Contract Information

University of Newcastle:

Contract Number	N00014-06-1-0669
Title of Research	Reliability-based performance assessment of damaged ships
Principal Investigator	Dr. Yongchang Pu, Dr. Hoi-Sang Chan, Prof. Atilla Incecik and Prof. Robert Dow
Organization	University of Newcastle Upon Tyne

University of Glasgow and Strathclyde:

Contract Number	N00014-06-1-0666
Title of Research	Reliability-based performance assessment of damaged ships
Principal Investigator	Prof. P K Das
Organization	University of Glasgow and Strathclyde

Technical Section

1. Technical Objectives

A large number of ship accidents continue to occur despite the advance with the navigation system. These accidents would cause the loss of cargos, pollution of environment, even loss of human beings. Based on statistical data of Lloyd's Register of Shipping (Lloyd's Register, 2000), a total of 1336 ships were lost with 6.6 million gross tonnage cargo loss between 1995 and 2000. 2727 people were reported killed or missing as a result of total losses in this period. So it is very important to ensure an acceptable safety level for damaged ships. Unfortunately adequate structural strength in intact condition does not necessarily guarantee an acceptable safety margin in damaged conditions. Conventionally only the structural strength in intact condition was assessed in the design.

When a ship is damaged, the operators need to decide the immediate repair actions by evaluating the effects of the damage on the safety of the ship using residual strength assessment procedure.

The objective is to develop a procedure and tools for operators and decision makers to assess the residual ultimate hull girder strength of damaged ships for a given damage scenario. The objective in the proposal is modified based on the discussions in the kick-off meeting held in Southampton on 21 August 2006 (see minutes of the kick-off meeting).

2. Technical Approach

A systematic approach will be adopted in this research. The wave excitation loads will be predicted by a 2D non-linear method, which complement the 2D linear method used in NICOP project. Experimental study will also be carried out to compare the results obtained from the numerical prediction with those obtained from measurements. Finite element method (FEM) will be used to evaluate ultimate hull girder strength of damaged ships in which the effect of horizontal bending moment and torsion will be considered. The results of FEM will be used to validate the results of a 2D method (Smith's method), which was completed in NICOP project.

3. Progress

Since the last progress report in July 2007, Newcastle University team has made some progress in numerical calculation of wave-induced loads, while the experiment has to be rescheduled in early 2008 due to two major refurbishments in the towing tank. University of Glasgow and Strathclyde team has worked on the prediction of ultimate strength of the hull girder using FEM and a 2D method. The details are presented in the following sections, while a brief summary is provided as follows:

(1) Reports/papers produced

A progress report of the work was written and submitted to ONR in July 2007.

(2) Work Accomplished

In Newcastle University:

- The effects of transverse weight distribution and different co-ordinate systems on dynamic torsion moment have been investigated.
- Extreme design wave-induced loads at different environmental conditions using 2D linear method have been calculated.

In University of Glasgow and Strathclyde:

- Ultimate hull girder strength calculation completed – for intact ship using MARS software using Elastic-Ideally Plastic Method and Beam-Column Method (Smith Method):
  - Vertical bending moment
  - Horizontal bending moment
  - Vertical and horizontal load combination/interaction
- Work completed using ANSYS FEA software:
  - Modeling of Hull 5415
    - Solid modeling of 3D 3 compartment mid part of the hull, work on sub-structuring/sub-modeling is in progress
    - 2Fr 3D model of the hull mid part for preliminary FEA run
    - One compartment 3D model of the hull mid part for preliminary run of FEA.
  - Vertical bending moment
    - Full plastic moment capacity
    - Elastic-perfectly plastic ultimate strength of hull girder, using 2 Fr 3D model with fine FE mesh.
    - Ultimate strength of hull girder for one compartment 3D model with coarse FE mesh and large load step to reduce computation time.

(3) Problem Areas Encountered Or Anticipated

In Newcastle University:

The experimental tests have to be postponed twice due to the extensive refurbishment in the towing tank. Hopefully the towing tank will be available this year.

In University of Glasgow and Strathclyde:

High Performance Computing (HPC) facilities available at University of Strathclyde are being used for FE analysis. The pre-processing and post processing is being done using desktop computer. Presently, some problems are being faced in allocation of disk space on HPC for ANSYS that are required to be sorted out. Further, RAM for desk top machine is required to be enhance 12 GB for local processing of results.

(4) Results Related To Previously Identified Problem Areas

In University of Glasgow and Strathclyde:

The residual stress/welding stress in the FE modeling and analysis is ignored. The correlation of ultimate strength results of intact conditioned obtained through established techniques such as Smith Method and FE analysis in intact condition shall be used to update FE results of damaged condition.

(5) Work Planned For Next Reporting Period (through April 1)

See section 3.3

(6) Expenditures to date

In Newcastle University:

£26,266.16

In University of Glasgow and Strathclyde:

£25,400.00

3.1 Prediction of wave-induced motions and loadings

Effects of transverse weight distribution and co-ordinate systems

As pointed out in the last report, the differences between the 2D linear numerical predictions and measurements of dynamic torsion moments are significant. The contributing factors for this difference could include ‘transverse distribution of weight’, ‘co-ordinate system for comparison of numerical and experimental results’, ‘the calibration of load sensors for torsion’, and ‘dynamic effects of flooded water in the damaged compartment’. The investigation of the effects of the first two factors has been completed. Some results are presented in Figs. 3.1.1 and 3.1.2. Fig. 3.1.1 shows the effects of both transverse and vertical gravity centre of the ship on torsion RAO in damage scenario 2 at stern quartering seas. The difference between the blue line and light blue line is noticeable especially in high frequency region. Fig.3.1.2 shows the effects of different co-ordinate systems on torsion RAO in damage scenario 3 at beam seas. Again the difference is significant.

These results clearly demonstrate that the effects of transverse gravity centre should be considered in numerical calculations of wave-induced torsion moment. Because the sample ship H5415 does not have information about transverse weight distribution, it is decided that 2D linear calculation will be carried out on the ship model, the transverse weight distribution of which could be measured with fairly good confidence.

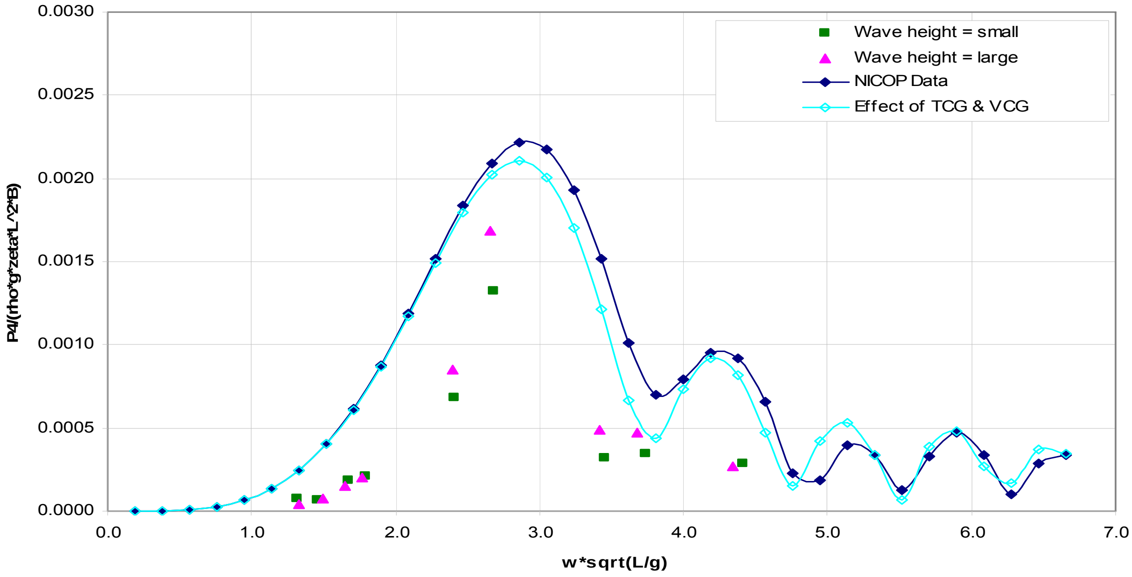


Fig. 3.1.1 Dynamic torsion moment RAO of DS2 H5415 at stern quartering waves (heading 315)

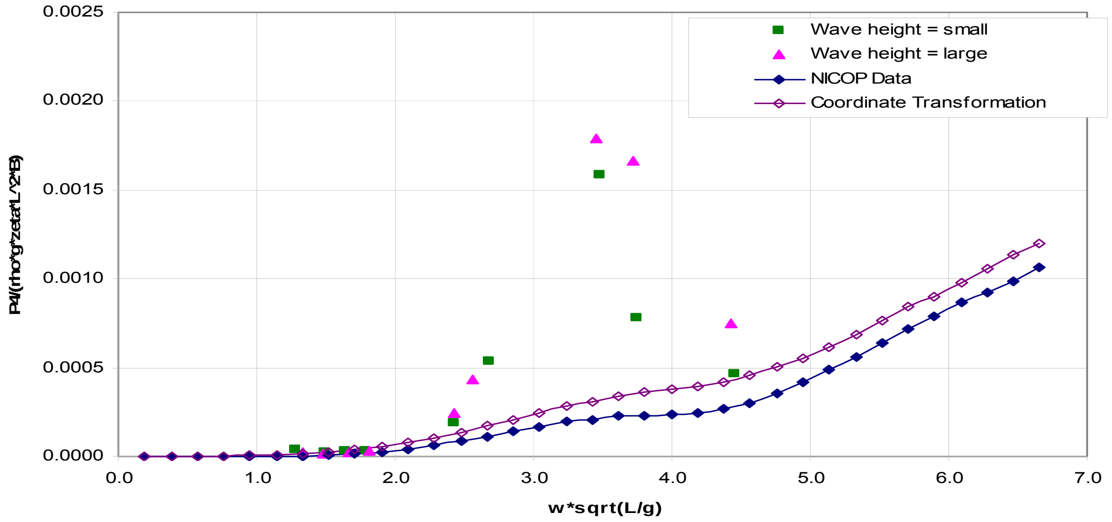


Fig.3.1.2 Dynamic torsion moment RAO of DS3 H5415 at beam waves (heading 90)

The extreme design wave loads

In NICOP project, the environmental conditions for predicting wave-induced loads are chosen as sea state 3 for 96 hours. In a joint project meeting between Newcastle University and the University of Glasgow and Strathclyde on 31 October 2007, it was felt that these conditions may not be realistic because a ship should be able to survive under the wave condition whenever and wherever the damage is incurred. So the wave conditions could be quite different. For this reason, the extreme design wave loads of H5415 under different sea states (3 – 7) have been calculated and passed onto the University of Glasgow and Strathclyde team for ultimate strength assessment and reliability analysis.

The most probable extreme amplitudes of dynamic wave induced vertical and horizontal bending moments, as well as torsion moment at mid-ship (70.5m from AP) on the sample vessel 'H5415' in 2 proposed damaged conditions were predicted. 2D linear method was used for the prediction of hydrodynamic response.

In computations of short term prediction, Pierson-Moskowitz spectrum was used at sea state 3-7. Pierson-Moskowitz spectrum can be expressed in the following form.

$$S(\omega) = 0.0081 g^2 \omega^5 \exp\left[-0.032\left(g / H_S \omega^2\right)^2\right]$$

Where, ω is wave frequency

H_S is significant wave height

The area m_0 of a response spectrum is given by

$$m_0 = \int_0^\infty S(\omega)\left|H(\omega)\right|^2 d\omega$$

The second moment m_2 of the area of the response spectrum is written as

$$m_2 = \int_0^\infty \omega^2 S(\omega)\left|H(\omega)\right|^2 d\omega$$

Hence, the most probable extreme response amplitude value in *N* waves can be written as

$$R_{\max} = \sqrt{2m_0 \ln(N)}$$

The probability of exceeding the response value given in the above equation for large *N* values is 0.632 (Ochi, 1973). The design extreme response amplitude value that will not be exceeded in *N* encounters with a probability of 0.99 is given by

$$R_{design} = \sqrt{2m_0 \ln(N / 0.01)}$$

Where the number of response N is given by

N=3600n*T

In which T is the duration in hours and n* is the average number of responses per unit time as expressed by

$$n^* = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}$$

Table 3.1.1- 3.1.7 represents the numerically calculated wave induced vertical, horizontal still water bending moment and torsion moment at sea state 3-7 for the duration of 96 hours. ‘R_Max’ is the most probable extreme design load, and ‘R_design’ is extreme design load with a probability of exceedance of 0.01 in N encounters.

Table 3.1.1: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS2 at stern quartering waves (heading 45) for 96 hours from sea state 3 to sea state 7

Heading 45	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				3.75E+07
R_Max	2.27E+08	1.10E+08	2.95E+07	
R_Design	2.79E+08	1.35E+08	3.61E+07	
Sea State 3.5				
R_Max	2.68E+08	1.23E+08	3.51E+07	
R_Design	3.28E+08	1.50E+08	4.31E+07	
Sea State 4				
R_Max	3.30E+08	1.38E+08	4.37E+07	
R_Design	4.05E+08	1.70E+08	5.36E+07	
Sea State 5				
R_Max	3.83E+08	1.48E+08	5.05E+07	
R_Design	4.70E+08	1.82E+08	6.21E+07	
Sea State 6				
R_Max	4.19E+08	1.53E+08	5.49E+07	
R_Design	5.15E+08	1.87E+08	6.74E+07	
Sea State 7				
R_Max	4.44E+08	1.55E+08	5.76E+07	
R_Design	5.46E+08	1.90E+08	7.09E+07	

Table 3.1.2: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS2 at head waves for 96 hours from sea state 3 to sea state 7

Heading 180	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				
R_Max	2.77E+08	2.07E+06	5.40E+05	
R_Design	3.40E+08	2.54E+06	6.61E+05	

Sea State 3.5				3.75E+07
R_Max	3.46E+08	2.33E+06	6.46E+05	
R_Design	4.25E+08	2.85E+06	7.91E+05	
Sea State 4				
R_Max	4.59E+08	2.69E+06	8.16E+05	
R_Design	5.64E+08	3.30E+06	1.00E+06	
Sea State 5				
R_Max	5.58E+08	2.95E+06	9.60E+05	
R_Design	6.86E+08	3.61E+06	1.18E+06	
Sea State 6				
R_Max	6.27E+08	3.08E+06	1.05E+06	
R_Design	7.72E+08	3.77E+06	1.30E+06	
Sea State 7				
R_Max	6.75E+08	3.14E+06	1.13E+06	
R_Design	8.32E+08	3.85E+06	1.39E+06	

Table 3.1.3: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS2 at beam waves (heading 90) for 96 hours from sea state 3 to sea state 7

Heading 90	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				3.75E+07
R_Max	8.12E+07	6.37E+07	5.38E+06	
R_Design	9.89E+07	7.75E+07	6.52E+06	
Sea State 3.5				
R_Max	8.50E+07	6.64E+07	5.46E+06	
R_Design	1.04E+08	8.09E+07	6.62E+06	
Sea State 4				
R_Max	8.99E+07	6.98E+07	5.55E+06	
R_Design	1.09E+08	8.50E+07	6.73E+06	
Sea State 5				
R_Max	9.35E+07	7.19E+07	5.61E+06	
R_Design	1.14E+08	8.75E+07	6.81E+06	
Sea State 6				
R_Max	9.63E+07	7.29E+07	5.66E+06	
R_Design	1.17E+08	8.88E+07	6.88E+06	
Sea State 7				
R_Max	9.94E+07	7.34E+07	5.77E+06	

R_Design	1.21E+08	8.94E+07	7.01E+06	

Table 3.1.4: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS2 at beam waves (heading 270) for 96 hours from sea state 3 to sea state 7

	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				3.75E+07
R_Max	8.29E+07	6.16E+07	5.38E+06	
R_Design	1.01E+08	7.50E+07	6.52E+06	
Sea State 3.5				
R_Max	8.67E+07	6.43E+07	5.46E+06	
R_Design	1.06E+08	7.83E+07	6.62E+06	
Sea State 4				
R_Max	9.15E+07	6.77E+07	5.55E+06	
R_Design	1.11E+08	8.24E+07	6.73E+06	
Sea State 5				
R_Max	9.51E+07	6.97E+07	5.61E+06	
R_Design	1.16E+08	8.49E+07	6.81E+06	
Sea State 6				
R_Max	9.78E+07	7.07E+07	5.66E+06	
R_Design	1.19E+08	8.62E+07	6.88E+06	
Sea State 7				
R_Max	1.01E+08	7.12E+07	5.77E+06	
R_Design	1.23E+08	8.68E+07	7.01E+06	

Table 3.1.5: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS2 at stern quartering waves (heading 315) for 96 hours from sea state 3 to sea state 7

Heading 315	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				3.75E+07
R_Max	2.27E+08	1.12E+08	2.95E+07	
R_Design	2.79E+08	1.37E+08	3.61E+07	
Sea State 3.5				
R_Max	2.68E+08	1.25E+08	3.51E+07	
R_Design	3.28E+08	1.53E+08	4.31E+07	
Sea State 4				
R_Max	3.30E+08	1.41E+08	4.37E+07	
R_Design	4.05E+08	1.73E+08	5.36E+07	

Sea State 5				
R_Max	3.83E+08	1.51E+08	5.05E+07	
R_Design	4.70E+08	1.85E+08	6.21E+07	
Sea State 6				
R_Max	4.19E+08	1.56E+08	5.49E+07	
R_Design	5.15E+08	1.91E+08	6.74E+07	
Sea State 7				
R_Max	4.44E+08	1.58E+08	5.76E+07	
R_Design	5.46E+08	1.94E+08	7.09E+07	

Table 3.1.6: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS3 at stern quartering waves (heading 45) for 96 hours from sea state 3 to sea state 7

Heading 45	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				-2.47E+08
R_Max	2.08E+08	1.02E+08	2.51E+07	
R_Design	2.55E+08	1.25E+08	3.08E+07	
Sea State 3.5				
R_Max	2.41E+08	1.16E+08	2.94E+07	
R_Design	2.95E+08	1.42E+08	3.61E+07	
Sea State 4				
R_Max	2.87E+08	1.35E+08	3.58E+07	
R_Design	3.52E+08	1.66E+08	4.39E+07	
Sea State 5				
R_Max	3.22E+08	1.50E+08	4.06E+07	
R_Design	3.95E+08	1.84E+08	4.99E+07	
Sea State 6				
R_Max	3.42E+08	1.59E+08	4.37E+07	
R_Design	4.20E+08	1.95E+08	5.36E+07	
Sea State 7				
R_Max	3.54E+08	1.66E+08	4.55E+07	
R_Design	4.35E+08	2.04E+08	5.59E+07	

Table 3.1.7: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS3 at head waves for 96 hours from sea state 3 to sea state 7

	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				

R_Max	2.54E+08	2.04E-03	6.31E-05	-2.47E+08
R_Design	3.11E+08	2.48E-03	7.66E-05	
Sea State 3.5				
R_Max	3.12E+08	2.06E-03	6.37E-05	
R_Design	3.83E+08	2.50E-03	7.73E-05	
Sea State 4				
R_Max	4.03E+08	2.08E-03	6.43E-05	
R_Design	4.95E+08	2.53E-03	7.80E-05	
Sea State 5				
R_Max	4.79E+08	2.09E-03	6.46E-05	
R_Design	5.89E+08	2.54E-03	7.84E-05	
Sea State 6				
R_Max	5.28E+08	2.10E-03	6.48E-05	
R_Design	6.50E+08	2.54E-03	7.86E-05	
Sea State 7				
R_Max	5.58E+08	2.10E-03	6.48E-05	
R_Design	6.87E+08	2.55E-03	7.86E-05	

Table 3.1.8: Extreme design loads in mid-ship (at 70.5m from AP) of hull 5415 in DS3 at beam waves for 96 hours from sea state 3 to sea state 7

Heading 90	M_{wv} (Nm)	M_{wh} (Nm)	TM (Nm)	M_S (Nm)
Sea State 3				-2.47E+08
R_Max	3.31E+07	4.03E+07	3.07E+06	
R_Design	4.03E+07	4.91E+07	3.72E+06	
Sea State 3.5				
R_Max	3.74E+07	4.57E+07	3.15E+06	
R_Design	4.57E+07	5.58E+07	3.82E+06	
Sea State 4				
R_Max	4.52E+07	5.57E+07	3.26E+06	
R_Design	5.53E+07	6.82E+07	3.96E+06	
Sea State 5				
R_Max	5.38E+07	6.70E+07	3.33E+06	
R_Design	6.59E+07	8.21E+07	4.04E+06	
Sea State 6				
R_Max	6.22E+07	7.83E+07	3.37E+06	
R_Design	7.64E+07	9.62E+07	4.09E+06	

Sea State 7				
R_Max	7.22E+07	9.19E+07	3.39E+06	
R_Design	8.88E+07	1.13E+08	4.12E+06	

Experimental investigation of wave loads

The preparation of experiment has been completed. The experimental tests were initially scheduled in June 2007, but they had to be postponed due to an unexpected repair work in the workshop of the towing tank. Shortly after the repair work, the old wave maker had to be replaced with a new one. So the tests are unfortunately further postponed. Hopefully the tests could commence in February 2008.

3.2 Prediction of ultimate strength of hull girder by FEM

The ultimate bending moment for intact ship using the Smith Method like approach using the MARS software of BV classification society have been calculated for various load combination. Further, equations for interaction of horizontal and vertical bending moment are also developed for the hull 5415.

In parallel to work on modelling and sub-modelling of the main 3 compartment FE model, the FE analysis are carried out using 2 frame 3D fine mesh model of the hull 5415 and 1 compartment coarse FE mesh model. The initial results obtained from the preliminary analysis are described in the report.

The response surface methods are very efficient in term of computational efforts needed to simulate a system response. However, for highly non-linear system the accuracy may be an issue which may or may not be predictable by statistical measures of goodness of fit of the regression polynomial, especially for higher order polynomial having oscillation between data points, Bucher et al (2006).
The good accuracy in fitting of response surface function with comparatively fewer data point may be achieved if type of response of structural system is known a prior. For example, interaction of ultimate hull girder bending strength in presence combined vertical and horizontal is characterize by the following relation (Paik & Thayamballi, 2003)

$$\left(\frac{M_V}{M_{VU}}\right)^{C1}+\left(\frac{M_H}{M_{HU}}\right)^{c2}=1 \qquad (5)$$

Where M_{VU} and M_{HU} are ultimate vertical and ultimate horizontal bending moment capacities of ship section; M_V and M_H are vertical and horizontal bending moments, respectively. The C1 and C2 are characteristic parameters describing the interaction relationship of vertical and horizontal bending moments. Similarly, interaction relation of shear with the vertical and horizontal bending moments is as follows:

$$\left(\frac{M_V}{M_{VU}\sqrt[c3]{1-(F/Fu)^{c4}}}\right)^{C1}+\left(\frac{M_H}{M_{HU}\sqrt[c5]{1-(F/Fu)^{c6}}}\right)^{c2}=1 \qquad (6)$$

Where M_{VU}, $M_{HU,}$ M_V and M_H are as mentioned above and, F_U and F are ultimate shear and shear force of ship section and C3, C4, C5 and C6 are parameters for shear force interaction with bending moments.

In view of the foregoing, the hull girder ultimate strength response function of the form given in (7) shall be used to fit data from FE analysis and this response function shall subsequently be used for reliability analysis.

$$M_V = \sqrt[C1]{1 - \left(\frac{M_H}{M_{HU} \sqrt[c5]{1-(F/Fu)^{c6}}} \right)^{c2}} \left(M_{VU} \sqrt[c3]{1-(F/Fu)^{c4}} \right) \tag{7}$$

Case Study – Hull 5415

These studies are performed for the Notional USN Combatant ship, the Hull Form 5415. The principal dimensions of Hull 5415 are given in Table 3.2.1.

Table 3.2.1: Principal dimension of USN Hull 5415

Principal Dimensions	Value
Length Between Perpendiculars	142.04 metres (466 ft)
Overall Length	151.18 metres (496 ft)
Maximum Beam	21.15 metres (69.4 ft)
Beam at Water Line	20.03 metres (65.7 ft)
Depth of Hull	12.74 metres (41.8 ft)
Design Draught (moulded)	6.31 metres (20.7 ft)
Displacement at Load Draught	9032.24 tonnes (8890 LTons)

The ships layout plan and damaged scenario for this study is shown in Figure 3.2.2. The collision damage scenario is based on Lloyd's Register Rules for naval ships that for collision damage of level A is given in Table 3.2.2. It is also graphically illustrated in Figure 3.2.2.

Table 3.2.2: LR Rules; collision damage extent

Military threats	The extent of damage due to military threats defined as the minimum of the shock or blast damage that is likely to result from a specified weapon threat.	
Collision damage to the side shell	Level A	- 5 m longitudinally between bulkheads
		- from the waterline up to the main deck
		- inboard for B/5 m

The structural design of the Hull 5415 is developed on two types of steel HY80 and HSS. The relevant properties of the steel materials are given in Table 3.2.3. The detail of midship section of the Hull 5415 is given in Figure 3.2.3. The relevant cross sectional properties are listed in Table 3.2.4 that includes the values obtained from MARS (Bureau Veritas software for structural calculation) and ANSYS (FE analysis software) for comparison of structural model for each software.

Table 3.2.3. Properties of steel materials

Material	Yield Strength
<u>**HY80**</u>	
σ_y (MN/m^2)	552
<u>**High Strength Steel**</u>	
σ_y (MN/m^2)	351

Table 3.2.4: Cross section characteristics

Parameter	Value (MARS)	Value (ANSYS)
Total Section Area	1.2592 m^2	1.2576 m^2
Neutral axis above baseline	6.57486 m	6.5119 m
Vertical Moment of Inertia	28.968810 m^4	28.995 m^4
Horizontal Moment of Inertia	43.141570 m^4	43.11 m^4

<u>Ultimate Hull Girder Strength – using MARS</u>

The MARS software from Bureau Veritas is used to calculate ultimate hull girder strength using beam-column idealization as of Smith Method. The MARS software provides different algorithms that include Elastic Ideally Plastic (EIP) failure mode and Beam-Column (BC) failure mode apart from the others.

For EIP failure mode, material beyond elastic limit is considered fully plastic in both under tension and compression. Beam-Column method of MARS uses the following load-end shortening curves to determine ultimate bending moment capacity of ship section:

$$\sigma_{CR1} = \Phi\sigma_{C1}\frac{A_S + 10b_E t_P}{A_S + 10st_P} \tag{8}$$

Where Φ is edge function defined, σ_{C1} is critical stress, A_S is net sectional area, b_E effective width of plating attached to stiffener, t_P net thickness of plating and $_S$ is spacing of stiffeners. The detail of the methods may be found in BV Rules, Part B, Chapter 6, and Appendix 1.

The figure 3.2.4 shows the MARS calculation results of ultimate strength in pure horizontal bending of Hull 5415 for elastic ideally plastic failure mode and figure 5 shows results for ultimate strength in pure vertical bending for beam-column failure mode. The detailed results of elastic-ideally plastic failure mode for various combination of vertical and horizontal bending moment are calculated using MARS which are given in figure 6 and figure 8 for EIP and BC ultimate strength, respectively. The M_V and M_H interaction formula in the form of equation (5) are found as follows

For M_V and M_H interaction formula elastic ideally plastic failure mode (see figure 3.2.7 also).

$$\left(\frac{M_V}{M_{VU}}\right)^{1.62467} + \left(\frac{M_H}{M_{HU}}\right)^{2.04339} = 1 \tag{9}$$

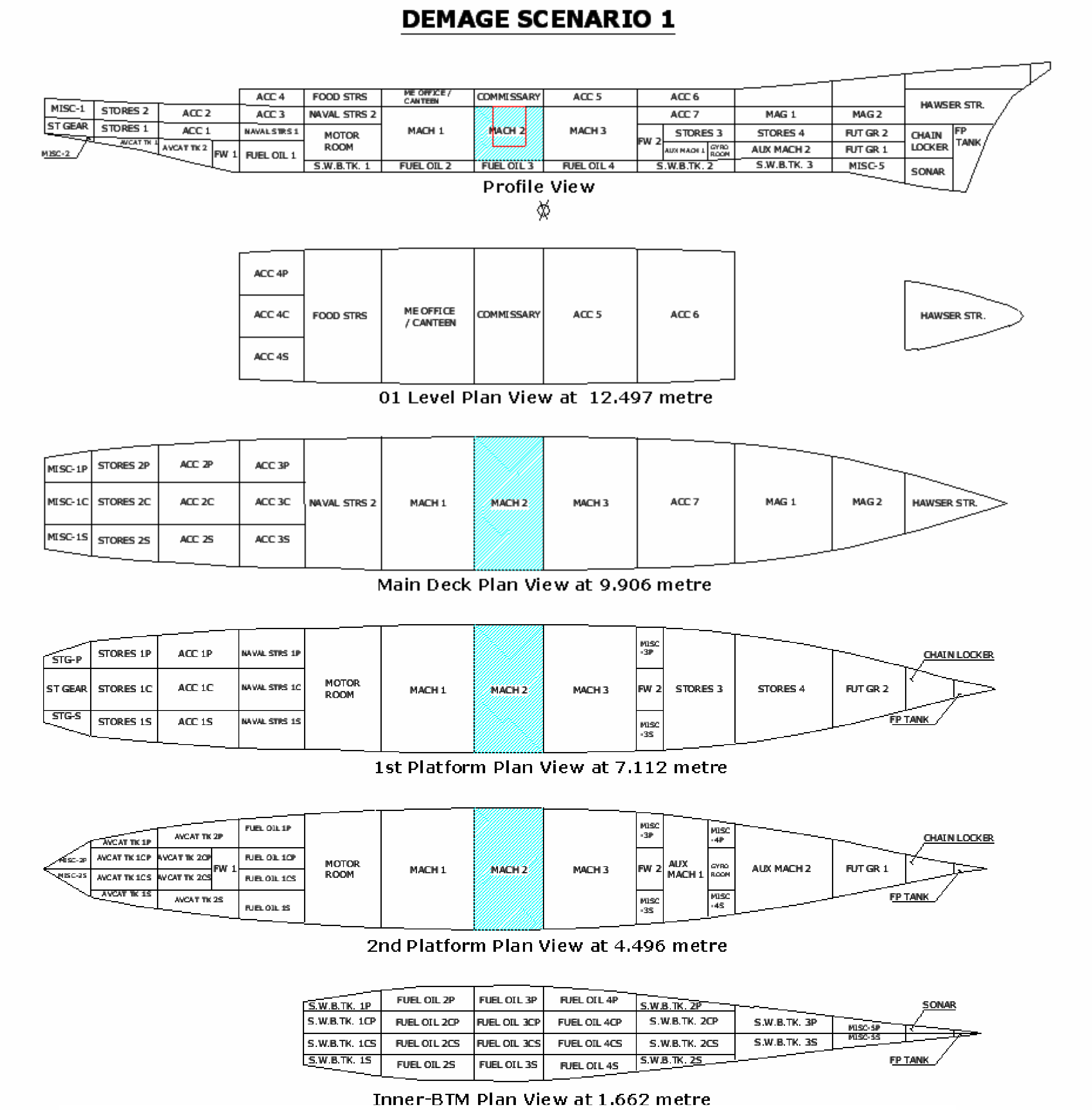


Figure 3.2.2: Hull5415 layout and damaged scenario

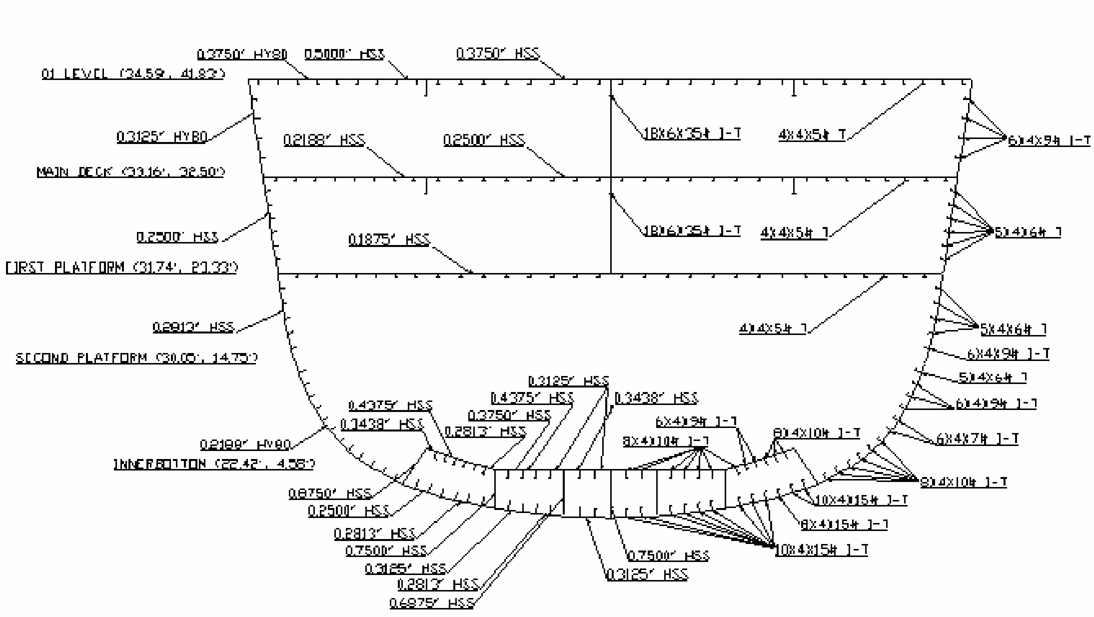


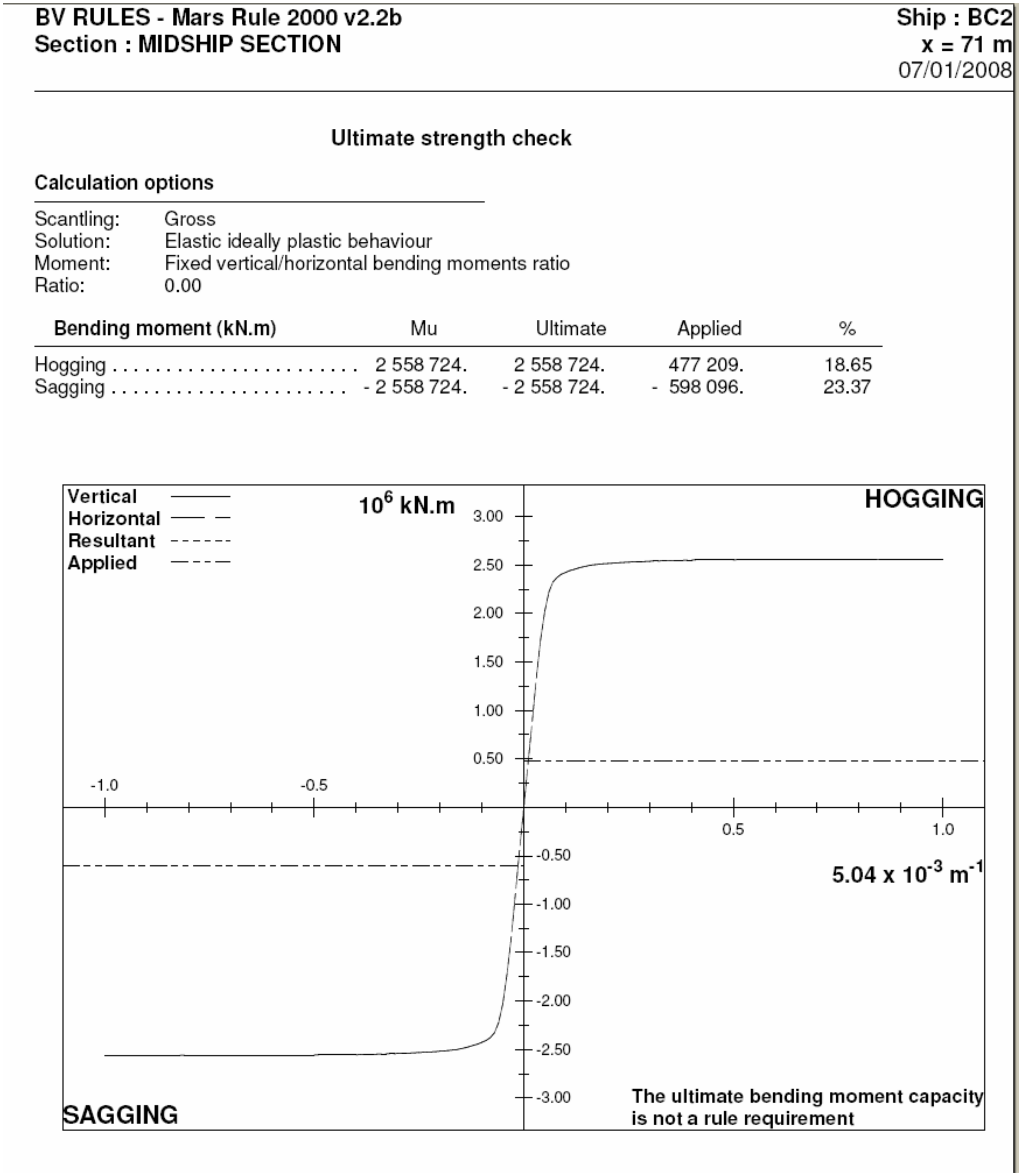
Figure 3.2.3: Midship scantling of Hull 5415

For M_V and M_H interaction formula beam-column failure mode (see figure 3.2.9 also).

$$\left(\frac{M_V}{M_{VU}}\right)^{4.53198} + \left(\frac{M_H}{M_{HU}}\right)^{2.35511} = 1 \qquad (10)$$

Ultimate Hull Girder Strength –using ANSYS

The ANSYS is used for finite element analysis of Hull5415 to determine ultimate strength of the hull girder. In FE analysis, the range of the FE model requires to be carefully determined. Some suggestions were made in the Kick-off Meeting (21 Aug 2006) to model using top-down procedure starting from a coarse model of the whole ship. Considering the enormous amount of computing time in non-linear analysis, this procedure was considered not realistic for the project because of budget constraints and enormous amount of computing time and effort. It was decided that a three compartment model shall be sufficient. Three compartment part of the Hull 5415 as shown in Figure 3.2.10 shall be modelled for finite element analysis.



BV RULES - Mars Rule 2000 v2.2b
Section : MIDSHIP SECTION

Ship : BC2
x = 71 m
07/01/2008

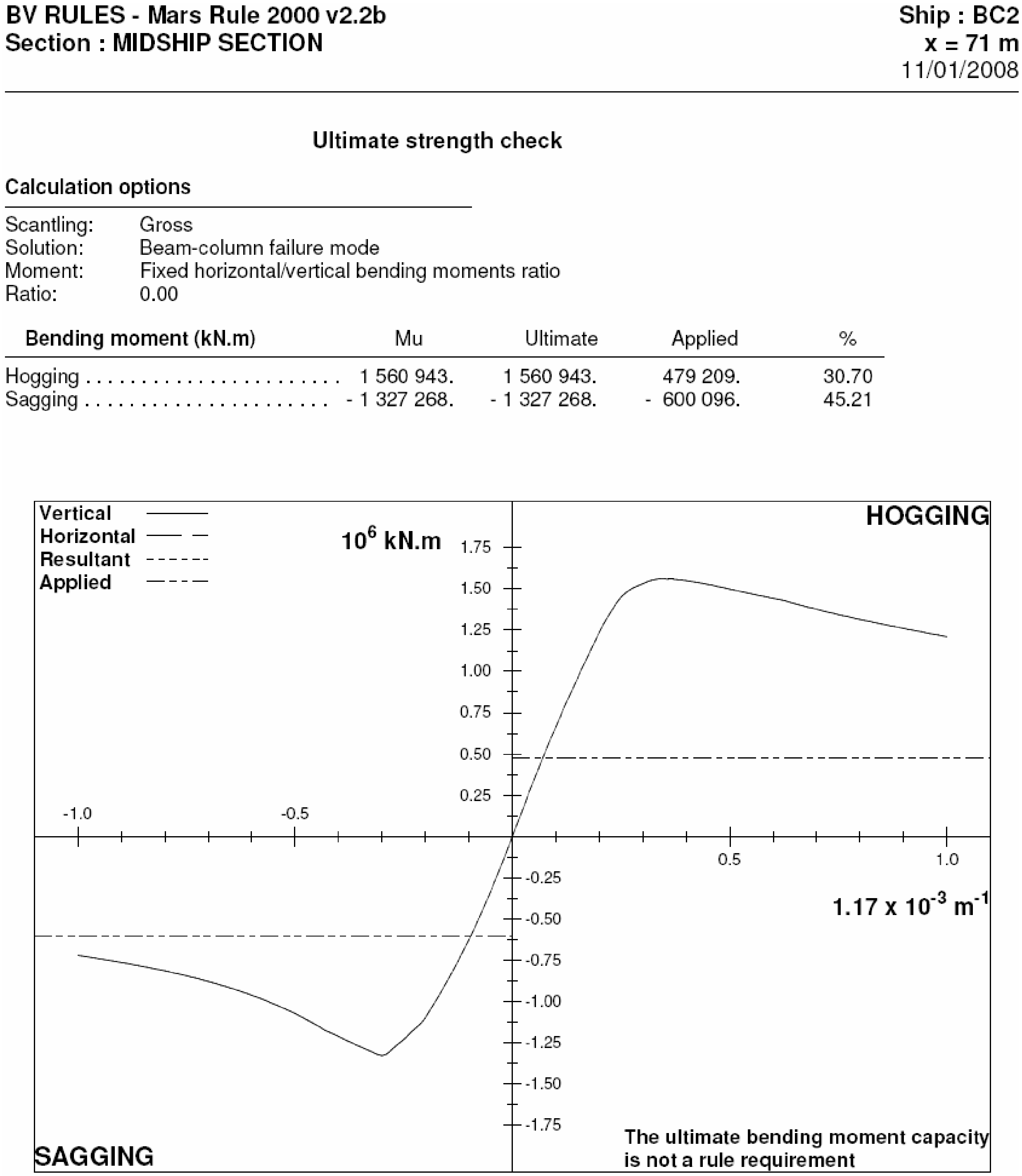
Ultimate strength check

Calculation options

Scantling:	Gross
Solution:	Elastic ideally plastic behaviour
Moment:	Fixed vertical/horizontal bending moments ratio
Ratio:	0.00

Bending moment (kN.m)	Mu	Ultimate	Applied	%
Hogging	2 558 724.	2 558 724.	477 209.	18.65
Sagging	- 2 558 724.	- 2 558 724.	- 598 096.	23.37

Figure 3.2.4: Elastic – Ideally Plastic ultimate strength of Hull 5415 in pure horizontal bending.



BV RULES - Mars Rule 2000 v2.2b
Section : MIDSHIP SECTION

Ship : BC2
x = 71 m
11/01/2008

Ultimate strength check

Calculation options

Scantling: Gross
Solution: Beam-column failure mode
Moment: Fixed horizontal/vertical bending moments ratio
Ratio: 0.00

Bending moment (kN.m)	Mu	Ultimate	Applied	%
Hogging	1 560 943.	1 560 943.	479 209.	30.70
Sagging	- 1 327 268.	- 1 327 268.	- 600 096.	45.21

The ultimate bending moment capacity is not a rule requirement

Figure 3.2.5: Beam-Column failure ultimate strength of Hull 5415 in pure vertical bending

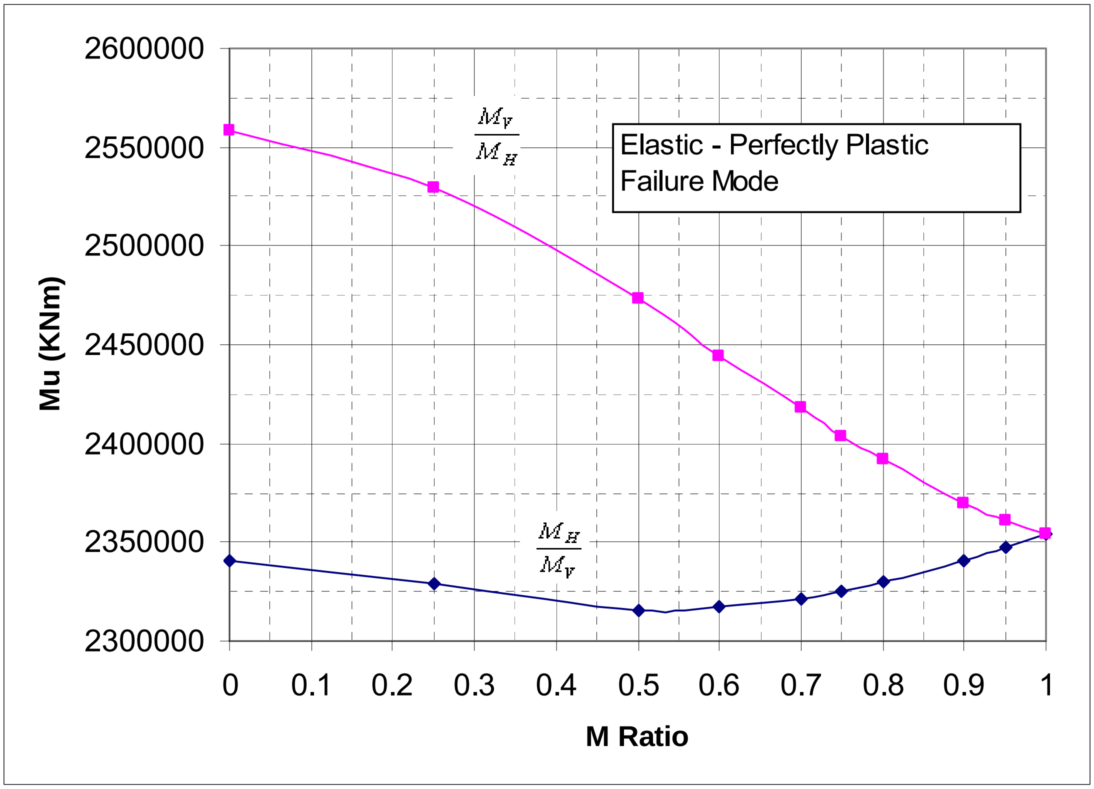


Figure 3.2.6: EIP Ultimate strength of Hull 5415 for vertical & horizontal moments

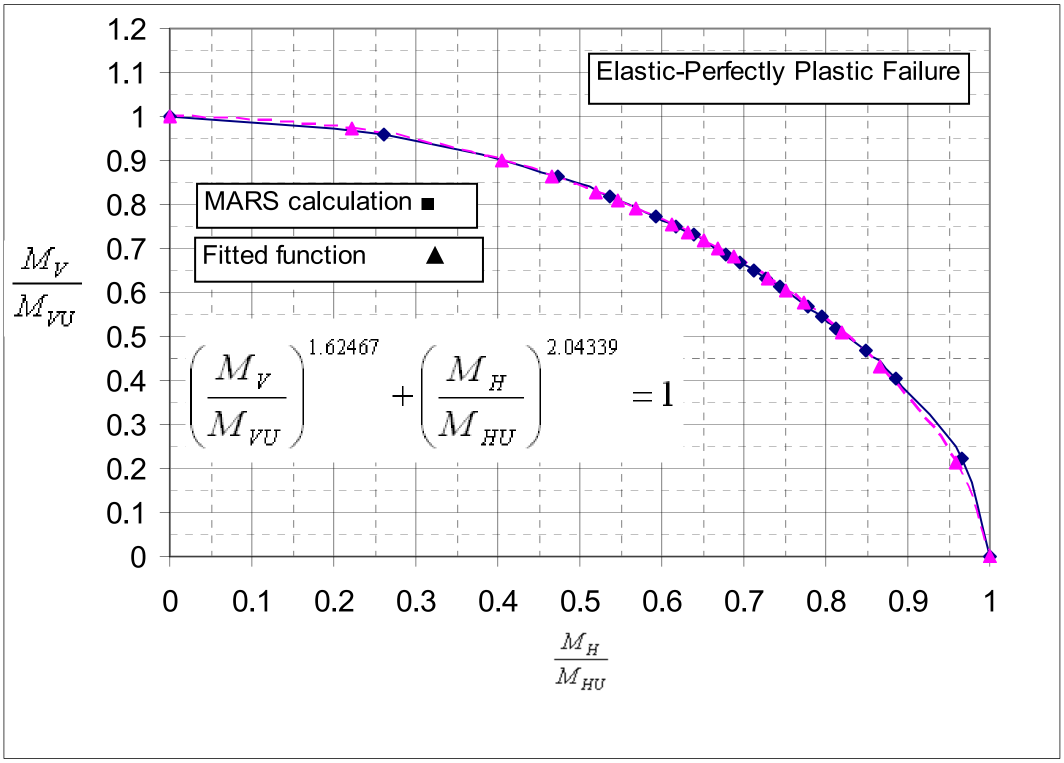


Figure 3.2.7: EIP Ultimate strength for vertical & horizontal moments interaction

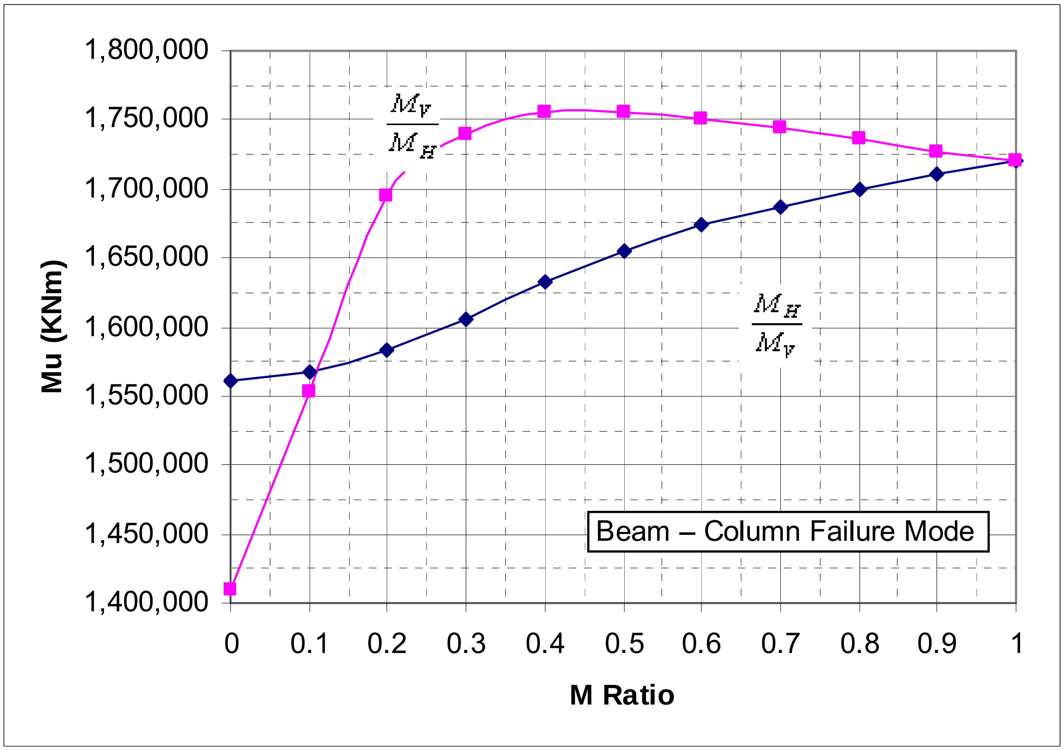


Figure 3.2.8: BC ultimate strength of Hull 5415 for vertical & horizontal moments

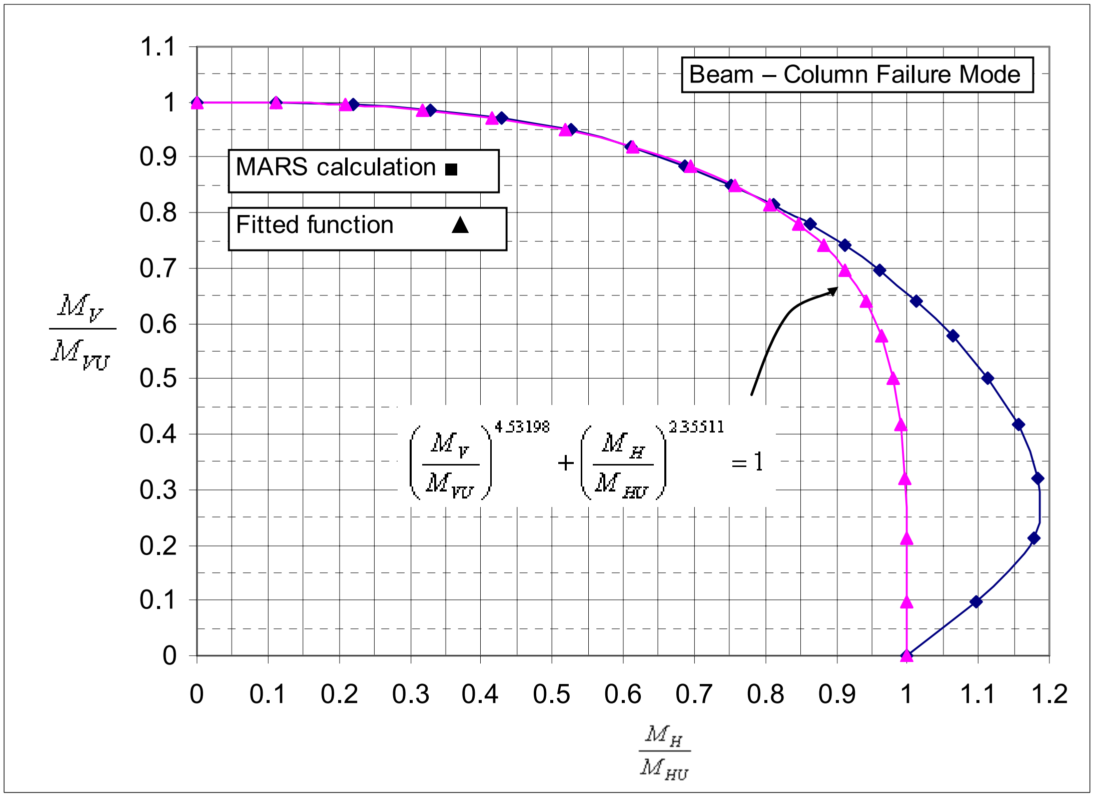


Figure 3.2.9: BC ultimate strength of Hull 5415 for vertical & horizontal interaction

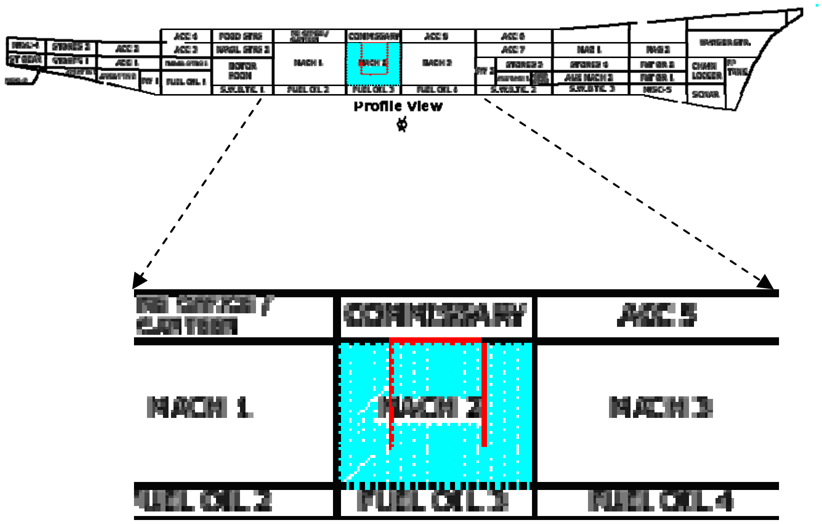


Figure 3.2.10: The range of ship for FE modelling of damaged ship analysis

However, structural details of the Hull 5415 are only available for midship section and the three compartments are considered to be same in cross section as the midship in these studies. Further, no FE based design assessment of intact ship is available to compare the results with that of the damaged ship. The FE analysis of the hull shall be carried out for both intact and damaged conditions.

3D Finite Element Model

The main particular of the ship are given in Table 1. Only three central compartments of the ship shall be used for 3D finite element analysis as already mentioned. Only structural detail of midship section is available and it is assumed that the structural details remain the same through three middle compartments. Further, superstructure of ship is often designed providing no contribution to overall main hull girder response. The superstructure is therefore not included in this analysis.

One compartment coarse mesh model and 2 frame fine mesh model are being used for evaluation/testing of solution procedures and algorithms. Some of the results obtained from analysis on these models are also presented in this interim report.

Geometric Model

The intact 3D modelling of the three mid compartments of the ship is used in this analysis. The figure 3.2.11 shows a half part of the model from centre line. For intact ship structural analysis vertical bending moment is often dominant loading condition and symmetry of hull structure about central plane can be utilized to reduce size of the FE model. Since, apart from vertical bending moment, horizontal bending and torsion are also important for damaged ship condition, it is, therefore, required that complete ship section is used for finite element analysis.

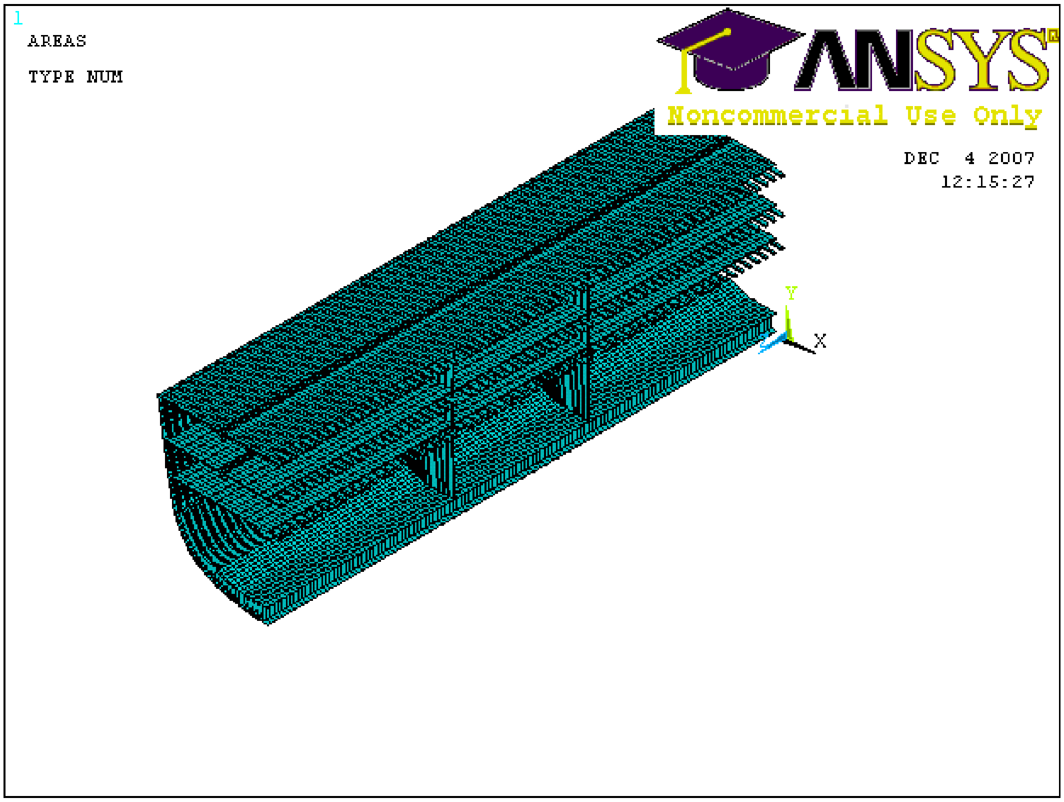


Figure 3.2.11: 3D modelling of the ship

Material Model

The ship is constructed of two types of steels. The properties of steels are listed in the Table 3.2.4 below. Both the types of steel materials are modelled as elastic-perfectly-plastic. Production related variations in strength of material such as residual stress due to welding, cold working etc are not considered directly but shall be counted for in reliability analysis using uncertainty factors.

Table 3.2.4. Properties of steel materials

Variables	Distribution	Mean	COV	Correlation
HY80				
σ_y (MN/m^2)	Lognormal	552	0.08	Independent
High Strength Steel				
σ_y (MN/m^2)	Lognormal	351	0.08	Independent

Load modelling

The important components of ships loads are vertical bending, horizontal bending, section shear and torsion. The finite element analysis shall be carried out to determine the ultimate strength for the following conditions:

- Vertical bending moment to determine ultimate vertical bending moment capacity
- Horizontal bending moment to determine ultimate horizontal bending moment capacity.
- Torsion to determine ultimate capacity of the section in torsion
- Combined load to determine response function for hull structure in the form similar to equation (7)

FE Mesh

The ANSYS SHELL181 element is this analysis. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a 4-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. SHELL181 counts for follower (load stiffness) effects of distributed pressures.

In order to reduce computational effort for nonlinear analysis of the large structure, it is planned to use sub-modelling techniques defining components as a super-element. The key parameters of mesh of three compartment model are given in Table 3.2.5.

The important features of one compartment model being used in these studies are given in Table 3.2.6.

Table 3.2.5: Import parameters of 3 compartment model

Item	Value
ELEMENTS	1666728
NODES	1662004
KEYPOINTS	101376
LINES	200100
AREAS	94202

Table 3.2.6: Important parameters of one compartment coarse mesh model

Item	Value
ELEMENTS	45874
NODES	42010
KEYPOINTS	29229
LINES	57449
AREAS	13568

Ultimate Strength – Vertical Bending Moment

In parallel to work on modeling and sub-modeling of the main 3 compartment model, FE analysis are carried out using 2 frame fine mesh model and 1 compartment coarse mesh model as already mentioned above. The ultimate vertical bending moment for elastic ideally plastic condition of 2 frame model is

given in table 3.2.7 comparing with those calculated using the MARS software and full plastic moment bearing capacity of the section.
The figure 3.2.12 and 3.2.13 show the 1 compartment coarse mesh FE model being used for initial analysis. The figure 3.2.14 illustrates the vertical bending moment equivalent end pressure load applied on section to determine ultimate bending moment capacity of the section. Under the pure vertical bending load, the top deck panel buckled about two frames abaft of forward bulkhead as shown in figure 3.2.15 at vertical bending moment of 1.0701 GNm. The location of neutral axis and vertical bending moment along the length of the compartment are plotted in figure 3.2.16 and 3.2.17, respectively.

The table 3.2.7 gives comparison of initial FE analysis results with those of MARS calculation. The ultimate vertical bending moment strength results for one compartment model is 19.38% less then the ultimate vertical bending moment results of beam-column (BC) method of MARS software. This big difference may be attributed to coarse mesh size that initiate early on set of large deformation resulting in non-convergence of the solution. Further, very large load step size was used in this analysis that also considerably influences the convergence of nonlinear analysis.

Table 3.2.7: Comparison of ultimate vertical bending moment from different methods

Method		MARS		ANSYS		
Item		EIP	BC	FPMC	EIP	CM
$M_{VU\ (GNm)}$	Hogging	2.3405	1.5609	2.1859	2.064	-
	Sagging	-2.3405	-1.3273	-2.1859	-	1.0701
$M_{HU\ (GNm)}$		2.5587	0.2188	2.5878	-	-

Key:
EIP : Elastic- Ideally Plastic Failure Mode
BC : Beam Column Failure Mode (Smith Method)
FPMC : Full Plastic Moment Capacity of the section
CM: Coarse Mesh Model (Top deck buckling failure)

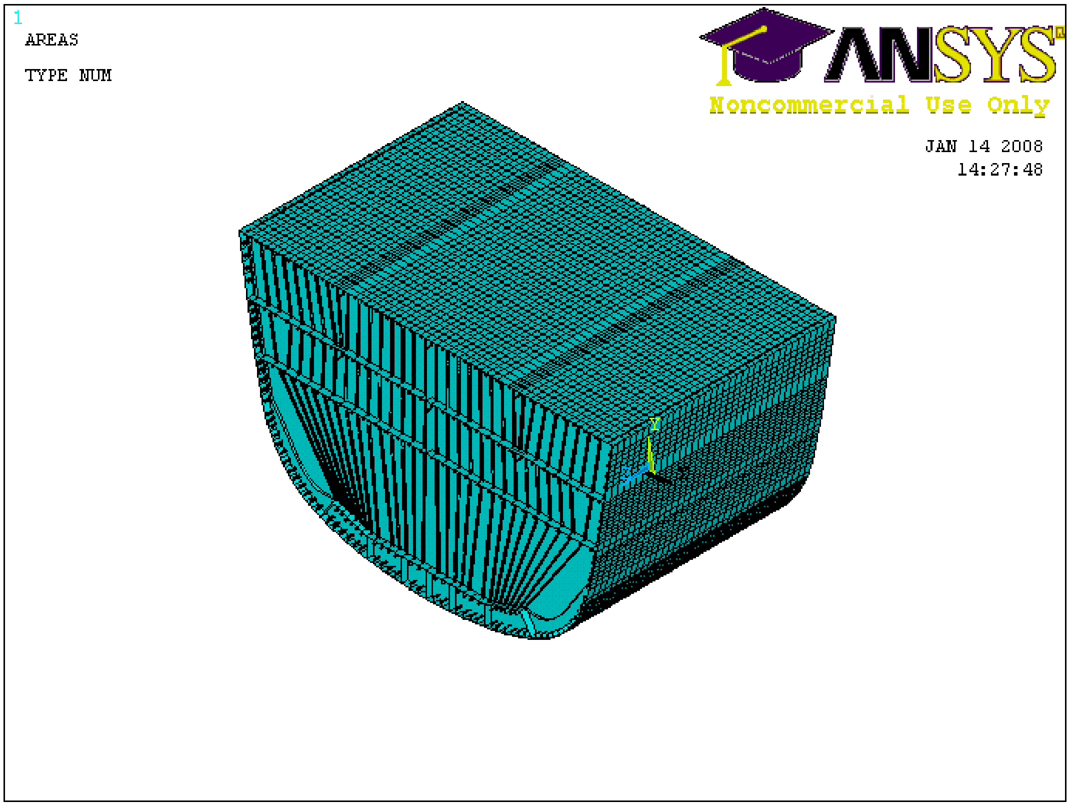


Figure 3.2.12 : One compartment model with end bulkheads

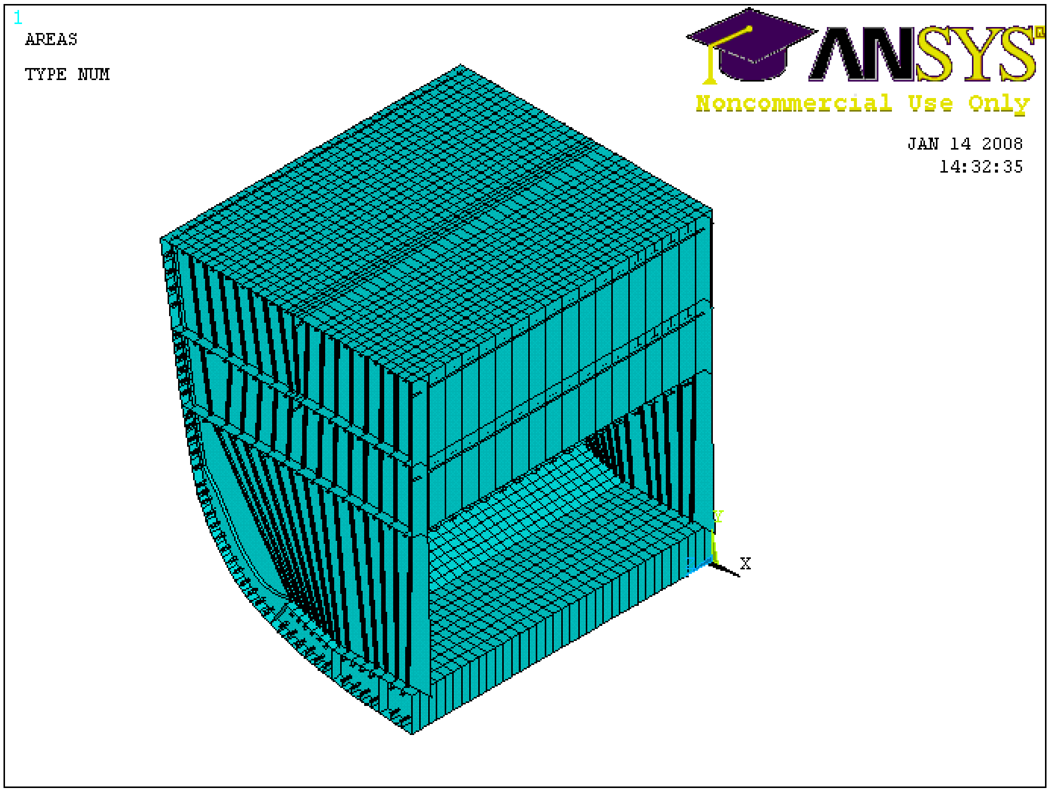


Figure 3.2.13 : Half-view of One compartment model with end bulkheads

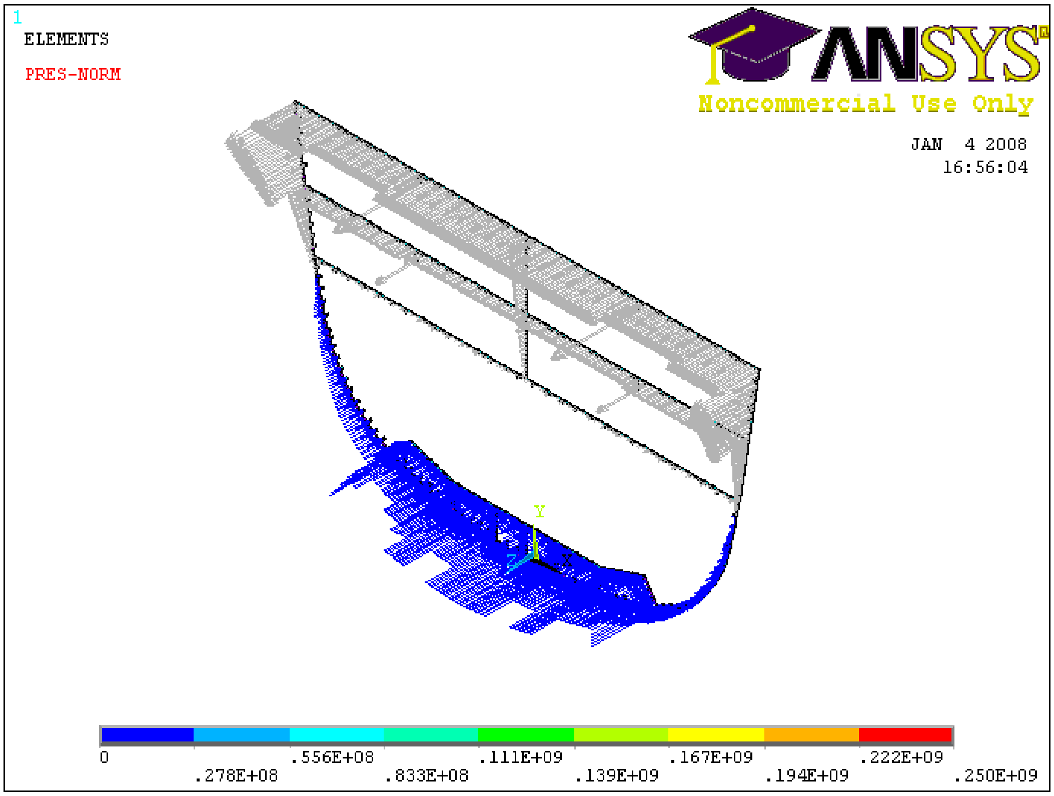


Figure 3.2.14 : Applied pure vertical bending moment equivalent force on section

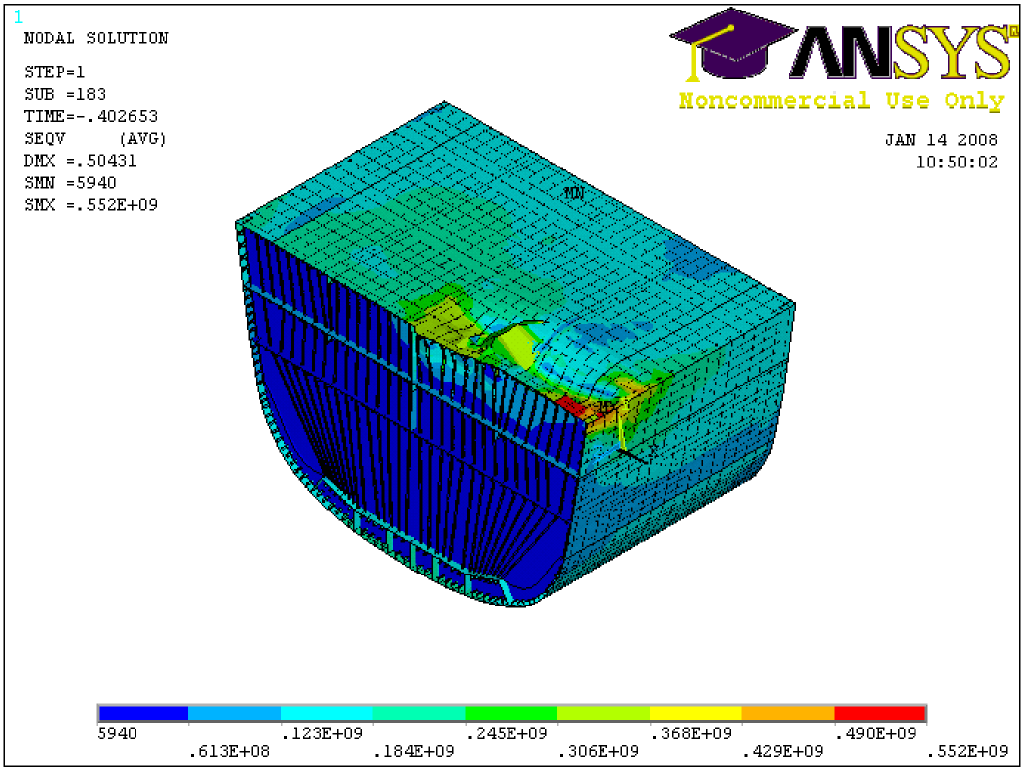


Figure 3.2.15 : Stress & deformation at ultimate failure of top deck

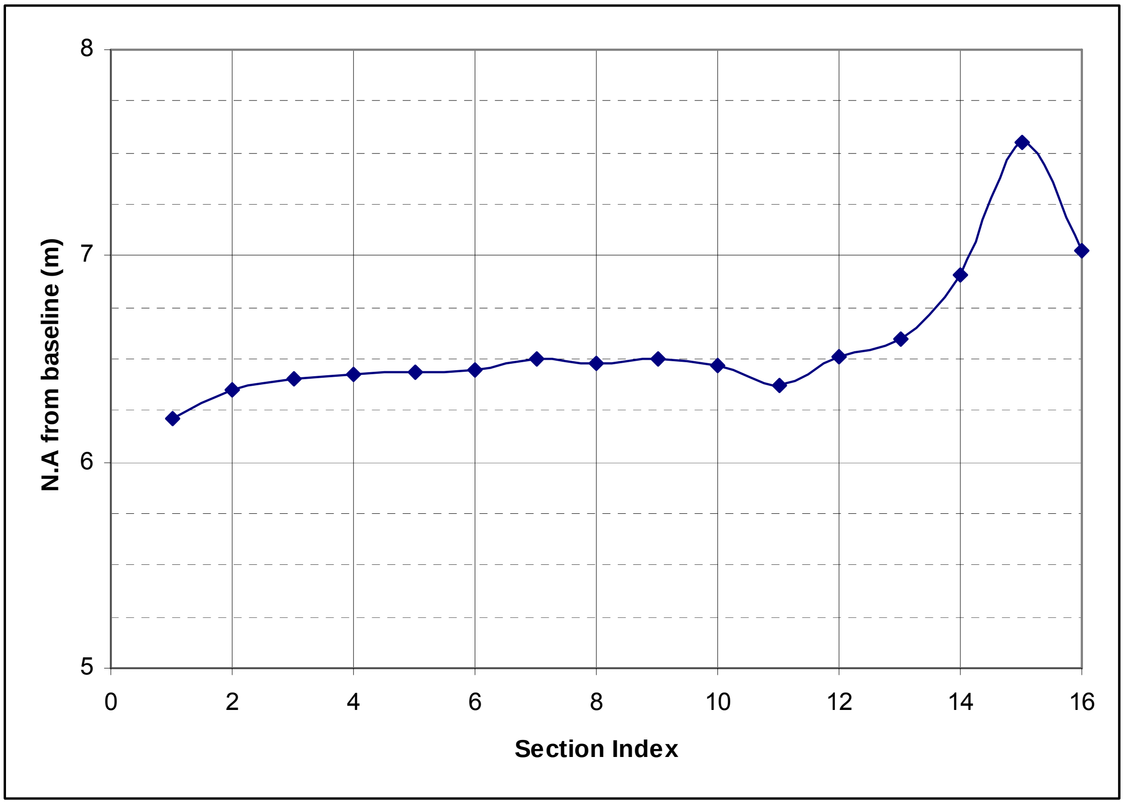


Figure 3.2.16: Location of neutral axis above baseline

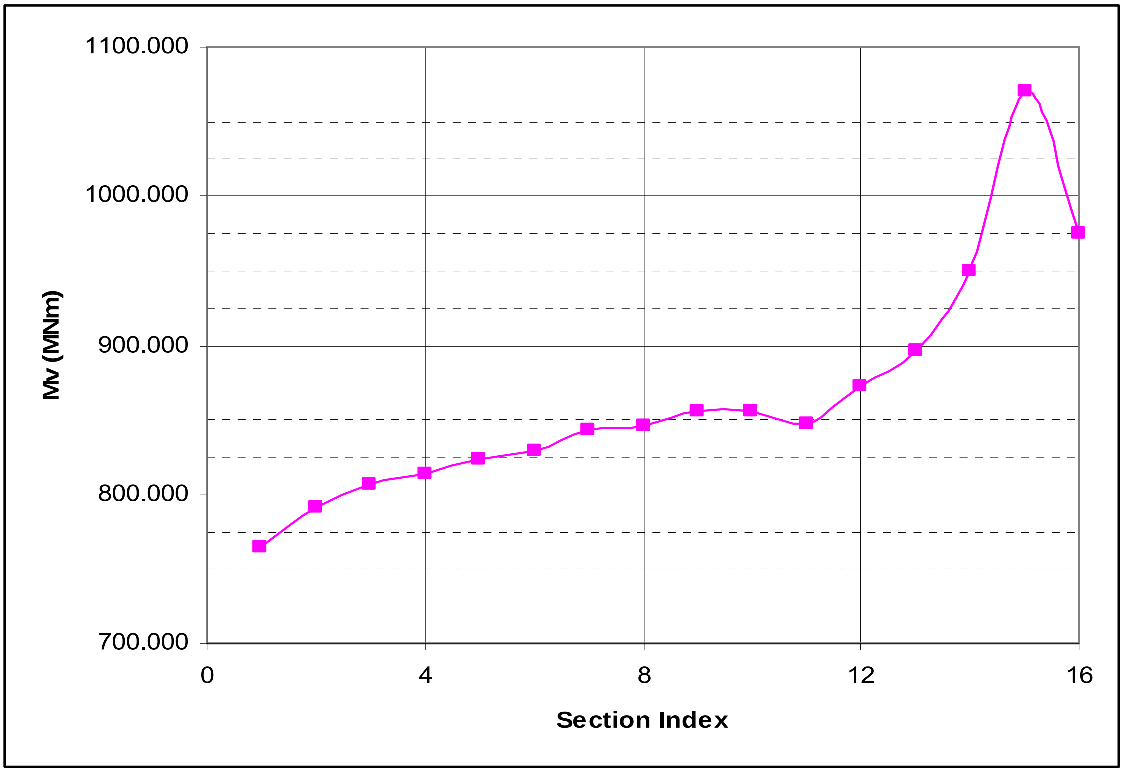


Figure 3.2.17: Vertical bending along length of the compartment at ultimate failure

3.3 Milestones of the remaining work

The milestones of Newcastle University are as follows:

Tasks	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08
Experimental tests		▬	▬	▬			
2D linear prediction of the ship model		▬					
2D nonlinear prediction of H5414				▬			
Calculate model uncertainty				▬			
Write report					▬		
Further polish of the report						▬	▬

The tentative milestones of the University of Glasgow and Strathclyde are as follows:

Tasks	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08
Sub Structuring 3D Model	▬	▬					
FEA intact condition			▬	▬	▬		
FEA damaged condition				▬	▬	▬	
Reliability Analysis						▬	
Write report							▬

4. Closing Remarks

In summary, the progress has broadly been in line with the expectation of the research teams so far although some unexpected delay has occurred in wave-induced load experiment. It is expected that the progress will be accelerated from now on since input data for non-linear loads calculation and test as well as preliminary run of FE models have now been prepared. The consortium is confident that all the proposed work will be completed according to the schedule given in the proposal.

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