode at the pin connections. Also, because no detailed information about these pin connections can be found in the available references, a detailed study of these connections is not possible in this project. It was thought that these connections were well designed in the initial design. The connection failure on A-B side was mainly due to the engineering misfortune during installation procedure and the unsuccessful repairs thereafter. There was no report in available references that indicated damage of pin connections on the other sides of the platform. In general, the failure of bracing systems on TT4's A-B side was not due to the failure of braces but due to the failure of over-stressed pin connections. It was a problem of damage accumulation – and subsequent deterioration in the natural period of the platform exposing it to have a natural period closer to those of the winter storm waves.

EDP Analyses

The failure analysis of TT4 by the EDP program was divided into 3 stages: verification of structure model, failure analysis by linear model, and failure analysis by nonlinear model. The major cases studied in these stages are:

1) Model building and verifications (Original structure configuration, no X-bracing):
2) Linear Failure analyses
3) Nonlinear failure analyses.

A series of Eigensolutions of TT4 in different situations was studied. The natural period predicted by EDP model (no X-bracing, intact structure, fixed foundation) was 2.0 sec, while the original calculation of natural period by the design engineers was 1.3-1.6 sec [5]. The difference in the natural period calculations was primarily due to different methods in determining the mass of the structure. The total mass by the design engineers was around 7500 tons. The designers omitted the hydrodynamic added mass and did not include the mass of water in flooded members. The EDP model automatically generates these masses and thus adds an extra about 3200 tons to total of about 10800 tons. A set of different fixity values were used in the sensitivity study. The best estimated footing fixity value was obtained and used in the analysis. Results from Brewer Engineering Laboratory's motion study of TT4 was used to verify the EDP model [6]. The study measured the natural period, motion, and stress of TT4 during 1958-59, when the upper K-brace tier on A-B side was not functioning. During that period of time, wind was up to 65 knots, wave height up to 30 ft, and no X-braces installed. The Brewer Engineering Laboratory results were:

- Translational period: 17 – 23 cycles per minute (cpm), ie. about 3 sec period
- Torsional period: 23 – 24 cpm, i.e. about a 2.5 sec period;
- Measured maximum movement: 3 inches translation and 0.1 degree rotation.

Results from the EDP model were compared with these measurements for model verification. The agreement between displacements and motion periods was very good. The results showed that the structure damage played a more important role than potential changes in foundation fixity and deck stiffness. It was also noted that with the damaged upper K-braces, the mode shapes changed. The primary mode became a combination of rotation and translation; the difference between the first and second mode periods was much larger.

Comparison was also made between the cases of fixed and pinned foundation to reflect the boundary rotation restraint effects. It was found that the differences were not as big as expected. The leg vertical bearing forces resist a large portion of the total global overturning moment. The total resisting bending moments in three legs is only 15-20% of the total overturning moment. This was the reason why the change of rotation stiffness at the foundation does not play a significant role in the Eigen solutions. This implies an insensitivity of the structure response to the foundation's rotational boundary condition.

The footing foundation stiffness was estimated using the equations for foundations supported by elastic half-space. For TT4's embedded footings, a correction factor reflecting the effects of embedment was applied.

Because of the big diameter of the platform leg, the brace member length in EDP code check model is taken as the pin to pin length, not as the default node to node length in usual finite element analysis models. This difference in member length is reflected in the member slenderness.

In a sensitivity study, two special cases were studied: all connections are pins and all connections are fixed. The Eigen solutions of both cases show very small differences. This implies that the change in stiffness of structure due to brace moment continuity is not big. And the secondary bending moments at the fixed connections are small, which contradicts the original argument of using the pin connections by TT4's design engineers

Equivalent mechanical properties of composite steel-concrete legs were developed. Special attention was paid to make the composite elements in EDP model have the right cross section properties, elastic modulus E, strength, stress-strain curves, and the correct weight density.

P-Δ effects in the linear model were simulated by adding P-Δ springs to each leg. These effects are simulated in the nonlinear model by the internal geometric stiffness of the beam-column and strut elements.

Linear Analyses

All the elements in the EDP model were elastic beam-column elements. To recognize the fact that TT4 was in a very weakened situation when it was hit by the fatal storm, the worst structure damage scenario was studied.

Code checks of TT4 structure were performed according to API RP2A 20th edition using the linear model. Cases with pined, fixed and flexible (with best estimate footing stiffness) foundations are studied to compare the member utilizations. It was found that the foundation rotational boundary conditions were not very important. The code check showed small differences in the results of maximum member utilizations among these different cases. However, the failure mode is different between fixed and pinned foundations. The fixed foundation critical locations are in the legs at the footing connections (where legs broke). The pinned foundation critical members are at the bottom of the concrete annuli in the legs (-50 feet). For the fixed and flexible foundations that are close to the real in-situ situation, the maximum code checks were 1.9, which implies excessive utilization of the leg element at the leg-footing connection.

The intact structure under dead and buoyancy load only was also studied to see whether the original design meets the modern design code. It is found that the maximum leg member utilization was slightly greater than unity, which means that the leg design would not pass current design criteria. It is possible the local buckling of the large diameter leg was overlooked.

Two cases of Hurricane Donna were studied for the intact structure. The maximum member utilizations were 2.0, but the maximum deck deflections are relatively small. This implies that the structure was in great danger. Many structural members were loaded beyond yield. This explains the extensive damage TT4 suffered during Donna. It was very lucky that TT4 didn't fail during Donna.

Nonlinear Failure Analyses

The EDP model was loaded by static wave-current-wind loads until the structure collapsed. A load factor of 1.0 represented the maximum loading that occurred during the storm on January 15, 1961. The worst damage scenario, in which all A-B frame bracing not functional was used to hindcast the failure.

The pinned diagonals were modeled as nonlinear struts while the legs, horizontals and welded diagonals were modeled as nonlinear beam-columns. A separate EDP analysis determines the nonlinear properties of the horizontals and diagonals. These properties are input as the parameters defining the nonlinear behavior of these elements.

For the tubular legs, there are two kinds of elements: steel elements and composite steel-concrete elements. The nonlinear behaviors of the composite leg elements are determined by introducing the tangential stiffness of the steel-concrete composite platform leg.

For the leg elements without concrete reinforcement, the nonlinear behavior is more complicated. Because of very large D/t ratio (D/t=185), local buckling in these unstiffened legs is an issue. According to the API RP2A guidelines[15], the nominal local buckling strength of this cross section is 23.76 ksi, about 80% of the 30 ksi yield strength. The nonlinear behavior is dominated by this local buckling. The nonlinear properties of these un-stiffened leg elements were calculated by replacing the yield strength with this local buckling strength. After local buckling occurs, the most important effect is the rapid degradation of the element's load-carrying capacity. Obviously, it is a difficult task to predict theoretically the occurrence of local buckling and its effects on the nonlinear post-buckling behavior of a tubular element. The beam-column elements in EDP have difficulties in simulating this behavior. But by introducing a stiffness and strength factor to the elements, upper bound and lower bound response of these elements can be bracketed which leads to reasonable interpretation of leg post-buckling behavior. In this way, the EDP model predicts the most likely failure mode of TT4– local buckling of Leg A at the leg-footing connection.

The worst damage scenario and the best estimate foundation stiffness are used to hindcast the failure. For an EDP run with 100% stiffness and strength of the unstiffened leg elements, the load factor can reach 1.9. This means the beam-column elements without post-buckling behavior make the structure very ductile, which was not real for TT4. But it is noticed that EDP reported the first yielding of leg element at a load factor of 0.55. It is highly possible that local buckling happened in the leg elements at the leg-footing connection during the fatal storm. For the case with 90% leg stiffness and strength, the load factor is only 1.1, about half the 100% stiffness and strength case. This is a very sharp drop in capacity. If the stiffness and strength of unstiffened leg elements are reduced to 80%, the structure even cannot withstand the dead load. Only 80% of the total dead load causes extensive element yielding in the structure, especially the leg portions that are not stiffened by concrete. This is consistent with the conclusion made by Brewer Engineering Laboratory that TT4 would have collapsed under its own weight if the bracing systems were not in place. The above results demonstrate that TT4's global strength is very sensitive to the change of leg stiffness and load-carrying capacity, which is the case if local buckling occurs. It can be expected that rapid load shedding will occur after the onset of local buckling, thus bringing the rest of the platform leg elements to failure. As a tripod has little redundancy in the leg failure mode, the failure of TT4 is very brittle.

There were reports indicating that during the storm the repaired horizontals in the middle tier of K-bracing broke. This case was studied as a medium damage scenario in which these horizontals are kept intact. The EDP results showed that the structure behaves almost linearly with this tier of K-bracing functioning. As to the leg yielding in this scenario, the first yielding happens when the load factor reaches 0.82, and the full yielding happens when load factor is near 1.0. This indicates that local buckling of the leg can still happen in this scenario.

CONCLUSIONS

Hindcast studies of the failure of the TT4 offshore radar platform were conducted using advanced analytical methods. The data collection, analysis procedure and analysis results are summarized in this paper.

TT4 was in a very weakened condition due to the accumulated structure damage. Analysis models recognizing this damage by TOPCAT and EDP were built for the failure hindcast study. Simplified ultimate state structure analyses were performed using TOPCAT. Total failure of platform legs is predicted in the worst damage scenario. More detailed linear and nonlinear analyses were conducted using EDP. The EDP model also predicts the failure of Leg A at the leg-footing connection in the worst damage scenario. Local buckling happened at this location and greatly reduced the load-carrying capacity of this leg, followed by failure of the other two legs. As the tripod has little redundancy, the failure was a sudden collapse. TT4 collapsed very quickly. This was the direct cause leading to TT4's failure during that fatal storm.

As described in the Congressional Hearings[1,2], accumulated damage was the indirect reason leading to TT4's final collapse. All this accumulated damage happened at pin connections. The design engineers used the pin connections intending to eliminate secondary bending stresses in these connections. However, structural analysis of TT4 in this study showed the secondary bending moments at the joints were small. This fact implies that any benefit from using pin connections instead of fully welded connections was questionable.[1,2,3] The obvious benefit of the welded connections, used in the fixed offshore platforms in Gulf of Mexico, is that they would not develop the degradation that happened to the pin connections.

Another important finding was that the original platform leg design could not pass code check by modern design criteria, even for the case of dead and buoyancy loading only. The leg segments without concrete reinforcement had a very big ratio of diameter to thickness, causing the local buckling to be an issue. This is the inherent problem in TT4's design. It is likely that the design engineers overlooked this problem.

The grave danger imposed by the continuing structural deterioration was underestimated by the decision-making officers. This is another typical human and organizational malfunction. The decision to leave people on board, even after the design engineers could not and refused to give an estimate of the residual strength of TT4 in later 1960, was partially due to the pressure to have guards onboard so that the Russian spy vessels nearby could not steal the sensitive radar equipment. This decision was understandable during the peak of cold war, but it is still worthy noting that casualties might have been avoided if evacuation had been ordered in time.

The causes of the failure of TT4 were centered and initiated in[1-4]:

1) the lack of prediction techniques to anticipate the extreme environmental loads, which led to insufficient design criteria;
2) the lack of advanced analysis tools and methodologies to formulate the wave loads and structural response, especially the effects of using the pin connections, which led to a design that had defects;
3) the human and organizational malfunctions during installation, repair, operation and decision making on evacuation, which contributed to total loss of the platform and heavy casualties.

The designers of TT4 had credit in recognizing the adverse dynamic impacts developed from the loose pins after installation.[6] But due to their limited knowledge and lack of advanced modern analysis tools and methodologies at the time, they didn't predict this dynamic effect inherent in the original design at the first place[5] Furthermore, their efforts to save TT4 also proved to be futile due to limited technologies available at the time. This kind of dynamic issue would have been well predicted by current methods if had been applied to current platforms, and the modern engineering technologies might save TT4 from failing.

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REFERENCES

[1] Committee on Armed Services, 1961, *Inquiry into the Collapse of Texas Tower No. 4*, Hearings before the Preparedness Investigating Subcommittee of the Committee on Armed Services, United States Senate, U.S. Government Printing Office, Washington, DC.

[2] Preparedness Investigating Subcommittee, 1961 *Investigation of the Preparedness Program,* Report by Preparedness Investigating Subcommittee of the Committee on Armed Services, United States Senate, U.S. Government Printing Office, Washington, DC.

[3] Air Defense Command, 1961, Loss of Texas Tower No.4, Report of Board Proceedings, U.S. Air Force, Government Printing Office, Washington, DC.

[4] Zimmaro, C., 2000, Collection of newspaper articles about Texas

Towers, Sketches of the current layout of Tower 4 wreckage, SITREP report from USS Wasp outlining wave height, wind direction and other weather related information as the carrier approached the Tower just prior to its collapse, Additional USS Wasp report logs outlining weather/sea conditions during the search for possible survivors, Track of the storm that hit Tower 4 starting from Jan. 14-16, 1961, Weather Log reports at Tower 4 and list of storms that hit Tower 4, Items from daily journal of Maj. Stark. (Commander of TT-4 at Otis Air Force base) including conversations with Tower 4 commander Capt. Phelan. During the storm on Jan. 15, 1961, Weather log and wave graph for hurricane Donna at Tower 4, Reports and memos about investigations of a K-brace on TT-4 that was recovered in late 1961, Sketches showing towers wreckage as reported on Jan. 28, 1961, Sketch showing the orientation of the Tower both before and after its collapse, Sketches of building and repairs of TT-4, Information on marine growth on TT-4, Photos showing repair works by divers, Harleysville, PA.

[5] Anderson Nichols & Company (Boston) and Moran, Proctor, Mueser & Rutledge (New York), 1959, *Design and Construction Report on the Texas Towers Offshore Radar Platforms*, District Public Works Office, First Naval District, Boston, Mass.

[6] Brewer Engineering Laboratories, Inc., 1959, *Final Report – Motion Analysis of Texas Tower No. 4*, Chicago, Ill.

[7] U.S. Weather Bureau, 1959, "Mariners Weather Log", **3**, 1-6, U.S. Government Printing Office, Washington, DC.

[8] U.S. Weather Bureau, 1960, "Mariners Weather Log", **4**, 1-6, U.S. Government Printing Office, Washington, DC.

[9] U.S. Weather Bureau, 1961, "Mariners Weather Log", **5**, 1-6, U.S. Government Printing Office, Washington, DC.

[10] U.S. Weather Bureau, 1962, "Mariners Weather Log", **6**, 1-6, U.S. Government Printing Office, Washington, DC.

[11] Texas Tower Association, 2000, *The History of the Texas Towers in Air Defense 1952-1964,* http://www.texastower.com/.

[12] Anonymous, 1999, "Cold War Heroes Recognized 38 Years After Tragedy", Immersed Technical Diving Magazine, **4**, 4, New York, NY, p. 8-9.

[13] Bea, R. G., Mortazavi, M., Stear, J., and Z. Jin, 2000, "Development and Verification of TOPCAT," *Proceedings of the Offshore Technology Conference,* OTC 11935, Society of Petroleum Engineers, Richardson, Texas.

[14] Digital Structures Inc., 2000, *EDP Users Manual*, Digital Berkeley, California.

[15] American Petroleum Institute (API), 1993, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design (RP 2A-LRFD), First Edition, Washington, D.C.

Table 1 – History of storms affecting TT4

Date	Wind Speed (mph)	Max Wave Height (ft)	Notes
Aug. 28-29, 1958, "Daisy"	115+ (est.)	40	Tower evacuated
Sept. 28, 1958	86	28	
Nov. 30, 1958	83	20	
Dec. 6, 1958	81	21	
Jan. 5 – 6, 1959	92	33	
Feb. 4, 1959	81	29	
Dec. 7, 1959	71	20	
Feb.19–20, 1960	75–92	35	
Mar. 3, 1960	90	22	
Mar. 25, 1960	69	23	
Jul. 30, 1960	75 – 92	45	
Sep. 12, 1960 "Donna"	120–132	50 – 65	Heavy damage
Dec. 11, 1960	92	40	More damage
Jan. 14–15, 1961	45 – 85	30 – 40	TT-4 collapsed

Table 2 – Environmental criteria for design of TT4

Case	Wind Velocity (mph)	Wave Height (ft)	Wave Condition
1	70	60	Non-breaking
2	125	40	Non-breaking
3	125	35	Breaking
4 (towing)	50	15	Non-breaking

Table 3 – Storm parameters used in analyses

Storm	Wind (mph)	Wave (ft)	Wave Period(s)	Current (ft/s)	Surge (ft)
1/15/61	65.0	40.0	10	3.0	4.0
Donna	115.0	55.0	12.5	5.0	8.0

Fig. 1 – Texas Tower 4 (courtesy TTA)

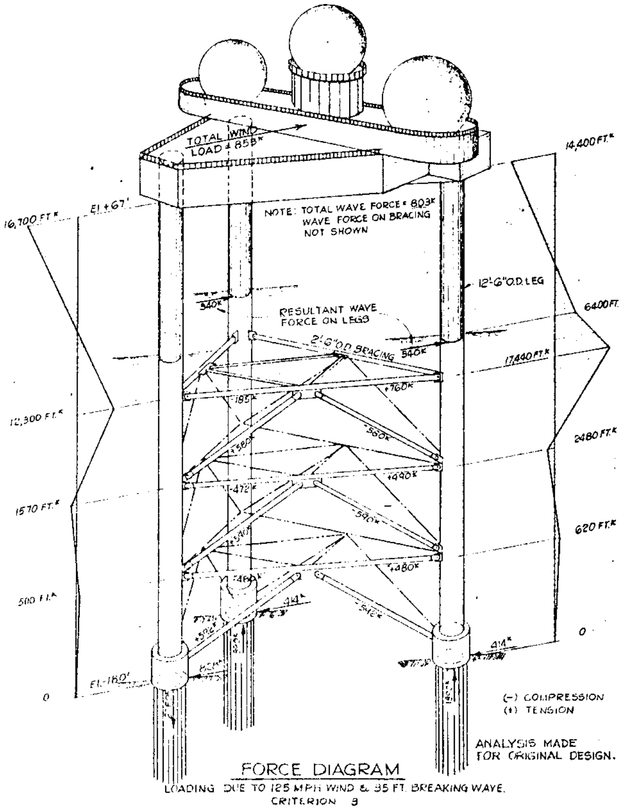

Fig. 2 – Configuration of TT4

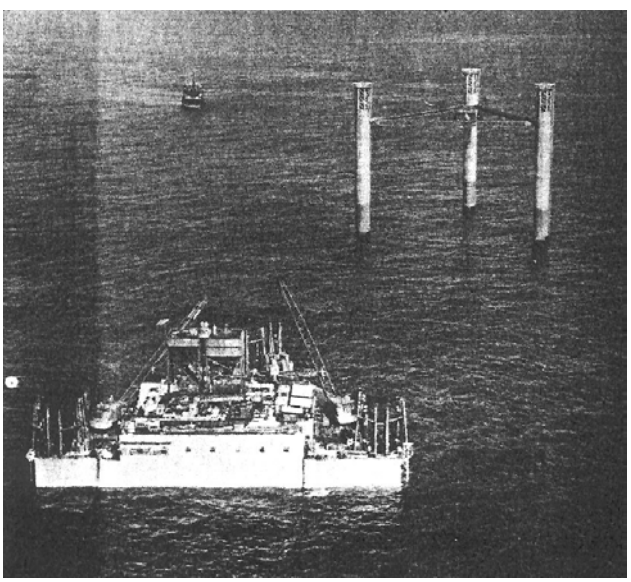

Fig. 3 – TT4 deck being towed to jack-up on substructure (courtesy TTA)

Fig. 4 – X-Bracing installed to stabilize TT4 (courtesy TTA)

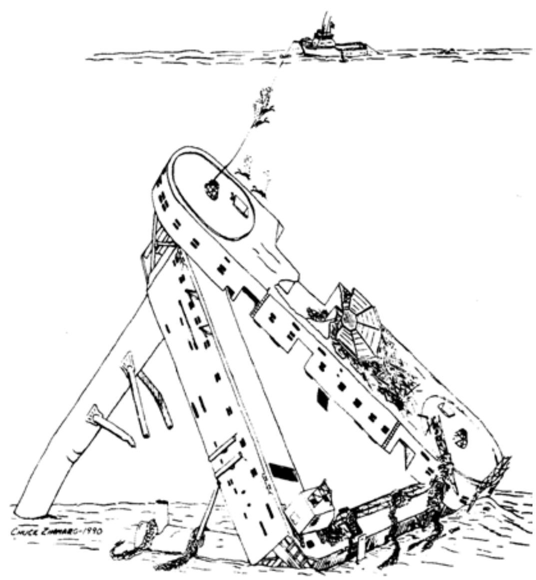

Fig. 5 – TT4 collapsed condition
(courtesy C. Zimmaro)