Progress in the Analysis and Design of Marine Structures – Guedes Soares & Garbatov (Eds)

Compressive strength of double-bottom under alternate hold loading condition

J.M. Gordo
Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal

ABSTRACT: The alternate bending of the bottom' structure of a ship as a result of the action of external pressure due to the sea and the internal loading in alternate holds, causes a bending of secondary order between the transversal bulkheads which overlaps the primary bending of the hull girder of the ship. It can be an important source of ultimate strength reduction when the vessel is in hogging. In this hogging condition, the double bottom is under compressive stresses and may collapse by elastic-plastic instability. The second-order bending due to loading on alternate holds, substantially increases the compressive stress in the bottom panels of unloaded holds and on double-bottom panels subjected to internal loading, usually leading to premature collapse, and consequently, a drastic reduction of the contribution of bottom and double bottom for the resistance to longitudinal bending of the ship. In this study, it is analysed and quantified the reduction of compressive strength of the double bottom of a bulk carrier through the finite element method. It is also introduced a method that account for the effect of such reduction on strength in estimated ultimate longitudinal strength of the ship under hogging conditions, by quantifying the negative impact on it.

1 INTRODUCTION

The structure of various types of ships are subject to combined action of bending of the hull girder and the action of alternate lateral pressure in tanks or holds during part of their service.

This alternate bending the double bottom results from the action of external sea pressure and alternate loading on consecutive holds, which causes secondary order bending of the structure between transversal bulkheads that overlaps the primary bending of the hull girder due to vertical bending moment. It can be a source of major strength reduction specially when the ship is in hogging (Amlashi & Moan 2008; Shu & Moan 2012) and (Toh & Yoshikawa 2015). In this situation, the double bottom is under compressive stresses and may collapse by elastic-plastic instability (Amlashi & Moan 2009). The second-order bending due to loading on alternate holds, substantially increases the compressive stress in the bottom panels of unloaded holds as noted in ISSC 2015 (Yoshikawa, Bayatfar et al. 2015) and on double-bottom panels subjected to internal loading, usually leading to premature collapse, and consequently, a drastic reduction of the contribution of bottom and double bottom for the resistance to longitudinal bending of the ship.

In this study, it is analysed and quantified the reduction of compressive strength of the double bottom of a bulk carrier through the finite element method.

It is also introduced a method that account for the effect of such reduction on strength in estimated ultimate longitudinal strength of the ship under hogging conditions, by quantifying the negative impact on it.

It is also analysed the importance of the design of longitudinal structures of the ship hull in controlling this strength degradation, including the effect of support and restriction given by the bilge and the longitudinal bulkheads.

2 ALTERNATE HOLD LOADING MODELLING

Bulk carriers are designed to carry bulk cargo that can often have a higher density than water. This means that these ships frequently sail with maximum draft despite the cargo spaces were not completely full. As a rule, the option is not to use partially filled holds to avoid the bulk cargo run to a board causing large angles of heel. Since the holds cannot go all full or half-empty is normal in these ships carry cargo in alternate loading condition, i.e. alternate full hold empty hold. This type of loading induces bending moments and high shear forces in the structures of the ship, since the structure of the double bottom is subjected to pressure caused by the load weight at the bottom of the holds and pressure caused by the sea water at the bottom plating. In Figure 1 one can see the usual loading scheme of bulk carriers and the lateral pressures that act on the double-bottom structures on the central holds.

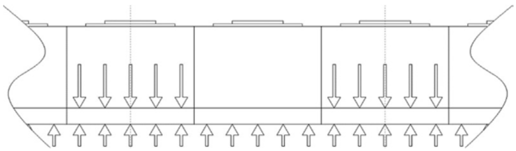

Figure 1. Lateral view of a ship in ALH condition.

The model built in finite elements to study the ultimate compressive strength of the double bottom of a bulk carrier was based on the model presented by (Amlashi & Moan 2008), as shown in Figure 2.

This model has previously used in a study of ISSC (Yao, Astrup et al. 2000) for the estimate of ultimate flexural strength of the ship without regard to the effect of lateral pressure.

2.1 *Finite element model*

The model adopted aims to simulate a double bottom of a bulk carrier which is loaded in alternate holds. To simplify calculations it was decided

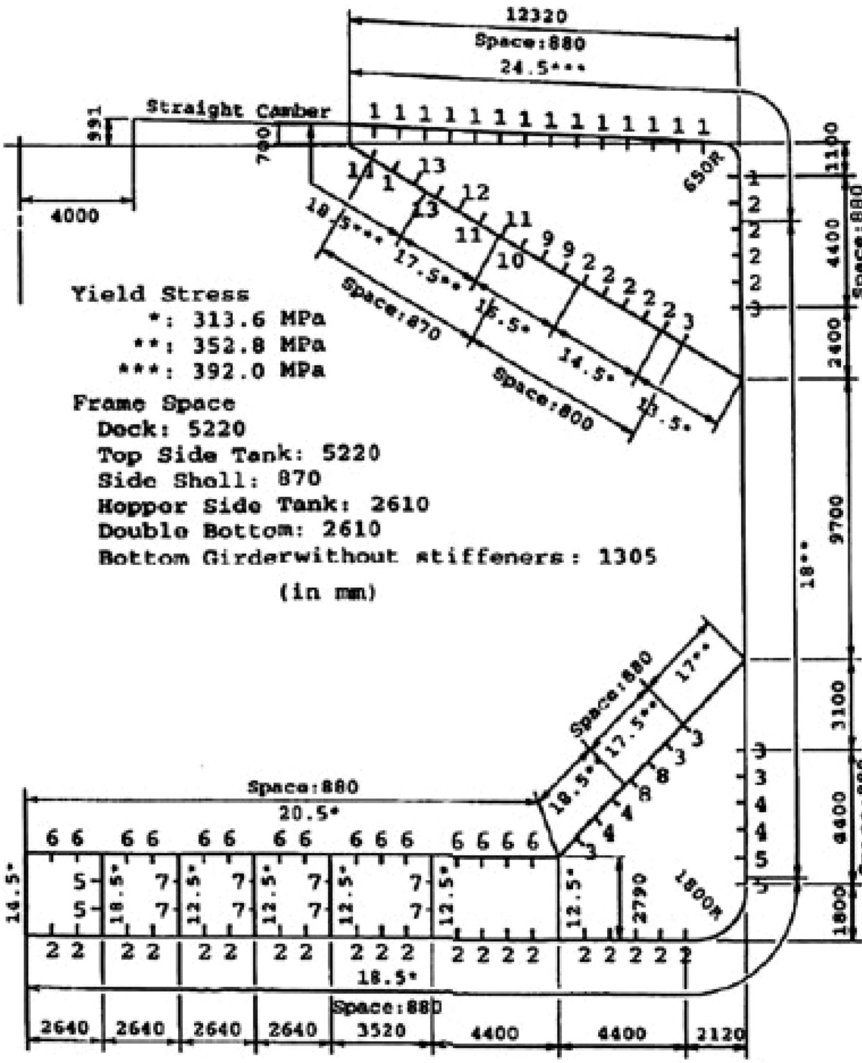

Figure 2. Mid-ship section of bulk carrier.

to reduce the model to the length of two holds, with an empty central hold and two half–holds loaded with cargo. Only half width of the holds were modelled since the other half is symmetrical and is therefore has the same structural response which can be simulated assuming symmetrical boundary conditions in the centre line of the ship.

It was used a second model with half the size of this, covering half of a loaded hold and half of unloaded hold since it was found that the structural response was the same, as expected, and the running and modelling time was appreciably reduced.

The transversal structure of the double bottom was also included in the model rather than simulated them with boundary conditions in order to account for the contribution of these frames to the global response of the double bottom. In fact the restraining action of the transverse frames induces biaxial state of stresses in the stiffened panels subjected longitudinal stress due to longitudinal bending of the structure (Gordo 2011).

2.2 *Geometry*

The cross section of the tank shown in Figure 2. The characterization of the scantlings is presented in Figure 3 which shows the geometric characteristics of the steel of each type and the corresponding yield stress, σ_y.

Longitudinal stiffeners of type 3 are originally bulb profiles. Due to the difficulty of modelling this type of profile in finite element, it was decided to turn them into bar profiles with the same cross-sectional area.

The spacing between stiffeners is 880 mm and the spacing between frames is 2610 mm. Each tank is reinforced by 10 transverse frames spacing equally, thus the total length of the model is 52 200 mm and 21 frames

2.3 *Boundary conditions*

The boundary conditions of the FE model are described by:

Longitudinal restraints—the transverse displacements are restricted along the keel and rotations along the longitudinal axis. Vertical displacement on the base of the external lateral girder of the model are not allowed. The restrictions allow simulate symmetry in central girder and the supporting effect of the bilge structure.

Transverse restraints—vertical displacements on frames 5 and 15 were restricted, which are the frames where the empty holds initiates and terminates, so that the model does not move vertically no matter the lateral load of the whole model is balanced. The reactions in these points should be minimal by that reason. In the first and last frame constraints applied to the longitudinal movement and vertical and transverse rotations to simulate symmetry, so it is allowed the vertical displacement of them.

2.4 *Mesh*

SHELL281 was the type of elements used in the analysis by the finite element software Ansys (2008). The mesh that was employed shows a refinement in areas that are expected to collapse the structure, between the first two transverse frames, between the four central frames and the last two frames. Figure 4 shows the detail of the mesh.

The complete model composed of 2 holds has a mesh with 87342 elements and 241129 nodes. The half model (2 halves tanks) is composed of 44130 elements and 121913 nodes.

Table 1. Steel properties.

Type	Geometry	Dimensions (mm)	σ_y (MPa)
1	T	333 × 9/100 × 16	352.8
2	T	283 × 9/100 × 16	352.8
3	Bar	180 × 12	235.2
4	T	333 × 9/100 × 17	352.8
	Bottom	18.5	
Plate	Double-bottom	20.5	313.6
	Frame	12.5	

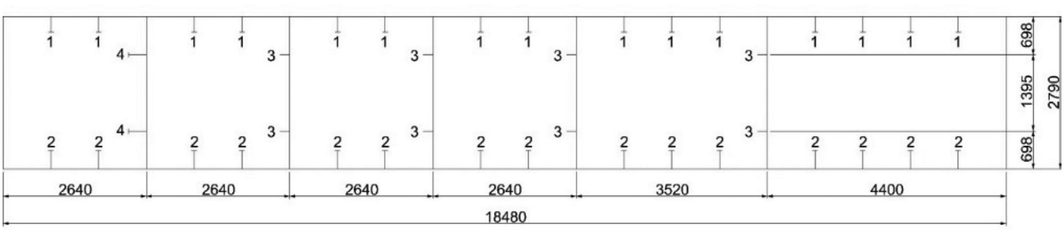

Figure 3. Cross section of the double-bottom for modelling.

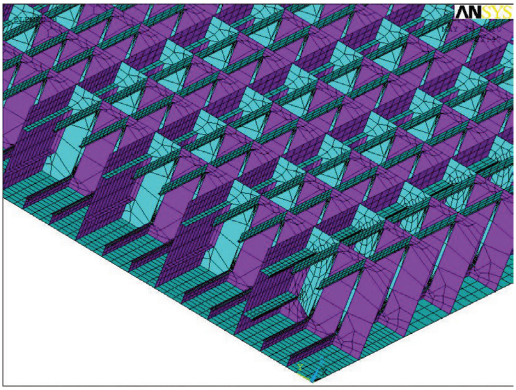

Figure 4. Mesh size in normal and critical regions, coarse mesh in transverse frames.

2.5 *Initial imperfections*

Initial imperfections were modelled by changing the vertical positions of the nodes of the initial model in between transversal bulkheads. The vertical coordinate *z* of each node was modified according to the formula:

$$\Delta z_1 = 26 \cdot \cos\left(\frac{\pi \cdot x}{20 \cdot sl}\right) \cdot \cos\left(\frac{\pi \cdot y}{42 \cdot sf}\right) \tag{1}$$

wherein x, y, z are the coordinates of each node, *sl* the distance between transverse frames and *sf* the distance between the longitudinal stiffeners. The formula for the half model was adapted since the model has only 10 frames instead of the 20 for the complete model. This equation simulates a doubly sinusoidal deformation of the bottom between the transverse bulkheads and the bilge stringers with maximum amplitude of 26 mm. The amplitude was estimated by 0.001 · (10 · *sl*), i.e. equal to one thousandth of the length of the tank.

The modelling of initial imperfections of the plate elements of bottom and double bottom was made in the same way adopting a sinusoidal deformation with half wave between longitudinal and three half waves between transverse frames. The surface is represented by the following equation:

$$\Delta z_2 = 4 \cdot \sin\left(\frac{3\pi \cdot x}{sl}\right) \cdot \cos\left(\frac{\pi \cdot y}{sf}\right) \tag{2}$$

The maximum amplitude of imperfections is 4 mm and the choice of the shape results from the aspect ratio of the plate elements which is approximately 3 (~2610/880), that corresponds to a mode of structural instability of 3 half waves in the longitudinal direction for simply supported plates.

2.6 *Loading condition*

The global model includes a central hold tank which is empty and two lateral tank with half of the length of the central one which are loaded inside with a pressure 2*p*. Sea water pressure are applied in the bottom with a pressure *p*. So only residual forces are applied in the supports of the model.

A simplified representation of the loading was presented in Figure 1.

3 MATERIAL AND EQUIVALENT MECHANICAL PROPERTIES

The double bottom has three different kinds of steel with the mechanical properties presented in Table 2.

The equivalent yield stress may be defined by the average of the yield stress of each kind weighted by the respective cross section, A., according to the expression (3) that leads to an average value of 317.2 MPa, as presented in the table.

$$\sigma_{oe} = \frac{\sum \sigma_{oi} \cdot A_i}{\sum A_i} \tag{3}$$

4 STRUCTURAL RESPONSE

The structural response of the double bottom depends greatly on the boundary conditions applied to the model. These boundary conditions, by their turn, try to reproduce the actual restrictions imposed by the surrounding structure of the vessel and the type of local loading.

Three different situations were analysed which correspond to different degrees of restriction and therefore different effect from the adjacent structure, i.e., different rigidity of bilge and longitudinal bulkheads:

1. Double-bottom supported exclusively by transversal bulkheads

Table 2. Mechanical properties and sectional area of each element.

Type	Yield stress (MPa)	Young's modulus (GPa)	Cross section area (mm^2)
Plate	313.6	200	987 165
T profile	352.8	200	140 354
Bulb plate	235.2	200	17 280
Total	317.2	200	1 144 799

2. Double-bottom supported vertically by the bilge and against rotation
3. Double-bottom supported vertically by the bilge and free to rotate.

4.1 *Transversal bulkheads support*

This condition is the one that gives less support to the bottom structure and therefore more flexibility. The double bottom behaves globally as a continuous beam between transverse supports with alternate loading switched to either side. Considering L as the length of each hold, b their breadth between the bilge girders and p the liquid side pressure applied to the structure, the maximum moment due to the secondary bending resulting from lateral pressure, M_2, is given by:

$$M_2 = \pm \frac{pbL^2}{8} \quad (4)$$

The maximum shear occurs in the supports (bulkheads) and has the value of:

$$q_2 = \pm \frac{pbL}{2} \quad (5)$$

For this situation it was analysed 8 finite element models: Three models of reduced dimensions (HM) and 5 with two spans between bulkheads of total length (M).

Figure 5 shows the response curves to compressive axial load at different levels of lateral pressure on the bottom (p = 10, 20, 50, 100, 150 and 200 kPa). The applied lateral pressure in the loaded holds is twice the hydrostatic pressure at the bottom. The normalization of the curves was performed using the equivalent stress and equivalent strain.

It was found that the models with half size (HM) had a response equal to that of the complete models, as expected, and it can be seen for the response of the models with the same pressure of 200 kPa, HM200 and M200, as presented in Figure 5.

In the elastic range, i.e. for small compressive loads, the lateral pressure does not affect the response. The maximum stress is reached gradually and with the development of large vertical deformation of the double bottom, not detecting a sharp point at which the stress decreases. This means that this is a very stocky structure that fails mostly by yielding of structural elements.

The maximum compressive strength depends largely on the level of pressure applied side as shown in Figure 6.

The maximum compressive axial strength on of the ship's bottom when subjected to external lateral pressure p (in kPa) varies by the expression:

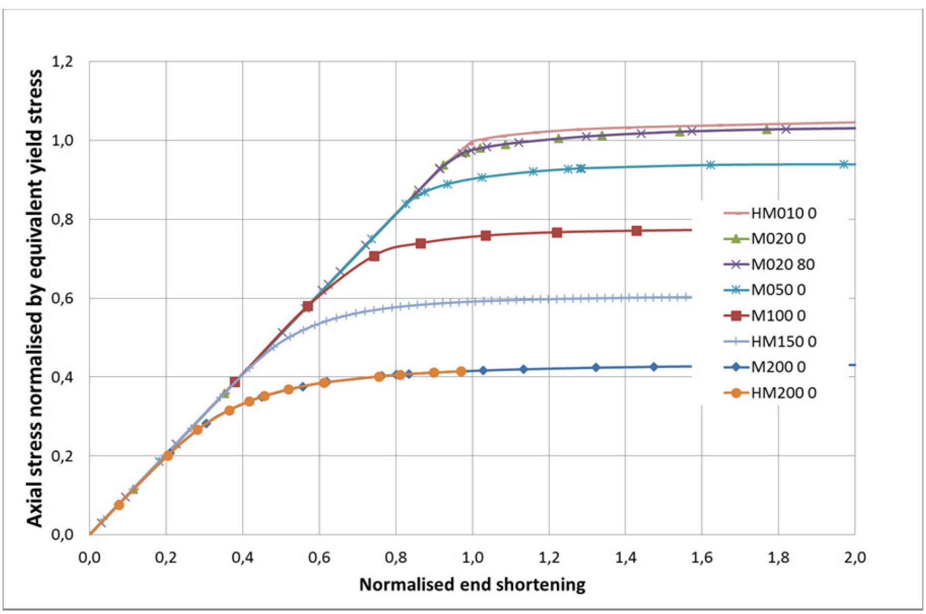

Figure 5. Normalized average compressive stress average shortening curves with different levels of lateral pressure (p = 10, 20, 50, 100, 150 e 200 kPa) for Half Model (HM) and full Model (M).

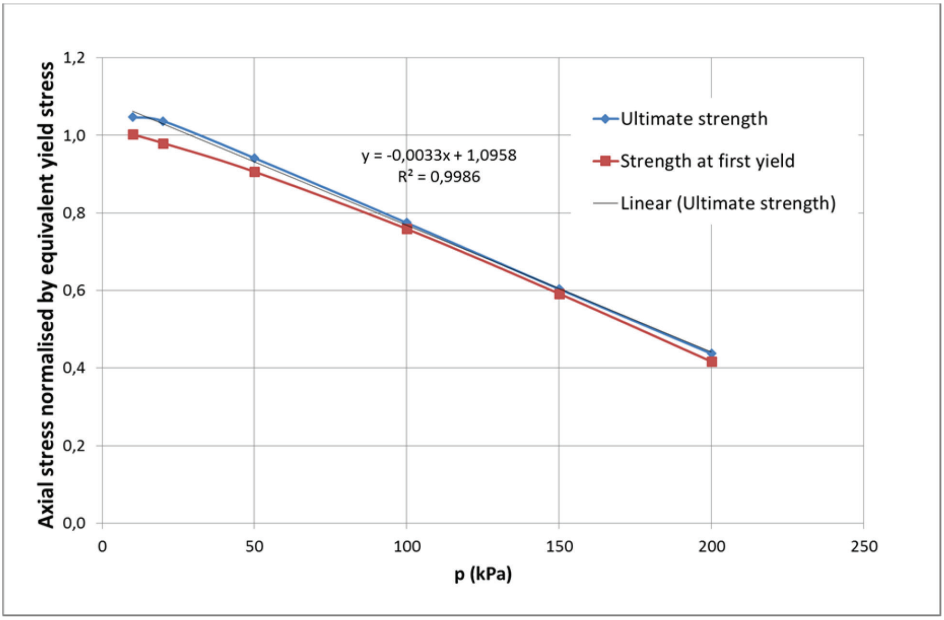

Figure 6. Ultimate compressive strength of double bottom under lateral loading on alternate holds supported by transverse bulkheads.

$$\frac{\sigma_u}{\sigma_{oe}} = 1.096 - 0.0033 \cdot p \tag{6}$$

One should note that the dependence is linear up to the ultimate stress exceeds the equivalent yield stress which occurs at very low lateral pressure levels, below 25 kPa. The constant value of 1.096 just confirms that the slenderness of the structural elements is very low leading to a failure by yielding.

The collapse of the double bottom occurs by failure at the mid-span between bulkheads, more precisely between the two central frames of each hold. For very low lateral pressure the collapse is dominated by the failure of plate elements or of longitudinal stiffeners by generating yield lines at 45º along the panels in compression, as shown in Figure 7 where it is presented two halves of the double bottom of cargo holds supported in the middle by a transverse frame that is replaced by the appropriate simply supported boundary conditions.

As seen in Figure 8, for a very high lateral pressure of 200 kPa, plastic deformations are limited to the area where the bending moment due to the lateral pressure is maximum, that is, in the central area of the hold. It is still possible to identify an area near the connection to the bulkhead, in the centre of the half model, where it occurs a strong plastic deformation due to shear.

4.2 *Double-bottom supported vertically by the bilge and restraint against rotation*

The lateral constraining condition is more rigid and provides great lateral support to the double bottom, reducing the bending moment by absorbing the lateral part of the lateral pressure. It is quite representative of a bilge heavily reinforced or of longitudinal bulkheads of wing tanks supported by a very sturdy transverse frame structure.

The vertical side constraint condition with freedom of rotation is a representative intermediate state of double bottom supported by little reinforced bilge.

Figure 9 shows the double bottom behaviour under compression in total lateral constraining conditions (FHM) and single vertical support (SSHM) without restraint against rotation compared to the unsupported model response and a very low level of lateral pressure ($p = 10$ kPa).

As expected, the increase of the double bottom lateral restraints increases the compressive strength and the compressive strength degradation with lateral pressure decreases. This result is shown in Figure 10, where it still has the indication of average axial stress to which the first yield occurs for each pressure level.

4.3 *Comparison with ISSC results*

In ISSC 2015 (Yoshikawa, Bayatfar et al. 2015) the effect of lateral loading on the ultimate bending

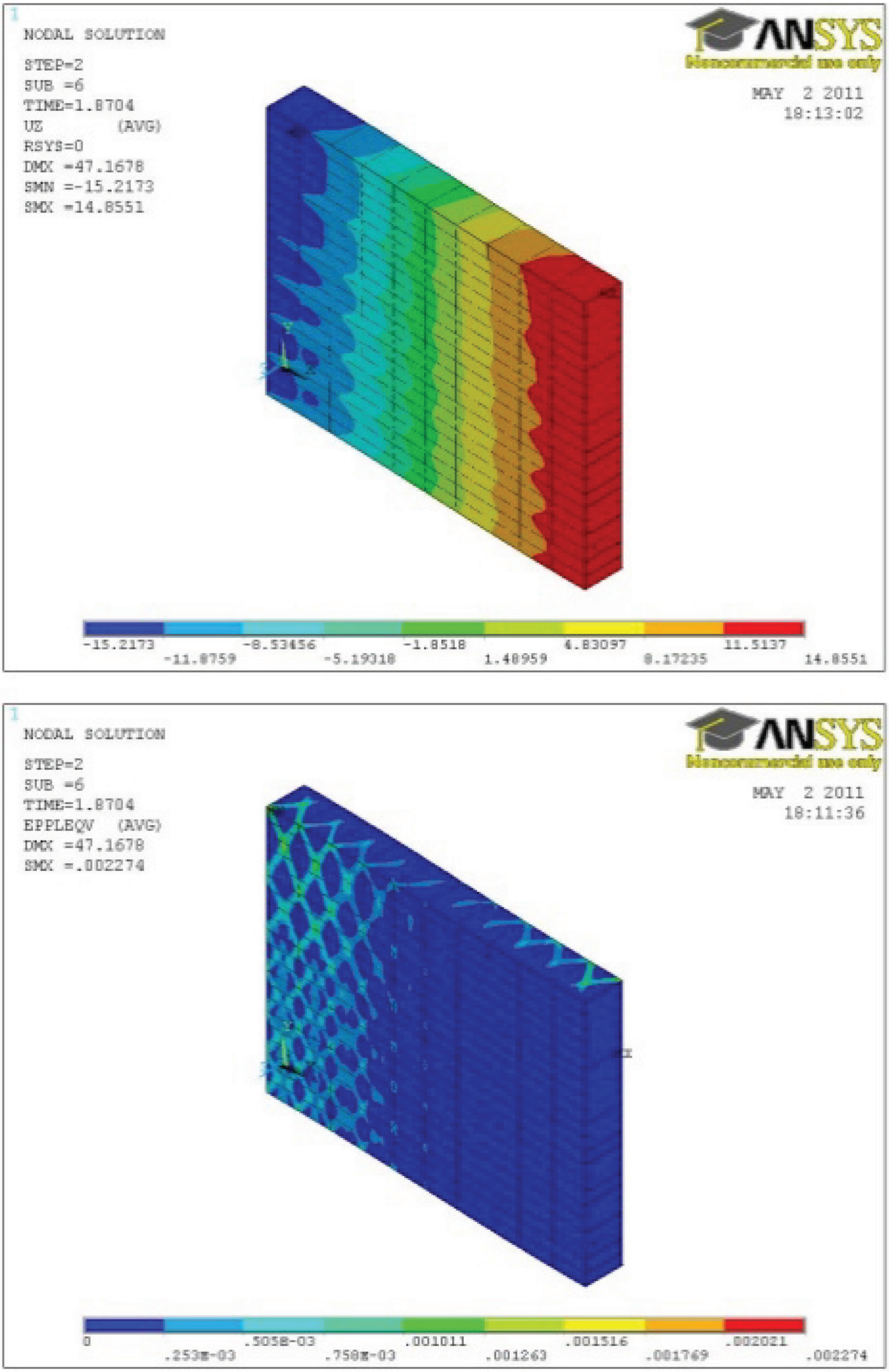

Figure 7. HM010 model: Vertical deformations (up) and von Mises plastic strain (down) at initial stage of collapse for a lateral pressure of 10 kPa.

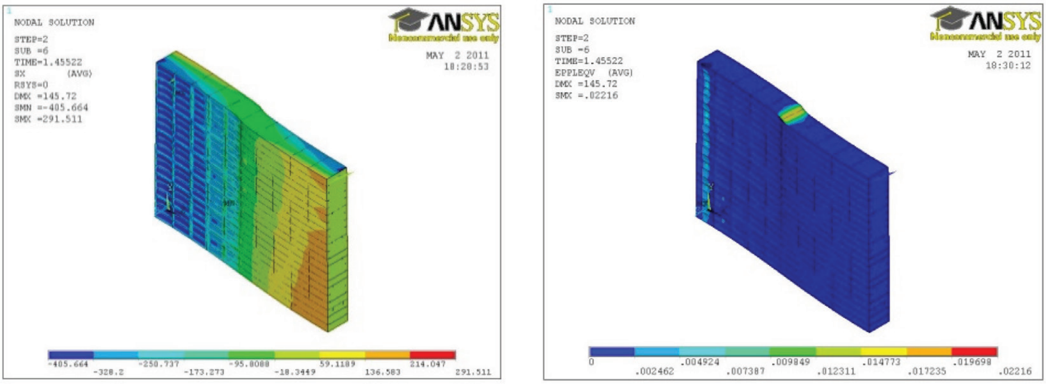

Figure 8. HM200 model: Vertical deformations (left) and von Mises plastic strain (right) at initial stage of collapse for a lateral pressure of 200 kPa.

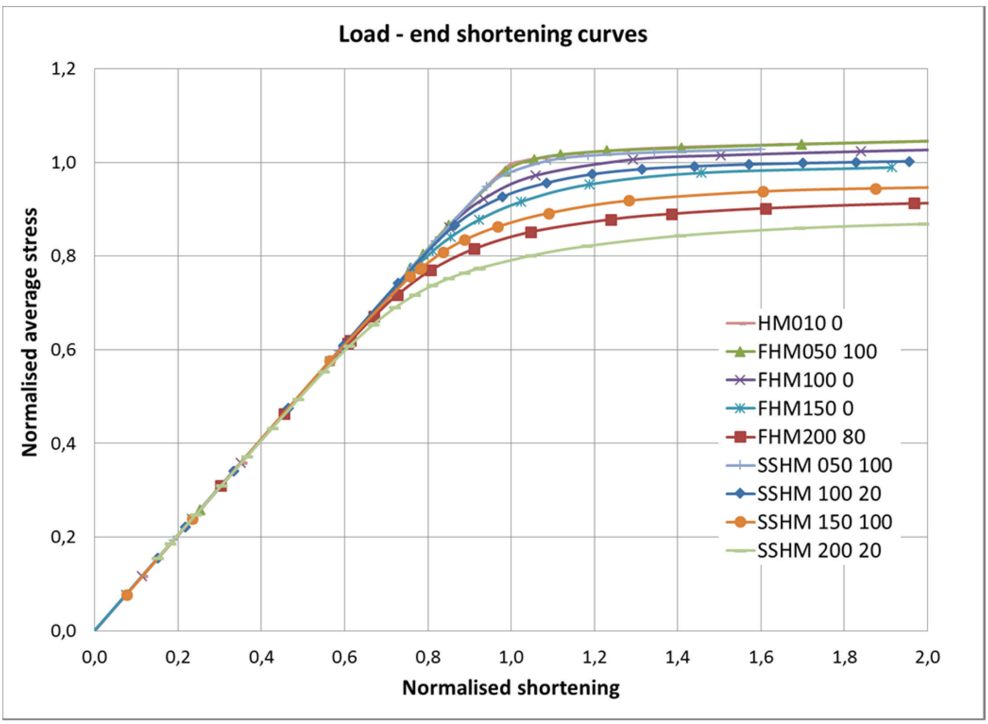

Figure 9. Normalized average compressive stress average shortening curves with different levels of lateral pressure ($p = 10$, 20, 50, 100, 150 e 200 kPa) on Half Model (HM) for fixed boundary conditions (FHM) and with free rotation (SSHM).

moment was investigated for the same ship. The reduction on the ultimate bending moment under hogging was found to be 26.2% which agrees quite well with the recommendations of IACS of 25%. The level of lateral load applied was 19.83 m of water.

In this study and for the same level of lateral load one has a reduction on the compressive axial strength of the double bottom of 56.4% (from eq. 6) and 13% for a simply supported bilge allowing for its rotation as can be seen in Figure 10.

This means that the model with free boundary conditions in the bilge region is the most representative for studying the effect of lateral load on the double bottom of ship structure.

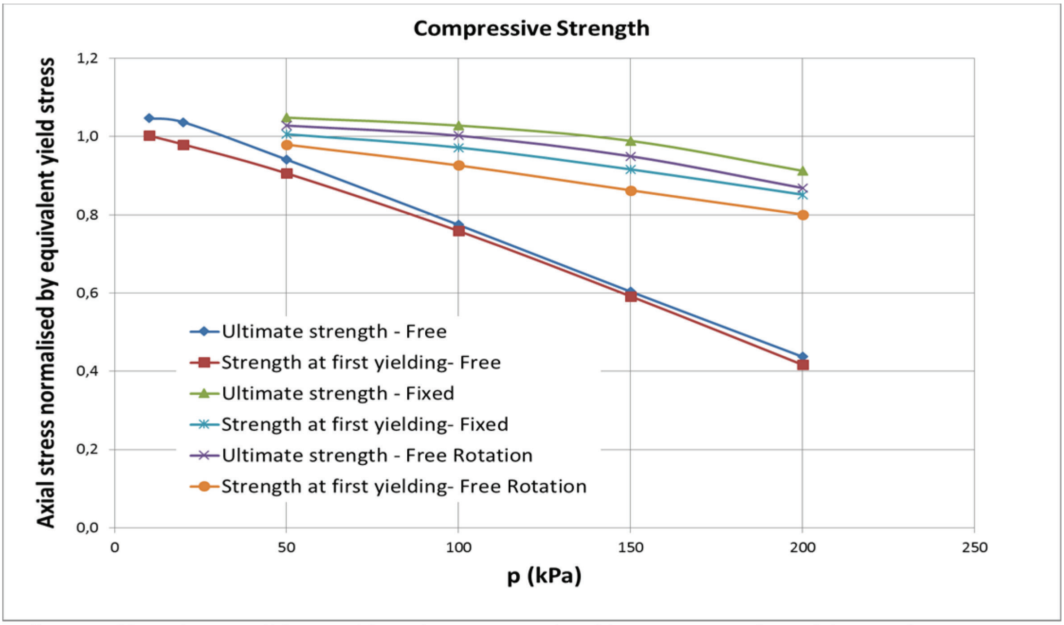

Figure 10. Influence of boundary conditions and lateral pressure on the ultimate compressive axial strength.

5 CONCLUSIONS

The lateral pressure significantly affects the double-bottom compressive strength in ships with holds loaded alternately. The degradation of the strength is linear and depends on the degree of support provided by bilge and longitudinal bulkhead or ship's side.

The increased stiffness of the surrounding structure increases the strength of double bottom on these loading conditions.

The degradation of the resistance of this structure adversely affects the strength to support longitudinal bending moment that is applied to the ship as a girder. When comparing the present results with the degradation of the ultimate bending moment of the hull girder due to alternate hold loading as done by ISSC 2015 one may conclude that the best model to study the effect of the alternate load condition is the one with free boundary conditions in the bilge side.

In the present ship the degradation of the axial strength of the double bottom under compression may reach 56.4% at the structural draft.

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