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Ultimate Strength of Ships Under Combined Vertical and Horizontal Moments

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Abstract

In this paper ALPS/ISUM will be used to analyze the ultimate strength of four ships under vertical moment. Two of the ships are commercial vessels and the other two are cruisers. A procedure is also developed to determine the ultimate strength of the four vessels under combined vertical and horizontal moments. A simple analytical expression for an interaction relation under combined moments is proposed based on the results obtained for the four ships and the earlier work.

Keywords : ultimate strength, ship strength, combined collapse load, interaction relations

1. Introduction

The determination of the collapse load, which defines the true ultimate strength of a ship's girder, has become a topic of increased interest to the ship research and design communities. One of the reasons behind this interest is that knowledge of the limiting conditions beyond which a hull girder will fail to perform its function will, undoubtedly, help in assessing more accurately the true margin of safety between the ultimate capacity of the hull and the maximum combined moment acting on the ship. Assessing the margins of safety more accurately will lead to a consistent measure of safety which can form a fair and a good basis for comparisons of ships of different sizes and types. It may also lead to changes in regulations and design requirements with the objective of achieving uniform safety standards among different ships.

The state-of-the-art in determining the true ultimate strength of a ship girder is at the point where some changes in design standards can be made. The definition and evaluation of the different modes of failure have been investigated in recent years. Various definitions of the ultimate strength of a hull have been proposed, but the most acceptable one is the recommendation reported by Committee 10 in the proceedings of the Third International Ship Structures Congress, Vol. 2, 1967, quoted as[ISSC proc., 1967]:

"This occurs when a structure is damaged so badly that it can no longer fulfill its function. The loss of function may be gradual as in the case of lengthening fatigue crack or spreading plasticity, or sudden, when failure occurs through plastic instability or through a propagation of a brittle crack. In all cases, the collapse load may be defined as the minimum load which will cause this loss of function"

Thus, besides instability(buckling), yielding, and spreading of plasticity, fracture may also be a sigificant mechanism of a hull girder failure under certain circumstances of repeated cyclic load. Fracture includes brittle and fatigue failures which demand careful attention to material quality and the design of details (brackets, stiffener's connections, welding, etc.) both of which are outside the scope of this paper. This study is concerned with the overall ductile failure of the hull as a girder in which yielding, spread of plasticity, buckling, and post-buckling strength are limiting factors. The hull is considered to be subjected to combinations of extreme seaway loads inducing vertical and lateral moments.

One of the pioneering work in the ultimate strength area is due to Caldwell,1965 in which a simplified analysis procedure was presented for calculating the ultimate load for a single-desk ship. His solution makes it necessary to define a structural instability factor to enable predicting the maximum strength of the box grider. Although this factor was not developed in that paper, it is the key requirement. Faulkner[1967] in a written discussion suggested a design method for taking this buckling effect into consideration, basically through a reduction factor. In the report of 1994 ISSC[4], the ultimate longitudinal strength of ships was thoroughly discussed. Attention was focused on available analytical techniques for predicting the load carrying capacity of a ship and on comparing the results with experimental data.

Unfortunately, most of the work conducted in the past relates to the ultimate strength under vertical bending moment only with very little attention given to the fact that the horizontal moment may have an effect on the ultimate strength. Although some earlier work has been done in the area of ultimate strength under combined loads(see Mansour and Thayamballi[1980]), additional work is necessary.

The comparisons performed in the 1994 ISSC Proceedings, report of the committee on ductile collapse[ISSC proc., 1994], indicated that one of the promising procedure is due to Paik[1993]. The procedure and the associated computer program is based on the work by Ueda and Rashed 1975 in the mid seventies who developed an idealized structural unit method(ISUM). In this method, a large size structural component can be modeled as one ISUM unit. It has been shown that this method is efficient and accurate and may be used for nonlinear analysis of large size structures.

2. Ultimate Strength of Four Ships under Vertical Bending Moment

Four ships, a tanker, an SL-7 container ship and two cruisers have been considered in this study. The ships have the characteristics as Table 1.

2.1. Impact of Residual Stresses on Ultimate Strength

The effect of residual stresses on the ultimate strength of the SL-7 containership was investigated using ALPS/ISUM. The vertical bending moment-curvature relation for the ship referenced to the fully plastic moment is shown in figure 1. Several values of the residual stress coefficient Cr are shown in the figure. Cr is defined as

$$C_r = \sigma_r / \sigma_o = \text{ratio of residual stress to yield strength} \qquad (1)$$

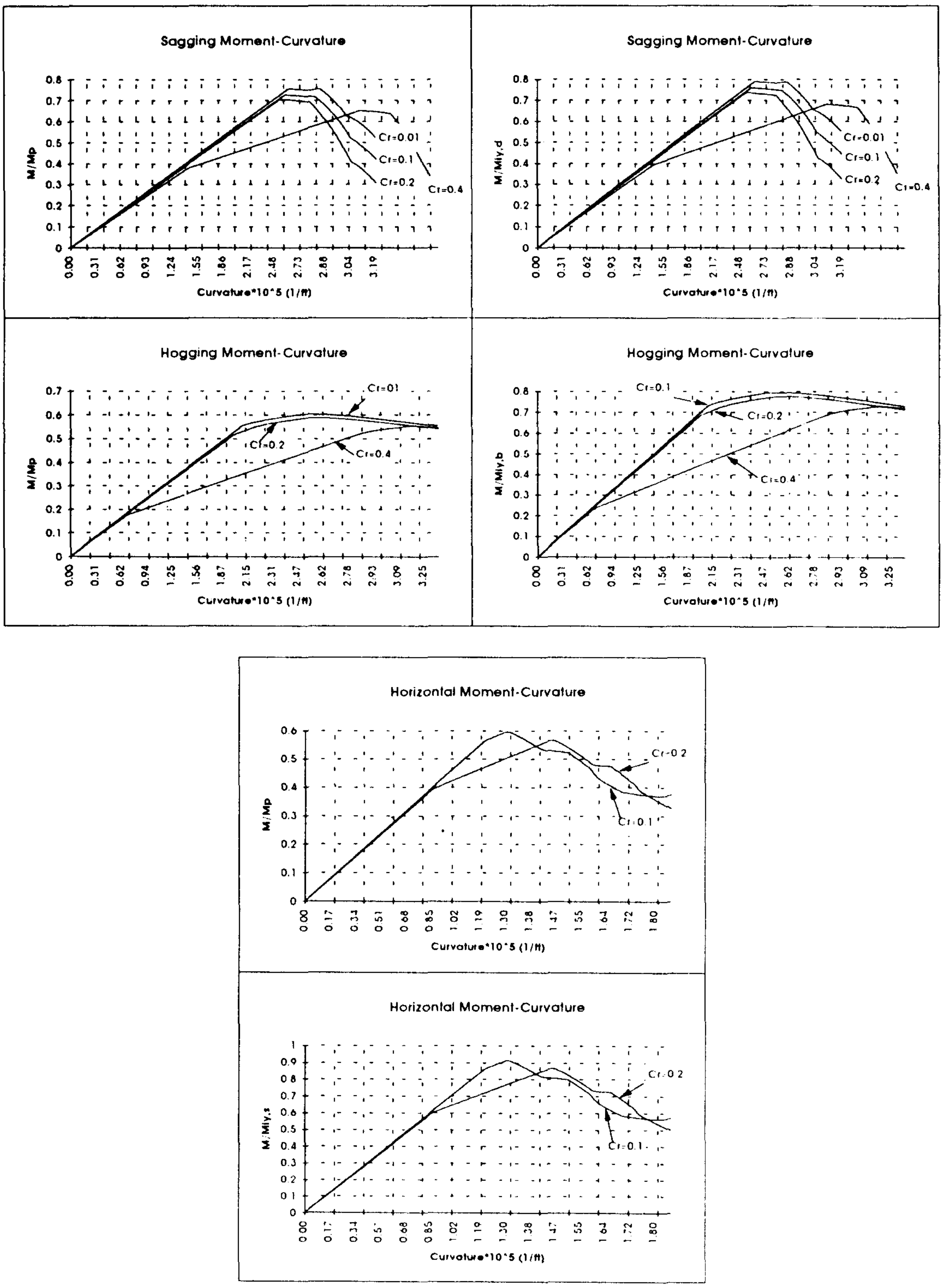

Figure 1. SL-7, Moment-Curvature Relations

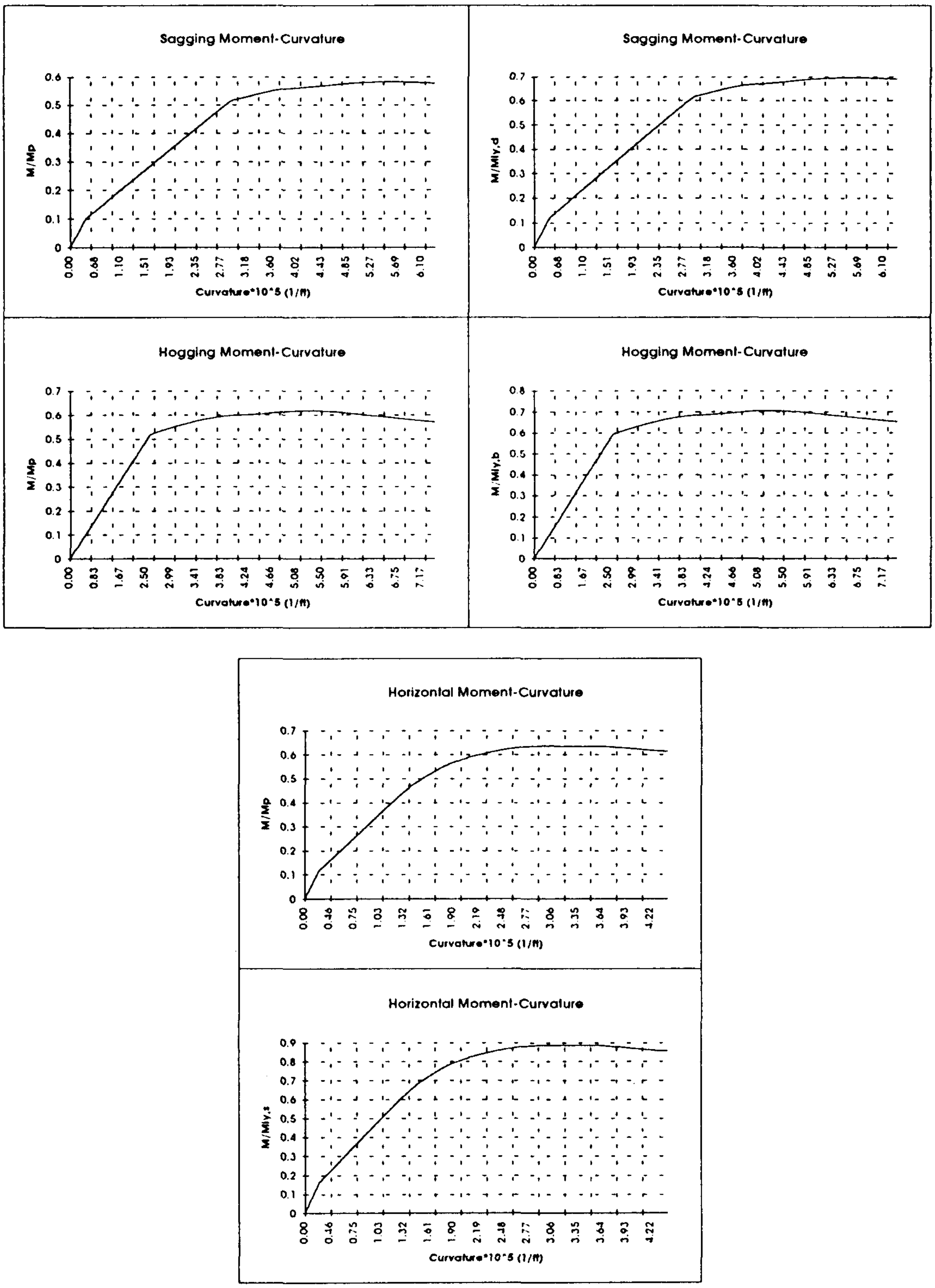

Figure 2. Tanker, Moment-Curvature Relations

Table 1. Characteristics of the four ships

ship	Cruiser 1	Cruiser 2	Tanker	SL-7
Length(ft)	529.0	529.0	625.0	880.5
Beam,molded(ft)	55.0	55.0	96.0	105.5
Draft amidship, molded(ft)	22.44	21.48	34.00	30.00
Displacement(LT)	9,400	7,800	44,513	50,315

It can be seen from figure 1 that increasing the residual stress will decrease the ultimate moment capacity. In particular, changing Cr from 0.2 to 0.4 decreases considerably the moment capacity of the ship. Figure 1 shows also results for sagging and hogging moments referenced to the initial yield moments.

Based on the study performed by Mansour, et al.[1990], the magnitude of the residual stress coefficient Cr will be taken as 0.1 in the following analysis for all four ships.

2.2. Impact of Initial Deformation on Ultimate Strength

The influence of initial deformation on ultimate strength was also studied using ALPS/ISUM. Figure 2 shows the vertical sagging moment-curvature relation for the double hull tanker for several values of initial deformation.

It can be seen that the impact of the initial deformation on the collapse moment is not small and careful consideration should be given in assigning a value for it. Based on the study conducted by Mansour, et al. 1990, an initial deformation coefficient of 0.5 will be used for all four ships in the following study.

2.3. The Moment Curvature Relations for the Four Ships

Figure 1 shows the sagging and hogging collapse moments for the SL-7 ship,referenced to the fully plastic moment and to the initial yield moment. The figure shows also the horizontal collapse bending moment versus curvature, referenced to both fully plastic and initial yield moments. Similar results for the vertical and horizontal collapse moments for the remaining ships are shown in Figures 2 to 4.

3. Ultimate Strength under Combined Vertical and Horizontal Moments

The ultimate moment capacity of a ship hull under combined moments may be investigated numerically by applying a fixed horizontal moment while the vertical moment is increased until the maximum hull capacity is reached. Conversely, a fixed vertical moment can be held constant while the horizontal moment is increased. In a third procedure, while is used in this study, both vertical and horizontal moments are increased at each time step until one of these moments reaches its maximum value(the collapse moment).

Figure 5 shows the SL-7 containership sagging moment-curvature relation and the horizontal

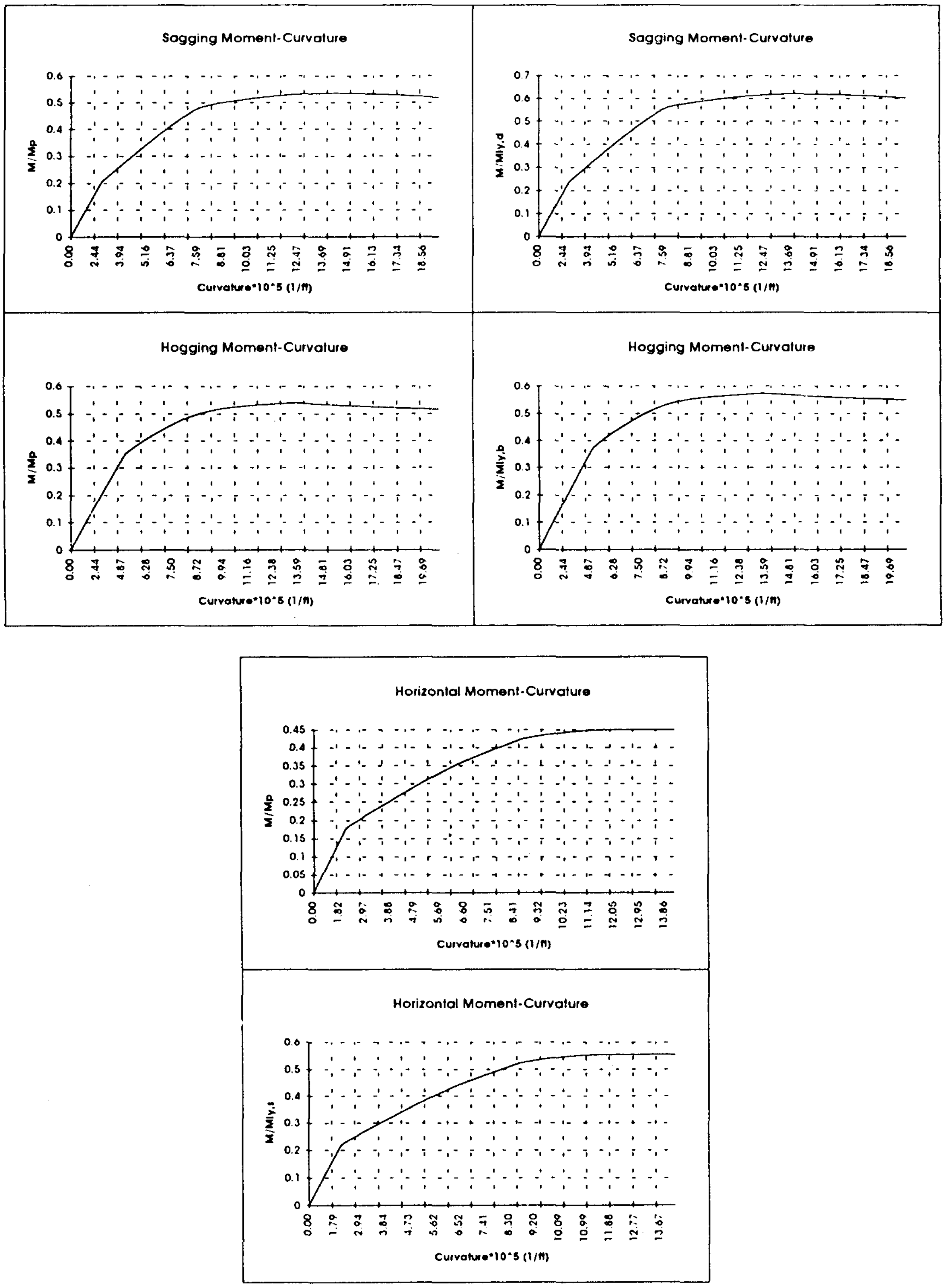

Figure 3. Cruiser 1, Moment-Curvature Relations

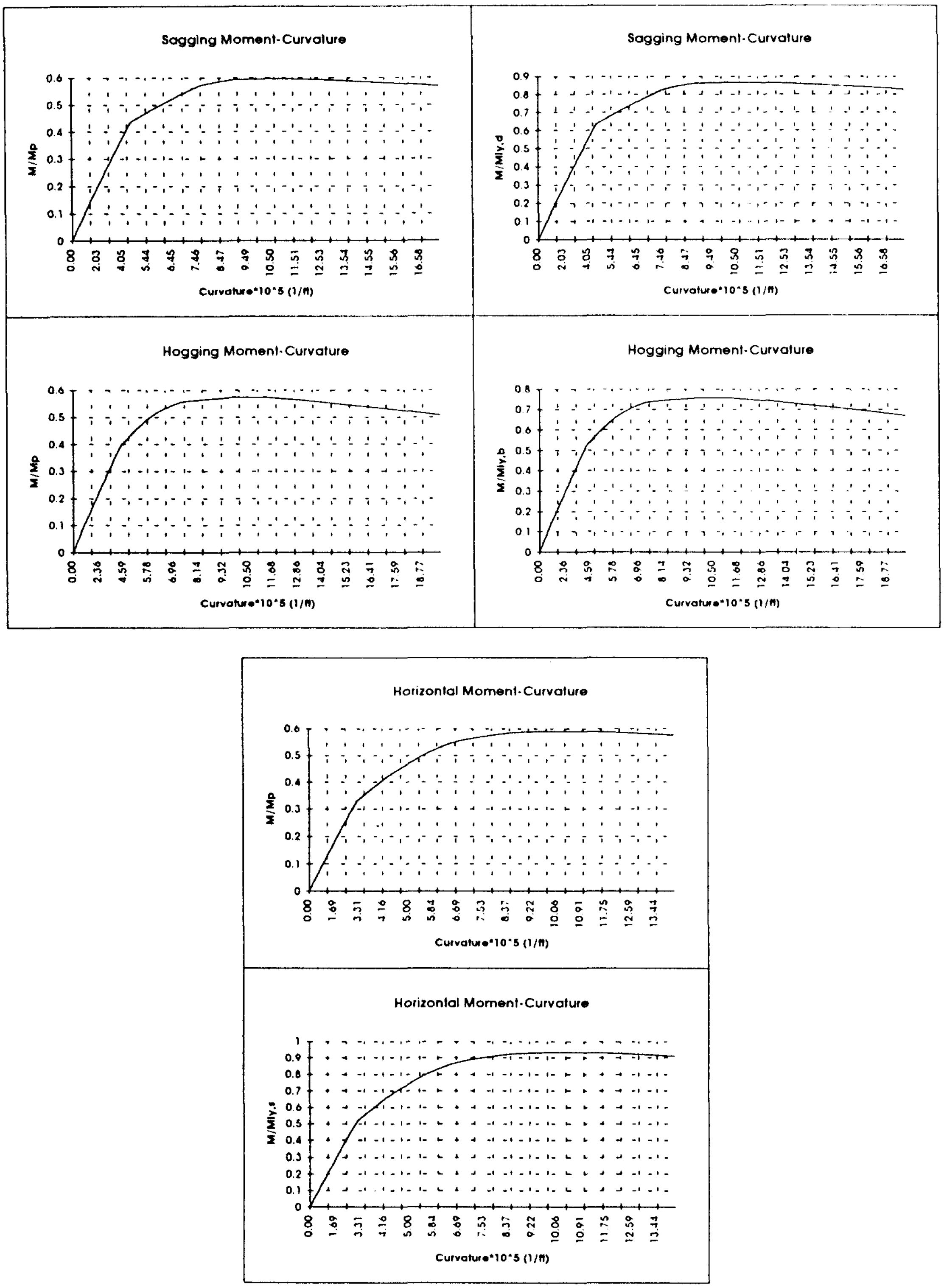

Figure 4. Cruiser 2, Moment-Curvature Relations

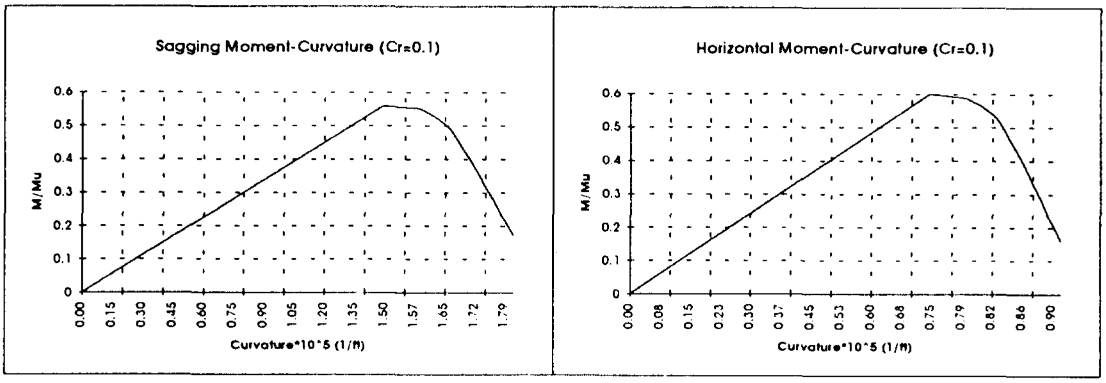

Figure 5. SL-7 Combined Vertical and Horizontal Moments

moment-curvature relation when applied simulataneously. Figure 6 show the intraction relation resulting from repeating the procedure at different rations of vertical to horizontal moments.

Figure 7 to 9 show similar results for the remaining three ships.

4. Approximate Analytical Moment Interaction Relation

The work by Mansour and Thayamballi[1980] gives the following expression for the interaction relation between vertical and horizontal moments:

$$m_x + k \cdot m_y^2 = 1 \qquad \text{if} \quad |m_y| < |m_x|$$

and

$$m_y + k \cdot m_x^2 = 1 \qquad \text{if} \quad |m_x| < |m_y| \tag{2}$$

where

$$\begin{aligned} m_x &= \frac{M_x}{M_{xu}} \\ k &= \frac{(A + 2A_s)^2}{16A_s(A - A_s) - 4(A_D - A_B)^2} \\ A &= A_D + A_B + 2A_S \end{aligned} \tag{3}$$

and

M_x = bending momemt in vertical direction

M_y = bending momemt in horizontal direction

M_{xu}= vertical ultimate collapse bending moment

M_{yu} = horizontal ultimate collapse bending momemt

A_D = cross-sectional area of the deck including stiffeners

A_B = cross-sectional area of the bottom including stiffeners

A_s = cross-sectional area of one side including stiffeners

The above relation was originally derived for vertical and horizontal fully plastic moments(see Mansour and Thayamballi[1980]). The applicability of this interaction relation has been tested for the four ships under consideration to examine if it is still valid when the vertical and horizontal moments are ultimate collapse moments instead of fully plastic moments, i.e., when buckling is included.

The results are shown in Figures 6 to 9. The shown curves, which fit the numerical data best, are all based on equation(2) with k=0.8. In Mansour and Thayamballi's report[1980], a value of k=0.78 was calculated for a Tanker according to equation(3). The interaction relation(2) for the SL-7 containership shown in Figure 6 does not fit the numerical results as well as the other ships(Figures 7 to 9). The reason may be attributed to lack of deck in the containership.

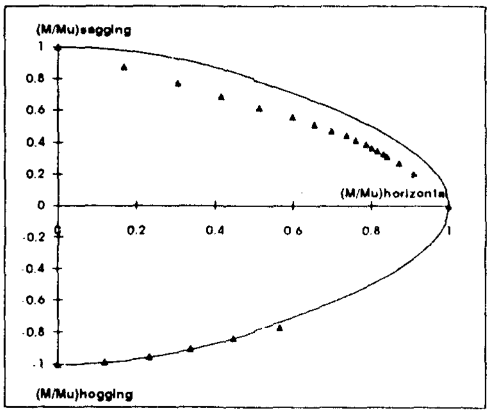

Figure 6. SL-7, Interaction Relation

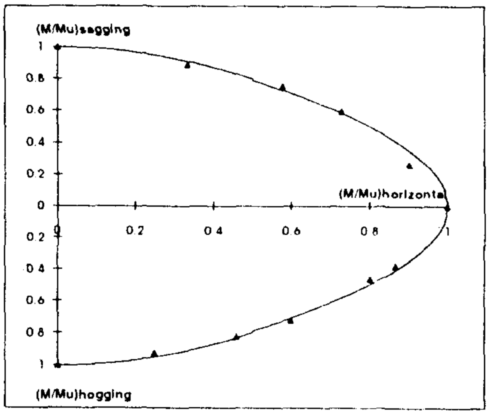

Figure 7. Tanker, Interaction Relation

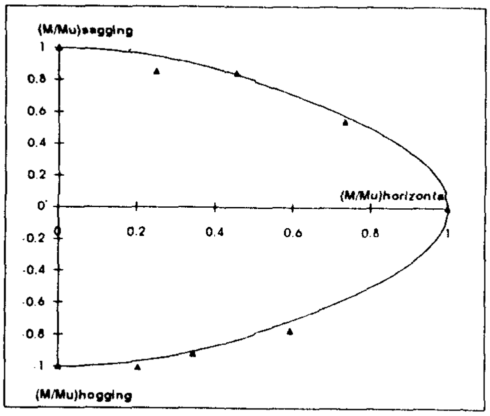

Figure 8. Cruiser 1, Interaction Relation

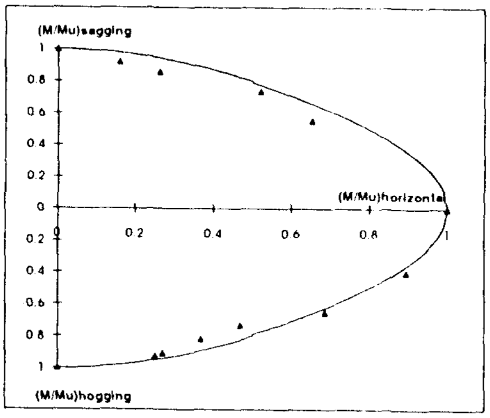

Figure 9. Cruiser 2, Interaction Relation

5. Summary and Conclusions

Table 2 shows, for each of the four ships, the elastic section modulus at deck and at bottom, the vertical and horizontal moments of inertia, the vertical and horizontal fully plastic moments, the

Table 2. Ultimate strength analysis of four ships

Ship	Cruiser 1	Cruiser 2	Tanker	SL-7
$SM_d(in^2 - ft)$	23,384	25,021	74,093	143,340
$SM_b(in^2 - ft)$	26,730	27,578	104,056	177,935
$I_v(ft^4)$	3,638	3,826	15,703	35,288
$I_h(ft^4)$	4,538	4,921	41,842	88,341
$M_{pv}(LT - ft)$	969,085	763,456	1,803,259	3,140,267
$M_{ph}(LT - ft)$	1,043,903	854,581	2,652,318	4,964,418
$M_{iy,d}(LT - ft)$	834,496	524,309	1,505,536	3,003,612
$M_{iy,b}(LT - ft)$	911,543	577,880	1,579,159	2,384,012
$M_{iy,s}(LT - ft)$	847,187	539,970	1,905,008	3,230,715
$M_u(LT - ft)$,hogging	523,050	437,737	1,118,237	1,898,130
$M_u(LT - ft)$,sagging	517,948	454,948	1,049,942	2,285,396
$M_u(LT - ft)$,horizontal	469,576	504,030	1,689,045	2,963,184

Table 3. Ultimate strength ratios

	Ship	Cruiser 1	Cruiser 2	Tanker	SL-7
hogging	$M_u(LT - ft)$	523,050	437,737	1,118,237	1,898,130
	M_u/M_p	0.540	0.573	0.620	0.604
	$M_u/M_{iy,b}$	0.574	0.758	0.708	0.796
sagging	$M_u(LT - ft)$	517,948	454,948	1,049,942	2,285,396
	M_u/M_p	0.535	0.596	0.582	0.728
	$M_u/M_{iy,b}$	0.621	0.868	0.697	0.761
horizontal	$M_u(LT - ft)$	469,576	504,030	1,689,045	2,963,184
	M_u/M_p	0.450	0.590	0.637	0.600
	$M_u/M_{iy,b}$	0.554	0.933	0.887	0.917

initial yield moments at deck, bottom and side, the ultimate hogging and sagging moments and the ultimate horizontal moment. From Table 2, it can be seen that, although the elastic section moduli of the two cruisers are not very different, the initial yield moments at deck and bottom for cruiser one are much larger than the corresponding values for cruiser two. The reason for this is that more higher strength steel is used in the construction of cruiser one than in two.

The intial yield and fully plastic moments for the double hull tanker and the SL-7 ship are considerably higher than those for the cruisers. The elastic section moduli and cross sectional areas for these ships are much larger than those for the cruisers.

Table3 shows the ratios of the hogging, sagging and horizontal ultimate moments for each ship to the fully plastic and initial yield moments. The ratio of the ultimate moment to the initial yield moment may be taken as an approximate measure of the efficiency of utilizing the material strength and the efficiency of the stiffening system against buckling. However, fatigue considerations which become more important for high strength steel limit the utilization of such a measure as a true indicator of the efficiency.

Returning to Table 3, one can see that extensive use of high strength steel in cruiser one led to large discrepancy between the ratios of the ultimate moments to the initial yield moments when compared to those of cruiser two. These ratios, 0.574 in hogging and 0.621 in sagging for cruiser one, are much smaller than the corresponding values, 0.758 and 0.868 for cruiser two. The same trend is true for the ratios of the ultimate moment to the fully plastic moment. In general, the ratios of the ultimate moments to the initial yield and to the fully plastic moments are higher for the two commercial vessels than for cruiser one. The commercial vessels are constructed from lower strength steel.

An interaction relation between the vertical and horizontal ultimate moments is proposed in this paper(see equation 2). This relation is based on the ALPS/ISUM numerical results for the four ships and on earlier analysis performed by Mansour and Thayamballi[1980]. This relation can be used to determine the ultimate vertical moment for a given value of the horizontal moment. Or, alternatively, it can be used to determine the safe region(the region inside the curves) when a combination of vertical and horizontal moments occurs on a ship.

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