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Evaluation of Ship-Bridge Pier Impact and of Islands as Protection

Chocs de bateaux contre des piles de ponts et îlots protecteurs

Schiffskollisionen mit Brückenpfeilern und Schutzinseln

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Vladimir Minorsky, born 1916, obtained a degree in Naval Architecture and Marine Engineering frem M.I.T., Cambridge 1939. Worked as Naval Architect 1939-1960 and 1966-1978 with George Sharp Inc. on the design of commercial and naval ships. During 1960-1966 he was Chief Design Engineer with DeLong Corp. of New York, working on the design of offshore platforms, and jack-up barges.

SUMMARY
The paper discusses the background of ship impact studies and provides a simple method to calculate impact forces delivered by ships when hitting relatively immovable objects such as bridge piers. It also offers a few thoughts on the hydrodynamic reasons for such collisions, and gives a method for calculating the ship stopping capability of artificial islands.

RÉSUMÉ
Le rapport rappelle les études de collisions de navires et propose une méthode simple de calcul des forces d'impact de navires en collision avec des objets relativement immobiles, tels que les piles de ponts. Le rapport traite des causes hydrodynamiques de ces collisions et donne une methode de calcul de la capacité à arrêter les navires qu'ont les îlots protecteurs.

ZUSAMMENFASSUNG
Der Bericht erörtert den Hintergrund der Untersuchungen im Bereich der verschiedenen Auswirkungen von Schiffen und stellt eine einfache Methode dar zur Berechnung der Auswirkungen der Schiffe, wenn sie mit verhältnismässig immobilen Gegenständen, wie z.B. Brückenpfeilern, zusammenstoßen. Dieser Bericht schließt ebenfalls einige Betrachtungen über die hydrodynamischen Ursachen solcher Kollisionen und eine Methode für die Berechnung der Fähigkeit künstlicher Inseln zur Anhaltung von Schiffen ein.

1. BACKGROUND

Before 1959 collisions interested Naval Architects only insofar as they resulted in explosions or the loss of a vessel. With the advent of nuclear propulsion, designers were faced with the possibility that the reactor could be broached in a collision. Other than the Russian icebreakers operating in the Arctic Ocean where the chances of a collision were almost nil, "Savannah" was the first non military nuclear vessel. It was designed to carry cargo and passengers world-wide. The question which had to be answered at the time was: "What is the size and speed of a vessel which can broach its reactor in a collision?".

In the US Maritime Administration's Safety Assessment for "Savannah" a semi-empirical solution was used which gave a relationship between energy absorbed in a collision and the volume of selected steel members destroyed [1]. The basis for the method was collision data compiled by the US Coast Guard. This concept was also used in the reactor protection calculations of "Otto Hahn" and "Mutsu". At the time of "Mutsu's" design a large amount of original work in the field of collision research was done in Japan by a team of distinguished scientists and engineers [2]. In the late 60's personnel of GKSS in West Germany ran collision tests on models of the "Otto Hahn" [3] and in the 1970's they developed the rationale for a structural protective grid made of webs and stringers spaced about 1 m apart at the side shell abreast of the reactor compartment. The grid was designed to stop virtually any striking vessel. This idea was also considered for "Savannah", but not incorporated for economic reasons; also, at the time, experiments could not be scheduled to verify the scheme.

In connection with their collision research GKSS tested a series of bow models built to scales of 1/7.5 and 1/12. These bow models, placed on a cart, ran down a ramp to meet the collision barrier at 90°. This experimental work is described in a number of papers [4] [5]. In these tests the collision barrier constituted an almost immovable obstacle, very much like a bridge pier.

About 1975, GKSS and the US Maritime Administration started upon a joint program of research where some of the tasks allocated to the US Maritime Administration included statistics on ship accidents and collision probability studies [7], as well as calculations of impact forces using, to some extent, formulae collected from various sources by Professor K.A. Reckling [6]. The object of these impact force calculations was to verify forces measured by GKSS on the model of the bulbous bow tanker "Esso Malaysia".

This particular research task ran into difficulties on both sides of the Atlantic: the GKSS established the penetration (bow destruction) for a known kinetic energy input which was accomplished in two separate, but additive, steps. Unfortunately, faulty instrumentation did not provide reliable impact force measurements; as for the calculation of these forces by a "bits and pieces" approach for successive bow sections, it also encountered problems.

The forces resulting from impact upon certain portions of the bow such as the centerline bulkhead, the decks and flats, and the hemisphere at the tip of the bulb, could be calculated with some confidence; however, no satisfactory formulae were available with which to calculate the contributions of the stiffened side shell plating and stringers which were inclined at an angle to the direction of impact, or for the curved portions of shell plating which form the transition from bulb to hull proper. In addition to these uncertainties, this method of calculation is laborious and time-consuming.

While engaged in an attempt to calculate these impact forces at successive points, the writer became acquainted with a semi-empirical method for calculating the crippling strength of multicorner (more than two corners) air frame sections. The method is simple and quick: it appears that it can be applied to the sections of a ship's bow to give answers sufficiently accurate to satisfy

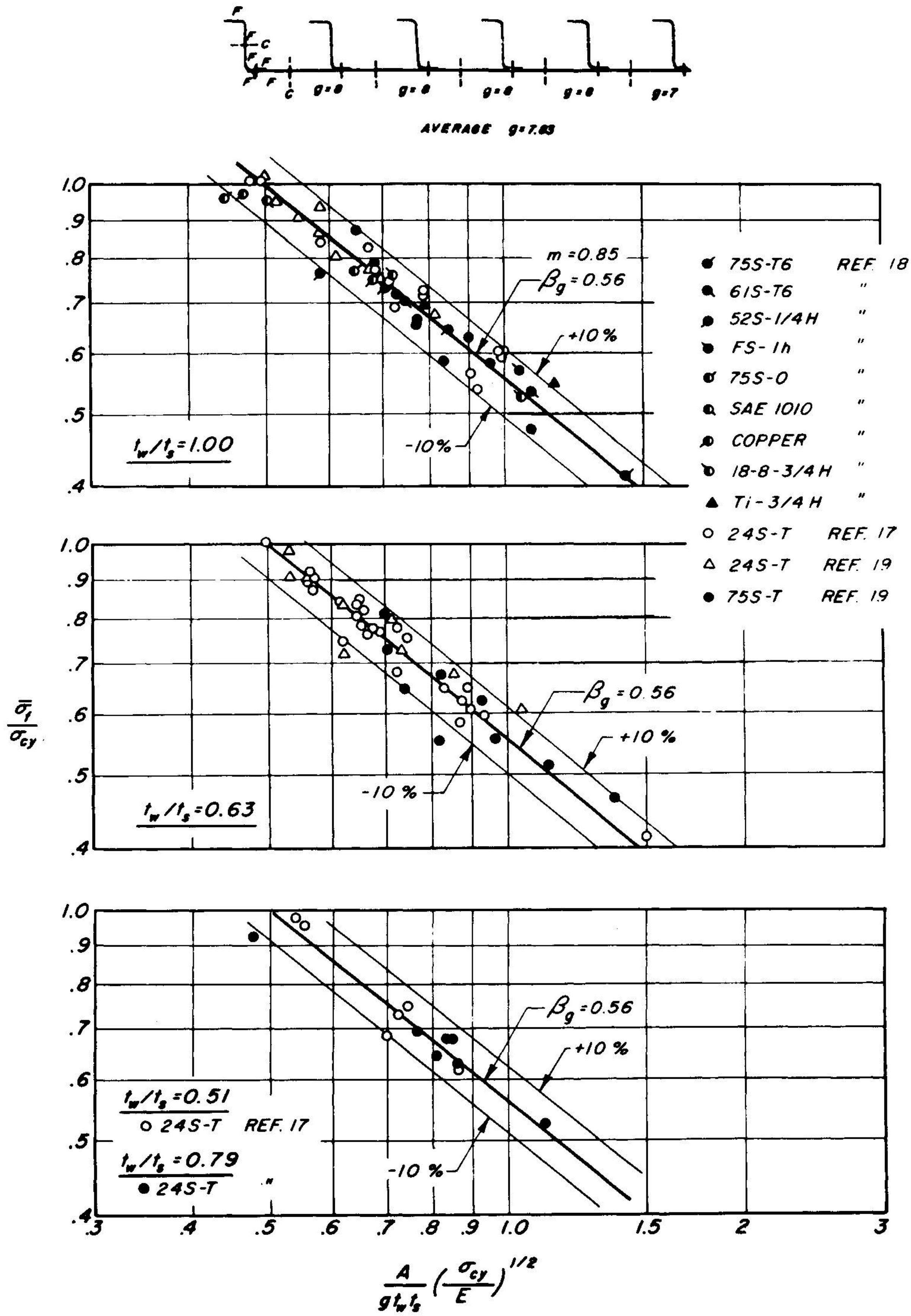

Fig. 1. Crippling data on Z-stiffened panels. (From ref. [8]).

designers interested in knowing impact forces against bridge piers. The method in question is described by Gerard in [8].

2. GERARD'S SEMI-EMPIRICAL METHOD

Gerard's method is based on many tests performed on stiffened plating using various types of stiffeners and many different materials including a number of aluminium alloys, steel, copper and titanium. Crippling strength is defined as the stress at which secondary instability occurs for thin wall compression members, in the form of a local failure in buckling which exceeds the elastic buckling load. The paper claims accuracy within ± 10%.

Gerard's relationship is defined by the curve of Fig. 1 taken from [8]. The basic equation is:

$$\sigma_F/\sigma_{cy} = 0.56\left[\left(\frac{g t_w t_s}{A}\right)\left(\frac{E}{\sigma_{cy}}\right)^{1/2}\right]^{0.85}$$

where:

- σ_F = the crippling strength (Kgf/cm^2),
- σ_{cy} = compression yield (Kgf/cm^2),
- g = number of cuts plus flanges,
- t_w = thickness of stiffening members (cm),
- t_s = thickness of skin (cm),
- A = area of element (cm^2) and
- E = modulus of elasticity (Kgf/cm^2).

Where there are variations in t_w and t_s within a section, a weighting factor can be introduced. In the simple sections considered by Gerard it was thought that an average value for t_w and t_s would be sufficiently accurate. In the case of the "Esso Malaysia" model which has been analysed using Gerard's method, all interior members have a thickness of 1 mm; the value of t_s used is that of most of the shell thickness at a given section; however, the area A of a section takes into account variations in shell thickness. At first impression, the 'g' value used by Gerard seems to be a non-rational and even arbitrary quantity, but upon closer examination, one perceives that it is at the heart of Gerard's method and is an original intuitive contribution.

Examples of 'g' values for different sections are given in Fig. 2 taken from Gerard's paper.

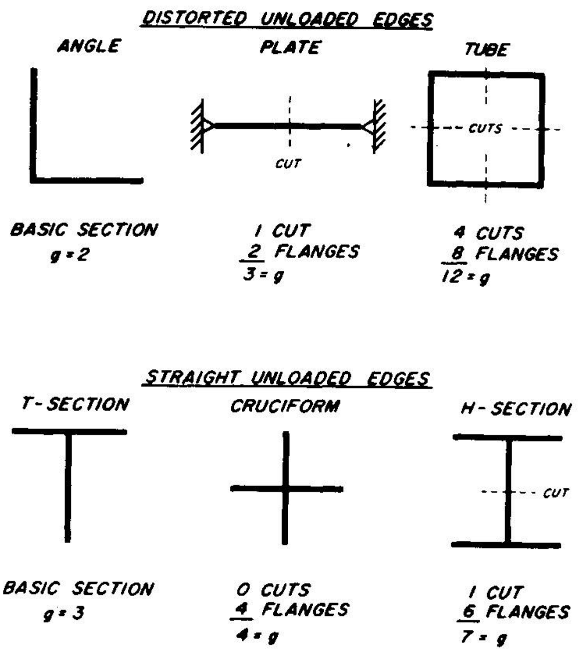

Fig. 2. Methods of cutting simple elements to determine "g".
(From ref. [8]).

The importance of the 'g' concept is illustrated numerically by Fig. 3a and 3b where ¢ indicates a cut.

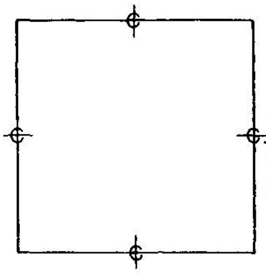

Fig. 3a
t = 1.0
g = 12

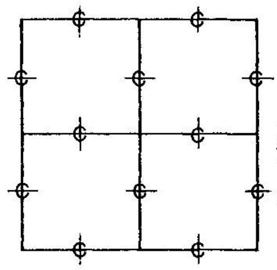

Fig. 3b
t = 2/3
g = 36

Figures 3a and 3b have the same outside dimensions. Cuts are made so as to produce simple flanged elements. The total cross sectional area A is the same for 3a and 3b when t = 1 in Fig. 3a and t = 2/3 in Fig. 3b. The application of Gerard's relationship shows that 3b has a crippling strength and a resistance to failure 27.6% greater than 3a; conversely, for the same crippling strength, 3b will be lighter than 3a.

3. RESULTS FOR "ESSO MALAYSIA" MODEL

The "Esso Malaysia" is a bulbous bow crude oil carrier built in 1967 by Howaldtswerke-Deutsche Werft. Its characteristics are LOA = 323.7 m, Beam = 47.2 m, Depth = 23.7 m and deadweight 195,000 tonnes. GKSS conducted collision tests (Test 12) on a welded model of its bow to a scale of 1/12.

The crushing of the bow was obtained in two separate blows: first, the model bow was raised 2.16 m to give a first impact energy of 39,100 Kgfm (383 kNm) which resulted in a penetration of 0.50 m; in a second impact the bow was released from a height of 5.35 m, adding 96,800 Kgfm (950 kNm) to the first impact energy for a total of 135,900 Kgfm (1333 kNm). The final penetration was 1.41 m. The model frame spacing is 5.083 cm.

The result of applying Gerard's formula to the model structure is shown in Fig. 4 which plots calculated impact forces in Kgf against frame spacing for the "Esso Malaysia" model.

In Fig. 4 the plot of impact forces OABCDE shows two discontinuities: at frame 158, where the bulb shell plating thickness drops from 0.275 cm to 0.20 cm, and at frame 147, where most of the shell plating thickness drops from 0.20 cm to 0.15 cm (Fig. A-2 in Appendix). Detail calculations are given for these two points in the Appendix.

Values for intermediate points are also given in the Appendix, as well as values which would be obtained if the shell were 0.20 cm thick throughout the bow. This would result in the curve OBCF in Fig. 4.

Returning to curve OABCDE, the average impact force for the range of first impact (0.50m penetration) is 69,000 Kgf (677 kN). The area under this part of the curve is 34,500 Kgfm representing work, as compared to 39,100 Kgfm of energy input, giving an error of 11.7%. The average impact value for the entire curve (1.41 m penetration) is 99,000 Kgfm (971 kNm); the area under the curve is 139,600 Kgfm (1370 kNm), representing work, as compared to 135,900 Kgfm (1333 kNm) of energy input, giving an error of 2.7%.

The maximum impact from calculations in the first phase is 81,900 Kgf (803 kN), and for the entire curve it is 151,000 Kgf (1481 kN). Unfortunately, there is no valid experimental data to compare with these calculated values. It is hoped that in the future satisfactory instrumentation will be available to verify the validity of Gerard's method for maximum impacts as well as for the work done by impact forces.

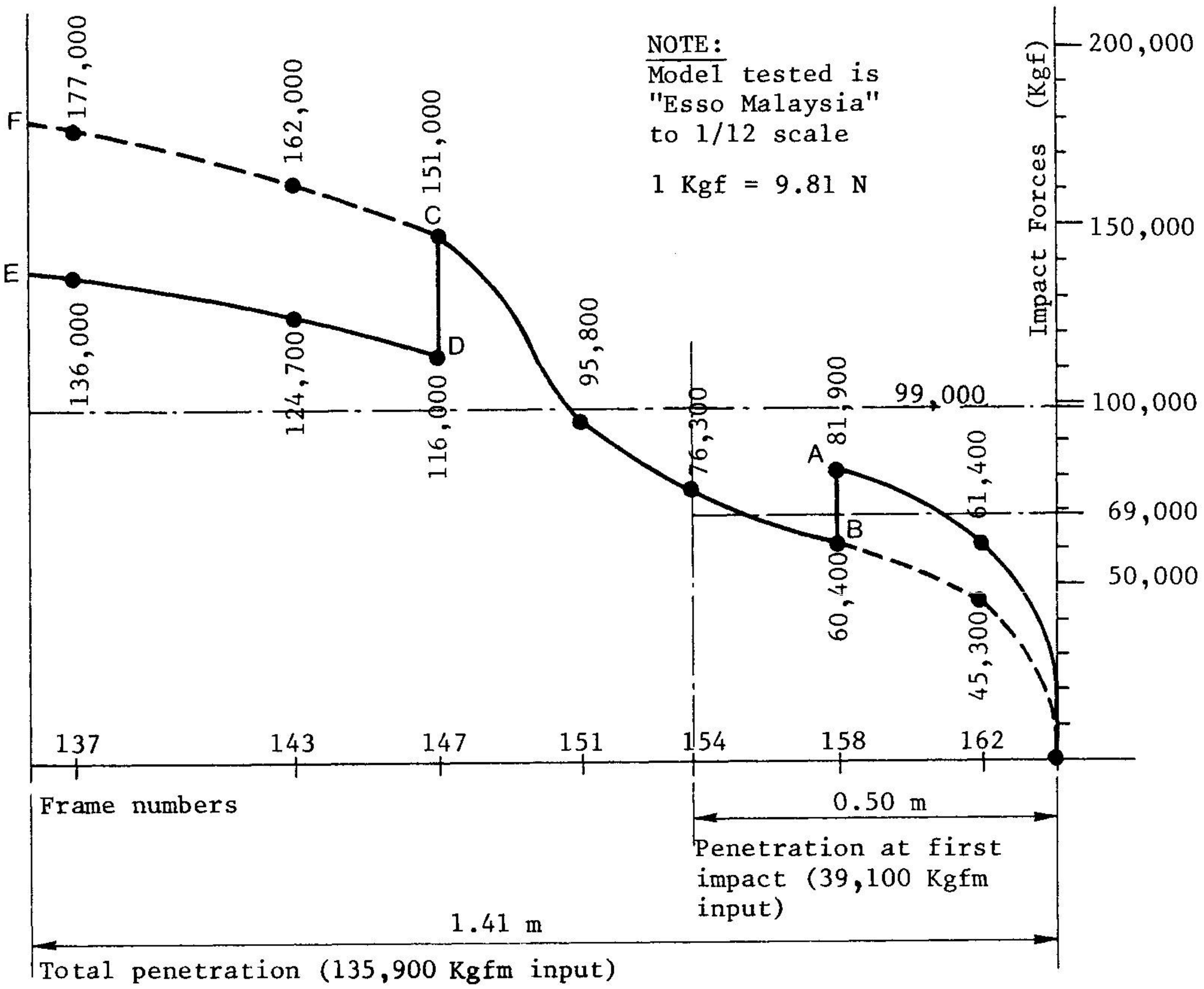

Fig. 4. GKSS model test penetrations versus impact forces from Gerard's method.

In comparing the calcutated energy with that known to have been spent in the testa, Gerard's method gives satisfactory results. It should be mentioned that the collision barrier in the tests was lower than "Esso Malaysia's" main deck. If the deck had been involved, the impact forces would have been higher.

Of particular interest to bridge designers is the full scale impact force: since forces are proportional to the square of scale ratio, the caximum full scale imapct would have been in theory, 12^2 x 151.0 tonnes or 21,700 tonnes. In actuality, one may expect the full scale impact force to be less than that derived from model tests. Scale effect is discussed in [5] for energy. The comments in [5] will also apply to forces: metal grain size is not to scale in the model, which is also subject to excessive strain hardening.

If properly instrumented tests should verify force calculations by Gerard's method, it will be possible to calculate impact directly from scantling drawings of a full size ship and thus eliminate the problems of scale effect.

It is interesting to note that in Fig. 4 the impact value at point A, 81,900 Kgf (803 kN), at frame 158 could be obtained at a penetration of only 0.30 m and an energy of only 20,700 Kgfm (203 kNm), so that a significant impact force can be obtained at a low energy. In studying various ship types which can hit a bridge pier it is important to singel out vessels with hard bows.

It should be easy to program Gerard's method for a computer solution, so that, once the bow sections are available, a solution such as that of Fig. 4, can be obtained in very little time.

The effect of the large lightening holes in the centerline bulkhead (Fig. A1 of Appendix) was studied: it was found that the stiffening at the edges of ligaments between holes introduced additional 'cuts and flanges' which compensated for the plating removed by the lightening holes.

Before leaving the subject of Gerard's method, the writer would like to mention that airframe methods of analysis were completely unknown to him prior to attempting the "Esso Malaysia" impact calculation. This points out that there is today an unfortunate tendency to produce narrow specialists. There is much to be gained in becoming aware of what is being done in other branches of engineering.

4. REASONS FOR COLLISIONS OF SHIPS WITH BRIDGES

It is puzzling, to say the least, that there should have been a number of cases where ships equipped with the latest navigational equipment and with beams of only 20 to 30 m hit piers where the clear span was 100 m or more. The Store Baelt report [9] states that the principal reasons for such collisions are human error, mechanical failure and weather conditions. Elsewhere in [9] an Australian correspondent lists tidal current in the navigation direction, ships in ballast, and strong winds as being local reasons for collisions.

There is little one can say about human errors such as that of the skipper who fell asleep at the helm. Perhaps there should be a rule requiring two officers to be present in a pilot house when approaching a bridge.

Mechanical failure seems a very remote possibility if one thinks of a steering breakdown happening at the precise moment when a ship comes to a bridge: the critical time preceding a collision is counted in minutes, compared to a sea voyage of several weeks. For any one voyage the probability that a steering failure will happen at the approach to a bridge is perhaps 5×10^{-5} which, of course, must be multiplied by the probability that a steering failure will happen at all in the lifetime of a ship. It is likely that in many cases collisions blamed on steering failure were caused by some of the reasons listed below.

Besides the above reasons there are hydrodynamic explanations for the loss of steerageway which may not always be understood. Only one such reason was mentioned in [9] : the case of tidal current running with the vessel. If the vessel is going slow ahead, or half ahead with a strong following current, the rudder may not respond to the helm because water is not flowing past the rudder at all, or not fast enough to produce lift on the rudder. The same situation will arise if the officer on watch should be so ill-advised as to order power astern with the object of reducing speed when approaching a bridge: with the screw race no longer impinging upon the rudder, the vessel will lose steerageway, as is well known from vessels executing crash stops on trial. Finally, a vessel moving slow ahead at a slight angle into a strong current may find that its hull acts as a hydrofoil, creating a greater turning moment than can be overcome by the rudder, as shown in Fig. 5.

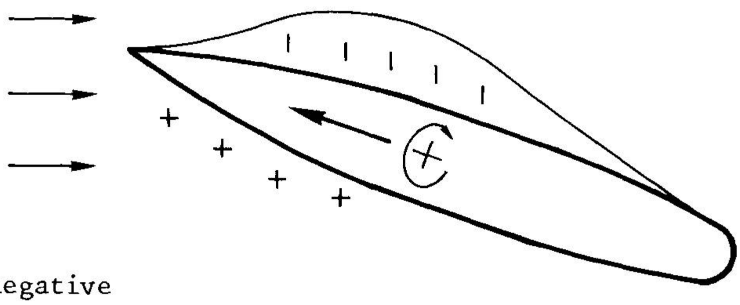

Fig. 5. Turning moment due to negative pressure field caused by current on hull.

The steering problems caused by hydrodynamic conditions, and even those caused by mechanical failure, can be overcome or improved by the use of a bow thruster. This device should be a requirement for any vessel which transits bridges frequently, or is engaged in a trade where it plies busy waterways. At the approach of a bridge the thruster should be activated and rotating at zero blade angle, ready to thrust.

5. THE PROTECTION OF BRIDGE PIERS

5.1 Protective devices

Piers can be protected by fenders on the pier itself, fenders on piles around the pier, clusters of piles, dolphins, or artificial islands.

- Fendering is suitable for protection from barges and small vessels. It cannot stop large vessels.
- Pile clusters (summation of individual piles) or dolphins (a group of piles rigidly tied together at the top) may be too limber in deep water; also, the driving of such piles and their maintenance may be costly. A fairly rigid dolphin of good-sized steel piles may have fair stopping qualities, but it may rupture the side shell of a ship in a glancing encounter: in the case of a tanker this may be disastrous for the environment.
- Artificial islands are without doubt the best and cheapest solution for large vessels. The cheapest material for an island is sand, which can be pumped in situ by dredges. Sand may not be suitable if the location is subject to a breaking surf in stormy weather, or to swift tidal currents; in both instances there may be a scouring action that will carry away part of the island. In such cases coarse gravel or stones (10-15 cm) or cobbles will be preferable. Rip rap of quarried stone or precast elements on an island will stop a vessel very effectively, but it will also rip out the ship's bottom, with consequent damage to the ecology. The writer was consulted for the artificial island protecting the planned nuclear power station for the Atlantic Generating Station. The semi-empirical method used for "Savannah" could be applied to predict the stopping ability of rip rap for an aircraft carrier hitting the island at 32 knots. As the writer recalls it, it was found that the rip rap would have stopped the aircraft carrier in some 35 m, but with considerable damage to the vessel's bottom. The model tests performed for the artificial island in connection with this project were not realistic, because the model island used sand, which could not have been used in that location on account of a heavy surf.

5.2 Calculations of an island's stopping capability

The stopping capability of an island for any vessel can be predicted with good accuracy if the coefficient of friction of the steel bottom sliding up the beach is known. If the vessel's forefoot slides, the coefficient of friction on gravel is 0.40. In the case where the beach of the island is steep, the forefoot may plow it up, with a resulting higher value for the coefficient of friction, the value of which will have to be determined. It should be noted that a vessel in ballast may trim by the stern as much as 2^o, which will reduce the angle between keel and beach. The assumption that the forefoot slides up the beach instead of digging into it will always be on the safe side.

In Fig. 6 a vessel is shown first contacting an artificial island at point 0_1, travelling up the beach a distance d, and stopping with the forefoot at the point 0_2.

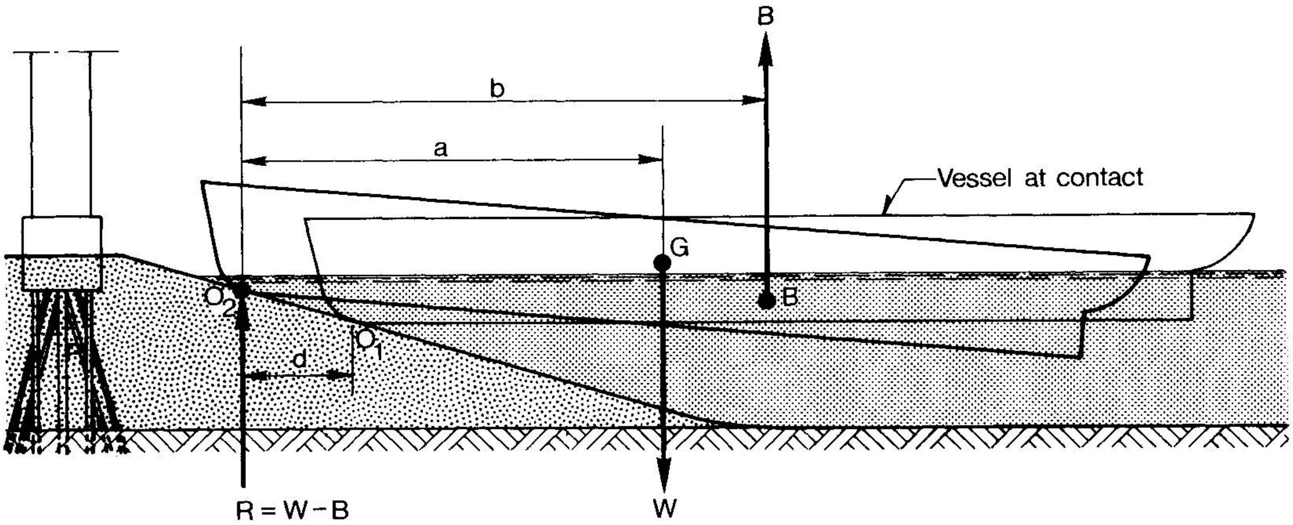

Fig. 6. Weight-buoyancy equations for ship meeting artificial island.

0 being any point along d between 0_1 and 0_2 and calling:
W - the ship's displacement,
B - its buoyancy,
a - the distance from center of gravity to point 0 and
b - the distance from center of buoyancy to 0.

The reaction R at point 0 is: $R = W - B$ (1)
For equilibrium, moments about 0 are: $Wa = Bb$ (2)
hence, $R = W(1 - a/b)$

The angle of the ships keel with the horizontal during the travel of the forefoot up the beach is unknown: if several trim lines are drawn when forefoot is at point 0, the corresponding ship buoyancy B and longitudinal center of buoyancy b can be determined for these trim lines using Bonjean curves. Plotting the product Bb against the trim line angles, the trim angle for which equation (2) is satisfied can be established, and knowing B, the reaction R at point 0 is determined.

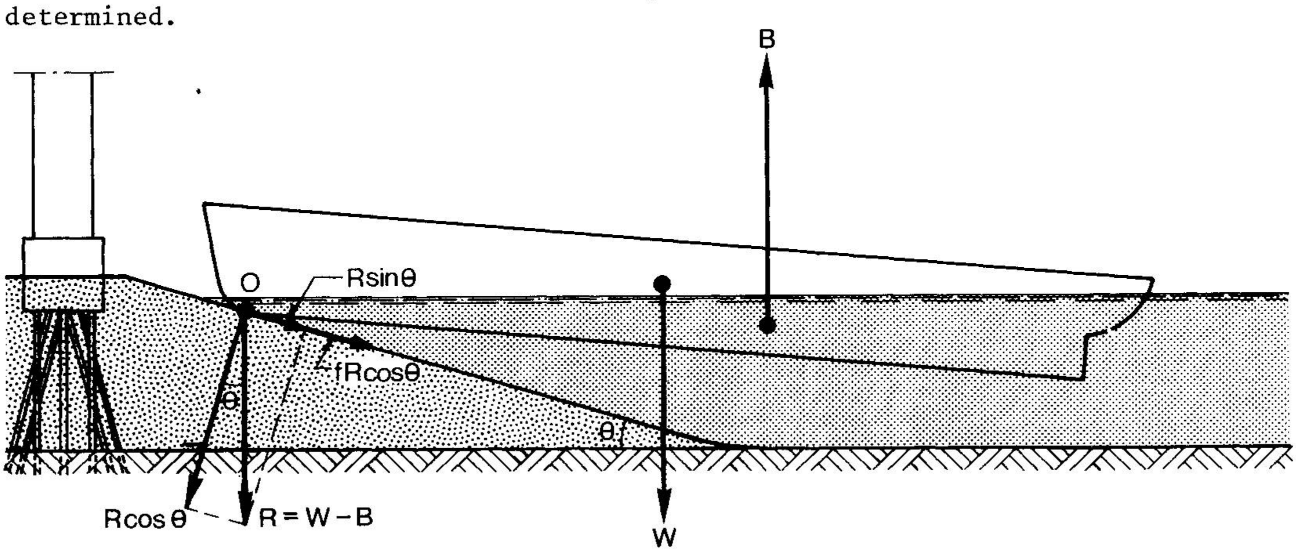

Fig. 7. Forces on ship forefoot.

In Fig. 7 the down slope component of R is R sin θ. The component normal to the beach is R cos θ. In sliding up the beach the forefoot has to overcome a force:

$$F = R \sin \theta + fR \cos \theta \quad (3)$$

where f is the frictional coefficient.
If $f = 0.40$ and $\theta = 20^{\circ}$, then $F = 0.718R = 0.718W(1 - a/b)$ (4)
If F is plotted against distance travelled by the forefoot, the area under such

curve is work. The stopping point is where the area equals the kinetic energy of the vessel at contact. As a sample calculation, if a vessel of displacement W = 100,000 tonnes travelling at 7.5 m/sec coasts into an island, its kinetic energy is 286.6×10^6 Kgfm (2810 MNm). Assuming that the curve described above is drawn, and that the average force F = 0.10W, the distance to stop is 286.6×10^6 Kgfm divided by 10×10^6 Kgf = 28.6 m.

5.3 Tests

While model tests on artificial islands are of great interest, the writer would like to be reassured concerning scale effects, especially for the coefficient of friction. In this connection, it should be fairly simple to run non-destructive tests on a full size ship instrumented to give the required information. It would then be possible to verify the accuracy of model tests by comparing them to full size results.

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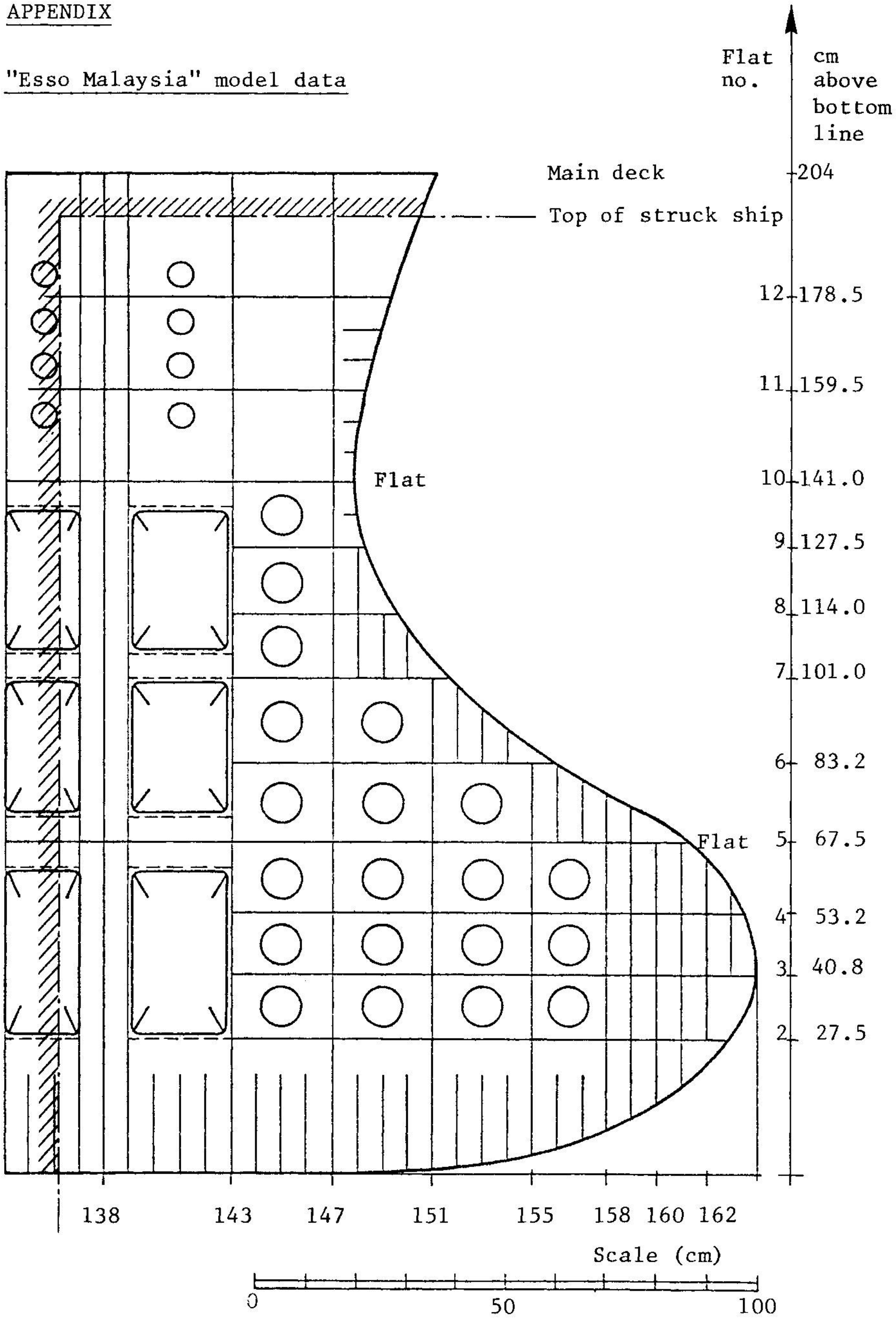
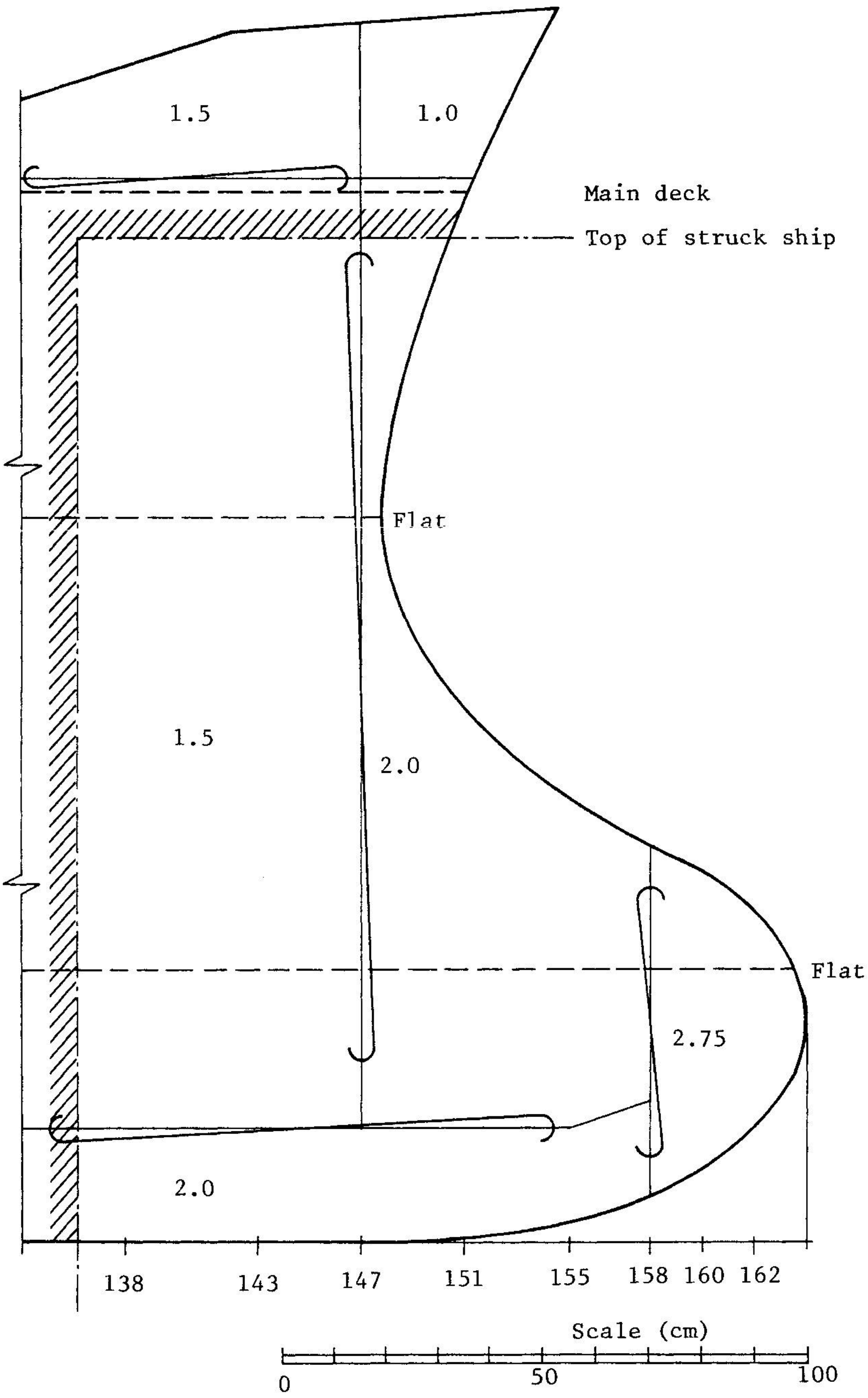
APPENDIX

"Esso Malaysia" model data



NOTE:
All plating: 1mm
Frame spacing 5.09 cm

Fig. A-1 "Esso Malaysia" model. Section at centerline of bulkhead.



NOTE:
Frame spacing: 5.09 cm

Fig. A-2 "Esso Malaysia" model. Bow shell plating in mm.

Calculation of crippling forces using Gerard's method.

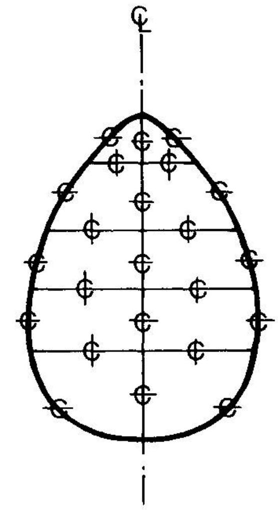


Fig. A-3. Section at frames 157½ - 158.

Frame 157½

g = 23(cuts) + 46 (flanges) = 69

t_w = 0.1 cm

t_s = 0.2 cm

Area = 64.2 cm^2

σ_{cy} = 2530 Kgf/cm^2

σ_F/σ_{cy} = 0.372

σ_F = 941 Kgf/cm^2

Force = 60,400 Kgf (592 kN)

Frame 158

g = 23 (cuts) + 46 (flanges) = 69

t_w = 0.1 cm

t_s = 0.275 cm

Area = 79.0 cm

σ_{cy} = 2530 Kgf/cm^2

σ_F/σ_{cy} = 0.4095

σ_F = 1036 Kgf/cm^2

Force = 81,900 Kgf (803 kN)

Frame 146½

g = 55 (cuts) + 121 (flanges) = 176

Area = 67.4 (shell)
+ 19.0 (bulkhead)
+ 24.6 (flats)
+ 10.4 (stringers)
+ 2.6 (keelson)

124.0 cm^2

$$\sigma_F/\sigma_{cy} = 0.56\left[\frac{176 x 0.1 x 0.15}{124.0} \; x \; 28.8\right]^{0.85}$$

= 0.369

σ_F = 935 Kgf/cm^2

Force = 116,000 Kgf (1138 kN)

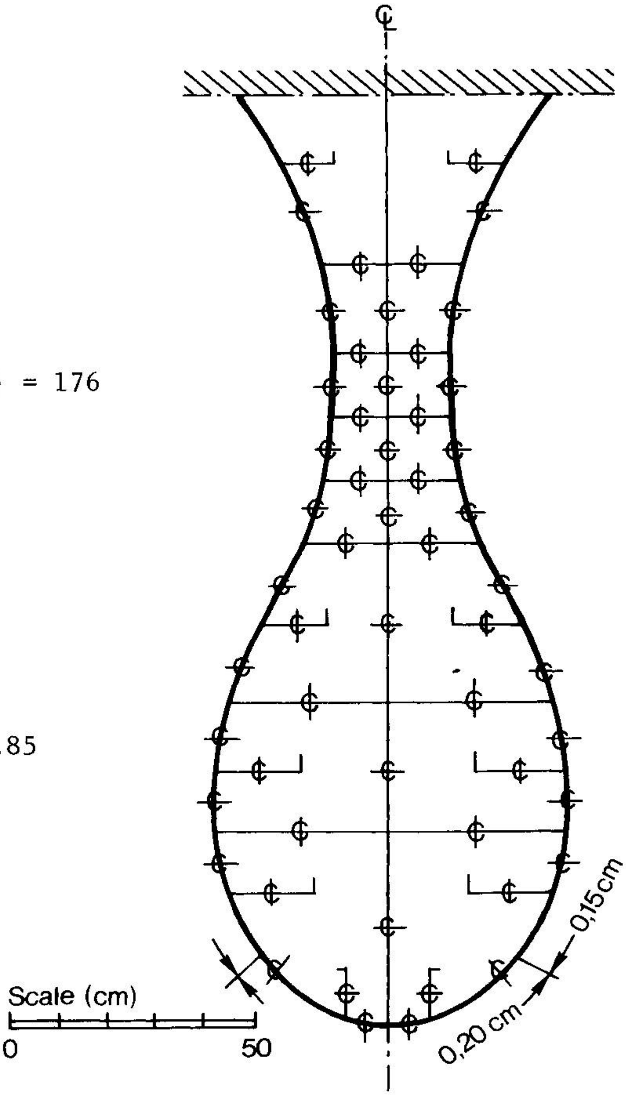


Fig. A-4. Section at frames 146½ - 147.

Frame 147

g = 55 (cuts) + 121 (flanges) = 176

Area = 84.4 (shell)
+ 19.0 (bulkhead)
+ 24.6 (flats)
+ 10.4 (stringers)
+ 2.6 (kellson)

141.0 cm^2

σ_F/σ_{cy} = 0.423

σ_F = 1070 Kgf/cm^2

Force = 151,000 Kgf (1481 kN)

Frame 162

g = 54

A = 46.7 cm^2

σ_F = 1314 Kgf/cm^2

Force = 61,360 Kgf (602 kN)

With t_s of skin = 20 cm, it would be 45,300 Kgf

Frame 154

g = 90

A = 67.2 cm^2

σ_F = 1136 Kgf/cm^2

Force = 76,300 Kgf (748 kN)

Frame 151

g = 112

σ_F = 1078 Kgf/cm^2

Force = 95,900 Kgf (940 kN)

Frame 143

g = 182

A = 168.8 cm^2

σ_F = 738 Kgf/cm^2

Force = 124,700 Kgf (1223 kN)

With t_s of skin = 0.20 cm, it would be 162,000 Kgf (1590 kN)

Frame 137

g	=	205
A	=	152,2 cm^2
σ_F	=	844 Kgf/cm^2
Force	=	136,000 Kgf (1334 kN)

With t_s of skin = 0.20 cm, it would be 177,000 Kgf (1736 kN)

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