Experiments on three mild steel box girders of different spans under pure bending moment

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ABSTRACT: An experimental study is presented of three box girders made of mild steel subjected to pure bending moment with different spacing between frames. The moment curvature curves are presented, allowing for the analysis of elastic-plastic behavior until collapse and the evaluation of the ultimate bending moment and post collapse behavior for each experiment. The residual stress relief during loading and unloading path is also analyzed. The effect of the span between transverse frames on the ultimate bending moment of the box girder is studied and, thus its dependence on the column slenderness of the panel under compression can be established. The results are compared with tests on similar box girders made of very high tensile steel. The effects of residual stresses on the behavior of the box girder are analyzed using a progressive collapse method for structures under longitudinal bending moment.

1 INTRODUCTION

The evaluation of ultimate capacity of ships under bending moment is a very important issue for the structural design. It is associated with a global failure of the hull and the final result is normally the loss of the ship, its cargo and human lives.

In the last years several works have been done on the subject, most of them on the evaluation of the ultimate bending moment of ships made of normal mild steel. The existing calculation methods may be divided into two groups: finite elements methods, and simplified methods. There has been a great activity and comparison between the different methods is available in the literature (Yao et al. 2000).

The development of the design of structures under bending has been made on the assumption that the structure can be divided into several simple stiffened plate elements that act independently. The authors have been working on a method based on these assumptions (Gordo et al. 1996), which has been validated against data from a full scale accident (Rutherford 1990) where the loading conditions could be well established and compared against some small scale experiments of models representing simplified typical sections of ships (Dow et al. 1981, Faulkner et al. 1984, Gordo & Guedes Soares 1996, Nishihara 1984). The results of these comparisons showed that the method can be used confidently on typical hull configurations and for normal steel.

Changing the span between frames will affect the non dimensional slenderness of those plate elements leading to different collapse strength despite using the same geometry. The change of frame spacing will induce collapse at different levels of column's slenderness and this call for new experimental results, covering the appropriate range of the governing parameters of the plating.

In this study the behavior of three box girders made of the same material with the same configuration but different spans is compared.

2 HULL STRENGTH EVALUATION

There are several methods available to evaluate the ultimate moment in sagging or hogging that a hull may sustain. The authors have been working on a method (Gordo et al. 1996) that is able to predict the overall behavior of the hull under bending moment. This method predicts not only the ultimate bending moment but also the pre and post collapse behavior. It considers all the modes of collapse of the structure and it also includes an algorithm to deal with residual stresses and corrosion.

This method and the software that has been developed to implement it, proved to give good prediction for normal steel ships when compared to the tests and hazards examples available in the literature.
In order to provide data for those comparisons a plan of experiments was developed for box girders subjected to pure bending moments. These box girders may reproduce in a simple manner the behavior of the ship's structure under bending, allowing the identification of the differences of using mild steel or high tensile steel, widening the range of validity of the method and covering the behavior of panels of high column slenderness.
The typical element of the box girders is a plate with a bar stiffener which has been proved to be representative of the actual type of structure of ship's hull (Gordo and Guedes Soares, 1993). In order to obtain information about the carrying capacity of different panel arrangements, like plates reinforced by complex stiffeners, another series of experiments has to be planned due to the geometric limitations for the reproduction of such scantlings at the present scale and limitations on the total loading that one may use in these box girders experiments.

2.1 *Main parameters of the structural design*

The main parameters affecting the structural design of ship hulls subjected to bending moment are the plate and column slenderness, because they affect directly the effectiveness of the panels under compression. These parameters are defined as follows:

- Plate slenderness, $\beta = \frac{b}{t}\sqrt{\frac{\sigma_o}{E}}$

- Column slenderness, $\lambda = \frac{a}{r}\sqrt{\frac{\sigma_o}{E}}$

and they depend directly from the geometry of the structural elements and from the material properties.
The geometric characteristics of interest are the width (*b*) and the span (*a*) of the structural elements, as well as their thickness (*t*) and the radii of gyration (*r*) of the cross section of the stiffener with an appropriate associated plate. Other geometric characteristics may affect the behavior of the stiffener in special cases. This may occur when the stiffener is very weak or it has low torsional rigidity, promoting a different mode of collapse known in the literature as tripping.
The material properties of interest are the yield stress (σ_o) and the modulus of elasticity (E). The shear modulus of elasticity (G) has some influence on the tripping stress of the stiffener. Also the nature of the stress-strain curve of different steels may affect the elasto-plastic behavior of the structural elements under compression, especially concerning on having or not having a constant yielding stress.
For the same geometry but changing the material of the stiffened plate element, if the plate and column slenderness increase this will lead to a weaker structure with lower buckling and ultimate stresses.

2.2 *Assessment of the hull girder strength*

The ability of the hull girder to sustain applied bending moment may be understood as the summation of individual contributions of each stiffened plate element that one may subdivide the entire cross section between two frames. This can be expressed as:

$$M = \int_A (z - z_n)\cdot\sigma(z)\cdot dA = \sum (z_i - z_n)\cdot \sigma_i(z_i)\cdot A_i \quad (1)$$

where the average stress σ on the stiffened panel is a function of the average strain ε and the latter is dependent of the location z_i of the element and of location of the neutral axis z_n:

$$\sigma(z_i) = f(\varepsilon_i) \text{ and } \varepsilon_i = g(z_i, z_n) \quad (2)$$

The main difficulty of this approach is to know the relation between the stress and the strain over a large range of strains including pre-collapse, collapse and post-collapse. The importance of the last region comes from the buckling of some elements before the ultimate bending moment is achieved.
The relation mentioned above depends on many parameters including residual stresses due to welding, geometric imperfections, transverse support due to frames rigidity, etc. Other effects to be considered are 3D effects or the lack of support on the middle of the large panels. Because the relation between stress and strain is far from being linear the position of the neutral axis of the whole section is changing with the loading and must be computed step by step.
The stress-strain curves may be obtained from a data base of pre-calculated load-shortening curves (Smith 1977) or by approximate methods (Gordo & Guedes Soares 1993, Yao & Nikolov 1991) based on the empirical formulas for the ultimate strength of panels under axial loading. Normally the design methods used for that purpose are: Faulkner's method, Perry-Robertson method and the critical stress for use as serviceability limit. These methods are already described in detail in Gordo & Guedes Soares, (1997).

3 TEST SETUP AND BOX GIRDERS' CHARACTERISTICS

3.1 *General information*

The boxes are made of mild steel of 270 MPa yield stress and the Young's modulus is considered to be of 200 GPa. The specimen N200 has five frames corresponding to four frame spacing of 200 mm each and a total length of 1400 mm, because there is 100 mm in each side of the top frames to allow the redistribution of stresses. The model has a nominal width of 800 mm and a nominal depth of 600 mm. The longitudinal stiffeners are five in total on the top panel 150 mm apart from each other.
The other two girders, N300 and N400, are similar to N200 except that they have only four transverse frames and the spacing between adjacent frames is 300 and 400 mm, respectively for N300 and N400.
The experiment setup is presented in Figure 1 for box N300, showing the bold connections to the supporting side structures and the loading device.

Figure 1. Test setup for box N300.

3.2 *Type of experiment*

The tests consist on a four point bending of a beam like box girder. The beam is divided into three parts: two symmetric supporting parts and, in the middle, one has the box girder structure. Each supporting part is 2 m long.
The box girder is subjected to pure bending moment, inducing tension on the bottom and compression on the top of the box.
So it is expected to have some plasticity in tension on the bottom and a marked buckling collapse of the top panel at the maximum load. Since the former is not very much affected by the span between frames, the maximum bending moment will be controlled by the buckling average stress of the top panel which is sensitive to the distance between frames.

3.3 *Geometric properties of the models*

The boxes are made of 4mm thick plate. The spacing between stiffeners is 150mm, (Figure 2), which leads to width to thickness ratio of 37.5. The span between frames is 200, 300 and 400 mm, (Figure 3). The nominal column slenderness covered is from 0.97 to 1.94. The plate slenderness β is constant at the top panel and equal to 1.38 with a *b/t* of 37.5, which a very common value in ship structures.
The stiffeners are bars of 4 mm by 20 mm, leading to a cross sectional area of 680 mm^2, for each relevant stiffened plate element. The plating area of the individual stiffened plate on the top panel is 600 mm^2 and the stiffener area is 80 mm^2.

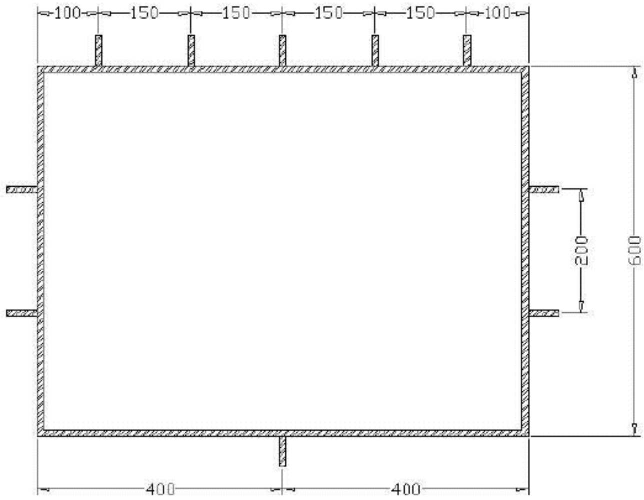

Figure 2. Cross section of the box girders.

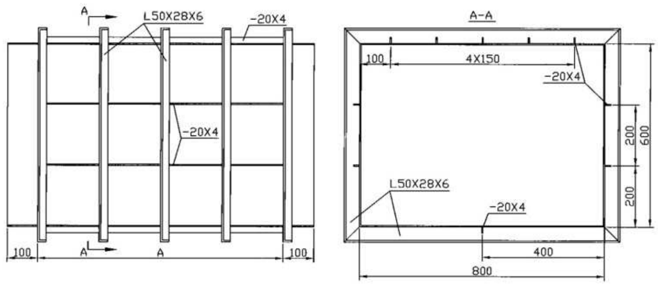

Figure 3. Geometry of the box girder N200.

4 EXPERIMENT OF BOX-GIRDER N200

The box girder, which was denoted as N200, was tested applying four cycles of loading followed by discharge as shown in Figure 4. The first cycle reached the total vertical load of 250.5 kN with a corresponding vertical displacement at the loading point of 10.16 mm. The following cycles achieved 501.1 kN at 23.87 mm, 619.6 kN at 37.68 mm and the maximum load was 643.0 kN when the vertical displacement at the loading point reached 45.3 mm.

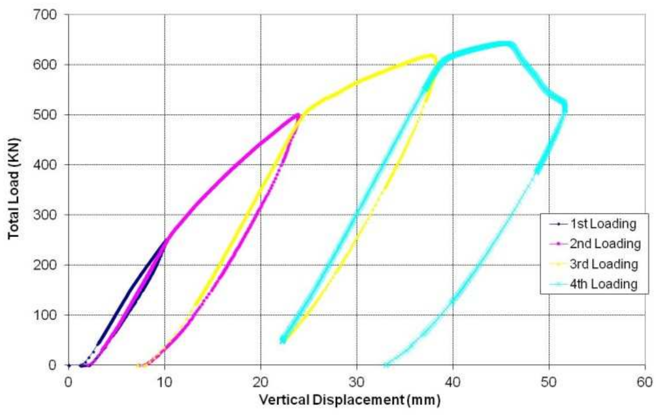

Figure 4. Vertical load versus vertical displacement on N200 test

The different cycles of loading allow identifying and quantifying the shakedown of residual stresses due to plastic deformations on the initially high stressed parts of the box girder due to manufacturing. As known from the typical residual stress pattern, regions close to the welding are in tension with stresses close to the yield stress of the material. Thus, when these regions are loaded with external tensile loads they just yield at the squash stress without supporting any further load but retaining some permanent elongation. When the load is removed, the stress in those points reduces according to the Hooke's law.

The final result for the next cycle is to have a higher effective structural modulus in the initial stages of load until the load reaches the maximum level of load of the previous cycle. After that point the same process repeats itself resulting in an increase of the shake down of residual stresses until they disappear completely. However, note that this process only occurs on the panels under tension due to the bending of the structure.

If the structure has asymmetric welding, which is the case for these box girders, the load may become unbalanced leading to the rotation of the structure, even if the structure is symmetric. That seems to be the reason for the differences on the measurements of the displacement transducers that read the rotation of the box girders during the first cycle of loading, as represented in Figure 5, by Rot_L and Rot_R transducers. These two transducers are used to evaluate the curvature of the structure at each loading step and they are located on opposite sides of the box, as shown in Figure 6. If there is no transverse rotation of the box then the readings should be the same in both transducers.

As may be seen from the figure, the left transducer, Rot_L, remains almost unchanged, while the right transducer displaces until 2 mm during the uploading and keeps some permanent of 0.3 mm after the downloading. Since there is a welding on the right side most probably this behavior comes from the yielding of the welding in the early stage of the loading due to residual stresses. The global effect for all cycles of load is a constant difference of 25% between the readings of the two gauges (Gordo and Guedes Soares, 2008).

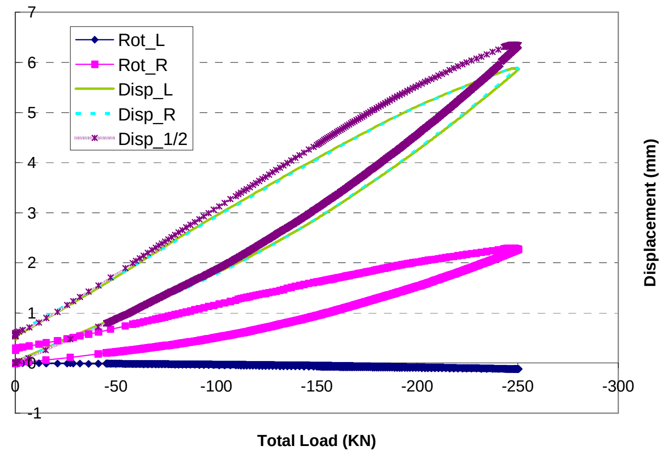

Figure 5 Measurements on the displacement transducers on first cycle.

Figure 6 Setup of one of displacement transducers for measuring the rotation over top panel (N400)

Disp_L and Disp_R represent the vertical displacement at the opposite tops of the box and Disp_1/2 gives the vertical displacement at middle length of the box. As expected the top transducers give the same readings due to symmetry and the middle transducer gives higher values than the top ones due to curvature of the box. Again there are residual values after discharge meaning that plasticity and stress relief have occurred.

4.1 *Moment curvature relationship*

Having the load and rotations, it is possible to generate the curve that relates the applied bending moment with the curvature. That relationship is plotted in Figure 7 where the curvature is the average curvature of whole box girder. It can be seen from the figure that if no discharge was done then the resulting moment curvature relationship would be the upper envelope of the four cycles of loading. In that case the behavior would be elasto-plastic in the whole range of the curvatures due to permanent plasticity on the welding regions of the panel under tension and on the panel under compression in the late stage of loading.

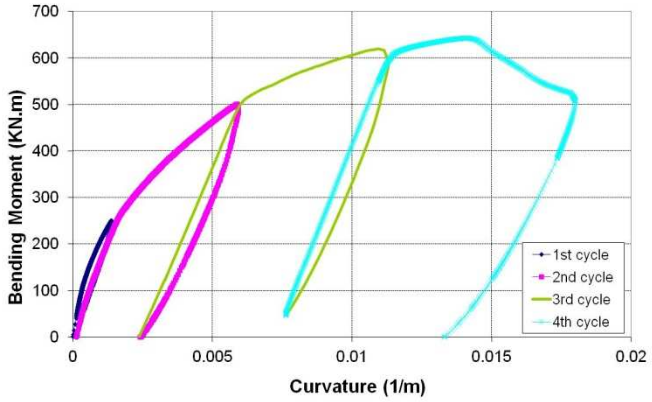

Figure 7. Moment curvature relationship of N200 specimen

But the intermediate discharge of loading between cycles cancels the direct effects of the residual stresses during the following loading path and that allows identifying the elastic behavior of the structure free of residual stresses. The linear nature of the relation between the bending moment and the curvature is perfectly identified in the third and forth cycles of loading; on the second cycle, the transverse rotation of the box already mentioned before introduces non linear effects when the average curvature calculated from the two rotations is used.
This affects directly the performance of the effective structural modulus, which is the slope of the bending moment curvature curve.

4.2 *Effective structural modulus*

The nominal structural modulus is EI, as known from the linear elastic beam theory, where E is the Young's modulus of the material and I is the moment of inertia of the cross section of the box girder. The nominal structural modulus is the maximum value that one may expect for the effective structural modulus. Initial imperfections and residual stresses cause a decrease in the rigidity in the load shortening curves of the panels that constitutes the structure, thus the effective structural modulus is always less than EI, which is 153 MNm^2 for theses boxes.
On the first cycle the effective structural modulus has initially very high values with large scatter but reduces rapidly due to the plasticity developed on the welding of the panel under tension and rearrangement of the initial imperfections of the box. One has to note that the loaded box has panels under tension where the initial imperfections tend to reduce with increasing load and panels under compression where they tend to increase. These panels are connected and the performance of one affects the behavior of the adjacent one.
Figure 8 compares the evolution of the structural modulus during the loading path for the different cycles. There are two main tendencies to be observed: the constant value of the structural modulus in the range of loading already reached in previous cycles, between 140 and 160 MNm^2; and a lower evolving curve corresponding to an experiment with only one cycle of loading.
This lower curve is always decreasing smoothly and vanishes at the ultimate bending moment where one has a null structural tangent modulus. What is rather interesting is that the curve is almost straight from the maximum load of the first cycle until the collapse. This straight line intercepts the y axis at a value similar to those found for the effective structural modulus in the elastic range after shakedown of residual stresses.

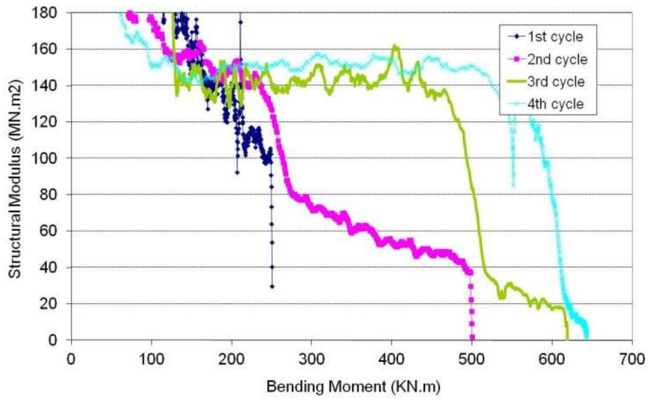

Figure 8. Structural modulus during loading path for different cycles

5 EXPERIMENT OF BOX-GIRDER N300

The box girder N300 is similar to the previous one but the space between frames is 300 mm. Also the number of frames is 4 instead of 5. The total length of box is 1100 mm. The plate slenderness on the top panel subject to compression is 1.38 and column slender of the stiffened panel composed by stiffener and associated plate is 1.45.

5.1 *Load vertical displacement relationship*

This test was performed in 3 stages: the first cycle until a load of 200 kN which approximately one third of the maximum load, the second cycle until 400 kN, and the last cycle until collapse and beyond, as shown in Figure 9. The maximum vertical displacement achieved was 50 mm but the measurement of the vertical displacement is not very relevant because it depends on the length of the lateral supporting structure. Nevertheless it may be used to evaluate the absorbed energy in every cycle of load. This information can be used to estimate indirectly the residual stresses of the structure (Gordo & Guedes Soares, 2004).

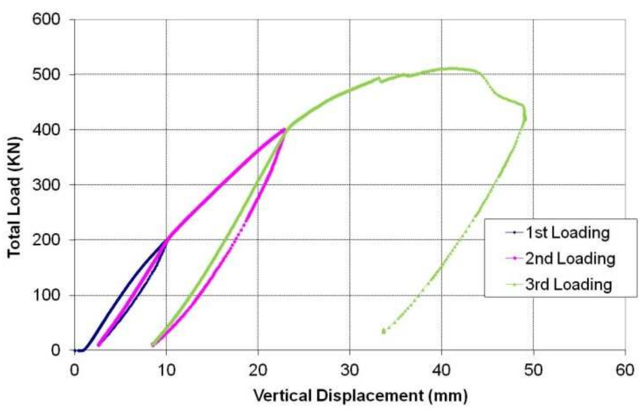

Figure 9 - Vertical load versus vertical displacement on N300 test

Most important aspects of the curve are the evolving curve of the 3 cycles that represents the behavior of the box under bending without residual stresses relief, a strong reduction in the slope above 400 kN and several small discharges around 500 kN that lead to the collapse of the entire upper panel in compression and consequently to the failure of the box under pure bending moment.
Figure 10 presents the measurements of displacements used for the evaluation of the rotation and curvature of the box during loading and in both sides.
They agree very well until the collapse which means that there is not any substantial lateral rotation of the box due to asymmetric welding or initial imperfections. In fact, at small discharge close to 500 kN, one has some differences on the readings indicating that the buckling of the top panel in compression was initiated in the left side propagating quickly to the entire panel. After collapse the box acquired some lateral rotation, which is expected due to development of very large deformations in the entire structure after the collapse.

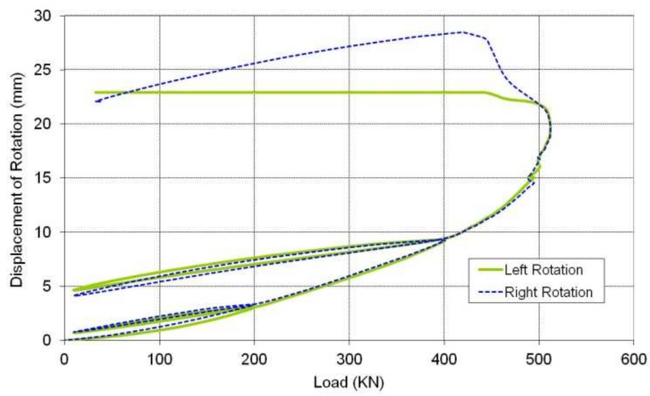

Figure 10 - Measurements on the displacement transducers for N300.

5.2 *Moment curvature relationship*

Based on the data from Figure 10, one may generate the moment curvature relationship which is presented in Figure 11.
The most important aspect on this curve is the same as those of the load versus vertical displacement presented in Figure 9. The maximum bending moment is 512 kNm and it is located in the plateau where the bending moment kept almost constant value in a broad range of curvatures, i.e., from a curvature of 0.012/m to 0.014/m with a variation of less than 1% in the bending moment, which represents a very smooth collapse of the structure developing very large deformations at constant bending moment.
The discharge of the buckled structure is almost vertical meaning that the permanently deformed box does not present much elastic recovery as expected.

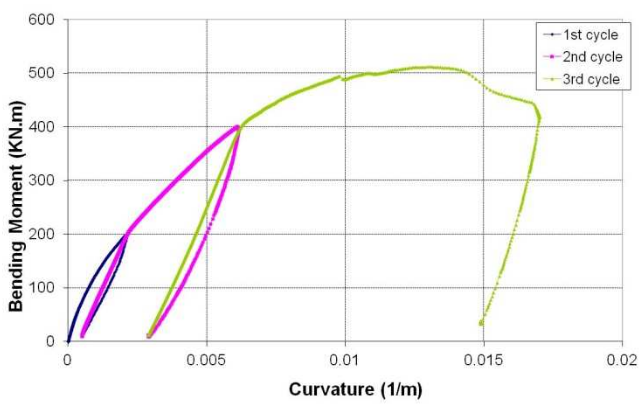

Figure 11. Moment curvature relationship of N300 specimen

5.3 *Effective structural modulus*

The relation between the effective structural modulus and the bending moment presents similar properties than those observed for the box N200. However the calculated modulus is approximately 10% below the one of the stockier box girder, N200. Also the moment presents slightly lower values at lower loads than those at high loads after the relief of residual stresses in the bottom panel during the second cycle, as can be observed on the curve of the third cycle.

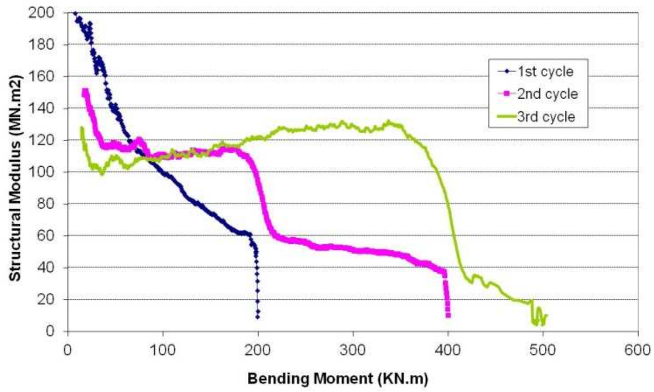

Figure 12. Structural modulus during loading path for different cycles (N300)

6 EXPERIMENT OF BOX-GIRDER N400

The box girder N400 has the same space between frames which is 400 mm. Also the number of frames is 4. The total length of the box is 1400 mm. The plate slenderness on the top panel subject to compression is 1.38 and the column slenderness of the stiffened panel composed by stiffener and associated plate is 1.94.

6.1 *Load vertical displacement relationship*

This test was performed in 4 stages: the first cycle until a load of 200 kN, the second cycle goes to 300 kN, the third until 400 kN and the last cycle until collapse and beyond, as shown in Figure 13. The maximum vertical displacement achieved was 40 mm.

Qualitatively one has obtained a similar curve to the ones of experiments N200 and N300. The maximum vertical load is the lowest of the 3 experiments which is in accordance to the theory of stability of structures that indicates a decrease of ultimate strength of compressed panels with the increase on column slenderness. The reduction on the ultimate strength of the top panel leads naturally to reduction on the ultimate moment supported by the structure.

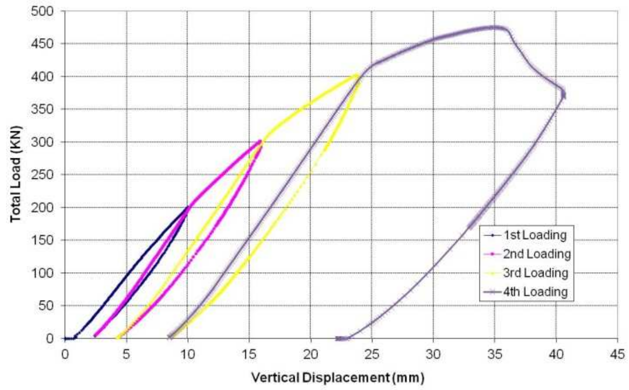

Figure 13 - Vertical load versus vertical displacement on N400 test

Figure 14 presents the displacements associated with rotations of the structure. In the first cycle, a residual difference of rotation is generated, and is kept constant along the other intermediate cycles. This means that the structure has no transversal rotation in cycles 2 and 3.

On the last cycle the structure presents some lateral rotation in the collapse phase due to the asymmetric nature of residual stresses on the whole structure and asymmetric large permanent deformations after collapse.

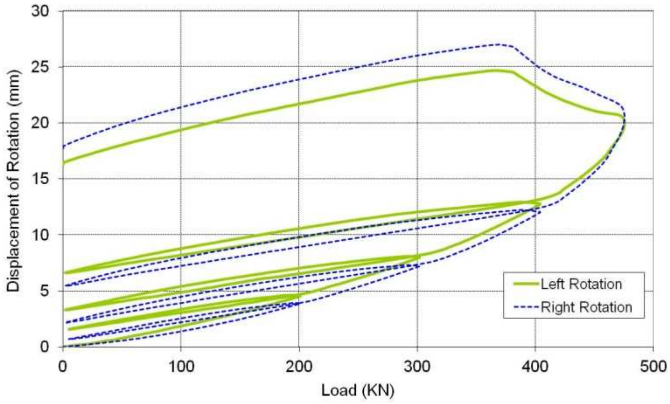

Figure 14- Measurements on the displacement transducers for N400.

6.2 *Moment curvature relationship*

The moment curvature relationship is presented in Figure 15.

The maximum bending moment is 475 kNm at a curvature of 0.0086/m. The plateau where the bending moment kept an almost constant value is very narrow compared to the one found in experiment N300.

One particular aspect is noteworthy: in cycles 2 and 3 the discharge of load is, initially, associated with an increase in the curvature, demonstrating that plasticity needs time to spread during the loading of the structure.

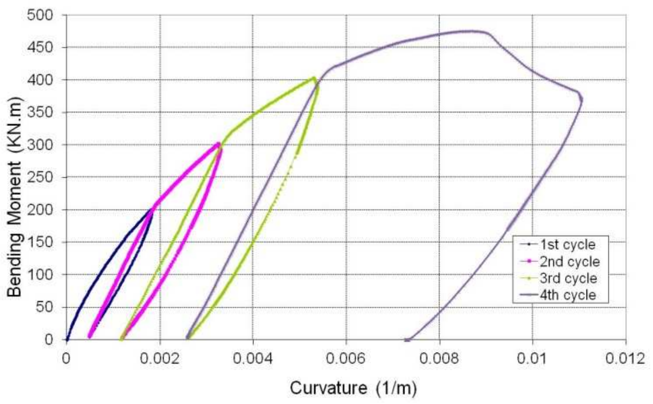

Figure 15. Moment curvature relationship of N400 specimen

6.3 *Effective structural modulus*

Figure 16 shows the variation of the structural modulus with the bending moment.

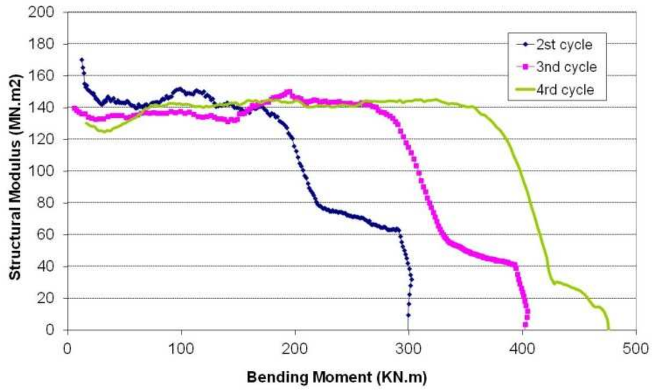

Figure 16 - Structural modulus during loading path for different cycles (N400)

The average value in the 'elastic' range is 143 MNm^2 and it is located in a narrow band between 140 and 145 MNm^2 on the fourth cycle for bending moments above 80 kNm. The others characteristics of the curves confirm the comments made for box N200.

7 EFFECT OF FRAME SPACING ON THE ULTIMATE BENDING MOMENT

The frame spacing on ship structures increases the column slenderness of the stiffener panel and, as a consequence, the critical stress of the panel reduces according to the elastic theory and the ultimate stress under axial compression. In these experiments having equal cross section, the top panel is under compression, thus the maximum strength of this panel decreases with increasing the space between frames. According to equation (1) the maximum bending moment that may be achieved reduces with a reduction on the compressive strength of the constitutive structural component.

Figure 17 presents the compilation of tests results for the ultimate bending moment and the structural modulus at last cycle of loading in the 'elastic' range. It confirms the decrease of ultimate bending moment with the increase on the frame's spacing.

As expected, the effective structural modulus is independent of this variable and the very slight decrease may be attributed to panel's initial imperfections and experimental uncertainties.

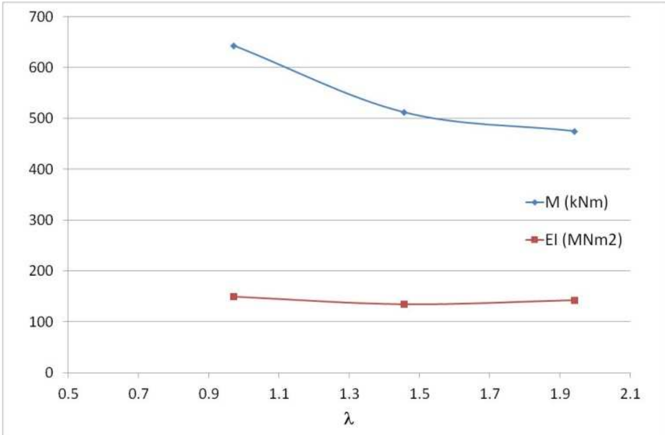

Figure 17 Ultimate bending moment and structural modulus versus column' slenderness of top panel

8 CONCLUSIONS

Three tests on the bending of box girders were performed varying the span between transverse frames. It was found that the transverse frame spacing is an important parameter on the strength of a thin walled box subjected to bending moment. The increase of the span reduces the ultimate bending moment of the structure due to a decrease of the buckling stress of the panels under compression.

Residual stresses are very important in this type of experiment and the moment curvature curves depend very much on their level according to the manufacturing process. However it is possible to have a good understanding of the behavior of the structure without residual stress by performing a series of loading cycles prior to the collapse of the structure. With those cycles one removes the residual stresses on the panels in tension allowing for the observation of the elastic behavior of the structure.

The column slenderness controls the type of collapse of the structure: high column slenderness leads to more sudden collapse, follow by large discharge of load during the failure of the structure. That was found during the experiments and it is represented

by the shedding pattern of experimental moment curvature curves.
The structural modulus in the elastic range of the structure free of residual stresses does not change with the frame spacing.

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