## FasdHTS TD 04.52.09.01

 Proposal:
 GRD1-1999-10558

 Contract:
 G3RD-CT 2000-00100

# Buckling tests on hull box girders

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Doc. Ref :	TD 04.52.09	0.01	<b>Date:</b> 30 <sup>st</sup> Jun	ie2004			
Directory:							
Title: <b>Buc</b>	kling test	s on hull box girder	rs				
Author(s):	J. M. Gordo	and C. Guedes Soares					
Issued by:	IST	ce					
Summary:		-					
This report presents the main results of the buckling tests performed on box girders subjected to pure bending moments.							
Revision:	date:	description:	pages:	checked:	approved:		
00	30-06-2004	Draft	21		CGS		
01	23-07-2004	Final	21				

## **1 INTRODUCTION**

The evaluation of ultimate capacity of ships under bending moment is a very important issue of 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 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 steel. The existing calculation methods may be divided into two groups: finite elements methods, and simplified methods. In the first two groups there has been a great activity and comparison between the different methods are available in the literature [10].

The authors have been working a a method that has been validated against data from a full scale accident [7] were the loading conditions could be well established and against some small scale experiments of models representing simplified typical sections of ships [1,2,5 and 6]. The results of these comparisons showed that the method can be used confidently on typical hull configurations and for normal steel.

The development of the design in the present project does not use the traditional hull configuration as it is aimed at taking advantage of the use of HTS 690 steel. Therefore this is a change that would be made more confidently if some experimental results were available.

Furthermore the validation referred earlier was made with models made of normal steel or steel with much lower strength than the HTS 690 and they are very limited in number. 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.

For these reasons a limited series of experiments were conducted with moderate size specimens made of HTS 690, as reported here, which should provide a good basis to assess the ultimate strength of various hull configurations based on the existing computational tool [3].

## 2 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 behaviour 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 ( $\sigma_0$ ) and the modulus of elasticity (E). The transverse 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 behaviour of the structural elements under compression, especially concerning on having or not having a constant yielding stress.

The use of HTS 690 instead of other normal steels (NS, H32, etc.) on the fabrication of the ship's hull has three different effects on the ultimate bending moment:

- an increase on the global strength proportional to the ratio between the yield strength corresponding to the types of steel under comparison, for the same geometry;
- a reduction on the effectiveness of the structural elements, plates and stiffened plates, due to an increase on their slenderness. For example, the slenderness of a plate made of HTS 69 is higher by 1.7 than the one of normal steel (NS), as there are differences in the yield strength but the modulus of elasticity is the same
- a reduction on the thickness of the scantlings due to a greater yield stress of HTS69 in comparison to others steels, which leads to a further increase on the slenderness, reducing the effectiveness of those structural elements.

In the view of these points the efficiency of HTS 69 must be investigated and the applicability of current methods to this type of structures must be evaluated based on experimental results.

# **3 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 [3] that is able to predict the overall behaviour of the hull under bending moment. This method predicts not only the ultimate bending moment but also the pre and post collapse behaviour. 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 made ships when compared to the tests and hazards examples available in the literature. However they have not been tested against results obtained for HTS 69 made hulls.

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 behaviour of the ship's structure under bending, allowing the identification of the differences of using HTS 69, widening the range of validity of the method and covering the behaviour of panels of high column slenderness.

The typical element of the box girders is a plate with a bar stiffener which have been proved to be representative of the actual type of structure of ship's hull. 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.

The present box girder experiments were complemented with a series of compressive tests on stiffened panels where the geometry may be scaled more precisely. These other tests are described in another report.

### 3.1 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:

$$M = \int_{A} (z - z_n) \cdot \mathbf{\sigma}(z) \cdot dA = \int_{A} (z_i - z_n) \cdot \mathbf{\sigma}_i(\varepsilon_i) \cdot dA$$

where the average stress  $\sigma$  on the stiffened panel is a function of the average strain  $\varepsilon$  and the last one is dependent of the location  $z_i$  of the element and of location of the neutral axis  $z_n$ :

$$\sigma_i(z_i) = f(\varepsilon_i)$$
 and  $\varepsilon_i = g(z_i, z_n)$ 

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 pos-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 [9] or by approximate methods [4,11] based on the empirical formulas for the ultimate strength of panels under axial loading. Normally the design methods used for that propose are: 1) Faulkner's method, Perry-Robertson method and the critical stress for use as serviceable limit. These methods are already described in detail on a previous report.

### 3.2 Influence of HTS on the strength of stiffened plates

The evaluation of the average column strength is based on the strength of the effective stiffened plate reduced by a factor that is the ratio between the effective area and the total area of the element.

$$\phi_{u.col} = \phi_{u.ef.col} \left[ \frac{A_s + b_e t}{A_s + bt} \right]$$

This formula considers the same yield stress for the stiffener and the plate. The effective width of the plate affects both terms of the second member and depends very much on the slenderness of the plating.

$$b_e = b \cdot f(\beta, \sigma_r, \delta)$$
 and  $\beta = b/t \sqrt{\sigma_o/E}$ 

So, when the yield stress rises the thickness may be lowered and one has a magnified increase on the plate slenderness, which has an inverse influence on the effective width reducing it very much. Thus one has a reduction of weight and on the plate buckling stress (effective width) that may originate design corrections to satisfy buckling criteria.

The increase on the yield stress of the material generates a reduction on the ultimate strength of the effective column with two main contributions to that reduction: the reduction on the effective width of the associated plate reduces normally the radii of gyration and the yield stress itself. Both effects originate an increase on the column slenderness that reduces the strength of the effective column.

In conclusion the average column strength is very much affected by the reduction of both terms when the yield stress of the material increases.

One may define the concept of effectiveness as equivalent to the normalised strength of the column and then say that the increase on the yield stress generates a double reduction on the effectiveness of the panel.

The global efficiency of the panel made on HTS may be evaluated by the ratio between the effectiveness of the panel on HTS and the effectiveness of the mild steel panel.

Efficiency of HTS = 
$$\frac{\Phi_{ucol}^{HTS}}{\Phi_{ucol}^{MS}}$$

The important design parameters to be controlled when using HTS are: b, t, l, and t<sub>k</sub>. The control shall be made b/t,  $l^2\sigma_o$  and evaluation of the tripping stress in order to avoid large reduction on the global efficiency.

## **4 PLAN OF EXPERIMENTS**

### 4.1 General information

Material: HTS 690

Material properties: Yield stress=690MPa; Young modulus=200 GPa.

Models are three or four bays span in length

Number of models=3

Main dimensions of models

Length =1400mm=100+3\*400+100mm =1000mm=100+4\*200+100mm =1100mm=100+3\*300+100mm Width =800mm Depth =600mm Type of stiffeners: bars

## 4.2 <u>Type of experiment</u>

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.



Figure 1 Finite element model of one bay box girder.

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



Figure 2 Support and loading to generate pure bending on the box girder.

### 4.3 Geometric properties of the models

All models are made of 4mm thick plate. The spacing between stiffeners varies between 50 and 200, which leads to width to thickness ratio varying from 12.5 to 50. The span between frames is 200mm (1 model), 300mm (1) and 400mm (1). The range of nominal column slenderness covered is from 0.97 to 1.93. The plate slenderness  $\beta$  is constant and equal to 2.2 but with a *b/t* of 37.5 (in normal steel this ratio corresponds to a  $\beta$ <1).

Model	Length (mm)	b (mm)	t (mm)	h (mm)	th (mm)	Area (mm <sup>2</sup> )	N. of Frames
H4-150/200	1000	150	4	20	4	680	5
H4-150/300	1100	150	4	20	4	680	4
H4-150/400	1400	150	4	20	4	680	4



Figure 3 Test on a box girder. Setup of the test.

### 4.4 <u>Slenderness and strength of the panels in compression</u>

The plate slenderness is the same for all models ( $\beta$ =2.2) with a corresponding effectiveness of 0.702. The nominal column slenderness varies from 0.97 to 1.93 which corresponds to a variation of the average ultimate strength from 0.604 to 0.255.

Model	b/t	β	$\lambda_{nom}$	$\lambda_{ef}$	ф <sub>р</sub>	фs	Ap/At
H4-150/200	37.5	2.20	0.97	0.85	0.702	0.604	0.88
H4-150/300	37.5	2.20	1.45	1.28	0.702	0.437	0.88
H4-150/400	37.5	2.20	1.93	1.70	0.702	0.255	0.88

# **5 EXPERIMENTAL RESULTS**

The experiments were performed using several cycles of loading in order to obtain some stress relief on the panel in tension. The evaluation of the energy absorption in this region allows the indirect estimation of the residual stresses level due to welding [6].

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### 5.1 Load vertical displacement relationship

The load displacement curves of the three box girders are shown in next figures.



Box Girder B200



Box Girder B300



Figure 5 B300 - Load displacement curve

#### Box Girder B400



Figure 6 B400 - Load displacement curve

#### 5.2 <u>Moment curvature relationship</u>

Table 1 presents the estimated yield moment and compares it with the results of the tests for the box girders. In the last two lines a measure of the efficiency of the structure due to structural instability (called here structural efficiency) is calculated and the last line present presents the global efficiency on the use of S69 instead of mild steel of 240MPa yield stress. The global efficiency varies from 1.72 to 2.56.

Box Girder Identification	B200	B300	B400
Structural tangent modulus (MNm <sup>2</sup> ) - HTS	162		
Yield bending moment (MNm) – HTS	(MNm) – HTS 1711		
Ultimate bending moment (MNm) - HTS	1526	1269	1026
Yield bending moment (MNm) – MS	595		
$\sigma_{\text{HTS}}/\sigma_{\text{MS}}$ and $M_{\text{HTS}}/M_{\text{MS}}$ (yield)	2.875		
Structural Efficiency	0.892	0.742	0.600
Global efficiency: Mult/MMS	2.56	2.13	1.72

 Table 1
 Comparison prediction and test results. Efficiency of S69.

This variation is mainly due to the increase of span since the cross section characteristics rest unchangeable. The next figure shows the dependence of the ultimate moment from the column slenderness. **FasdHTS** TD. 04.52.09.01



Figure 7 Dependence of the structural and global efficiency on the nominal column slenderness



Figure 8 Bending moment average curvature relationship for box B200



Figure 9 Bending moment curvature relationship at opposite sides of box B200



Figure 10 Bending moment average curvature relationship for box B300

Box B200



Figure 11 Bending moment curvature relationship at opposite sides of box B300

Box B400



Figure 12 Bending moment average curvature relationship for box B400





#### Figure 13 Bending moment curvature relationship at opposite sides of box B400

#### 5.3 <u>Modes of collapse</u>

The modes of collapse obtained for the three box girders present three different configurations corresponding to different histories.

The B200 box had a sudden noisy collapse with a great discharge of load and large deformations due to the formation of plastic hinges at the middle span of the stiffeners under large compressive loading. Only the two central bays were affected: one with deformations toward the stiffener and the other towards the plating. The formation of the plastic hinges in all stiffeners means that they were loaded at the stresses close to the yield stress and after the local discharge of loading associated with formation of the first plastic hinge the load was transferred to nearest stiffeners promoting the simultaneous collapse of the panel. That is a typical column failure mode expected for short span stiffened panels.

The box B300 showed a smoother collapse but presented a similar mode of deformations after collapse. However the plastic hinges did not originate a neck in most of the stiffeners. That should be the reason for the absence of noise during the collapse. So there was a plastic flow at the middle span of the stiffeners without any out of plane deformations for most of them.

The box B400 is also a 3 bay model like the box B300 but it has presented a more complex history of the out of plane deformations on the top panel (compression). Visible semi sinusoidal deformations between frames might be observed during the loading path, inwards in the end spans and outwards in the middle span. This deformed mode generates high level of stress on the extreme of the stiffeners but of different nature, compression on the top of the stiffeners between the lateral frames and tension on the top of the stiffeners at the middle bay. It was a more marked and global collapse due to the large span between frames. The mode of collapse shall be classified like the others as column induced failure.



Figure 14 B200: general deformations after the collapse load



Figure 15 B200: Column collapse between frames





Figure 16 B200: Overall view of deformations after collapse



Figure 17 B200: Stiffener collapse on top panel and side deformation





Figure 18 B200: Inside view of collapse after cutting



Figure 19 B300: general deformations at collapse load



Figure 20 B300: Buckling of the compression panel



Figure 21 B300: Residual deformations on the side panel



Figure 22 B400: Overall view of the test before collapse



Figure 23 B400: Residual deformations after collapse on top panel



Figure 24 B400: Residual deformations after collapse at middle span

## **6** CONCLUSIONS

The main overall conclusions are:

- 1. The efficiency of the S69 is very good when the steel is applied on box girders subjected to bending moment.
- 2. The structural efficiency decreases as the span between frames increases. The increase of span increases the column slenderness. The structural efficiency decreases linearly with column slenderness in the range considered for this parameter.
- 3. The global efficiency, which includes structural and material efficiency, is higher than that expected from the effectiveness of the plate and the column of the panel under compression affected by the material efficiency.
- 4. The modes of collapse obtained are all classified as column mode of failure, as expected. However the final deformed shape presents different configurations resulting different histories.
- 5. The plating induced failure could not be achieved because of the incompatibilities between plate thickness available, setup of the test, geometry of the models, etc.
- 6. The range of the column slenderness is very high due to the high ratio between the plate and the total area of the representative stiffened plate (Ap/At=0.88). It means that for actual design practice one may obtain a global efficiency of the S69 on the order of 2.5 taking as basis the normal steel structure.

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