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Strength Analysis of Unconventional Cargo Ships by the Finite Element Method

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Resumen

El diseño de buques cargueros no convencionales está siendo analizado cada vez más, utilizando el método por elementos finitos.

Esto se debe principalmente a la complejidad de las estructuras del casco y las cargas aplicadas. La resistencia local (fatiga) y global, así como el comportamiento vibracional, puede ser predecido muy bien con el método por elementos finitos en una etapa inicial del diseño, cuando modificaciones estructurales de importancia son aún posibles.

Este trabajo describe los métodos utilizados por los autores, para el análisis de las tensiones en buques cargueros no convencionales.

Varios ejemplos de aplicación son presentados, mostrando ya gran flexibilidad en su aplicación tanto en estructuras locales como globales.

El análisis está puesto en el desarrollo de modernos diseños de buques portacontenedores, por ejemplo: portacontenedores con escotillas, relativamente anchas y buques multipropósito con escotillas muy largas.

1. Introduction

During the past twenty-five years the size of ships, in particular that of tankers and bulk carriers, has increased drastically and completely new ship types, such as container and ro-ro-ships, have appeared. This development was possible only with the aid of modern numerical tools, such as the finite element (FE) method.

The overall analysis of ship hull structures requires the solution of relatively large systems of equations which can be facilitated by the application of substructure techniques. For dynamic problems, special methods of solution have been developed, which are particularly suited for large problems.

Today, the finite element method forms an integral part of the development of new and unconventional ships. It allows the dimensioning and optimization of structures where no experience is existing. Research and development activities have been intensified in the recent years. Special methods and techniques have been developed particularly for the structural analysis of ships by the finite element method. In the following, an overview of these methods and their application to unconvenional cargo ships is given.

2. Structural Analysis

The structural behaviour of ships can be rather complicated which is mainly due to the complex geometry of hull structures. In many cases the application only of the beam theory is not sufficient to predict the structural behaviour of the hull with the accuracy required. Examples for such cases are the so-called "open deck" ships with extremely wide and/or long deck openings. The interaction between different primary members as well as further load effects such as torsional moments and high transverse loads may play an important part.

The finite element method (FEM) is a well-suited tool for the structural analysis of such complex structures. Deformations and stresses of all individual structural members can be predicted with relatively high accuracy. In several cases new and unconventional cargo ships, for which no experience was existing, were analyzed and optimized by this method.

The whole hull structure is modelled in such analyses using mainly membrane and truss elements. Normally all primary structural members of the hull such as girders, stringers and transverse webs are modelled. In this way they determine the mesh fineness and size of the model, see Fig. 1. In the case of large container ships the FE-model may contain up to 15,000 nodal points, which corresponds to 45,000 equations to be solved by the computer.

Within the advisory services of Germanischer Lloyd a special procedure of structural analysis is applied, which has been refined during the past years and verified by several on-board measurements. One important step within this procedure is the definition of realistic load cases for the vessel under consideration. Hydrodynamic pressure loads are calculated using an advanced design wave concept. This is based on long-term statistics of the operation area considered, e.g. the North Atlantic, as well as realistic pressure distribution on the hull. The latter is calculated taking into account non-linear effects due to the actual hull shape. For this reason remarkable differences between wave hogging and sagging moments may occur in particular for ships with pronounced bow flare, as exemplified in Fig. 2.

A number of deterministic load cases representing the most unfavourable sea-conditions is selected from all possible sea-states by variation of the wave length and direction. Particularly oblique waves as well as heeled positions have turned out to be significant for the structural design of "open deck" ships.

Fig. 3 shows the deformations of a container ship calculated for different load cases with extreme bending and torsional moments. The "snaking" of the hull, being typical for "open deck" ships subjected to torsional loads, can clearly be seen especially in the load cases with consideration of heeling.

The results of the different load cases, as shown in Fig. 4 for the deck of a container ship, are carefully analyzed with respect to stresses in the individual structural members as well as to the deformation behaviour to obtain, for instance, the movements of the hatch covers. Furthermore, the buckling strength of individual plate panels and local stresses at the most critical points, e.g. at hatch corners, are calculated and assessed with respect to ultimate as well as fatigue strength. These calculations are performed by special post-processing programs. In several cases the finite element model was also used for vibration analyses to predict the expected global vibration level due to propeller-and engine-induced excitations.

Further details of the procedure can be found e.g. in [1]-[3].

In the following, examples of new and unconventional cargo ships will be described. For these ships no experience was available from similar ships, but their design and operation were regarded as being feasible, not at least due to comprehensive finite element calculations performed in the way described above.

3. Modern PANAMAX Container Ships

The Panama Canal restrictions in length and breadth (approx. 284 x 32.3 m) have determined the main dimensions of several large container ships. Since the introduction of the third container ship generation in the early 70s it was usual to arrange 10 container stacks across in the holds of PANAMAX ships. This practice was abandoned a few years ago when a new container ship generation was introduced having eleven stacks across [4]. The container capacity grew to far more than 4,000 TEU compared with approx. 3000 TEU of the third generation.

The first of the new container ships were built with the traditional arrangement of three hatches abreast, divided by two longitudinal hatch girders, see Fig. 4. The remaining width of the wing wall structure is reduced to about 1,5 m. A different concept is realized by new PANAMAX container ships at present being delivered to German owners, which are built without longitudinal hatch girders, as can be seen from Fig. 1. the two main advantages of this arrangement are:

-the material is more effectively utilized at the topsides because the effectiveness of the longitudinal hatch girders is reduced with respect to longitudinal strength (typically to 60 - 80 %), and it is rather low with respect to torsional strength;

-without longitudinal hatch girders the width of the wing wall structures can be increased to nearly 2 m. This results in an increased torsional stiffness and reduced plate thicknesses, particularly if an effective topside box girder with an additional intermediate deck is arranged. By this arrangement also the stiffness of the connection between longitudinal and cross deck strips is increased.

Extensive finite element calculations were performed to optimize the design with respect to structural weight. The deformation behaviour was carefully analyzed, because the relatively long hold area and the reduced widths of the wing walls could result in increased warping deformations. Fig. 5 shows the max. warping deformations Δu (between port and starboard side) as a function of ship length, obtained from strength calculations of different container ships under realistic loads, including load cases with consideration of heeling. The warping deformations have to be observed with respect to relative displacements between hatch top and hatch cover and also to stresses in the transverse box girders and hatch corners.

As higher-tensile steel has been used for the major part of the ships, resulting in reduced plate thicknesses, it is important to check the buckling strength of the plate panels particularly in the lower part of the hull girder. In global strength analyses this can be performed by postprocessing programs which require the dimensions and orientation of typical plate panels as input data for the areas considered. In this way it is possible to perform an extensive check of the buckling strength even for very large structures in a reasonable amount of time.

Other remarkable features of the ships are so-called lashing bridges between the hatches. From these it is possible to lash the deck containers in the higher layers of the stack from more favourable positions. By this the amount of material and time for lashing is reduced considerably.

However, in addition to the loads arising from the containers, there are further loads acting in the lashing bars due to the relative displacements betwen hatch coaming and hatch covers or deck containers, respectively. To take these into account, finite element calculations were performed with a model of a lashing bridge containing also the end frames of the containers, see Fig. 6. Their stiffness as well as the relative displacements between hatch cover and coaming affect the results considerably.

4. Ships with Long Hatch Openings

Contrary to pure container ships having relatively short hatch openings, so-called multi-purpose cargo vessels are characterized by relatively long and wide hatches which make them more flexible to transport different types of cargo. In many cases a hatch length of 3 x 40' (about 37 m) is realized, in some cases even more.

In such ships the deformation of the hull sides is increased due to local pressures and cargo loads. Therefore, the transverse strength has to be considered together with the longitudinal and torsional strength. Fig. 7 shows the deformations of a typical multi-purpose vessel with a very long single deck opening for a heeled load case with high transverse loads.

This example illustrates the typical strength problems and critical areas of ships with relatively long hatch openings. Apart from the ends of the deck strips, the transverse members at approximately half hatch length are highly stressed, especially at the connection between the double bottom and side boxes. In many cases sufficient transverse strength can only be achieved by means of suitably reinforced and supported hatch covers. These limit the deformations and carry part of the transverse loads.

In such cases the finite element method is a valuable tool for a realistic prediction of the complex load transfer into both the longitudinal and transverse directions and of the interaction forces between hull and hatch covers. Within the calculation procedure described above, critical load cases can be defined also with respect to transverse strength. Particularly load cases in the heeled condition have to be considered in conjunction with the wave crest or trough at about half ship length in order to calculate the largest possible relative displacement between ship and hatch covers as well as the interaction forces between them. The same applies to the correct load transfer from the hold containers to the ship depending on the chosen type of stowage system.

Fig. 8 shows a typical supporting system (stoppers) of hatch covers in transverse direction frequently applied in multi-purpose ships with long hatch openings. The transverse forces from the deck are distributed to both sides, thereby limiting the transverse deflections and stresses to feasible values. In order to define the necessary clearance Δ at the stoppers allowing the covers to be handled at port, additional still water (harbour) load cases have to be analyzed.

The selected clearance, which allows limited sliding, causes a non-linear problem. This is normally solved by assuming in a first step zero horizontal interaction forces at those stoppers which allow limited sliding. Instead, additional load cases with pairs of unit forces at the stoppers are introduced. These are, in a second step, superimposed to the actual load cases such that the relative displacements at the stoppers do not exceed the given limits. Further details and results are described in [2].

The effect of friction forces can be considered in global finite element calculations, too, by superimposing additional unit load cases in a similar way as described above for the stopper forces [5].

5. Multi-Purpose Ships with Side Doors

For the handling of special cargo, such as paper rolls, additional side doors are sometimes arranged in multi-purpose cargo ships. If an elevator is located behind the side door, the opening is generally extended into the upper and lower decks. Large side openings require special reinforcements in that area. The case becomes rather complicated, if the deck is also opened by long and wide hatches. The structural behaviour and the necessary reinforcements required for such a ship can be well analyzed with the aid of an overall finite element model.

Fig. 9 shows the model of such a ship, which has been designed for the transport of paper rolls in addition to containers and general cargo. The transverse connection between the ship's sides in the hold area is formed by two cross deck strips arranged at the top of coaming forward and aft of the side door. A second deck with an elevator opening is arranged above the water line.

Both, wave bending and torsional load cases had to be considered for this ship. Due to the non-symmetrical geometry, the structure shows a complicated three-dimensional deformation behaviour. This is illustrated by the deformations and stresses at the top of coaming plotted in Fig. 10 for a wave hogging load case. The additional in-plane bending of the cross deck strips and local stress peaks due to the side opening can clearly be seen.

6. Concluding Remarks

The previous sections have shown that the finite element method is a valuable tool for the prediction and assessment of the strength and vibration behaviour of ships. It is in particular useful for new and unconventional vessels, for which no experience exists. Calculation results can be obtained with a high degree of reliability which enable rational design decisions to be made concerning the structure as well as the propulsion plant.

After the analysis of a large number of strength and vibration investigations for different types of ships, comprehensive experience has been gained, which is steadily verified by additional research work and onboard measurements. Experience and advisory service are made available to yards, as well as to shipowners, in order to solve specific problems and to find appropriate and efficient technical solutions for future designs.

7. Acknowledgements

Permission to publish the models and results of FE-calculations was kindly granted by Samsung Shipbuilding and Heavy Industries, Korea (PANAMAX container ships), HDW Kiel (various container ships) and J. J. Sietas KG, Hamburg (multi-purpose ships).

8. References

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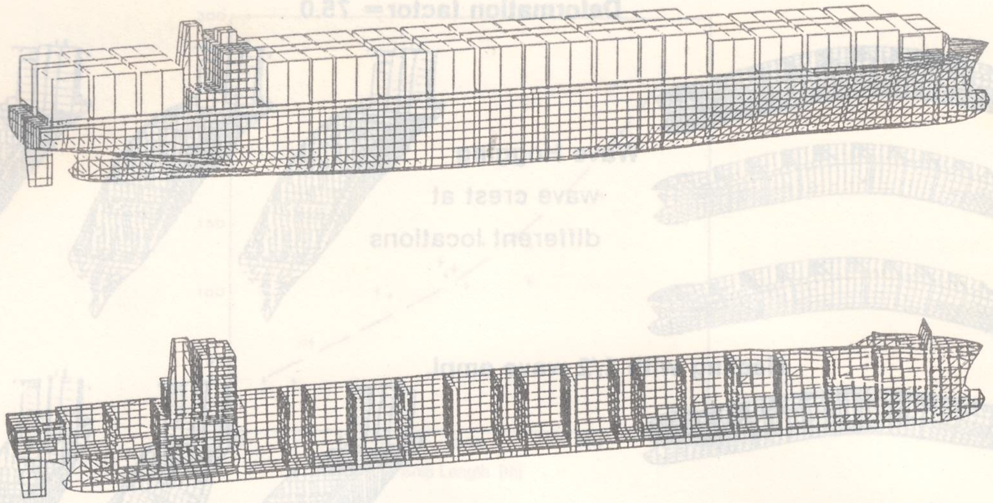

Fig. 1: Finite element model of the PANAMAX container ship "Hannover Express"

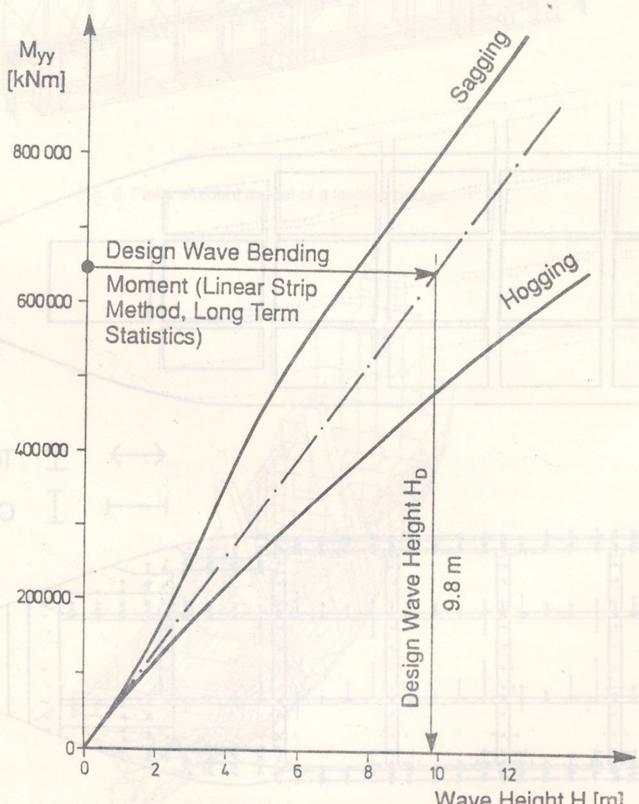

Fig. 2: Determination of design load parameters including non-linear effects

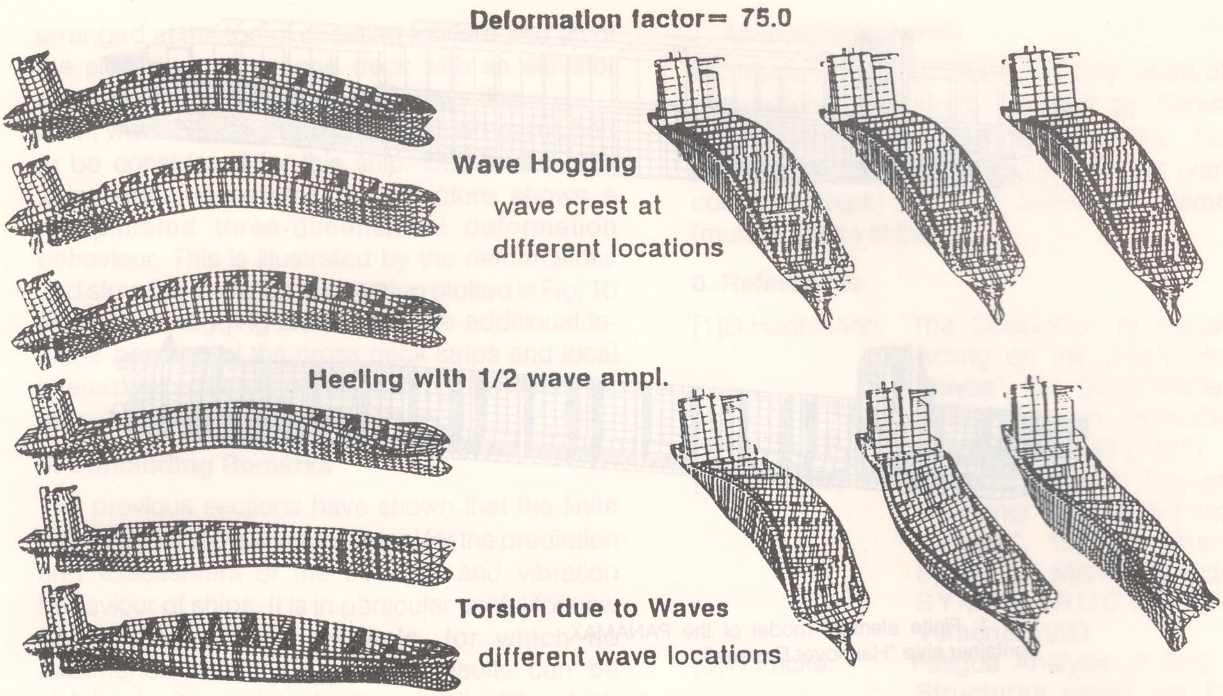

Fig. 3: Deformations of a container ship calculated for different load cases (Scale increased)

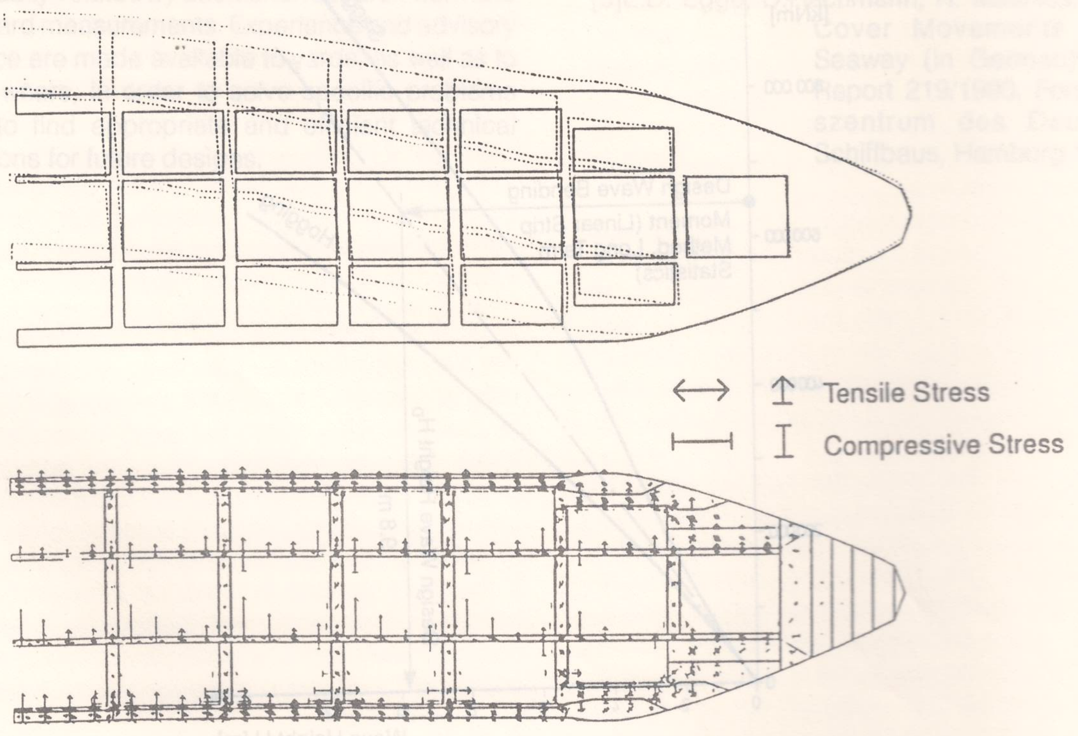

Fig. 4: Deformations and stresses of the upper deck of a container ship

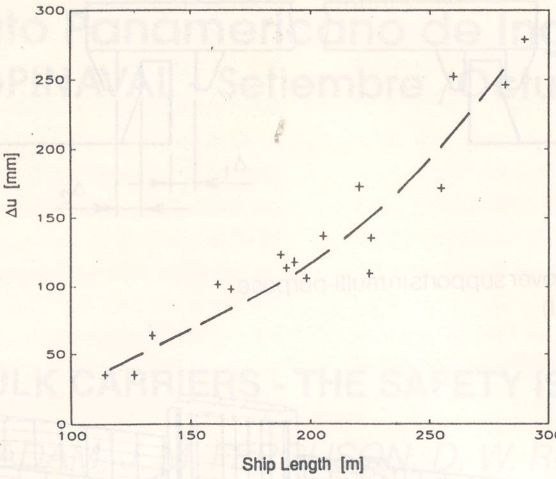

Fig. 5: Max. warping deflection ((LETRA GRIEGA DELTA))u calculated for container ships

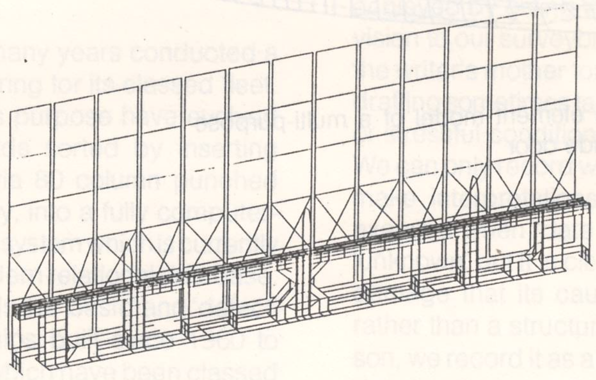

Fig. 6: Finite element model of a lashing bridge

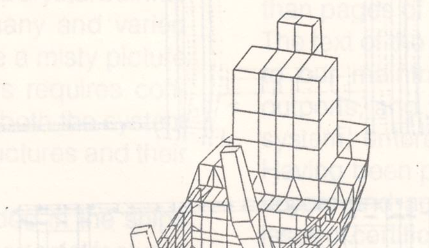

Fig. 7: Calculated transverse deformations of a multi-purpose vessel (Scale increased)

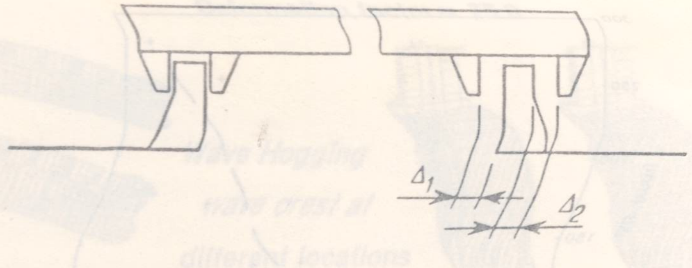

Fig. 8: Typical hatch cover supports in multi-purpose vessels (schematical)

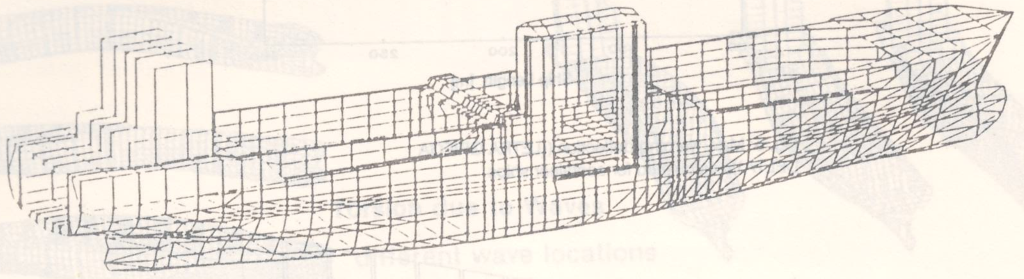

Fig. 9: Finite element model of a multi-purpose vessel with side door

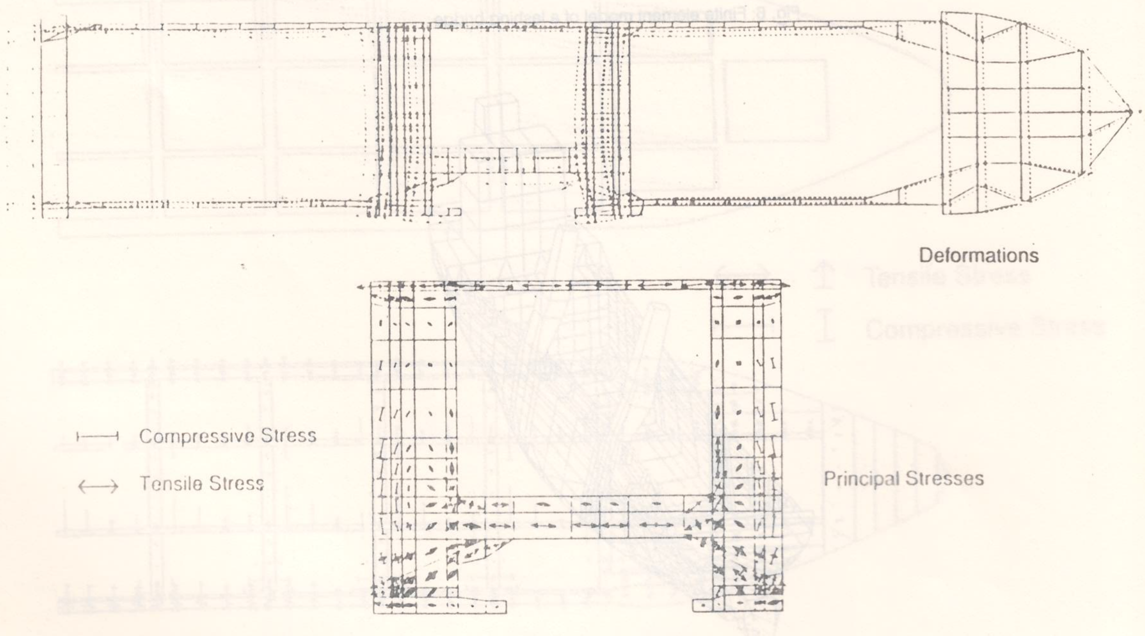

Fig. 10: Deformations and stresses at the top of coaming of a multi-purpose vessel with side door