

Ultimate Strength Analysis of Inland Tank Barges

**Prepared by:
LCDR John Cameron
LT John Nadeau
LT Joe LoSciuto**

**USCG Marine Safety Center
June 16, 1997**

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EXECUTIVE SUMMARY

In an effort to understand the cause of recent catastrophic failures of inland tank barges and reduce the possibility of future casualties, the Coast Guard Marine Safety Center (MSC) studied the “buckling” phenomenon. Various methods for predicting the compressive strength of a longitudinally framed deck were researched. The method presented by Owen F. Hughes in *Ship Structural Design* (SNAME, 1988) was adopted by the MSC to compute the ultimate strength of inland tank barges. This method has been verified through testing and was adopted by Lloyd’s Register of Shipping. It is also used in MAESTRO, a software package developed specifically for ship structures.

Using this method, the ultimate strength was computed for 23 existing, longitudinally framed, inland tank barges, randomly selected to represent the inland tank barge fleet. Assuming “as built” thicknesses, a compressive transverse stress of 1 ksi in the deck, and a stiffened panel deflection of 1/8”, the average ultimate strength was 16.5 ksi (in compression), less than 50% of the required material yield strength. Although this is the stress level which will produce failure, it is considered an acceptable stress by all current regulations and the latest edition (1995) of the ABS Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways (ABS Inland Rules).

Three existing inland tank barges with lengths of 297’, 248’, and 195’ were modeled using naval architecture software. These models were used to determine the magnitude of compressive still water bending stresses possible in inland tank barges. Because current rules and regulations do not require loading guidelines for vessels under 300’, the distribution of the cargo in these models was varied to represent several possible loading conditions. The MSC obtained compressive still water bending stresses exceeding the average ultimate strength by as much as 40%

The MSC researched casualty records and surveyed industry to identify “buckling” casualties. For each of the 14 inland barges which were positively identified as having experienced a serious “buckling” casualty, various design factors and parameters were examined. No parameter or characteristic was identified as common to a majority of the failures.

In an effort to develop both operational and design solutions, which would guarantee continued loading flexibility for the operators and avoid costly stress analyses for each barge, the MSC studied different loading and ballast possibilities. The MSC was able to develop some loading options which, if followed at all times, would guarantee acceptable stress levels.

In conclusion, inland tank barges are not as strong as originally believed. The ABS Inland Rules and current regulations do not address the potential for compressive failure of the hull. A stress analysis should be performed and loading guidance should be developed for each existing barge to ensure compressive stresses in the deck never exceed -9 ksi. Finally, although more stringent inspection standards are not the solution, marine inspectors, surveyors, operators, and owners should be exposed to the factors affecting the ultimate strength so they can better understand the “buckling” phenomenon.

1.0 INTRODUCTION

The purpose of this study was to identify inland tank barge design features and operational practices which could possibly contribute to a catastrophic collapse of the hull, and develop recommendations to prevent future casualties.

This report summarizes the work completed and the results obtained to date. Section 2 describes the current strength requirements, the collapse mechanism, and outlines the strength model adopted. In section 3, the recent casualties are analyzed and the chosen strength model is applied to several barges to determine the factor of safety in existing barges. Casualty data, common myths surrounding the recent failures, and the possible effects of various construction methods are discussed in Section 4. Section 5 details our efforts to develop guidance for industry. Finally, conclusions and recommendations are discussed in Section 6 and 7.

1.1 Background

In the spring of 1996, two certificated inland tank barges operating in Galveston Bay experienced catastrophic structural hull failures, both resulting in a major oil spill and harm to the environment. Per 46 CFR 32.60-1, these longitudinally framed barges were constructed to the standards of the American Bureau of Shipping (ABS) Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways and, by all accounts, met or exceeded these and all other applicable regulations. Similar to other barges used for bunkering, they often carried partial and split loads.

1.2 Objectives

- Determine the ultimate strength and structural safety factor of inland barges
- Support each of the Formal Boards of Marine Investigation investigating the Galveston Bay casualties.
- Determine the frequency of compressive failures and investigate the barges which failed to determine if there are any common factors which indicate a vulnerability
- Assist Commandant (G-MOC & G-MSE) and industry in the evaluation and determination of action necessary to prevent future casualties.

2.0 ULTIMATE STRENGTH UNDER COMPRESSIVE LOADING

2.1 Current Rules & Regulations

The American Bureau of Shipping (ABS) Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways, hereinafter referred to as the ABS Inland Rules, are applicable to vessels operating on rivers and the connecting intracoastal waterways, and to vessels in service on “comparatively smooth” waters. Traditionally, the Coast Guard has considered the ABS Inland Rules appropriate for vessels operating on most Lakes, Bays and Sounds routes. Since the 1980 edition, the ABS Inland Rules have included a deck plating requirement to deter buckling. The minimum deck plate thickness is specified in a table as a function of the longitudinal stiffener spacing, hull girder section modulus, and barge length, breadth and depth.

Prior editions of the ABS Inland Rules had no requirements which specifically addressed the compressive failure of the deck. Additionally, although the ABS Inland Rules specify a minimum section modulus for each individual stiffener/plating combination, there has never been a minimum hull girder section modulus requirement for inland tank barges.

However, Section 1/1.1.4, "Scope of Classification", of the 1995 edition of the ABS Inland Rules states they are published on the understanding that responsibility “*for reasonable handling and loading, as well as for avoidance of distributions of weight which are likely to set up abnormally severe stresses in vessels does not rest with the Committee.*” Older editions contain a similar disclaimer. Although it is vague, this disclaimer does alert the operator to the need to consider stresses encountered during operations, especially where the business requirements and economic demands can create unique cargo load distributions.

The following regulations contain longitudinal strength requirements for certain inland tank barges:

- 46 CFR 31.10-32 requires compliance with 46 CFR 42.15-1(a) or 45.105, which state the master shall be provided with loading information to enable him/her to arrange for the loading and ballasting of the vessel without creating “unacceptable stresses” in the vessel’s structure. This requirement is only applicable to tank barges greater than 300’ in length and built after September 6, 1977. The majority of inland tank barges are less than 300’ and do not have to meet this requirement.
- Per 46 CFR 31-10.21(a), unclassified tank vessels greater than 30 years old which carry pollution category I oils are required to have the midbody gauged. Based on the results of the survey, it must be demonstrated that the structure complies with 46 CFR 32.59-1, which specifies a minimum thickness for various structural members and requires that the hull section modulus be large enough to limit the still water bending stress developed under a full load to 8.25 LT/in^2 (18.5 ksi). The majority of inland tank barges are less than 30 years old.
- 46 CFR 151.10-20(b), applicable to certain barges certificated under 46 CFR Subchapter O, states that under the specified grounding condition, the hull bending stress must not exceed

50% of the minimum ultimate tensile strength or 70% of yield strength of the material, whichever is greater. The 1995 ABS Inland Rules specify a minimum ultimate tensile strength and a minimum yield strength of 58 ksi and 34 ksi, respectively, making the allowable hull bending stress 29 ksi.

2.2 “Collapse” Phenomenon

Like the vast majority of vessels, the decks of tank barges are constructed using a series of cross-stiffened panels, as shown in Figure 2.2. In general, the deck plating constitutes the majority of the cross sectional area of the deck/stiffener combination and absorbs most of the in-plane compressive load. The longitudinal stiffeners strengthen the plating, keeping it stable so it can carry the in-plane load. They also provide the support necessary to handle any lateral loads. The transverse members provide intermediate support to the longitudinal stiffeners.

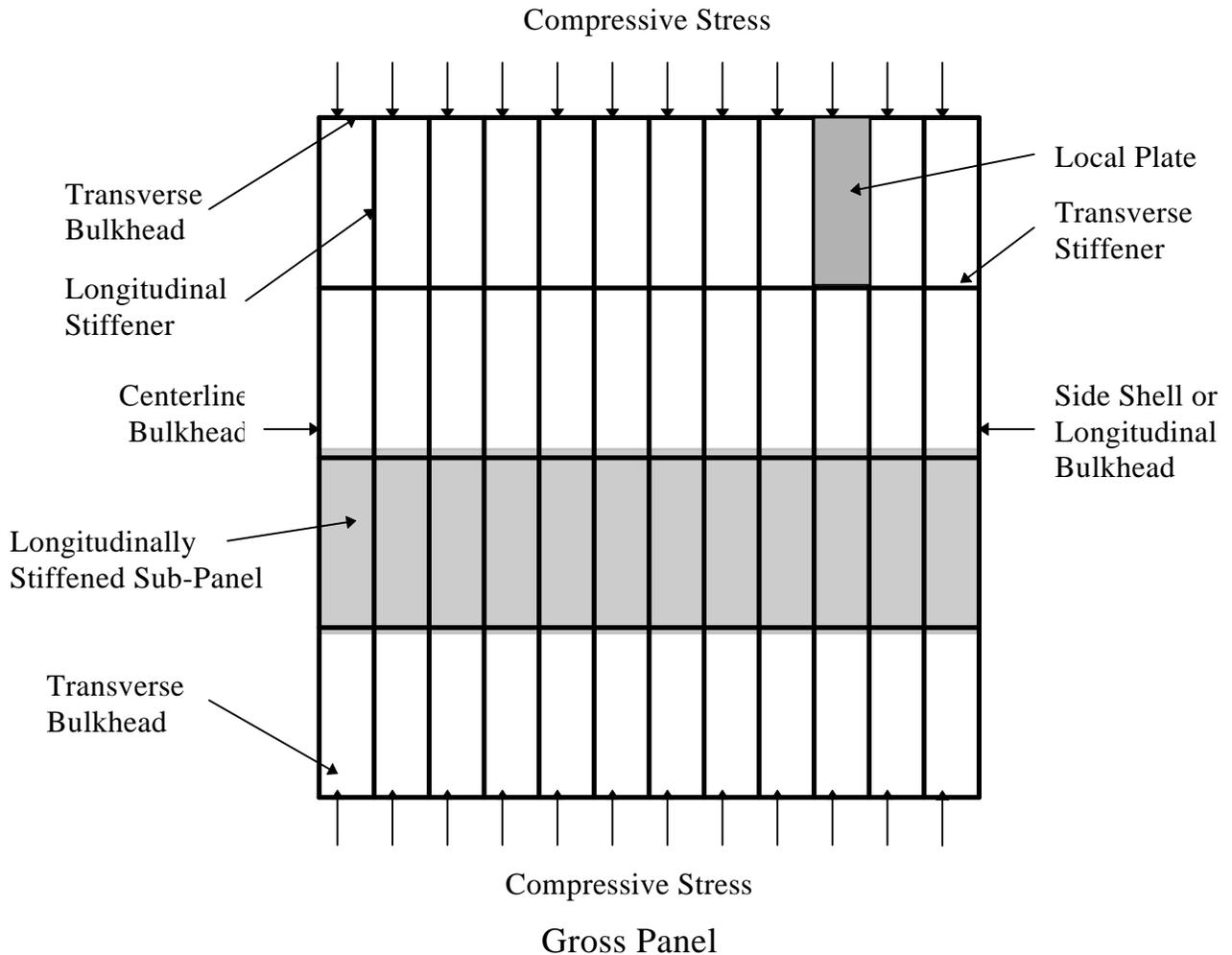


Figure 2.2 Deck Structural Members

“Gross”, or “grillage”, buckling occurs when the transverse members are not stiff enough to provide undeflecting support to the longitudinal stiffeners and they buckle together with the

longitudinal stiffeners. If the transverse members are rigid and provide adequate support to the longitudinals, failure will occur in the longitudinally stiffened sub-panels between the transverse members.

Like most structures, the transverse members of barges have substantially deeper webs and are more rigid than the longitudinal stiffeners, eliminating the possibility of grillage buckling. This was verified for a typical inland tank barge by the Naval Surface Warfare Center, Carderock Division (NSWCCD), using a program based on a discrete-beam energy approach [1]. With the possibility of grillage buckling eliminated, the longitudinally stiffened sub-panels between transverse members must be analyzed.

In general, longitudinally stiffened sub-panels can buckle elastically, commonly referred to as “buckling”, or they can buckle inelastically, known as “collapse”. Elastic buckling occurs in two different ways, depending on the stiffeners’ geometries and arrangements, and the loading. In “overall buckling”, the longitudinal stiffeners do not have sufficient lateral rigidity and they buckle together with the plating. “Local buckling” occurs when either the longitudinal stiffeners buckle or the plating between the longitudinal stiffeners buckles, deflecting out of plane. If the longitudinal stiffeners buckle, the plate loses its lateral rigidity and overall buckling becomes imminent. Similarly, if the plating between the longitudinal stiffeners buckles, the stiffeners, behaving like individual columns, would eventually buckle when forced to carry the entire load.

To prevent these elastic buckling failures, the longitudinal stiffeners must have sufficient torsional stability to prevent tripping and sufficient lateral rigidity to prevent overall buckling. The ABS Inland Rules empirically specify a minimum section modulus for all stiffeners based on the length, spacing, and the hydrostatic pressure, or “head.” Because the minimum allowable scantling head is four feet, and the deck longitudinal and transverse stiffener spacings used in most designs are 24" to 26" and 72" to 97", respectively, the longitudinal and transverse stiffeners typically used in inland tank barge construction are large enough to prevent both types of elastic buckling. Therefore, a more complicated inelastic failure, or collapse, is more likely.

Similar to elastic buckling, inelastic collapse of a gross panel can occur in two different ways. “Interframe” collapse occurs when the longitudinally stiffened sub-panels between transverse stiffeners collapse, while “gross panel” collapse is the failure of the longitudinal and transverse members together. Again, because of the minimum requirements specified in the ABS Inland Rules and generally accepted design practices, the transverse stiffeners are typically sufficient to prevent gross panel collapse. Therefore, the likely failure mode for a typical longitudinally framed inland tank barge meeting the ABS Inland Rules is inelastic interframe collapse.

It is important to recognize this and all other theories assume the stiffeners are “effective”, which is normally interpreted to mean the stiffeners are continuously welded. The possible detrimental effects of the construction techniques used in barge design are discussed in section 4.3.

2.3 Available Methods and Tools

The US Navy publishes a series of “design data sheets” (DDS) which provide a simple method to size various structural members. Typically, they provide minimum required sizes or specify minimum properties, such as section modulus, for each member. DDS 100-4, *Strength of Structural Members*, is based on the work of Dr. Friedrich Bleich in the 1950’s. The level of safety and accuracy are unknown because the modeling does not account for the interaction between the plate and stiffeners and arbitrary factors of safety have been introduced.

Methods have been developed which model the inelastic compressive failure. Most are based on either the Johnson-Ostenfeld approximation or the Perry-Robertson formulation. They differ in the way they treat residual stress, initial deflections, and the eccentricity created when the plating between stiffeners begins to deflect out of plane and becomes ineffective. However, most of them try to account for this loss of stiffness by considering only a portion, or “effective width” of the plating, rather than the total width between the stiffeners [2].

2.4 Method Adopted

Although the basic theory is described below, the model and method of analysis chosen for this study is described by Owen F. in *Ship Structural Design*, published by SNAME in 1988 [3]. Chapter 14 of this book, "Ultimate Strength of Stiffened Panels", has been attached to this paper as Appendix A. Example calculations for a typical longitudinally framed tank barge are included in Appendix B.

This method was originally developed in the United Kingdom under the sponsorship of the Merrison Committee and used to develop standards for constructing steel box girder bridges. It was chosen because its wide acceptance and proven accuracy. It has been adopted by Lloyd’s Register of Shipping for use in their program for panel strength and is used in MAESTRO, a software package developed specifically for ship structures. Favorable comparisons between experimental data and predictions using this method are presented by Hughes at the end of chapter 14. Additionally, recent testing has shown this method predicts the ultimate strength within approximately 10%, usually slightly underestimating the strength [4].

In this model, each stiffener is treated as an individual beam-column, with the plating acting as one of the flanges. The neutral axis of the beam-column is closest to the plating because the plate flange is much larger than the flange of the stiffener, making the section unsymmetric about the neutral axis. Additionally, since angles are typically used as longitudinal stiffeners, the section is also unsymmetric about the web.

Due to the existence of residual stresses in the plating, which are introduced when the longitudinals are welded to the plating, the slope of the stress vs. strain curve is changed. Rather than remaining linear and elastic until reaching the yield strength of the steel, the slope decreases gradually and the response to the loading becomes inelastic, as shown in figure 2.4.1. This inelastic response of the plate is modeled by treating the plate as a different material with a reduced modulus of elasticity. Collapse is considered to occur when the stress in the extreme fiber of the flange in compression reaches failure. For the stiffener flange, failure is the yield stress. However, for the plate flange, it is some reduced value which accounts for the nonlinearity of the stress vs. strain curve.

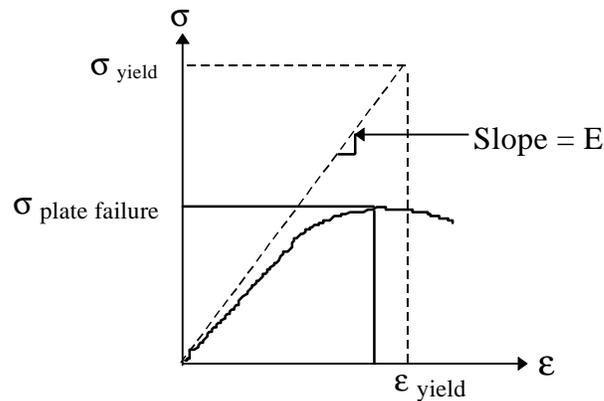


Figure 2.4.1 Typical Curve of Stress vs. Strain for Local Plate

When an axial load is applied to the deck, the stiffened sub-panel deflects either toward the plating or away from the plating, as shown in figure 2.4.2. Due to the unsymmetrical nature of the beam-column, the stresses in the stiffener flange and plate flange tend to be significantly different, depending on the direction of bending. When the bending deflection is toward the plating, a compressive flexural stress is developed in the stiffener flange, in addition to the axial compressive stress. With both the flexural and the axial stresses compressive, the highest stress occurs in the stiffener flange. If the loads are sufficiently increased, the stress in the stiffener flange will eventually reach the yield stress of the material, causing the beam-column to collapse. This mode of failure is referred to as a “stiffener-induced” failure. Alternatively, when the bending deflection is toward the stiffener, the compressive flexural stress is developed in the plating and coupled with the axial compressive stress. As the loads are increased, the compressive stresses continue to increase until the plate buckles, usually at a stress significantly less than the material yield stress. Without the plate, the beam-column has lost its major flange and will collapse. This mode of failure is referred to as “plate-induced” failure.

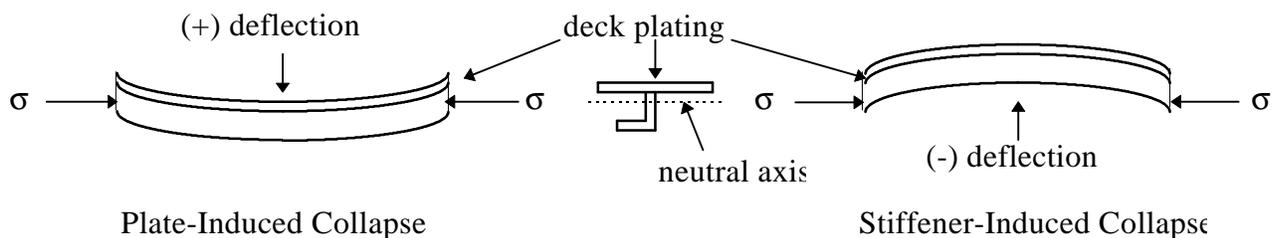


Figure 2.4.2 Collapse Mechanisms of Typical Longitudinally Framed Deck

The ultimate strength of the deck is the compressive stress which will cause a stiffener-induced or plate-induced failure. It is the maximum compressive stress the deck is capable of withstanding. If the compressive stress in the deck equals the ultimate strength of the deck, and the “load” creating the compressive stress is not removed, the deck will collapse, or fail.

Here we have discussed the compressive stresses necessary for only the deck to fail, and some might argue this does not indicate failure of the entire hull. However, once the deck has failed, collapse of the entire hull is probably inevitable. Without the deck, it is unlikely the remaining side shell and side stiffeners above the neutral axis will be capable of absorbing the entire compressive load. Unlike some other vessels which have multiple decks and other redundancy in the structure, the shallow hull of a barge offers only the deck plating and the attached longitudinal stiffeners to absorb the compressive stresses from a sagging load condition.

3.0 ANALYSIS OF THE INLAND TANK BARGE FLEET

3.1 Selecting Representative Samples

Using the Marine Safety Information System (MSIS), a vessel database maintained by the Coast Guard, a search was conducted to identify the tank barges certificated under 46 CFR Subchapter D for rivers and/or lakes, bays and sounds service, and with lengths between 150' and 300'. From this group, 26 barges were selected to represent the fleet for our analysis. Although it was not a truly random selection because only those barges for which adequate drawings were readily available at the Marine Safety Center were eligible, this group represented both single and double hull barges, eight different builders, lengths ranging from 195' to 297', and build dates from 1962 to 1996. Of the 26 barges selected, 23 were longitudinally framed and 3 were transversely framed.

The geometry, material properties, spacing of the longitudinal and transverse stiffeners, and the thickness and material properties of the plate are needed to compute the ultimate strength using the method adopted. Most of this information was available for each of the selected barges from builder's drawings. The similarities among the selected tank barges are noteworthy. Of the 26 barges chosen, 23, or 91%, had deck plating 0.3125" thick, and the longitudinal stiffener spacing varied only from 23.5" to 26".

3.2 Determination of Transverse Stress & Initial Deflection

Since they have a marked impact on the ultimate strength, the transverse stress in the deck and the initial deflection of the stiffened sub-panel are required when computing the compressive strength of the hull. The transverse stress in the deck is needed so a solution for the desired longitudinal component of stress can be obtained. Because it is the greatest component and usually the designer's area of concern, commercial naval architecture software, such as GHS and HECSALV, provide only the longitudinal component of hull girder bending stress.

As part of the Barge 2 casualty investigation, a finite element analysis (FEA) was performed to determine both the longitudinal and transverse stresses in the deck at the time of the casualty and under other load conditions. Although the transverse stress is a significant factor when computing the ultimate strength using the method selected, the observed failure was primarily a result of longitudinal bending in the vertical plane. Therefore, rather than varying the cargo loading and distribution to search for the maximum compressive transverse stress possible, we chose to use the transverse stress in the deck associated with a load creating high longitudinal stresses, such as the loading at the time of failure. Based on this reasoning and the results of the FEA, a transverse

stress of -1 ksi was chosen as a representative magnitude associated with loads likely to produce high longitudinal stresses¹.

The final piece of data necessary for computing the ultimate strength using the method chosen is the initial deflection, or distortion, of the deck sub-panel. In reality, no installed plating or stiffener on any vessel is perfectly flat or straight. Some initial deflections exist from the fabrication, fit-up, and installation. The initial deflection of the deck sub-panels normally determines the mode of failure (stiffener-induced vs. plate-induced) and typically weakens the structure by lowering the ultimate strength. Some experimental data is available for estimating the initial deflection of sub-panels, but most of this is based on measurements from scaled models. To obtain accurate data for our analysis, members from the MSC took measurements from an existing inland tank barge operating in Lakes, Bays and Sounds service.

Staging was arranged in three pairs of tanks. The emphasis was placed on the stiffeners in the tanks closest to amidships, the area typically exposed to the highest bending stresses. By carefully using a string, two clamps, and a ruler, five measurements were taken for each of the twelve longitudinal stiffeners between each pair of transverse stiffeners. The data collected was statistically analyzed. For any given longitudinally stiffened sub-panel, consisting of all 12 longitudinal stiffeners between any pair of transverse stiffeners, there is approximately an 80% chance the sub-panel will be distorted 1/8" or less and only a 5% chance they will approach 1/4". Based on these measurements, a standard deflection of 1/8" was used in calculating the ultimate strength of each of the 23 barges selected. It should be noted, only deflections of any of the longitudinally stiffened sub-panels, each bound by a pair of transverse stiffeners and extending transversely from the side shell to the centerline bulkhead, have a significant impact on the ultimate strength.

3.3 Ultimate Strength of the Deck of the Selected Barges

With all the necessary information for each tank barge either available or accurately estimated, the ultimate strength of the deck of each barge was calculated and the results are displayed in Table 3.3. The average "in service" ultimate strength, which included the 1/8" deflection and -1 ksi transverse stress discussed above, was -16.5 ksi. Due to the similarities in the deck plating thickness, stiffener size, and stiffener spacing, the ultimate strength varied very little among the 23 longitudinally framed barges analyzed. The standard deviation for the sample was less than 0.7 ksi.

Using the most optimistic approach possible, which included original "as built" thicknesses and disregarded transverse stresses and any initial deflections, the average "ideal" ultimate strength for the deck of the 23 longitudinally framed barges examined was -20 ksi. This is approximately 58% of the nominal yield strength of the steel, which was assumed to be 34 ksi based on the ABS Inland Rules

Table 3.3 Ultimate Strength of Inland Tank Barges

¹ With the exception of Appendices A and B, the sign convention used in this report for stresses is negative (-) for compression and positive (+) for tension.

Barge	“Ideal” Ultimate Strength (psi)	“In Service” Ultimate Strength (psi)	Double Hull	Trunk	Build Year	Length (ft)
1	19,401	15,865			1967	270
2	21,851	18,428	X	X	1994	272
3	19,902	16,135			1981	275
4	20,378	16,920	X	X	1989	280
5	20,002	16,565			1978	280
6	19,401	15,839			1981	285
7	19,902	16,111			1981	290
8	20,289	16,669	Dbl Side		1978	295
9	20,002	16,565			1979	297
10	20,134	16,703	X	X	1981	297.5
11	17,905	14,434	X	X	1980	297.5
12	20,378	16,538	X		1992	297.5
13	19,474	16,348	X	X	1996	297.5
14	20,204	16,733	X	X	1993	297.5
15	20,134	16,691	X	X	1991	297.5
16	20,204	16,733	X	X	1993	297.5
17	20,134	16,703	X	X	1993	297.5
18	20,731	17,481	X	X	1995	297.5
19	20,378	17,174	X	X	1993	297.5
20	20,731	17,247	X	X	1995	297.5
21	20,002	16,565			1978	292.5
22	20,378	16,575			1979	282
23	19,474	16,348	X	X	1995	276

In addition to deflections and transverse stress, a conservative approach would account for corrosion. With the deck plating and deck longitudinal stiffeners corroded 25%, typically allowed under current inspection guidelines, the ultimate strength is reduced to approximately -14 ksi. If the longitudinal stiffeners and plating are wasted 40% and 25%, respectively, as allowed in Navigation and Vessel Inspection Circular 7-68, *Notes on Inspection and Repair of Steel Hulls*, the ultimate strength is reduced to approximately -13.5 ksi, 33% less than the “Ideal” ultimate strength and only 40% of the nominal yield strength of the steel.

The ultimate strength for each of the three transversely framed barges was also calculated. Because no longitudinal stiffeners are present, the analysis of these barges is much simpler. The ultimate strength is determined by examining the unsupported plating between transverse stiffeners. As expected, the ultimate strength decreases significantly because, in effect, the middle portion of the plating receives no support from the side shell or center bulkhead, and behaves similar to a wide column. Treated as such, the mean ultimate strength calculated for the three transversely framed barges was 5.2 ksi.

This contrast between the strengths of the longitudinally and transversely framed barges was expected. Using simple buckling theory, it can be shown the buckling strength of a longitudinally

framed plate is as much as four times greater than that of a transversely framed plate with the same plating thickness and stiffener spacing.

3.4 Actual Compressive Stress

Knowing the stress level at which complete failure becomes likely, the next logical step was to determine the likelihood of approaching these stress levels in typical inland tank barges of various lengths. The hull and section modulus of three existing longitudinally framed inland tank barges were modeled. Each of these models was analyzed with two different arrangements, one with 3 pairs of tanks and one with 5 pairs. By varying the cargo loading and distribution, the still water stresses outlined in Table 3.4 were obtained. It should be noted higher stresses are possible and, as expected, the highest stresses are reached under partial rather than full load conditions

The results indicate that in some cases it is possible to exceed the ultimate strength of the deck of the barge and cause serious damage while loading/unloading at the dock. Traditionally, 2.0 to 4.0 has been considered a reasonable safety factor for ship structures. When these stresses are compared to the mean ultimate strength, the safety factor is certainly less than 2.0, if one exists at all. If a safety factor of 2.0 is desired, the maximum longitudinal deck stress must be less than 8.25 ksi. Of course, these deck stresses increase and exacerbate the problem if the barge encounters waves.

Table 3.4 Possible Stresses for 3 Existing Inland Tank Barges

Length (ft)	Arrangement	Max Deck Stress (Still Water)
195	5 pairs of tanks	-9.3 ksi
248	3 pairs of tanks	-14.2 ksi
248	5 pairs of tanks	-17.7 ksi
297	3 pairs of tanks	-19.9 ksi
297	5 pairs of tanks	-23.6 ksi

The fact that the failure mode of the hull is likely to be in compression may seem surprising, but studies by respected structural experts have drawn similar conclusions. As pointed out by Mansour et al, the governing failure mode of a ship hull is typically due to instability, or collapse [5]. Therefore, it is more appropriate to compare global compressive stresses to the ultimate strength of the hull, rather than the yield strength of the material.

Based on these results, one wonders why compressive failures, such as “buckling”, are not more common. We suspect damage from excessive compressive stresses is more common than many believe. In many cases, it may not be catastrophic damage, particularly if the bending stresses were just momentarily increased, such as when crossing the wake of a large vessel. It is possible that because the high bending stresses subside after the wake is crossed or the large wave passes, a complete failure of the hull does not occur. However, the vessel may still have been damaged and weakened, even though the damage may be difficult to detect.

Additionally, although the yield strength of the material is not always the most important factor, it is significant when trying to predict the ultimate strength of the deck. As previously mentioned,

we have used the minimum yield strength specified in the ABS Inland Rules, which is typically done in design. However, the yield strength of the material tends to vary and is often greater than the advertised nominal yield strength. Finally, as pointed out earlier, the method used to calculate the ultimate strength is believed to be approximately 10% conservative.

Even though the collapse strengths reported in Section 3.3 are lower than commonly accepted failure stresses and may be higher than the prudent operator would willingly and knowingly induce, Table 3.4 demonstrates how the failure stresses may be dangerously approached and possibly exceeded, indicating that an inadequate margin of safety exists between the hull girder strength and the primary loading levels experienced.

3.5 Analysis of Representative Barges

In support of the casualty investigations, the MSC provided technical assistance to both of the Investigating Officers. The MSC modeled each barge in HECSALV using builder's drawings, computed the still water and wave induced bending stresses at the time of the casualty using loading data provided by the Investigating Officers, and performed an ultimate strength analysis using the method described in Section 2.4.

The still water bending stress in Barge 1 under the cargo load at the time of the failure was -13.06 ksi. Although it may be higher than what some other barges typically experience, this stress level is considered acceptable by current regulations.

Testimony revealed this barge had a pre-existing upward deflection extending transversely across the entire deck. Both the deck plating and the attached stiffeners were deflected 1". This is considerably greater than the deflections measured in a similar barge and those generally assumed for ship structures. When this information was incorporated, the predicted ultimate strength was -13.6 ksi.

The fact that the barge collapsed at the exact location of this pre-existing deflection is probably not coincidental, and in this case, the results of the structural analysis seem to explain the failure. Although the deflection was only 1" and all welds were probably intact, the deflection of the deck and stiffeners out of the plane of the axial load had significantly reduced the ultimate strength of the barge.

Unlike the Barge 1, the results of the Barge 2 analysis do not immediately indicate collapse was imminent. Under the cargo loading at the time of the casualty, a hull stress of -15.88 ksi was calculated for the Barge 2 using HECSALV, which is slightly less than the predicted ultimate strength of -18.9 ksi.

The stresses obtained using HECSALV compare well with those determined by the Naval Surface Warfare Center, Carderock Division (NSWCCD). Under the cargo loading at the time of the casualty, a maximum longitudinal bending stress of -16.61 ksi was computed by the NSWCCD using finite element methods. Other possible load cases were examined and it was determined that higher compressive stresses were easily attainable. For example, if only the #3 and #4 tanks

are filled and all other tanks remained empty, the maximum still water longitudinal bending stress in the deck is -20.63 ksi.

Table 3.5 Construction & Loading Summary for Barge 1 and 2.

	Barge 1	Barge 2
Length	275'	290'
Depth	12'	11' 6"
Beam	54'	54'
Arrangement	6 Pairs of Tanks	6 Pairs of tank
Section Modulus	3386 in ² ft	3257 in ² ft
Deck Plating	5/16"	5/16"
Deck Longitudinals	5 1/2 x 2 1/2 x 5/16" Serrated Stiffener	5 1/2 x 2 1/2 x 5/16" Serrated Stiffener
Build Date	July, 1968	December, 1969
Cargo load at time of casualty	2-5 P/S ~ 75-95% full	2-5 P/S ~ 65-95% full
Still Water Bending Stress	-13.06 ksi	-15.88 ksi
Predicted Ultimate Strength	-13.6 ksi	-18.9 ksi

As part of the NSWCCD study, the stresses and displacements computed using finite element methods were used in a limit state analysis to assist in assessing the adequacy of the structure. The limit state equations used include a check for buckling of individual members and for collapse of the overall structure, and are described in detail by Hughes [3] and in Volume 3 of the Maestro Users Manual. With the cargo load at the time of casualty, this limit state analysis indicated the safety factors relating to collapse were 1.08 (stiffener-column buckling) and 1.04 (local plate buckling). Although slightly more conservative, these results were also consistent with the results from MSC's analysis, which also indicated a small margin of safety existed.

The analysis performed by the NSWCCD was based on a material yield stress of 32 ksi, as recommended by Billingsley [6]. However, testing of material samples removed from the Barge 2 later revealed an actual yield strength of approximately 42 ksi, making the NSWCCD strength predictions conservative.

All of the data indicates that the Barge 2 was marginally adequate for the stresses created by the cargo load; however, we know the hull catastrophically collapsed under the loading. The NSWCCD has identified factors which probably degrade the ultimate strength of some inland barges, but are difficult to model and incorporate into an analysis due to their complexity. First, based on their experiences, they immediately questioned the effectiveness of the serrated stiffeners and intermittent welds. This is discussed in detail in section (4.3).

They also suggested some inland barges may be experiencing "progressive damage", a phenomenon currently under investigation by the Navy. Recent testing has shown that when a hull girder is loaded and unloaded such that the bending stresses exceed the elastic limit, permanent deflections are produced and the strength is permanently degraded. Even if the

loading is reversed and the deflections are corrected, the effects of the damage remain. Given the frequent and seemingly haphazard loading and unloading of barges in the bunkering business, it is conceivable that some of the loads are great enough to reduce the strength of the hull in both hogging and sagging.

Even though the numbers do not immediately explain both of these barge casualties, the ultimate strength and actual operating stresses for these two barges are consistent with those obtained for other inland barges, as discussed in Sections 3.3 and 3.4.

4.0 OTHER POINTS OF INTEREST

4.1 Historical Data

In an effort to identify common factors and propensities for failure, extensive research was conducted to identify similar casualties. A formal survey soliciting information regarding casualties was developed by the MSC and distributed to industry via the Towing Safety Advisory Committee (TSAC) and Coast Guard field offices. Additionally, the Marine Safety Information System (MSIS) was queried, limiting the search to only inland tank barges certificated under 46 CFR Subchapter D, and casualty records maintained at Coast Guard Headquarters (G-MAO) were searched. Fourteen (14) casualties were identified which were definitely attributed to “buckling”, a compressive failure of the hull

A study of each barge identified was conducted. The following parameters were noted for each: builder, year built, age at time of casualty, length, beam, depth, route, capacity, frame spacing, and if serrated stiffeners were used or if the barge was double/single hull. Several different ratios, such as L/B, L/D, B/D and L/(BD) were compared

Table 4.1 is a collection of data from the vessel files for each vessel. The information listed is only a portion of the information collected. The information not listed was either the same for every vessel or statistically irrelevant. No single characteristic or parameter was identified as common to a majority of the failures or separates these barges from the general population.

Although we were only able to verify compressive failure for these 14 cases, many of the other casualties could have been caused by compressive loads. Because of the vague or missing descriptions of the “structural failure type” in the Coast Guard database, we could not identify the cause of failure for many of the casualties.

Table 4.1 Documented “Buckling” Failures

	Builder	Build Year	Age @ Failure	Length	Beam	Depth	L/B Ratio	L/D Ratio	B/D Ratio	L/BD Ratio
1	Dravo	1949	40.9	178'	38.1'	14'	4.67	12.71	2.72	0.33
2	Dravo	1949	36.9	178	38.1'	14'	4.67	12.71	2.72	0.33
3	St Louis	1947	39.6	235'	45.1'	10.1'	5.21	23.27	4.47	0.52
4	Beth Steel	1963	23.4	250'	50.1'	12.2'	4.99	20.49	4.11	0.41
5	Port Houston	1961	26.1	264'	52.5'	12'	5.03	22	4.38	0.42

6	Nash Bridge	1968	27.7	275'	54'	12.5'	5.09	22	4.32	0.41
7	Nash Bridge	1992	0.1	290'	54'	12'	5.37	24.17	4.5	0.45
8	Nash Bridge	1969	26.4	290'	54'	12'	5.37	24.17	4.5	0.45
9	Jeffboat	1973	22	295'	54'	12'	5.46	24.58	4.5	0.46
10	Ingalls	1955	34.7	335'	54'	12'	6.2	19.71	3.18	0.36
11	Bergeron	1980	5.1	370'	54'	12'	6.85	33.64	4.91	0.62
12	Sabine	1968	17	230'	43'	16'	5.34	14.4	2.7	0.33
13	Dravo	1964	23	275'	54'	11'	5.1	25	4.9	0.46
14	Unknown	1957	29	323'	43'	14'	7.51	23.1	3.1	0.55

Because not all compressive failures are immediately catastrophic, many are probably not considered a Class 1 structural failure as defined by COMDTINST M16000.7, Marine Safety Manual, Volume II. Therefore, they go unreported or are attributed to some other cause such as “operational damage.” The deck structure may get “wrinkled”, or appear “wavy”, and this deformation may get repaired without it ever being identified as a compressive failure. We have received reports from respected members of industry that vessels they own or operate have “buckled”, but were not reported to the Coast Guard as such because no oil was spilled and repairs were considered minor.

An informal survey was conducted with the help of several leading companies who operate inland tank barges. Some contacted our office for information regarding our study and offered information, while we personally solicited information from others during routine phone conversations. Several companies had barges which had experienced some extent of damage due to compressive loading and stated “operational” damage did sometimes occur. Examples of the cases reported by individual representatives from industry include a double-sided chemical barge that needed to have the tank sides replaced because they buckled after hauling a high density cargo, a former tank barge which collapsed while carrying gravel, and frequent replacement of deck plate in the samemidship area on a barge engaging in the bunkering trade.

As part of a study to assess the strength requirements of double hull barges, George G. Sharpe was contracted by the Coast Guard to research structural casualties which occurred on tank barges certificated for Rivers, Lakes, Bays and Sounds service [7]. They determined that from 1982 until early 1993, forty-five (45) single skin barges had major structural failures, some of which we independently identified in our research. Six (6) casualties involved structural failures in open waters, some of which were operating outside the limits specified on the Certificate of Inspection; (15) casualties involved fractures of unknown origin; twelve (12) casualties involved contact with the ground or another vessel; six (6) casualties involved holing attributed to wastage or fatigue; three (3) involved causes not relevant to the study; and three (3) casualties involved improper loading. One conclusion reached in this study was that the most common structural casualty on double hull barges was “buckling”, and deck buckling is the only casualty that caused significant oil spillage for double hull barges.

4.2 Myths & Rumors

In the aftermath of recent casualties, rumors were circulated suggesting different causes and contributing factors. Many of these were investigated to determine their significance and are explained below for clarification.

Some suggested the Barges 1 and 2 were an anomaly because they were not constructed to the ABS Inland Rules. Using builder's drawings, the structure of each barge was reviewed to the standards of the 1965 ABS Inland Rules and the 1995 ABS Inland Rules. Barge 1 met or exceeded the structural requirements of both the 1965 and 1995 edition of the ABS Inland Rules, including the minimum deck thickness requirement intended to deter buckling. Although barge 2 met the 1965 ABS Inland Rules, it did not meet the deck thickness requirements of Section 3/3.5.1 of the 1995 ABS Inland Rules. A minimum thickness of 0.343" was required, and the original design thickness of 0.3125" was 9% less. With the minimum thickness required by the 1995 ABS Inland Rules (0.343"), the ultimate strength of the deck would have been increased only 6%.

One rumor suggested the tugs were too large and induced excessive stress while pushing the barges. To soundly refute this theory, we conducted an extremely conservative first principles analysis for Barge 2. The axial force of the tug was assumed to be distributed only to the plating and stiffeners in the deck, and the barge was "fixed", unable to move. In this condition, with the deck absorbing the brunt of a 10,000 HP tug, the compressive deck stress was less than 1 ksi.

Another theory pointed to the damage these barges receive due to the rough handling during routine operations. While maneuvering and making up the tow, the barges often bump and get dented in the sides and gunwales. However, it is unlikely this routine damage significantly lowers the ultimate strength. Due to the shallow hull form, the side shell comprises only a small percentage of the cross sectional area under compression and the collapse strength of the hull is dominated by the deck plating and stiffeners. Therefore, even though they may reduce the effective section modulus and increase the actual stress in the deck at that location, localized dents in the side plating and deflections of the stiffeners attached to the side shell have little effect on the ultimate strength.

Many feel double hull barges are less susceptible to failure. This is not necessarily true, as pointed out in the Sharpe study [7]. The ultimate strength of the deck is independent of the bottom and side structure, and the deck plating and stiffener requirements in the ABS Inland Rules are similar for double hull and single skin barges. Therefore, double hull barges are not likely to withstand significantly greater compressive stresses than single skin barges, if in fact there is any increase in strength at all.

Double hull barges may or may not experience lower stresses in the deck. The section modulus to the deck is critical in determining the magnitude of the stresses the deck experiences. When compared with the properties of a typical single skin barge, a double hull certainly has a greater inertia, but it does not necessarily have a greater section modulus to the deck. Because a majority of the steel in the double hull is in the bottom and inner bottom, the neutral axis of the cross section is shifted downward, away from the deck. As the neutral axis shifts downward, the section modulus to the deck is effectively lowered and the stress in the deck is increased. For example, while conducting the research described in Section 5.3, we found that the section

modulus to the deck for a particular 297.5' double hull tank barge was significantly less than the section modulus to the deck on an existing 276' double hull tank barge and an existing 236' single hull barge.

Lastly, because many inland tank barges operating in Lakes, Bays and Sounds service are often exposed to waves, some question the applicability of the ABS Inland Rules, which are intended for rivers or "comparatively smooth waters." Although exposure to waves will certainly increase the hull stresses, it is important to realize that stresses exceeding the ultimate strength of the deck can be reached in still water, as shown in Section 3.4. Some of the failures listed in Table 4.1 occurred during loading, while the vessels were afloat in still water

4.3 Effects of Common Construction Techniques

All theories which predict the ultimate strength of stiffened sub-panels are based on the assumption that the longitudinal stiffeners are continuously welded to the plating. The longitudinal stiffeners on the decks of inland tank barges are usually intermittently welded. For typical stiffener sizes and deck plate thickness, the ABS Inland Rules require 2 1/2" welds on 12" centers. Additionally, the ABS Inland Rules allow serrated sections to be used as stiffeners, which are required to be in contact with the plating only where they are welded. Since the introduction and widespread use of welding machines in the late 70's and early 80's, few barges have been constructed using serrated sections. However, many of the barges with serrated deck longitudinals are still in service. Although it is difficult to quantify the impact of these accepted construction techniques, any effects will likely act to lower the ultimate strength.

The NSWCCD also commented on these construction techniques in their report. Recently, the Navy was conducting scaled model testing using models which included full scale weepholes and created significant portions of unsupported plating. During testing, they witnessed a premature collapse of the hull. Further investigation revealed the weepholes in the model had reduced the strength of the hull by 18-20%. This becomes particularly interesting when the geometry of the model is compared to that of a typical barge with serrated sections. The unsupported span length to plate thickness ratio for the model was 30. For a typical barge with serrated stiffeners and 5/16" plating, the same ratio is 28.8.

Currently, testing is being performed at the US Naval Academy to determine the impact of these construction techniques. Six test panels have been constructed, scaled to represent the typical deck structure on inland tank barges; two with continuously welded stiffeners, two with intermittently welded continuous stiffeners, and two with intermittently welded serrated stiffeners. Each of the panels will be compressed until failure. The ultimate strength will be measured, the progression of events and mode of failure will be determined, and the results will be compared to assess the impact of each of the construction techniques.

5.0 EFFORTS TO MINIMIZE RISK

5.1 Discussion

In an effort to allow continued loading flexibility for the operators and to avoid costly stress analyses for each barge, the MSC strived to develop suitable solutions. The MSC's goal was to determine options which would eliminate the possibility of unacceptably high hull stresses in any barge built to the ABS Inland Rules and loaded in any conceivable manner. Due to the similarities in structural design and construction this seemed like a reasonable approach.

The idea was to determine specific amounts of weight, which when placed at certain predetermined fore and aft locations of the barge, would eliminate the possibility of excessive sagging conditions and allow any combination of loading in all other tanks. The "weight" could be either cargo, liquid ballast, or fixed ballast. The difficulty involved with this approach is introduced when one tries to specify a weight and location, or certain tanks at specific percentages full, which will guarantee compressive bending stresses are less than the allowable stress for any loading condition on absolutely any tank barge (of any length and tank arrangement).

It should be noted that all of our efforts were focused on the strength of the barges, not the stability. Our solutions and recommendations include many slack tanks, which will have a negative effect on the vessel's stability. We are confident that typical barges arranged with pairs of tanks will still have adequate intact stability. **However, the stability of tank barges without a centerline bulkhead must be checked.**

5.2 Industry & ABS Involvement

From the beginning, the MSC recognized the importance of industry and ABS participation in all aspects of this study and has fostered a cohesive working relationship. It is an underlying value at the MSC and common practice to involve all stakeholders in problem resolution. In this manner, all perspectives can be considered and the most practical solutions obtained.

The Towing Safety Advisory Committee's (TSAC) cooperation and assistance has been invaluable. After the MSC presented their initial findings and concerns to the committee in June 1996, they eagerly agreed to participate in the efforts to determine the extent of the problem and identify possible causes for these failures and formed an ad-hoc Working Group to address these issues. In response to a survey generated by the MSC, the Working Group provided honest and sincere responses vital to the direction of our study.

In June 1996, a letter was sent to ABS summarizing our findings to date, briefly outlining our plan, indicating our final results would undoubtedly be of interest to them, and soliciting their input and participation in the study. ABS agreed to review and comment on MSC calculations and assumptions, expressed interest in attending panel testing at the USNA, and wished to review any policy drafted to address this issue.

5.3 Modeling

To determine the amount of weight and precise location necessary for each barge length, we had to develop generic barge models. Using these models, we could experiment with different cargo loads in search of acceptable solutions. Due to the similarities of the pertinent parameters and

resulting ultimate strengths among the barges, as discussed in Section 3.1 and 3.3, respectively, we felt comfortable deriving an allowable stress based on our analysis of the inland tank barge fleet. A maximum allowable compressive stress of 9 ksi was chosen for our study. This provides a factor of safety of approximately 1.8, based on the likely “in service” ultimate strength prediction of 16.5 ksi. This margin of safety must account for the uncertainties discussed in section 4.3 and any increase in stresses from waves. Tensile stresses exceeding 9 ksi were accepted.

The tank arrangement, hull form (box vs. rake), and section modulus of a barge are all variables in determining the maximum still water bending moment. The hull form affects the bending moment created by the buoyancy of the hull. The location of transverse bulkheads controls the cargo load distribution possibilities and cargo induced bending moment. Because many different tank configurations are found in the fleet, and the possibilities are infinite, we examined the worst possible tank arrangement for each given barge length. In most cases, we found the worst possible bending moment arises when the volume bound by two bulkheads, located forward and aft of amidships by a distance approximately 25% of the barge length, is filled with cargo. It makes no difference if the volume between these two bulkheads is divided into 3 tanks, 10 tanks, or just one tank.

Because we had established an acceptable compressive stress, it was the maximum compressive bending stress we were interested in, rather than the bending moment. In order to convert the bending moment to a bending stress, the section modulus of the hull is required. Although the ABS Inland Rules specify the individual section modulus of each stiffener and its associated plating, they do not specify a minimum global section modulus for the hull. In an attempt to determine the relationship between hull section modulus and length in existing tank barges, we examined the section modulus of seven inland tank barges of various lengths. The maximum possible bending moment typically increases with length. In order to maintain the same stress levels, the hull section modulus must also increase with length,. However, for inland tank barges, section modulus does not necessarily increase with length. As shown in Table 5.3 (a) and Figure 5.3 (b), no definite correlation exists. For example, the 236’ barge, although 20% shorter and likely to have smaller bending moments, had a section modulus 32% greater than the 297.5’ barge.

Table 5.3(a) Section Modulus vs. Length

Length (ft)	Section Modulus [Deck] (in ³ ft)
195	2444
236	4410
240	2726
245	3173
248	3055
276	4176
297.5	3335

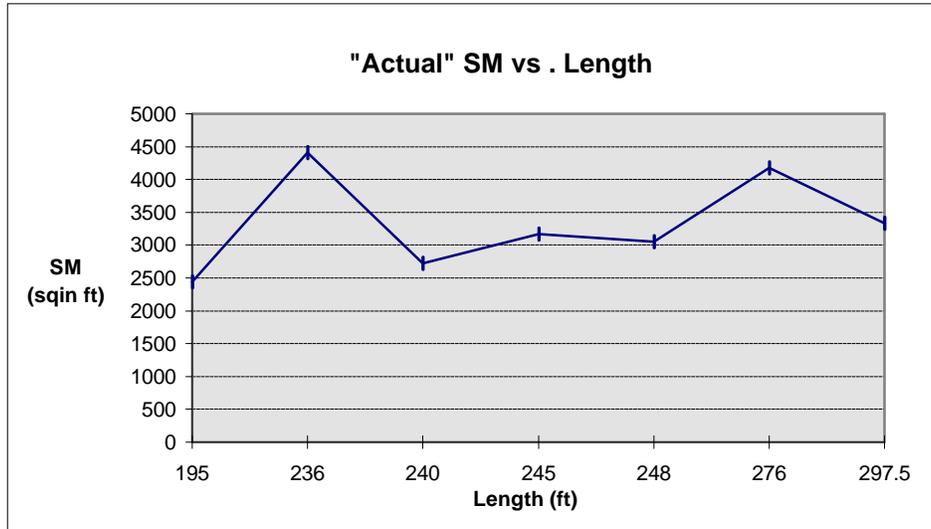


Figure 5.3(b) Plot of Section Modulus vs. Length

For our analysis, we derived a minimum section modulus for each barge length using Section 3/3.5.1 and Table 3/3.1b of the 1995 ABS Inland Rules. These requirements are intended to deter buckling and specify the minimum deck plate thickness as a function of hull section modulus, stiffener spacing, and barge length, breadth, and depth. As pointed out in section 4.1, the deck plate is typically 5/16", and most have a 24" or 25" stiffener spacing. Due to draft limitations and towing constraints, the barges usually have a depth of 12' and a breadth of 54' (35' for the smaller ones). By assuming the deck plate thickness, stiffener spacing, breadth, and depth, we solved for section modulus as a function of length.

Using this method, we determined the minimum section modulus for a 300' barge with 5/16" deck plating, a longitudinal stiffener spacing of 24", a 54' breadth and 12' depth, was 3770 in²ft (Figure 5.3 (c)). However, the existing 297.5' barge we analyzed had a section modulus 12% less. To account for the barges built prior to the addition of the deck thickness requirement to the ABS Inland Rules in 1980, we decided to use 85% of our calculated section modulus, or 3204 in²ft for a 300' barge, 4% less than the actual 297.5' barge analyzed.

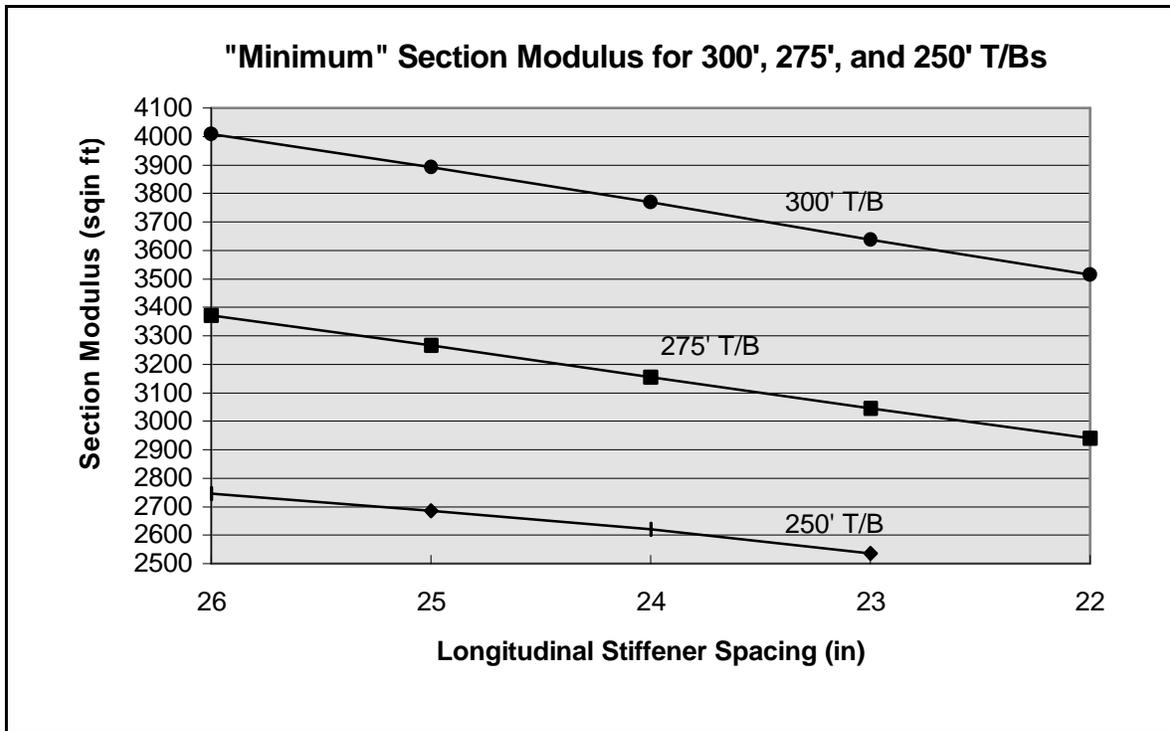


Figure 5.3(c) Section Modulus vs. Stiffener Spacing

Using our assumed tank arrangements and these section modulus estimates, we could now compute the maximum stresses in the deck for any given barge length and compare them to our allowable stress. To facilitate our study, three different models were made in HECSALV. As shown in table 5.3 (d), we focused our analysis on longer barges because preliminary work indicated solutions for larger barges would work equally well on the smaller barges. For each load case, a cargo specific gravity of 1.0 was used.

Table 5.3(d) Models Used to Research Solutions

	Length	SM (in ² ft)	Type	Location of Tanks 1,2, & 3	Voids
A	297'	3204	rake	25-79', 79-229', 229-292'	25' fwd & 5' aft
B	275'	2682	box	5-69', 69-206', 206-270'	5' fwd & 5' aft
C	297'	3204	box	5-74', 74-224', 224-292'	5' fwd & 5' aft

5.4 Approach #1: Fixed/"Locked-in" Ballast/Cargo

If the foremost and aftmost rakes or tanks are always kept full, or a significant weight of any kind is placed in the fore and aft portions of the hull, the compressive stresses in the deck will be reduced, regardless of how the barge is loaded. However, the magnitude of the compressive stress reduction is determined by the location and size of the foremost and aftmost tanks, or the magnitude and location of the weight.

Rather than focusing immediately on the feasibility of these possibilities or the associated contentious dirty water/ballast disposal and inspection issues, we initially approached this with an open mind and strictly from an engineering point of view. Although it was not adequate for all barges we examined, we found this solution worked for some of the actual existing barge models we had on file at the MSC. However, with a countless number of arrangements possible, the task of determining a percentage full or weight for the foremost and aftmost tanks of any barge which allows the remaining tanks to be loaded in any manner becomes impossible without making assumptions regarding tank sizes and locations.

In general, one or more of the following eliminated this solution for our models and many other barges examined:

- 1) typical rakes were not large enough to hold the amount of water necessary to be effective for all load cases, or
- 2) the weight necessary was so great it significantly reduced the cargo capacity,
- 3) the hogging moment created when the barge had no cargo and only the ballast or fixed weight at the ends created excessive stresses on the bottom plating (Section 5.8).

A few sample calculations involving a 290' barge, with a forward and after rake of typical dimensions, are included in the Appendix F to demonstrate some of the problems encountered. These calculations demonstrate the use of ballast in the rakes eliminates excessive compressive stresses in the deck for only some of the load cases. Additionally, if the rakes are ballasted and the cargo tanks are empty, the barge is severely "hogged". In this condition, the bottom is experiencing high compressive stresses and the deck is under relatively high tensile loads. Although the deck certainly will not collapse when in tension, high tensile stresses may accelerate fatigue in the welds between the stiffeners and deck, an area in which cracks are difficult to detect during routine inspections.

Encouraged by the results we obtained using this "ballast" approach in some models of actual existing barges, we decided to narrow the applicability of our work. Additionally, to avoid some of the contentious issues mentioned above, we chose not to use the voids and varied only liquids in the tanks. Rather than searching for a solution for any conceivable barge using this approach we focused on a subset of barges in the fleet which meet the following criteria:

1. 175' - 297' longitudinally framed barge with a forward rake and built in accordance with the ABS Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways
2. Not more than one void forward and one void aft (including rakes);
3. Aft bulkhead of forward void 15' - 26' aft of forward perpendicular;
4. Forward bulkhead of aft void not more than 15' forward of the aft perpendicular;
5. All tanks 25-55' long, and maximum difference in length between any two tanks does not exceed 10';
6. The specific gravity of any cargo does not exceed 1.05, and the maximum difference between the specific gravities of any two cargoes carried simultaneously does not exceed 0.15;

We found that any barge meeting this criteria could be afforded considerable loading flexibility without compromising the strength of the vessel, if loaded in the following manner:

1. The tank pairs are loaded in the following order:
 - a. Aftermost pair of tanks loaded to 50% full;
 - b. Forwardmost pair of tanks loaded to 50% full;
 - c. Pair of tanks closest to amidships loaded to 50% full;
 - d. Aftermost pair of tanks topped off (~95% full);
 - e. Forwardmost pair of tanks topped off (~95% full).
2. At this point, theremaining tanks may be loaded in any manner desired

Although using strategically placed “ballast” requires some planning prior to loading, it gives the operator some flexibility. Our example for a specific set of barges demonstrates creative loading schemes can probably be achieved and tailored to offer the flexibility necessary for most operators. However, each owner/operator adopting this method will need to devote time and effort in determining the specific solution suitable for their barges and needs.

5.5 Approach #2: “Uniform” Loading

Given a barge is being uniformly loaded, we attempted to determine at what percentage full one could stray from the uniform loading and load the additional cargo in any of the tanks without the possibility of exceeding the acceptable stress.

Table 5.5 Varying from Uniform Loading Using Model A

Tank #1 % Full	Tank #2 % Full	Tank #3 % Full	Bending Moment	Max Deck Stress
50	100	50	27,446 (sag)	-19.2 ksi
80	100	80	18,188 (sag)	-12.7 ksi
90	100	90	15,259 (sag)	-10.7 ksi
83	93	83	13,955 (sag)	-9.8 ksi
100	100	100	12,398 (sag)	-8.7 ksi

As shown in Table 5.5, for the arrangement assumed, at no point during uniform loading does one reach a percentage full at which the cargo distribution is sufficiently adequate to support non-uniform loading for the remaining cargo. At first glance, using only three tanks seems unrealistic. However, as mentioned in Section 5.3, each of these three tanks could be divided into any number of smaller tanks and the same results could be obtained. In this case, the governing factor is the location of the two bulkheads bounding tank #2 in our model. These results can be reproduced in any arrangement with any number of tanks as long as any two of the tank bulkheads are located at 79’ and 229’ aft of the forward perpendicular.

5.6 Approach #3: “Uniform/Sequential” Loading

Although there is no percentage full at which uniform loading of all tanks can cease and the remaining cargo loaded in any manner, we found it is possible to create a loading sequence which allows any amount of cargo to be safely loaded in any given barge

All tanks, or alternate tanks in the case of “checkerboard” loads, are first loaded to 50% full, either simultaneously or starting with the aftmost, followed by the foremost, and continuing with the tanks furthest from amidships. Once all tanks are 50% full, each tank is loaded until it is full, beginning with the aftmost tank, followed by the foremost, and continuing with the tanks furthest from amidships until all cargo is loaded. If the cargo to be loaded is less than 50% of the total capacity, it can be loaded following this sequence by either loading all tanks simultaneously or individually, alternating between tanks fore and aft of amidships, until the cargo is equally distributed to all the tanks or alternating tanks (checkerboard load). This sequence was verified using Models A and B (Table 5.6 (a))

Table 5.6 (a) Uniform/Sequential Loading Using Models A and B

Model	Tank #1 % Full	Tank #2 % Full	Tank #3 % Full	BM (ft-LT)	Max Deck Stress
A	0	0	50	10,317 (H)	7.2 ksi
A	50	0	50	17,071 (H)	11.9 ksi
A	50	50	50	4,708 (S)	-3.3 ksi
A	50	50	100	5395 (H)	3.8 ksi
A	100	50	100	11,665 (H)	8.1 ksi
A	100	100	100	10,217 (S)	-7.1 ksi
B	0	0	50	8,772 (H)	7.3 ksi
B	50	0	50	17,317 (H)	14.4 ksi
B	50	50	50	2,837 (S)	-2.4 ksi
B	50	50	100	6,055 (H)	5.1 ksi
B	100	50	100	14,560 (H)	12.1 ksi
B	100	100	100	5,674 (S)	-4.7 ksi

This method was also verified using a model of the actual 248’ barge used in the section modulus study (Table 5.3 (a)) and in determining actual operating stresses (Section 3.4). This barge was arranged with 5 pairs of tanks, a 32’ forward rake, and an 8’ aft void, and had a section modulus of 3055 in²ft. Results are displayed in Table 5.6 (b).

Calculations were performed in an effort to explicitly define “uniform”. Models A and C were used to find the maximum difference in percentage full between any two adjacent tanks. Based on the results presented in Table 5.6 (c), it was decided any load in which the difference in percentage full between any two tanks does not exceed 15% could be considered a uniform load for the purposes of study and this loading approach. Although a “uniform” load as defined above could possibly lead to compressive stresses exceeding our allowable stress by as much as 25%, because of our conservative modeling, we are confident an adequate margin of safety exists.

Table 5.6 (b) Uniform/Sequential Loading Using Actual 248’ Barge

Tank #1 % Full	Tank #2 % Full	Tank #3 % Full	Tank #4 % Full	Tank #5 % Full	Max Deck Stress
0	0	0	0	50	4.3 ksi
50	0	0	0	50	7.6 ksi
50	0	0	50	50	5.9 ksi
50	50	0	50	50	3.5 ksi
50	50	50	50	50	-2.0 ksi
50	50	50	50	100	-2.3 ksi
100	50	50	50	100	3.8 ksi
100	50	50	100	100	-3.0 ksi
100	100	50	100	100	-3.3 ksi
100	100	100	100	100	-6.5 ksi

Table 5.6 (c) Determining Acceptable Differences in % Full

Model	Tank #1 % Full	Tank #2 % Full	Tank #3 % Full	BM (ft-LT)	Max Deck Stress
A	30	50	30	11,186 (S)	-7.8 ksi
A	80	100	80	18,185 (S)	-12.7 ksi
A	80	95	80	15,848 (S)	-11.1 ksi
C	25	50	25	13,117 (S)	-9.2 ksi
C	30	50	30	11,097 (S)	-7.8 ksi
C	80	100	80	14,115 (S)	-9.9 ksi
C	80	95	80	11,794 (S)	-8.2 ksi
C	50	70	50	12,304 (S)	-8.6 ksi

5.7 Approach #4: Gradient Loading

This loading option is similar to the Uniform/Sequential Loading described in Section 5.6 and required no additional calculations to verify its accuracy. Each cargo load is distributed such that each tank has a greater percentage full than the adjacent tank toward amidships. In the case of a “checkerboard” arrangement, the loaded tank of each transverse pair must have more cargo by percentage than the loaded tank of the adjacent pair towards amidships. It relies on the same basic principle: distribute the cargo away from amidships to mitigate the compressive stresses in the deck. As discussed below in Section 5.8, the maximum difference between any two tanks must be limited to 50% to control the compression of the bottom plating.

5.8 Compression of the Bottom Plating

Because most buckling failures are a result of excessive compression of the deck, one might immediately try to eliminate the risk of failure by simply ensuring the barge is always in a

“hogging” condition, placing the deck in tension and the bottom in compression. Because the plating and stiffeners in the bottom are more substantial than those in the deck, the MSC initially did not consider the stresses in the bottom of the hull when performing the analyses. However, when researching the feasibility of adding ballast or fixed weights in the forward and after regions of the barge, as discussed in Section 5.4, high compressive stresses were created when the tanks near amidships were empty. It soon became evident the MSC needed to examine the effects of these actions on the bottom structure of the barge.

Table 5.8 (a) Ultimate Strength of a Typical Bottom Sub-panel

Lateral Pressure / Head	Ultimate Strength
None	23.9 ksi
1.0 psi/2.3'	22.7 ksi
2.0 psi/4.6'	21.4 ksi
3.0 psi/6.9'	20.3 ksi
4.76 psi/11.0'	19.5 ksi

When analyzing the bottom plating, in addition to the factors discussed in Section 3.1, the lateral load on the bottom sub-panel created by the hydrostatic pressure must also be considered. Fortunately, the method chosen for determining the ultimate strength of longitudinally stiffened sub-panels can also accommodate lateral pressures. As the draft increases, the corresponding increase in hydrostatic pressure causes the ultimate strength of the bottom to decrease, as shown in Table 5.8 (a).

As previously discussed, the compressive stresses from partial loads often exceed those resulting from a full load. The greatest compressive loads are likely to occur in the bottom plating when the foremost and aftmost tanks have much more cargo than the tanks closer to amidships. As with the deck, to obtain the compressive stress in the bottom the section modulus to the bottom is needed.

Table 5.8(b) Difference Between Section Modulus to the Deck and to the Bottom

Length	Hull	SM Bottom > SM Deck by %
195	Double Hull	57%
236	Single Hull	21%
240	Single Hull	47%
245	Single Hull	32%
248	Single Hull	14%
276	Double Hull	79%
297.5	Double Hull	36%

The section modulus to the bottom for each of the barges used in Table 5.3 (a) was calculated. As shown in Table 5.8 (b), the data varied widely, but in each case the section modulus to the bottom was at least 14% greater than that to the deck. In the absence of better data, we conservatively used the section modulus to the deck calculated in Section 5.3 and analyzed various conditions using Models A and C. Although the analysis was conservative, the results in Table 5.8(c) demonstrate it is not impossible for the bottom to fail under compression.

Table 58(c) Maximum Compressive Stress in the Bottom

Model	Tank #1 % Full	Tank #2 % Full	Tank #3 % Full	BM (ft-LT)	Max Bottom Stress
A	100	0	100	33,959 (H)	-23.5 ksi
A	100	35	100	18,441 (H)	-12.4 ksi
A	100	50	100	11,665 (H)	-7.8 ksi
A	57.5	0	57.5	19,642 (H)	-13.6 ksi
C	100	0	100	40,397 (H)	-23.2 ksi
C	100	35	100	24,146 (H)	-16.6 ksi
C	100	50	100	17,181 (H)	-11.9 ksi
C	57	0	57	23,027 (H)	-15.9 ksi

When placing the vessel in a hogging condition, not only should precaution be taken to prevent failure or damage to the bottom, one must also be aware of the tensile stresses in the deck. Although they probably are not high enough to damage the structural members, the tensile stresses may accelerate fatigue in the welds connecting the stiffeners to the deck, which can be extremely difficult to detect during routine inspections.

6.0 CONCLUSIONS

- Inland tank barges are not as strong as originally believed. In many cases, stresses exceeding the ultimate strength of the barge are not difficult to obtain. Without loading guidance, many barges are at risk.
- There is little regard for ultimate strength in barge design, construction, and regulation.
- Buckling is not only a problem for bunkering barges. Due to the similarities in construction of the deck, the ultimate strength of different inland tank barges varies very little. Even in barges used in line haul service, significant compressive stresses can be reached, especially while loading and unloading.
- The 1995 ABS Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways may not adequately address the potential for compressive failure of tank barges.
- Current regulations do not address the potential for compressive failure of inland tank barges.
- Structural failures are not adequately identified, recorded, and tracked by the Coast Guard.
- In most cases, more stringent inspection standards are not likely to prevent compressive failures. Minor deflections from fit-up and welding during construction and from loading/unloading in service are unavoidable. Small deflections of a broad area of the deck plating and the attached stiffeners can significantly reduce the ultimate strength, while larger

deflections, typical of localized dents in the side shell and gunwales, have little effect on the ultimate strength.

- Current theories used to predict the ultimate strength of stiffened sub-panels assume the stiffeners are continuously welded to the plating. Due to the widespread use of serrated sections in the past, and the continued use of intermittent welding to attach the longitudinal stiffeners to the plating, the MSC's ultimate strength predictions for inland tank barges may be too high, i.e. collapse may be possible at lower stresses.

7.0 RECOMMENDATIONS

- Existing barges built in accordance with the ABS Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways should be analyzed by their operators. The compressive stresses produced in the deck under all expected loading conditions, including loading/unloading and transiting, should be determined and compared to an allowable stress, which should not exceed 60% of the ultimate strength of the hull. The operating environment and the corresponding wave induced bending stresses should be considered in the analysis.
- For existing barges, the compressive stresses in the deck should never exceed 9.0 ksi. Although this may seem low, the margin of safety is actually slightly less than what has historically been considered reasonable for ship structures, i.e. 2:1.
- The ABS Rules for Building and Classing Steel Vessels for Service on Rivers and Intracoastal Waterways should be reviewed for consideration of:
 - a. An ultimate strength analysis for all barges greater than 175' in length.
 - b. As recommended by Sharpe [8], a minimum hull girder section modulus as a function of barge length.
- The Regulations should be reviewed for consideration of:
 - a. 46 CFR 31.10-32 application to all inland tank barges greater than 175' in length. This is consistent with Billingsley's recommendation to provide adequate loading guidance for the dispatchers and operators of each tank barge [6].
 - b. A definition for "unacceptable stresses" in 46 CFR 42.15-1(a) and 45.105 as a percentage of the ultimate strength of the hull.
 - c. 46 CFR 32.59-1 limiting the still water compressive bending stress of the hull under any expected loading condition, including loading/unloading and transit, to 9 ksi.
 - d. The assumed grounding conditions in 46 CFR 151.10-20(a) are very conservative, however, the allowable stresses are extremely high. Research should be conducted to ensure that the extreme grounding condition provides an adequate margin of safety.
- Designers and owners should ensure new barges are designed with an adequate ultimate strength for their intended and anticipated loading conditions, regardless of the existing regulatory requirements.

- The collapse phenomenon and theories used to predict the ultimate strength of the hull should become widely understood and accepted, allowing the development of a new convention for design safety factors based on ultimate strength.
- Based on the results of the testing currently underway at the U.S. Naval Academy to determine the impact of using intermittent welding and serrated sections as longitudinal stiffeners, revisions should be made to any loading guidance as necessary.
- Discussion of the collapse mechanism and buckling phenomenon should be included in the curriculum for the Marine Inspector's course at Reserve Training Center, Yorktown, Virginia. Inspectors should be exposed to the factors affecting hull ultimate strength and the significance of deflection and distortions in longitudinally framed sub-panels.
- Owners and operators of barges should be exposed to the factors affecting hull ultimate strength and hull stress. They should understand how cargo load distribution affects hull stress and the significance and implications of deflections and distortions in longitudinally framed sub-panels.

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