Experimental evaluation of the behavior of a mild steel box girder under bending moment

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ABSTRACT: An experimental study is presented of a box girder made of mild steel subjected to pure bending moment. The moment curvature curves are presented allowing for the analysis of elastic-plastic behavior until collapse, the evaluation of the ultimate bending moment and post collapse behavior. The residual stress relief during loading and unloading path is also analyzed. The results are compared with a test on a similar box girder made of very high tensile steel.

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 material will affect the non dimensional slenderness of those plate elements leading to different collapse strength despite using the same geometry. The use of steel of much different strength will induce collapse at different levels of plate and columns 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 two box girders made of different material but with the same configuration is compared. The results on the collapse of a box girder made of high tensile steel already performed are now complemented with a new experiment on a similar specimen but made of mild steel under the same conditions in order to have a good basis of comparison and to establish experimentally the effect of material properties on the collapse strength.

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 OF N-200 BOX GIRDER

3.1 *General information*

The box girder is made of mild steel of 270 MPa yield stress and the Young modulus is considered to be of 200 GPa. The specimen has five frames corresponding to four frame spacings 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.

A similar experiment is presented in Figure 1, showing the welding connections to the supporting side structures.

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 model.

The box girder is subjected to pure bending moment, inducing tension on the bottom and compression on the top of the box.

Figure 1. Supports and model during manufacturing.

3.3 *Geometric properties of the models*

The model is 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 200m, Figure 3. The nominal column slenderness covered is from 0.97. The estimated plate slenderness β is constant 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 stiffened plate on the top panel is 600 mm^2 and the stiffener area is 80 mm^2.

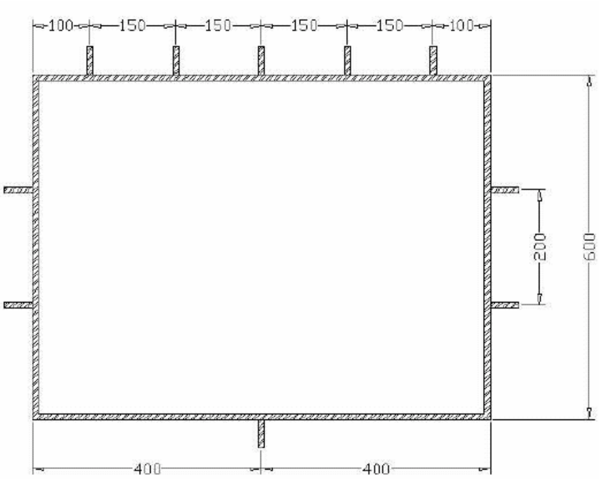

Figure 2. Cross section of the box girders.

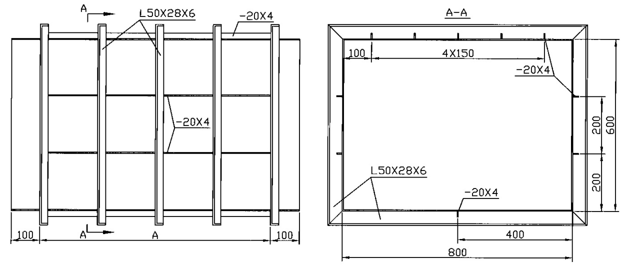

Figure 3. Geometry of the box girders.

3.4 *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.

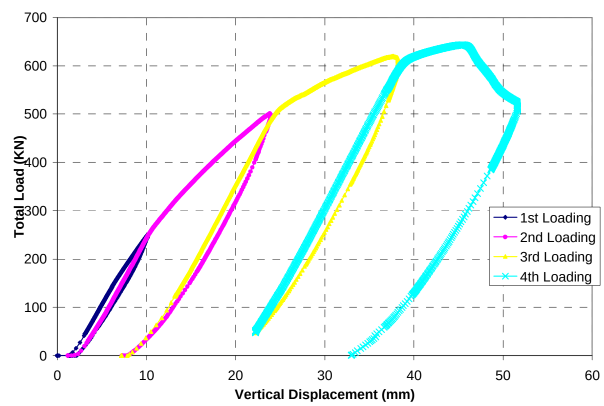

Figure 4. Vertical load versus vertical displacement on N200 test

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 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. If one has no transverse rotation of the box then the readings should be the same in both transducers.

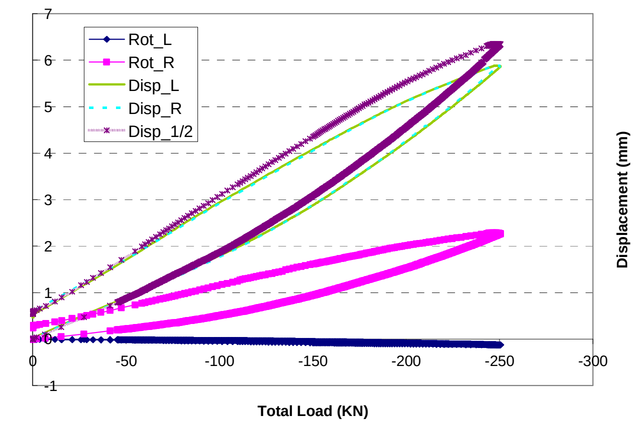

Figure 5. Measurements on the displacement transducers on first cycle.

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.

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.

Figure 6 shows the measurements of the displacements of rotation at the sides of the box for the whole experiment. The differences between the readings increase with the load and the cycles. Also the permanent set of displacements after the unloading of each cycle increases to very high values. It shows that elastic-plastic effects become more important as the applied load increases and approaches the ultimate load.

The ratio between the left and right rotations, which is the same as the ratio between the curvatures measured at opposite sides of the box, is plotted in Figure 7. One may note that this ratio tends to be stable after the first cycle of load. The ratio on the loading path of one cycle tends to be the same of the unloading path of the previous one, which means that the loading is in the elastic but not linear range until the previous maximum load is achieved. The maximum correlation is above 0.7 on the second cycle, but has lower values with reduction of the load.

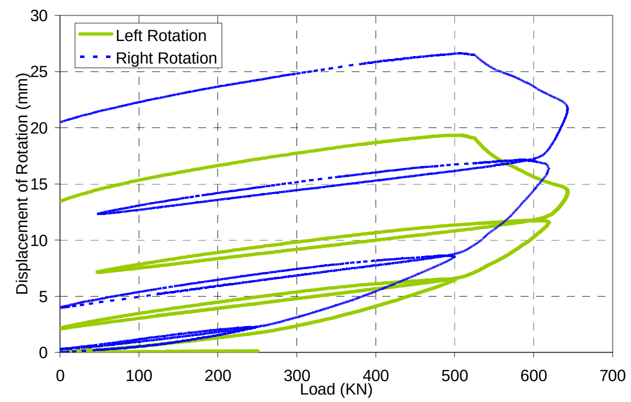

Figure 6. Evolution of the rotation in each model's side

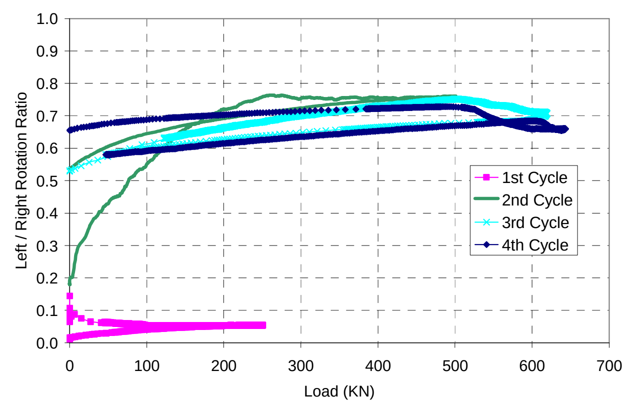

Figure 7. Ratio of rotations measured in each side of the model

3.5 *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 8 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.

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 transversal 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.

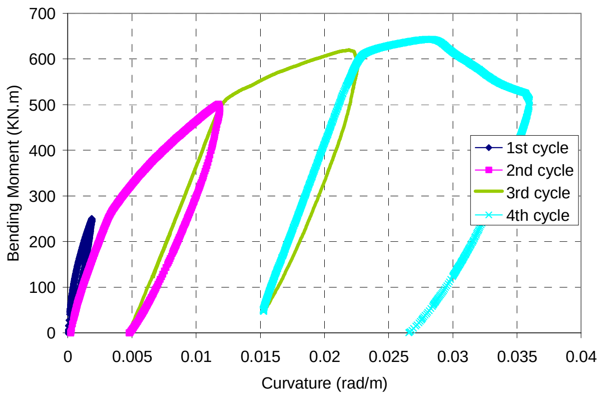

Figure 8. Moment curvature relationship of N200 specimen

3.6 *Effective structural modulus*

Figure 9 shows the effective structural modulus against the applied bending moment for the four cycles of loading. The nominal structural modulus is EI, as known from the linear elastic beam theory, where E is the Young 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. Due to initial imperfections and residual stresses that cause a decrease in the rigidity in the load shortening curves of the panels that constitutes the structure, the effective structural modulus is always less than EI.

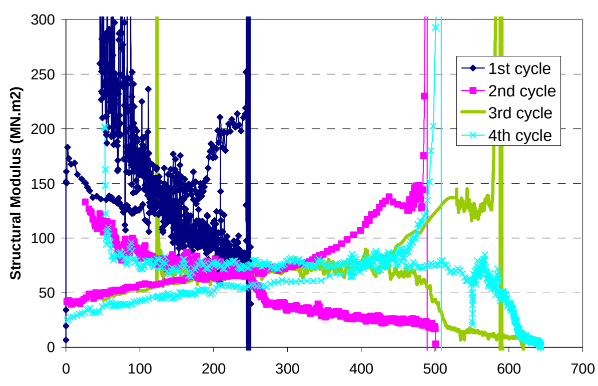

Figure 9. Effective structural modulus for the different cycles on load and unload.

On the first cycle the effective structural modulus has initially very high values with large scatter but reduce 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. The discharge presents a higher value than the loading and the scatter reduces very much meaning that the geometric deformations are stable during the discharge.

Figure 10 compares the evolution of the structural modulus during the loading path only, 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 70 and 80 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.

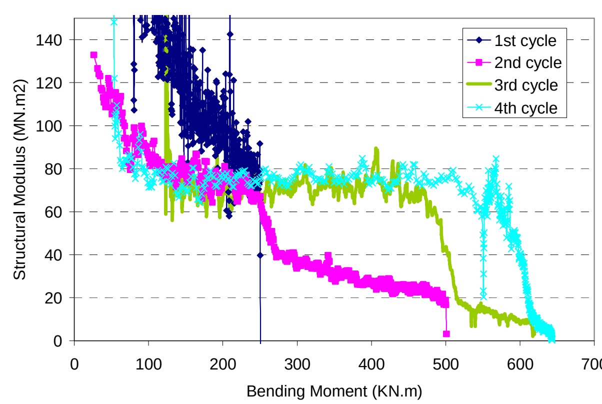

Figure 10. Structural modulus during loading path of the cycles

4 COMPARISON WITH VERY HIGH TENSILE STEEL BOX GIRDER

The experiment described above is now compared with a similar one with a box girder made of high tensile steel (Gordo & Guedes Soares, 2006). This model, designated as H200, has an identical configuration of the N200 box girder by the nominal yield stress of the material is 690 MPa.

The setup of the test is presented in Figure 11 where one may identify the loading device composed of two hydraulic cylinders and one of the supporting structures, being the other symmetric to this one.

The box H200 shows a sharp discharge immediately after collapsing at approximately 40mm of absolute vertical displacement (Figure 12). Before the collapse and after the maximum loading point of the last cycle of loading the curve reduces its slope, which may mean that the plasticity is spreading in some parts of the box where residual stresses are higher.

The maximum load achieved in each actuator was 459 kN at a global displacement of 39.5 mm. This means that the total vertical load supported by the box was 918 kN. This is 43% more than the ultimate load of the mild steel box N200, which collapse with a total load of 643 kN at 45.3 mm of vertical displacement.

Figure 11. Test on a box girder. Setup of the test from experiment on FasdHTS project on high tensile steel specimen.

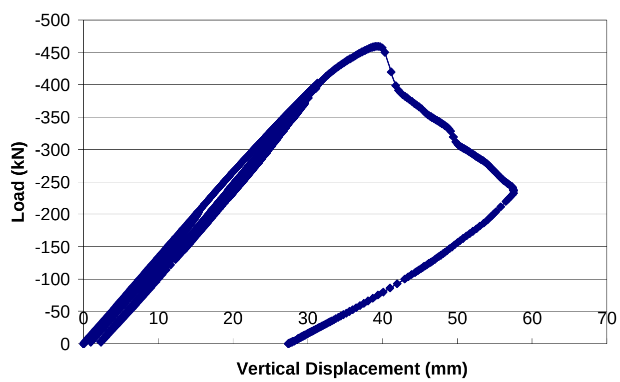

Figure 12. Load displacement curve in one actuator (half total load) for H200 box

There are several differences between the shapes of the curves. First of all, the vertical displacement of the mild steel box N200 is higher than that of H200 box due to much higher development of plasticity in the N200. This may be observed comparing the pre collapse cycles noting that the residual displacement after each cycle are much higher for N200 (Figure 4) than for H200. In fact the energy dissipated on the initial cycles of high tensile steel box is very low compared to the energy dissipated on the mild steel specimen. This energy is measured by the area involved by the whole cycle. There are two main reasons for this result: the material properties with respect to ductile behaviour is different for the two kinds of steel and the manufacturing was made in different factories with different technologies, resulting in different levels of residual stresses.

The discharge of load after collapse is more abrupt on the high tensile box than on the N200 box. This is an expected result since the slenderness of the panel in compression is higher for the H200 than for the N200 box girder. More than that, the discharge was continuous on the mild steel specimen but it was of snap-through type on H200. This can be observed by the vertical discharge of load at almost constant displacement in Figure 12 or by the very large increase in curvature after collapse in Figure 13.

This last figure represents the relation of the applied bending moment to the curvature and it confirms the comments made for the load displacement curve.

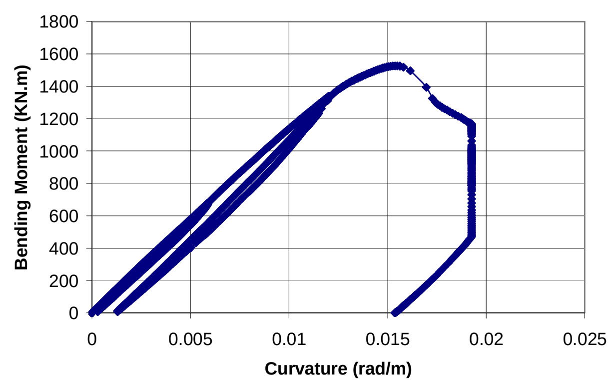

Figure 13. Bending moment average curvature relationship for box H200

The structural efficiency can be defined as a measure of the performance of one structure comparing the ultimate bending moment with the fully plastic bending moment for that particular structure, M_{HTS}. The global structural efficiency compares the performance, in this case the ultimate bending moment, of one structure made of one type of material with the fully plastic bending moment of a similar structure made of normal steel, M_{MS}.

The ultimate bending moment of the H200 box is 1526 kN.m which compares with the maximum value of 643kN.m obtained for the N200 box. The ratio between the two values is 2.37 while the ratio between the nominal yield stresses of the two materials, respectively 690 and 270 MPa, is 2.56 and so one may conclude that the structural efficiency of the panel in compression made of high tensile steel is lower than the one of mild steel as expected.

Table 1 presents the comparison between the tests showing that, apart the slightly lower structural efficiency, the global efficiency of the high tensile steel is very good:128% of the mild steel efficiency.

Table 1 - Comparison of test results.

Box Girder Identification	H200	N200
Yield bending moment (kNm)	1711	669
Ultimate bending moment (kNm) - M_{ult}	1526	643
σ_{yield}/σ_N	2.56	1.00
Structural Efficiency: M_{ult}/M_{HTS}	0.89	0.96
Global efficiency of HTS: M_{ult}/M_{MS}	2.28	0.96

CONCLUSIONS

The tests showed that the performance of the box girders are as expected and the performance of the high tensile steel model is very good obtaining a global efficiency of 2.28 while the maximum available is 2.56 due to the difference of the yield stress of the two different materials employed. The lower value results from the effect of the increase on the column slenderness of the panel under compression, as expected.

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 both experimental moment curvature curves.

ACKNOWLEDGEMENTS

This paper has been prepared within the project “MARSTRUCT – Network of Excellence on Marine Structures”, (www.mar.ist.utl.pt/marstruct/), which has been funded by the European Union through the Growth program under contract TNE3-CT-2003-506141.

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