# Experimental analysis of a box girder with double span subject to pure bending moment

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# Experimental analysis of a box girder with double span subject to pure bending moment

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ABSTRACT: The results of a four points bending test on a box girder are presented. The experiment is part of series of tests with similar configuration but different thickness and span between frames. The experiment includes initial loading cycles allowing for residual stresses relief. The moment curvature relationship is established for a large range of curvature. The ultimate bending moment of the box is evaluated and compared with the first yield moment and the plastic moment allowing the evaluation of the efficiency of the structure. The post buckling behavior and collapse mode are characterized. Comparison of the experiment with a progressive collapse method is made taking into consideration the effect of residual stresses on the moment curvature relationship of the structure.

## 1 INTRODUCTION

The ultimate bending moment that the transverse section of a ship or a floating production and offloading platform (FPSO) can resist under overall longitudinal bending, is one of the main criteria for design of these structures. The move of the industry towards more accurate predictions of the strength of these structures in overall bending to resist still water and wave induced loads requires accurate and expedite methods to assess the ultimate strength.

Caldwell (1965) was the first who addressed the plastic collapse of a ship hull under overall bending although he did not allow for buckling of plate elements as pointed out by Faulkner (1965). The first attempt to incorporate the influence of the buckling collapse of some elements of the cross section was due to Smith (1977), who used load shortening curves of individual plate elements to calculate their contribution to the ultimate bending moment of the structure. Other methods based on this general idea were developed including the earlier ones of Billingsley (1980), Adamchak (1984) and Gordo et al. (1996).

This type of progressive collapse methods usually consider that the structural behaviour of the hull girder under bending moment may be represented by the summation of the individual contributions of each longitudinal stiffened plate that is part of the cross section. The two main assumptions are that the net longitudinal force in a cross section is zero and the bending moment resulting from the external loads is equal to the first moment of the forces developed in the cross section due to the curvature of the hull girder. The first assumption requires the re-evaluation of the location of the neutral axis at every incremental curvature change because of the elastic-plastic nature of the load shortening relationship for each stiffened plate element.

The ultimate moment supported by the hull is achieved after some of the elements have already collapsed, so the knowledge of the shedding pattern after buckling of such elements is of great importance. Usually these methods ignore the interaction between adjacent elements thus the calculated ultimate moment may be considered as an upper limit for the maximum bending moment. The main problem associated with such structures is the nonlinear behaviour of the components under compression, which is a source of uncertainty on the determination of the ultimate carrying capacity of the structure, especially in a situation of overall bending where some parts are in compression and others in tension.

Because of their nature, these methods require validation by experimental results. However the number of test results available in the open literature is limited. Two box girders representative of bridges were tested by Dowling et al. (1973) and Nishihara (1984) tested seven models of scaled and simplified ship cross sections. An experiment on 1/3 scale model of a frigate was performed by Dow (1991), but this was a transversely framed ship which is not representative of most present day structures.

The predictions of the method of Gordo et al. (1996) reproduced well these tests results (Gordo and Guedes Soares 1996), but due to the limited extend of geometries involved it was decided to initiate a series of tests that would consider other geometries, covering a wider range of the different parameters that affect the ultimate carrying capacity of such structures under bending.

In this work the results of a test on a box girder representing the mid-ship region of a ship type structure are presented and analysed. The specimen is subjected to pure bending leading to a mode of collapse in which the upper flange failed under compressive loads.

This result belongs to a series of 5 tests on mild steel box girders (Gordo 2002; Gordo and Guedes Soares 2004; 2014b) where different plate's thickness and frame's spacing where used for the same transverse configuration of the box.

After that the authors have performed tests on high and very high tensile steel box girders (Gordo and Guedes Soares 2009) that allow understanding the influence of the material properties on the ultimate bending moment supported by this type of structure.

## 2 EXPERIMENTAL DETAILS

### 2.1 *Geometry of the specimen*

The specimen is a one-meter long box girder supported by two blocks of two meters with much higher rigidity than the first. The liaison between them is bolted in order to allow the use of the supports in the future to test other models.

The four points bending test is sketched in Figure 1 and it allows obtaining pure constant bending throughout the whole specimen.

The central block represents the cross section of a rectangular box girder and has the major dimensions of 800mm wide and 600mm of depth. The span between the three frames of the specimen is 400mm allowing 100mm in each side for redistribution of stresses.

The horizontal top panel has five longitudinal stiffeners equally spaced (150mm) and the bottom has three stiffeners spaced by 200mm. The lateral webs have two stiffeners each, one located in the middle and the other 100 mm below the top panel, as presented in Figure 2. The plate is 3mm thick and the stiffeners are bars with a thickness of 3mm and 20mm of depth. This specimen was designated M3-150.

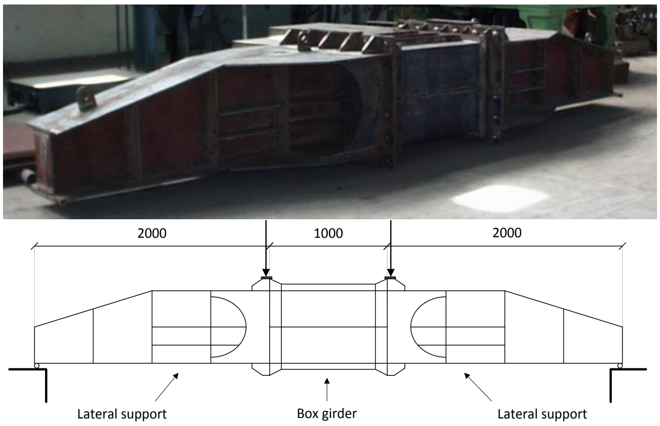


Figure 1. Layout of the experiment and real structure.

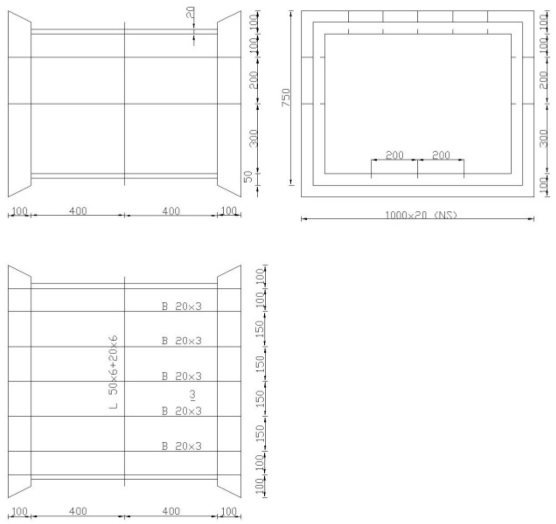


Figure 2. Cross section and stiffeners arrangement.

### 2.2 *Material Properties*

This box girder was built in the Laboratory of Structures belonging to the Department of Civil Engineering of IST. The steel used in the manufacture is normal steel for civil engineering and the material properties were determined by tensile tests on specimens cut in the longitudinal direction of the plating and bar stiffeners in order to coincide with the direction of loading in the experiments.

The tensile tests results are presented graphically in Figure 3, both for plating and stiffeners. The most relevant information for the experiments and design are the yield stress, maximum stress, yielding plateau and modulus of elasticity.

The yield stress of plating specimens is 290 MPa and the stiffeners show a yielding plateau at 340 MPa, with a proportional limit stress at 320 MPa. The maximum stress is of 360 MPa for plating and 450

MPa for bar stiffeners. The modulus of elasticity is 210 GPa.

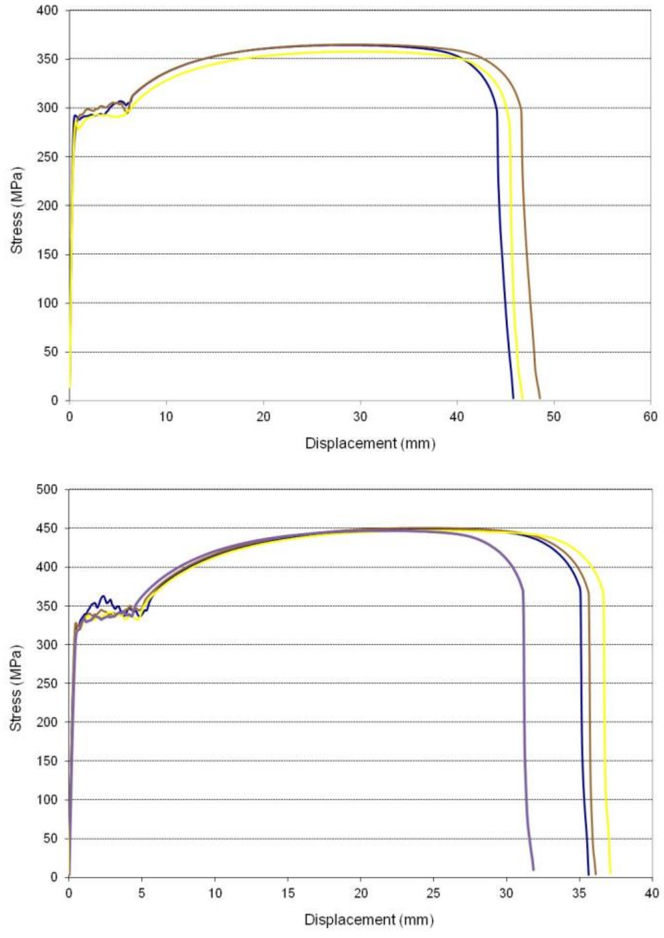


Figure 3. Tensile tests of 3mm thick steel for plating (up) and for the stiffeners (bottom)

## 3 RELATIONSHIP BETWEEN THE MOMENT AND THE CURVATURE

The relationship between the applied force and imposed displacement is represented in Figure 4. It shows several initial cycles of loading followed by cycle to collapse of the structure continuing beyond collapse. The collapse is achieved with an absolute maximum displacement of 17 and 19 mm which corresponds to the maximum applied force of 328 kN in both cases. The first phase of collapse is given by the local rearrangement and a slight decrease of resistance, being followed by a mild increase in load capacity up to the same the bending moment already achieved and from that point the load capacity of the girder decreases smoothly but irregularly.

Approximately at 25mm of vertical displacement and well into the post-collapse region, a sharper fall of resistance is observed and after that point the decrease of flexural strength is much more smooth and stable.

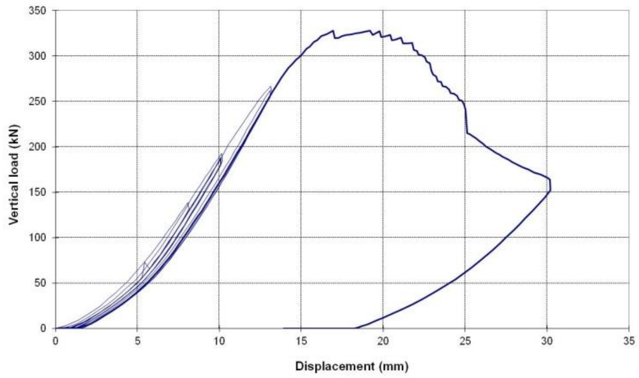


Figure 4. Relationship between the vertical load and the vertical displacement

### 3.1 *Initial cycles of charge*

The first cycle of load was applied to a maximum displacement of 8 mm which corresponds to a bending moment of 139 kNm, as presented in Figure 5.

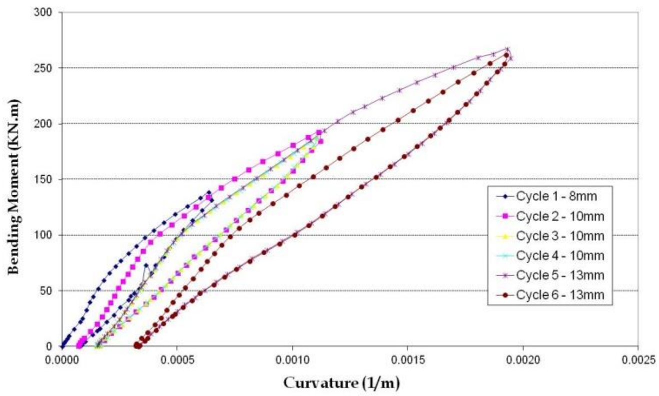


Figure 5. Moment curvature curve of initial cycles of load.

This was followed by three identical cycles up to 10 mm vertical displacement whereby it was possible to observe that from the moment the first loop was performed until the maximum value determined with the consequent residual stress relief and energy dissipation in the form of strain plastic, all subsequent cycles of load to that level of loading have an elastic response of the structure with fully reversible deformations. This conclusion can be drawn from the total agreement of the third and fourth cycles where there is no increase in the residual curvature, which is equal to the residual curvature of the second cycle having the same maximum load. The difference between the loading curve of the second cycle on one hand and the third and fourth cycles is due to the relief of residual stresses and the consequent rearrangement of initial imperfections.

The comparison of the response of the fifth and sixth cycles subjected to a maximum load substantially greater than the others cycles confirms previous claims, even though these cycles correspond to a loading close to maximum load supported by the box girder, more specifically 81.4% of the maximum bending moment.

### 3.1.1 *Structural tangent modulus*

Regarding the evolution of moment-curvature curves, it is evident some initial variability of box girder's stiffness in the first two loading cycles. These initial variations of the stiffness at low curvature tend to disappear with the stabilization of initial imperfections due to stress relief, with the remaining cycles presenting a bending rigidity at low curvature almost invariable. In the repeating cycles, 4 and 6, in which no energy dissipation by residual stresses relieve, it is observed the existence of two distinct zones in terms of structural tangent modulus: initial one with an average modulus of 240MNm$^2$ that extends to the bending moment of 106KNm; second, substantially straight well, with average structural tangent modulus of 135MNm$^2$ which is about half of the previous one but very close to the estimated 144MNm$^2$ structural modulus.

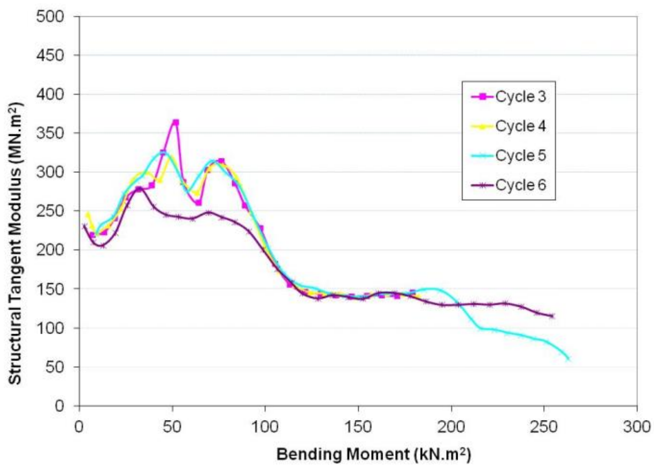


Figure 6. Structural tangent modulus by cycle as function of bending moment.

It is curious to notice once again that the changing value of the structural modulus corresponds to a value very close to the maximum bending moment in the first loading cycle time. Arise, therefore, again the question of memory of the structure for the first loading cycles where the residual stresses are relieved and definitely set the initial imperfections, Gordo and Guedes Soares (2004; 2014b).

### 3.1.2 *Cross Rotation*

Transverse rotation of the model exists in the initial loading phase; there is a proportional relationship between the curvatures measured in one and the other side of the girder that is not unitary. Beyond this initial phase where one has a twist of the model, the rotation acquired remains practically unchanged in these cycles of pre collapse, as seen in Figure 7.

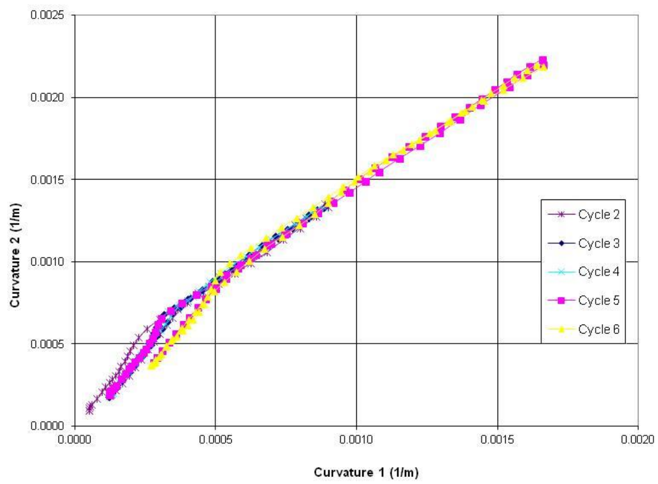


Figure 7. Relation between the curvature readings from different gauges located in opposite sides of the box

The moment corresponding to the points where the transverse rotation stops increasing, are precisely those points where the tangent structural modulus substantially reduces its value, i.e., points with very similar moment to the maximum moment of the first loading cycle.

## 3.2 *Cycle of maximum load*

The collapse cycle presents three distinct regions before collapse as shown in Figure 8. The first two of them were already described in the previous section; and the last starts at the maximum load prior to the collapse cycle presenting a marked loss of stiffness due to the elastic-plastic behavior of the structure at this stage of high load and to the dissipation of residual stresses not relieved earlier.

The box resists to a substantially constant maximum moment during a wide range of curvatures in which the increase of the same is accompanied by the development of large deformation and energy dissipation through plastic deformation.

The post collapse presents some initial irregularity in the relation between the curvature and the bending moment, but becoming much more regular discharge from the curvature that gives a sharp decrease of the moment. This break should be related to a prolonged period of the test at a vertical displacement of 25mm, originating a similar to that described for the other tests (Gordo and Guedes Soares 2004; 2014a), with increased curvature and decreased load carrying capacity during the stop time.

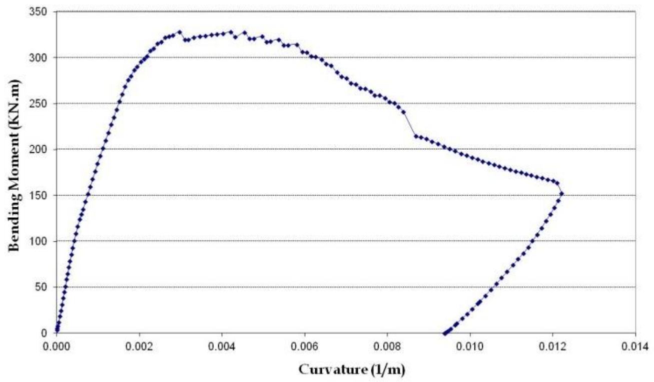


Figure 8. Moment-curvature relationship on collapse cycle

### 3.2.1 *Mode of collapse*

The collapse was initiated by the loss of effectiveness in the plating in one of the bays, developing out of plane displacement towards the stiffeners. These deformations in one of the bay induced rotation around the intermediate frame which increased the deformations towards the plating in the other bay. In consequence the top of the stiffeners at approximately the middle of this bay entered in plastic deformation, leading to the global collapse of the box under bending, as it is observed in Figure 9.

Figure 9. Collapse of box girder in one of the bay.

The transverse frame did not remain straight during this collapse phase and the points of collapse of the stiffeners were not located precisely in the middle of the bay but 230mm apart from the lateral frame in average. This indicates that the effective length of column is not equal to the frame spacing (400mm) but a little bigger (460mm) due to induced moment from the adjacent bay and the deformations in the transverse frame.

### 3.2.2 *Structural tangent module in final cycle*

The structural tangent modulus in the final cycle is fairly similar to that of the cycles with intermediate load characteristics, as discussed above. It presents an initial stiffness of about $240kNm^2$, reducing by half at the curvature of 0.0003/m and stabilizing during a wide range of curvatures to the maximum load point of the previous cycle is reached, Figure 10.

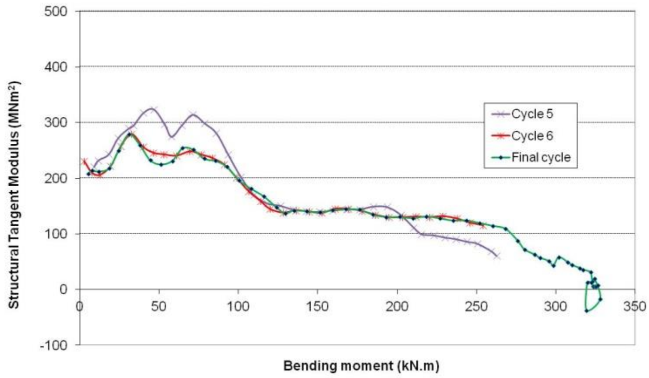


Figure 10. Structural tangent modulus versus bending moment for 3 last cycles of loading

Beyond this point the process of loss of stiffness begins as a result of the relief of residual stresses and out of plane deformations' development. It may be noticed in Figure 11 the similarity of the loss of stiffness between the 4th and final cycle after the maximum loading point of the previous cycle have been reached. In the graph curvatures are related to the residual curvature of the previous cycle in order to show the consistency between the curves.

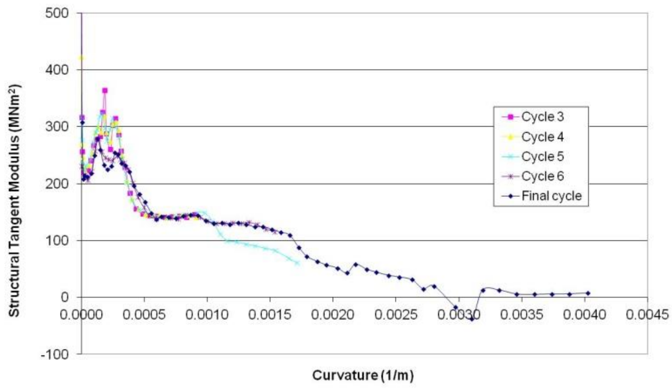


Figure 11. Tangent modulus by cycle with removal of residual curvature between cycles.

There is a remarkable agreement between the 6th cycle and the final one read in conjunction with which of the cycle 4 shows that the residual stress relief contributes to the development of a residual curvature and for setting a residual deformation, turning the moment curvature relationship gentler during the stress relief cycle in which the former exceeds the previous maximum load.

## 4 COMPARISON WITH THE APPROXIMATE METHOD

Figure 12 compares the curve of the final loading cycle with the proposed method predictions with and without residual stresses in nominal conditions. It is still shown the moment-curvature curve expected for a model with an effective frame's spacing of 460mm, according to the interpretation of the mode of collapse found in the box girder.

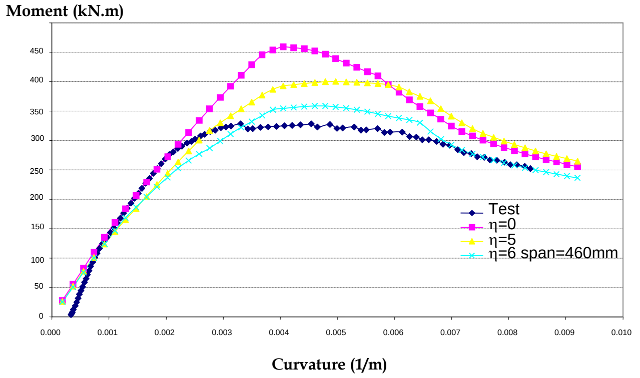


Figure 12. Comparison of test and predictive method for moment-curvature relationship with different residual stresses

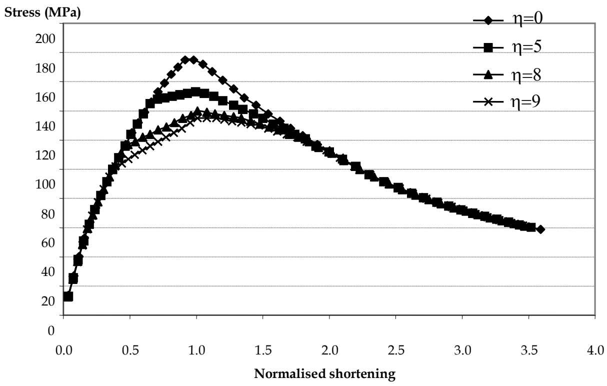


Figure 13. Average stress-strain curves for a typical stiffened plate element of the box girder under compression.

The initial curvature of the test curve was considered equal to the residual curvature of the last cycle of loading.
Again the agreement on pre and post collapse is quite satisfactory, emphasizing the proximity of the actual curve with the prediction using a corrected frame' spacing, which shows the validity of the interpretation of the shape of the collapse and its relationship with the efficiency frame in ensuring acceptable boundary conditions.

In Figure 13 is shown the action of residual stresses in the average stress strain curves in compression for a typical M3-150 stiffened plate element.

## 5 CONCLUSION

The results of a test of a box girder subjected to pure bending are presented. The existence of two adjacent bays showed to be important for the final mode of collapse leading to an ultimate bending moment lower than predicted by approximate method of progressive collapse analysis.
The final collapse is due to failure of the stiffeners in compression but mainly induced by the rotation resulting from a previous loss of effectiveness of the plating in the adjacent bay.
This influence of the adjacent bay originates a failure of the stiffeners not in the middle of the bay but towards the adjacent bay which corresponds of having an effective column's length bigger than the frame' spacing.

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