Journal of
Ship&Ocean Technology
©MARCH 2008

SOTECH Vol. 12, No. 1, pp. 45 ~ 56, 2008

Ultimate Longitudinal Strength Assessment of Ships' Hull Girders

Hun-Gon Lee[1] and Joo-Sung Lee[2]

[1] Department of Hull Initial Design, Division of Shipbuilding, Hyundai Heavy Industries, Ulsan, Korea
[2] School of Naval Architecture and Ocean Engineering, University of Ulsan, Ulsan, Korea; Corresponding Author: jslee2@mail.ulsan.ac.kr

Abstract

Recently, International Association Classification Societies (IACS) has adopted the Common Structural Rules (CSR) for Bulk Carriers and Tankers, which specifies the requirement associated with the ultimate strength of hull girder structure. The theoretical background and the results of verification study are neither well summarized nor released. Furthermore, the requirement is not a form of deterministic formula but a form of program in which source code is not disclosed.

The reliability of the non-linear structural analysis program is verified through the comparison with the results of the analysis and the model test.

Then, the reliability of the ultimate strength requirement in CSR is checked by comparing with the results of rigorous non-linear analysis.

Keywords: common structural rules, hull girder, non-linear finite element analysis, simplified ultimate hull strength formula, ultimate longitudinal strength

1 Introduction

With regard to the ultimate longitudinal strength assessment of ships' hull structure Caldwell firstly introduced a theoretical method based on plastic design in 1965 and many researchers have attempted to develop methods to predict it in more rational way. Also, several collapse tests for stiffened box girders were conducted and reported by many investigators. Especially, Dow(1991) conducted collapse test for the 1/3 frigate model which is similar to existing ship's hulls. Since the accident of the tanker, Prestige, happened in 2002, many organizations have been trying to make regulations on the ultimate strength of ships to improve their robustness. As a result of that, International Association Classification Societies (IACS) has adopted the Common Structural Rules (CSR) for Bulk Carriers and Tankers in January 2006, which contains the requirement related to the ultimate strength of hull girder structure for the first time.

As it has been mentioned above, many methods have been proposed on this subject. And recently new standards that may differ from CSR have been prepared by ISO. Based on this background, in this paper proposed is the practical guide to verify the reliability of the rule requirement based on the result of non-linear finite element analysis.

2 Criteria on the subject in CSR

Until now, any rules of IACS members do not have the requirement for evaluation of hull girder ultimate bending capacity. However, the requirement as the rule is described for the first time in common structural rules (CSR) for double hull oil tankers which have been adopted by IACS in January 2006. The criteria are applicable to intact ship structures in extreme conditions at sea but they do not cover hogging, harbor or damaged conditions. The vertical hull girder ultimate bending capacity is to satisfy the following criteria in Eq. (1).

$$\gamma_s M_{sw} + \gamma_w M_{wv\_sag} < M_u / \gamma_R \tag{1}$$

where M_{sw} : sagging still water bending moment

M_{wv_sag} : sagging vertical wave bending moment

M_u : hull girder ultimate bending capacity

$\gamma_s, \gamma_w, \gamma_R$: partial safety factors

Partial safety factors for the design load combinations are given in Table 1.

Table 1: Partial safety factors

Definition of Still Water Bending Moment, M_{sw}	γ_s	γ_s	γ_s
Permissible sagging still water bending moment	1.0	1.2	1.1
Maximum sagging still water bending moment for operational seagoing homogeneous full load condition	1.0	1.3	1.1

The definition and calculation of the hull girder ultimate bending capacity, M_u, is important to evaluate the abovementioned requirement. M_u is defined as the maximum bending capacity of the hull girder. Exceeding the maximum bending capacity leads to hull girder failure, which is controlled by buckling, ultimate strength and yielding of longitudinal structural elements. And also, this means that the maximum value of the static non-linear bending moment-curvature relationship M-κ, represents the progressive collapse behavior of hull girder under vertical bending.

As the simplified method of calculating the ultimate hull girder capacity, either the single step method or the incremental-iterative method in the rules can be used. Alternatively, non-linear finite element analysis by incremental-iterative procedure can be allowed.

3 Simplified method for M_u by IACS

The computer programs to evaluate the ultimate capacity according to CSR are recently provided by each classification society. In this paper, the results calculated by the DNV's program are used to compare with those calculated by non-linear analysis, assuming that the values are completely verified by IACS members.

3.1 Single step ultimate capacity method

This procedure for calculation of the sagging hull girder ultimate bending capacity is based on the reduced hull girder bending stiffness accounting for buckling of the deck. M_u is to be taken as maximum value of Eqs.(2) and (3) below.

$$M_{u\_dk} = Z_{red}\sigma_{yd\_dk} \tag{2}$$

where Z_{red} : reduced section modulus of deck $= I_{red} /(Z_{dk\_mean} - Z_{NA\_red})$

I_{red} : reduced moment of inertia calculated with A_{eff}

A_{eff} : effective area after buckling of each stiffened panel of deck $= \sigma_u / \sigma_{yd} A$

A : area of stiffened deck panel

σ_{u_dk} : buckling capacity of stiffened deck panel

σ_{yd_dk} : specified minimum yield stress of the material of deck

Z_{dk_mean} : vertical distance to the mean deck height

Z_{NA_red} : vertical distance to the neutral axis of the reduced section measured from the baseline

$$M_{u\_btm} = \sigma_{yd\_btm} I_{red} / Z_{NA\_red} \tag{3}$$

where σ_{yd_btm} : specified minimum yield stress of the material of bottom

3.2 Based on an incremental-iterative approach

In this approach, M_u is defined as the peak value of the vertical bending moment (M) and the curvature (κ) relation curve of the ship cross section as shown in Figure 1. The curve M-κ is obtained by using the incremental-iterative approach which is illustrated in the flow chart in Figure 3.

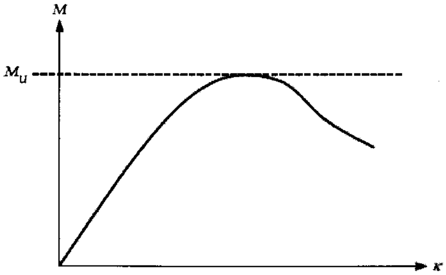


Figure 1: Bending moment – curvature curve *M*-κ

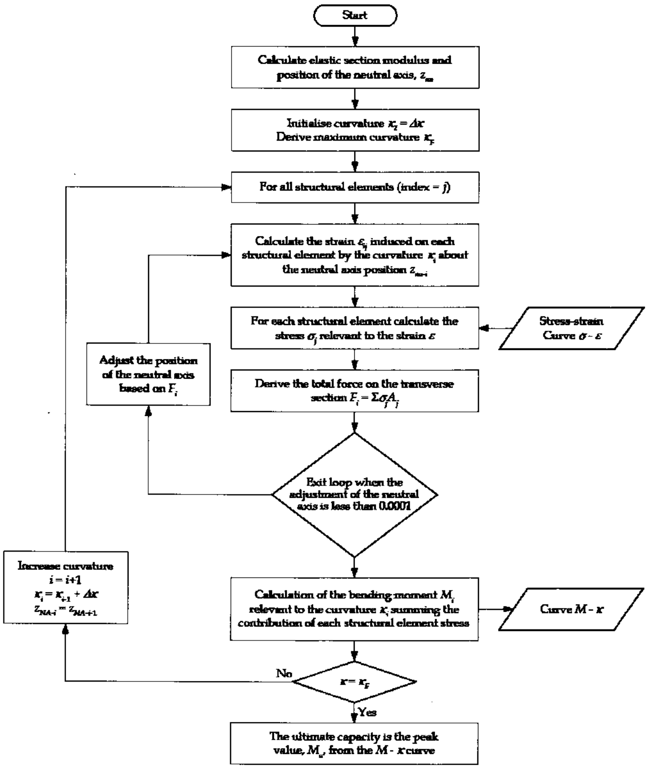


Figure 2: Flow chart of the procedure for the evaluation of the curve *M*-κ

4 Non-linear finite element analysis

Using the non-linear analysis for the ultimate strength, the progressive collapse as well as ultimate bending capacity of ships' hull girders is investigated. In this paper, the finite element analyses have been carried out using the ABAQUS/Standard code (ver.6.0) and the effects of the geometrical non-linearity and the material non-linearity are considered through the incremental load analysis.

4.1 Model and modeling details

The model used in the analyses is illustrated in Figure 3. This longitudinal extension is chosen within one web frame spacing with assuming that both transverse web frames at both ends of model are rigid enough. Transverse extension is the full hull breadth for symmetrical condition and the half hull breadth for the other. And vertical extension is the full hull depth.

4-node shell is to be used for all structural members, including buckling stiffeners. More than 6 elements are used in modeling the fine mesh region to allow buckling mode in both longitudinal and transverse directions, considering that buckling phenomenon appears in way of upper part for sagging and low part for hogging condition.

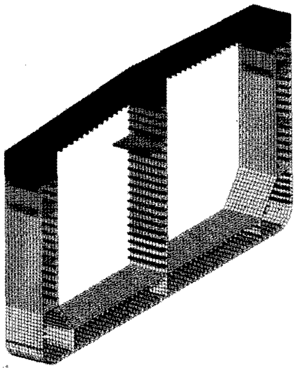


Figure 3: Analysis model in case of sagging condition

4.2 Initial deflection

To trigger buckling displacements and to ensure conservative results consistent with normal ship fabrication standard, the regular geometric model imperfections are given by Eq.(4) and the position and mode are shown in Figure 4.

$$w = A_0(\sin n\pi x / a \cdot \sin x\pi / b) \qquad (4)$$

where A_0 : initial imperfection tolerance
n : number of wave
a : length of stiffened panel
b : width of stiffened panel

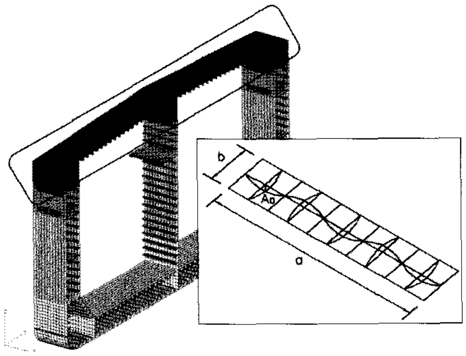
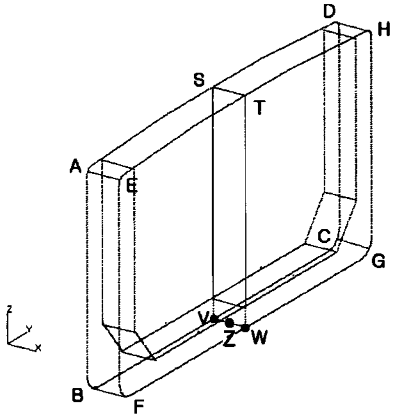


Figure 4: Initial imperfection of stiffened plate

4.3 Load and boundary conditions

Figure 5 shows the Boundary condition. The models ends are considered as rigid plane, which deform with same rotation angle. Enforced rotation angle is increased step by step at point V and W through the incremental displacement method.



Plane ABCD	Rigid plane : Independent point V Constrained in Dx, Rx, Ry, Rz
Plane EFGH	Rigid plane : Independent point W Constrained in Dx, Rx, Ry, Rz
Mid-plane between Plane ABCD and EFGH	Dx
Line ST, VW	In case of full model : Dy In case of half model : Dy, Rx, Rz
Point Z	Dz
Point V, W	$(\pm)\,\theta_Y$

Figure 5: Boundary constraint for enforced rotational displacement

4.4 Relationship of stress-strain

It assumes that the stress-strain relationship is perfect elasto-plastic and the Von-Mises yield criterion is applied.

5 Verification of FE analysis method

The reliability of the non-linear structural analysis program (ABAQUS) is verified through the comparison of the results of the analysis and of the model test on the 1/3 frigate model conducted by Dow (1991).

5.1 Analysis model

Figure 6 shows analysis model of Dow's 1/3 frigate and positions given initial imperfection. To evaluate the effect of the magnitude of initial imperfection, analyses of three cases are carried out by Eq. (5) and the amount of imperfection is shown in Table 2.

$$\begin{aligned} A_0 &= 0.025\beta^2 t && \text{for slight level} \\ A_0 &= 0.100\beta^2 t && \text{for average level} \\ A_0 &= 0.300\beta^2 t && \text{for severe level} \end{aligned} \tag{5}$$

where β : slendness ratio
t : panel thickness

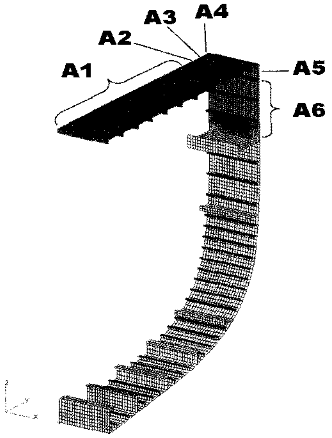


Figure 6: Analysis model of Dow's frigate model

Table 2: Value of initial deflection

	A1	A2	A3	A4	A5	A6
Slight	0.61	0.41	0.17	0.10	0.18	0.40
Average	2.43	1.62	0.68	0.40	0.73	1.59
Severe	7.29	4.86	2.04	1.19	2.18	4.76

5.2 Evaluation

The bending moment-curvature relationship of frigate model is shown in Figure 7.

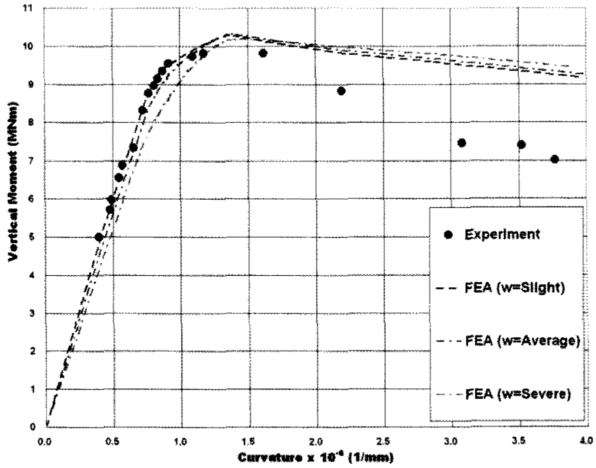


Figure 7: Bending moment-curvature relationship of frigate model

As it can be seen in Figure 7, the analysis result agrees quite well with the test one marked by point. The predicted buckling mode and collapse mode are illustrated in Figure 8 and Figure 9, respectively.

From this finding, the procedure of non-linear analysis, which is proposed in this paper, is regarded as a useful method for evaluating the ships' ultimate strength. In addition, three curves in Figure 6, which is calculated with different magnitude respectively, show that the hull girder capacity is not sensitive to changes in the magnitude of the initial imperfections, even though there are significant local differences in displacements and stresses.

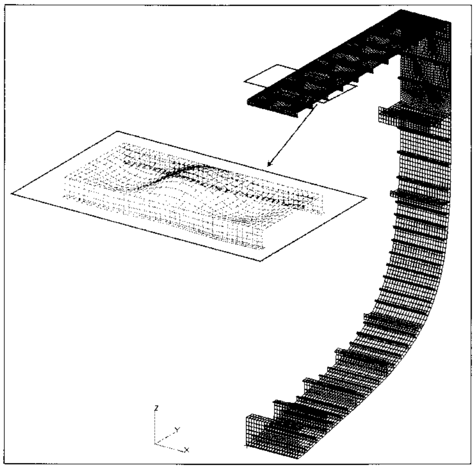


Figure 8: Buckling mode of frigate model

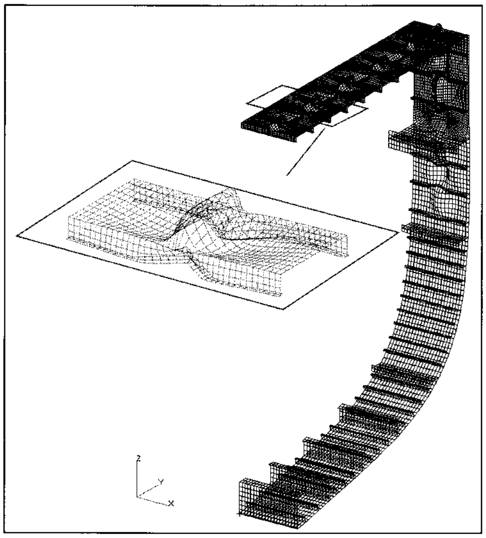


Figure 9: Collapse mode of frigate model

6 Comparison of results from CSR and FEM

The accuracy of the ultimate hull girder strength according to CSR is checked by comparing with the results obtained by the non-linear finite element analyses using

ABAQUS. The ultimate strength analyses of three different sized vessels are carried out by using DNV's program and ABAQUS, respectively. Table 3 shows the comparison with ultimate strength of 3 tankers (Model_1~3). And Figures 10~12 show the bending moment-curvature relation curves of three models.

Table 3 Comparison with ultimate strength of 3 tanker models [MNm]

Ship No. / Item		Model_1		Model_2		Model_3	
		M_u	Ratio	M_u	Ratio	M_u	Ratio
Sagging Condition	FEA	10872	97 %	7110	98%	5639	95 %
	CSR	10578		6997		5407	
Hogging Condition	FEA	13300	103%	9392	102%	7141	104%
	CSR	13747		9562		7502	

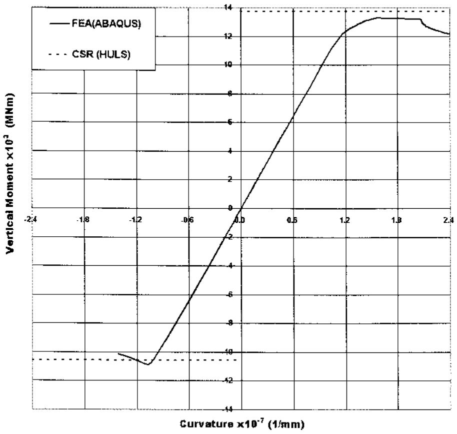


Figure 10: Bending moment-curvature relationship of Model 1

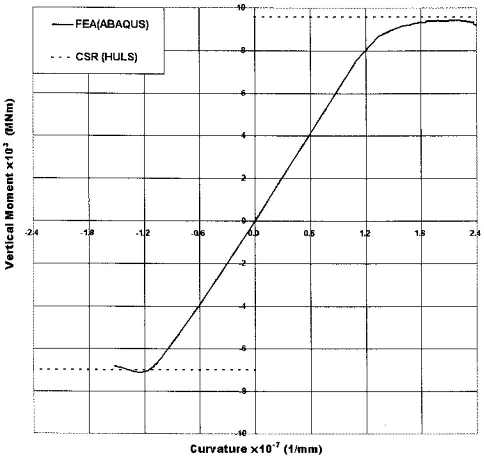


Figure 11: Bending moment-curvature relationship of Model 2

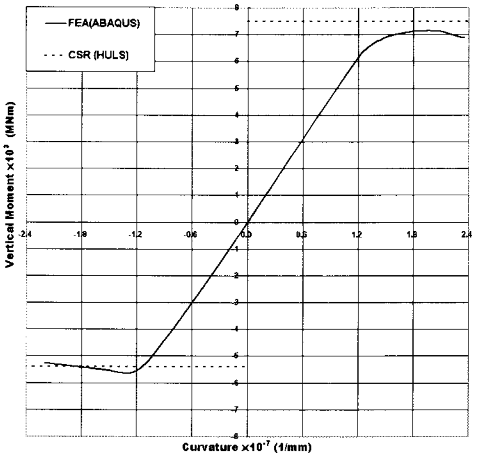


Figure 12: Bending moment-curvature relationship of Model 3

As shown in Table 3 and Figures 10~12, the results of the FE analysis and CSR are coincided well in sagging as well as hogging condition for three vessels.

7 Ultimate strength of ships by CSR

To check ultimate strength of the actual operated vessels, ten vessels are selected and checked if they have the significant ultimate strength or not according to Eq.(1). Tables 4 and 5 show the results. Most of vessels do not have the significant ultimate strength by about 10 percent. However, some vessels, which are designed with ratio of breadth to depth (B/D) less than 1.5, satisfy the requirement in CSR.

Table 4: Estimation of ultimate strength in sagging condition

	B/D	M_T①	M_u	$M_u/1.1$②	Ratio ②/①	Re-mark
T1	1.97	20291	20404	18549	0.914	×
T2	1.97	20291	20512	18647	0.919	×
T3	2.08	10394	10578	9616	0.925	×
T4	1.87	9389	10497	9543	1.016	○
T5	2.20	8335	7983	7257	0.871	×
T6	2.10	7689	7486	6805	0.885	×
T7	2.00	6888	6997	6361	0.923	×
T8	1.54	4654	5308	4825	1.037	○
T9	1.54	4654	5407	4915	1.056	○
T10	1.58	4624	4953	4503	0.974	×

Table 5: Estimation of ultimate strength in hogging condition

	B/D	M_T①	M_u	$M_u/1.1$①	Ratio ②/①	Re-mark
T1	1.97	20306	27483	24985	1.230	○
T2	1.97	20306	28067	25515	1.257	○
T3	2.08	10842	13747	12497	1.153	○
T4	1.87	10373	14176	12887	1.242	○
T5	2.20	8610	10469	9517	1.105	○
T6	2.10	8124	10322	9384	1.155	○
T7	2.00	7197	9562	8693	1.208	○
T8	1.54	5106	7457	6779	1.328	○
T9	1.54	5106	7502	6820	1.336	○
T10	1.58	4666	6994	6358	1.363	○

8 Conclusions

In the present paper, the reliability of the non-linear structural analysis program and procedure are verified through the comparison with the results of the analysis and the model test.

Then, the reliability of the ultimate strength requirement in CSR is checked by being compared with the results of non-linear analysis program.

The principle results are shown as follow ;

1) With ABAQUS program, the ultimate strength for hull girder strength can be evaluated.
2) In comparison between the results of 1/3 frigate model and analyses with ABAQUS, the result is similar to each other.
3) The hull girder capacity is insensitive to changes in the magnitude of the initial imperfections
4) In sagging and hogging conditions, the values of ultimate strength calculated according to CSR are similar to that with ABAQUS.
5) By evaluating ultimate strength for ten actual tankers according to CSR, most of vessels do not have significant ultimate strength by about 10 percent. However, some vessels, which designed with ratio of breadth to depth (B/D) less than 1.5, are satisfied with requirement in CSR

References

Dow, R.S. 1991. Testing and analysis of a 1/3-scale welded steel frigate model. Proc. Intl. Conf. on Advances in Marine Structures, Dunfermline Scotland, 749-773.

IACS Team for Joint Tanker Project. 2006. Common Structural Rules for Double Hull Oil Tankers. Appendix A.

Masahiko, F. 2005. Progressive collapse analysis of ship's hull girder in longitudinal bending using idealized structural unit method. Journal of the Japan Society of Naval Architects and Ocean Engineers, **1,** 187-196.

Smith, C.S. Davidson, P.C., Chapman, J.C. and Dowling, P.J. 1988. Strength and stiffness of ship's plating under in-plane compression and tension. RINA Transactions, **130,** 277-296.