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# On the Details of Structural Analysis of a Large Container Vessel

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**Abstract**

This paper deals with general procedure of the direct structural analysis of a container vessel and some difficulties encountered during the application of wave induced loads in real projects. Direct structural analysis requires a design wave representing the most probable extreme wave condition during its lifetime and an appropriate application scheme of wave loads into FE model of a hull. A design wave condition is determined by spectral analysis using the transfer function of a dominant load component, based on a given probability level. Dynamic and static load components are combined to get real condition of a vessel under waves. The effects of wave crest and trough are generated by modification of pressure distribution along the side shell. Counter accelerations are introduced to make the system in a state of equilibrium. FE model of the hull is also adjusted considering the realistic positions of center of gravity.

Several idealization schemes are adopted to apply inertia forces induced from the mass of a vessel combined with applied accelerations. Main attention is paid to keep global effects obtained in wave load analysis throughout structural analysis.

The results of rigorous application of wave loads into FE model are compared with those of simplified method in which only global effects such as vertical and horizontal bending moment and torsional moment are applied. It is shown that the proposed method gives more reliable results than the other methods, and is useful for practical uses.

## 1 Introduction

A vessel in waves meets with various forms of loads and the magnitude of load components will not be easily defined because of the variety of encountered sea states and randomness of wave loads. To ensure the safety of a vessel during its lifetime, designers should concentrate their efforts on defining the most probable extreme wave loads. It is widely accepted that some design waves can cover most of possible environmental loadings. Therefore, many studies on how to define design waves that can cover as many environmental conditions as possible have been proposed for decades. However only a few studies have been made

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for the topic on how to apply wave loads obtained from a selected design wave to FE model, for the application should overcome many tedious translation jobs and complicated problems such as equilibrium of a system and how to treat various cargo effects.

In this paper a scheme to determine design waves is shortly introduced and main attention is paid on the application procedure of wave loads into FE model of a container vessel. Before defining a design wave, a dominant load component should be chosen, the effects of which on the structural behavior of the vessel are critical for the purpose of design. The structure of container vessels is relatively weak against torsional moment compared with other kinds of vessels. In general torsional moment is considered a dominant load component for container vessels. Spectral analysis is performed using the Response Amplitude Operator(RAO) of torsional moment at critical points and modified Pierson-Moskowitz wave spectrum to define design waves.

Wave loads obtained from the design wave are modified to simulate a simultaneous condition in which torsional moment at a critical point becomes maximum, by considering the phase difference of real and imaginary components of wave loads. Static components of loads are also added to dynamic components to make the vessel under realistic condition in waves. The distribution of hydropressure near water line is adjusted to include the effects of wave elevation[1]. Wave loads obtained from the linear strip theory do not usually make themselves in a state of equilibrium. In addition to original unbalance, pressure distribution is modified as explained later. These bring the necessity of modifying the accelerations obtained from wave load analysis. The concept of counter acceleration is introduced to make the system in a state of equilibrium.

Even if well-organized wave loads are prepared, the application jobs of these loads into a FE model will induce additional errors which originate from many sources such as idealization scheme of the structure and cargo treatments. These error sources are investigated in the view point of practical uses. Mass distribution of a FE model is checked in terms of the longitudinal center of gravity(LCG) and the vertical center of gravity(VCG). Inertia loads applied on various forms of cargo are idealized considering interactions with the structures, and an additional model is devised to simulate force transmission mechanism. The distributions of dominant load component recalculated from FE model should be same to those of wave load analysis.

To assess validity of this rigorous application procedure, the results of simplified application procedure are provided and compared with those of the former.

# 2 Design Load

## 2.1 Design Wave Condition

In general major load components of seagoing vessels can be listed up as follows.

- global effects : vertical/horizontal bending moments
  and torsional moment
- motion responses

- accelerations and inertia forces
- hydropressure

A load component dominant to structural behaviors should be selected according to type of vessels and check points to get a relevant design wave condition. For example, Dynamic Load Approach(DLA) of ABS provides detail guides for selecting a relevant load component for each main structure member[2]. The concept of the design wave is utilized not only for the direct structural analysis but also for fatigue analysis which also requires the details of dynamic loads induced by waves.

For container vessels, there are two important components of dynamic loads. One is vertical wave bending moment and the other is torsional moment. These loads induce longitudinal stresses such as pure axial component and warping component, respectively. In a practical design procedure these two loads should be considered as dominant loads components. In this paper only torsional moment is chosen as a dominant load component for convenience sake.

The RAOs of torsional moment at aft and fore part are combined with wave spectrum to get short term responses. These points have large warping rigidity and are usually designed to resist high warping stress resulted from the abrupt changes of structure. The modified Pierson-Moskowitz spectrum is adopted as a wave spectrum and North Atlantic wave data of BMT is used to get long term responses. The probability level corresponding to ship's lifetime, 20 years, can be defined by various logics. In this paper zero-up-crossing period is used as the basis of defining the probability level.

If the long term distribution of torsional moment and the value of torsional moment corresponding to the probability level are obtained, an equivalent wave condition can be calculated. This wave condition has the effects of the most probable extreme torsional moment for 20 years. The wave frequency and heading angle corresponding to maximum RAO of torsional moment constitute the bases for the calculation of the height of the equivalent wave[3].

## 2.2 Modification of Wave Loads

Detail wave loads are calculated in frequency domain by linear strip theory using the design wave condition defined at the previous section, and are classified by hydrodynamic pressure, accelerations and global effects[4]. Wave loads consist of real and imaginary components, and the phase difference of every load component can be defined by simple manipulation of real and imaginary components.

For assessment of structural safety, the maximum value of the dominant load component should be applied to the structural model. By introducing the phase difference of design wave obtained from the dominant load component, the situation in which the dominant load component has the maximum value can be simulated. The simultaneous values of all load components are defined as shown below.

$$\text{(simultaneous value)} = \text{AMP} * \cos(\text{load} - \text{design}) * \text{Adesign}$$

where AMP = absolute value of every transfer function
load = phase difference of every load transfer function
design = phase difference of the design wave
Adesign = design wave amplitude

To simulate a realistic situation of the vessel in waves, the value of static component should be added to that of dynamic component defined by the formula shown above. Hydrostatic pressure and gravitational acceleration are to be added to the corresponding dynamic component. If only dynamic component of pressure is considered, negative pressure will have the physical meaning of 'suction'. The cases of negative pressure will be still common, even when dynamic pressure is combined with static pressure. In that case negative pressure can not be considered having physical meanings. Neither does positive hydro-pressure just at the water line have physical meanings because an abrupt change to zero pressure above water line is not a realistic phenomenon. The linear strip theory gives hydrodynamic pressure only below water line and assigns zero pressure above water line. Therefore following modifications of pressure distribution near the water line is inevitable to avoid the unrealistic conditions.

The scheme of combination with static pressure and modification of combined pressure is depicted in Fig.1. If the value of combined pressure at the water line is positive, pressure distribution will be extrapolated along the ship side above water line by hydrostatic rule. If negative pressure happens after the combination with static component, it will be substituted by zero pressure. The effects of wave elevation can be introduced by this modification scheme. Resultant water line at the position of wave crest goes up along the side shell because hydrodynamic pressure at the water line has positive value. Resultant water line at the position of wave trough goes down along the ship side because of negative value of hydrodynamic pressure at the water line. An example of modification of pressure distribution is shown in Fig.2. It can be easily found that wave elevation is automatically introduced by the modification scheme.

Wave loads are originally to be in a state of equilibrium. Hydro-pressure, acceleration, mass distribution of the vessel and additional global effects should meet themselves without unbalanced force and moment. Although depending on solvers, the linear strip theory does not give perfectly self-balanced loads in general. Besides the original unbalance of wave loads, pressure distribution is modified in the way shown above. Therefore another job to dissolve the unbalance of wave loads is required for a meaningful structural analysis. Based on the mass distribution and modified pressure, six degrees of acceleration which make the system in a state of equilibrium can be calculated reversely. These accelerations are called 'counter acceleration' to be distinguished from the original accelerations obtained from the wave load analysis. The global effects, i.e. vertical and horizontal bending moments and torsional moment should be recalculated because pressure distribution and accelerations are changed from the originals. But in this paper torsional moment , one of global effects, is adopted as the dominant load component which is the basis of the design wave condition. The design torsional moment should be kept constant through all analysis procedures. There is no other choice but modifying design wave amplitude to keep the design torsional moment constant on the basis of the changed pressure distribution and accelerations. Other global effects are determined based on the design torsional moment finally at this step.

# 3 Load Component and FE Model

A FE model of full breadth and full length of a container vessel of 4800 TEU is used as the model for direct structural analysis. The hull is idealized in the way widely used in ship yards and Classification Societies. The model and coordinate convention are shown in Fig.3. ANSYS is used as a preprocessor and solver, and several routines for simple calculations are made using the program language of ANSYS(APDL).

Wave loads based on a given design condition are obtained at the previous chapter and the components are classified as follows.

- hydropressure
- counter acceleration
- global effects : vertical/horizontal bending moments and torsional moment

The first two components are considered as local components directly applied to the FE model of the hull and the last is considered as secondary loading rather than directly applied load. At this chapter difficulties of application of the two local loads to the FE model are treated. The treatments of global effects will be made at next chapter.

The application of hydro-pressure requires information of surface element of the FE model and this is easily achieved by the help of a simple routine which transforms the pressures into nodal forces.

The mechanism of translation of inertia force applied on mass components of the vessel into the hull model depends on the forms of cargo. Before inertia force is generated, the distribution of mass of the vessel including various forms of cargo should be investigated. In this paper the mass components of container vessels are classified as follows for convenience sake.

- light weight and machinery
- consumable
- ballast water
- hold container
- deck container

Explanation about how to consider inertia forces induced from these items is made at the following sections.

## 3.1 Control of Distribution of Basic mass

Light weight and consumable are called basic mass in this paper and they are treated as one item. Consumable can be idealized by the lumped mass. Its portion, however, is not large compared with other items, so it is combined with light weight and controlled by density value of the FE model at once.

Basic mass is directly connected with the FE model of the hull and its distribution can be controlled by different types of density. Total mass, longitudinal center of gravity(LCG) and distribution form are adjusted by following steps.

- to devide FE model longitudinally into many sections
- to assign different material types to the elements of each section as shown in Fig.4
- to adjust density value of each material type and make mass distribution conform the required distribution

The adjustment of mass distribution is carried out by a routine prepared using APDL which assigns relevant density values to every section automatically.

## 3.2 Idealization of Ballast Water

Ballast water will induce internal pressure as the form of inertia force, when combined with acceleration. The feature for internal pressure to be applied to hull is depicted in Fig.5. The purpose of direct structural analysis with a whole FE model should be noted before an idealization scheme for ballast water is devised. The purpose is to get global behaviors of the vessel rather than local responses such as deflections and stress contour within a local panel. Therefore the details of internal pressure generated in ballast tank do not have to be fully considered and a simple idealization can be assumed enough for global behaviors of the vessel. The mass of ballast water is distributed into node points comprising ballast tank in the form of mass element as shown in Fig.7. In general ballast tank is modeled like honey cells bounded by stringer, transverse frame, longitudinal bulkhead and side shell as shown in Fig.6, which makes the inertia forces evenly transmitted to the primary structures.

## 3.3 Idealization of Hold Containers

The feature of transmission of inertia force applied on hold container is similar to the case of ballast tank. The structure of container holds, however, can not be modeled into the form of honey cells as the case of ballast tank, which requires another idealization scheme of transmission for the inertia forces on hold containers.

The force transmission mechanisms are shown in Fig.8. Loading patterns should be distinguished between the cases of TEU(twenty feet equivalent unit) and FEU(forty feet equivalent unit) because the contact points are different. Friction forces occurring at the contact area are neglected. Consideration of friction force, however, will be desirable, if information of friction coefficients for the contact areas is available. Applied forces are automatically calculated in the form of nodal force using the information of hold container, counter acceleration and node numbers corresponding contact points by APDL.

### 3.4 Idealization of Deck Containers

The idealization of inertia force applied on deck containers needs a special consideration different from the cases of ballast water and hold container. The position of center of gravity of deck container is above the supporting points on the hatch cover, which causes additional heeling moment when transverse acceleration is applied. The heeling moment should be balanced by additional reactions as shown in Fig.9.

Additional reactions compensating the heeling moment may be defined for every tier of deck containers manually. This job, however, will be complicated as well as tedious. Much efforts should be made to define the additional reaction forces and the force transmission effects of hatch covers which are not included into the FE model. Deck container is idealized into FE model instead of the substitution of the inertia force by nodal forces. Following attentions are paid to idealization of deck containers into the FE model.

- to simulate the force transmission mechanism adequately
- not to have any effect on the original stiffness of the hull
- to meet the position of center of gravity of deck containers

The diagram of FE model for deck container is shown in Fig.10. Beam elements are introduced to include the loading distribution role of hatch cover and to calibrate the position of gravity of the idealized deck container model. The position of gravity center of the hull can not be fully controlled only by longitudinal division explained at the previous section. Vertical gravity center of the whole hull combined with those of deck containers can be controlled by density adjustment of the solid and beam elements. Spring Elements with very small stiffness are idealized to avoid interference of the stiffness of the idealization with the hull stiffness. It will be accepted although this idealization scheme gives abnormally large deflection of deck containers. For the deflection of deck container is not a main concerning point of direct structural analysis.

## 4 Load Application and FE Analysis

To verify reliability of the proposed rigorous application of wave loads, a simplified application of wave loads is tried additionally. Only the global effects are simulated using the concept of simple beam theory, and local forces such as hydropressure and inertia force are not included.

## 4.1 Rigorous Application of Wave Loads

One of main purposes of direct structural analysis is to ensure global strength of the hull. To perform a reliable structural analysis, the original global effects based on design wave are to be applied to FE model as they are. After load components are prepared and applied to FE model, global effects, i.e. vertical and horizontal bending moments and torsional moment should be verified. In general it is very common that the global effects calculated from FE model differ from the originals because the details of mass distribution, i.e. gyration radius of roll, pitch, and yaw of FE model are difficult to be evaluated exactly. The global effects of FE model are calibrated automatically using APDL by adjusting mass distribution of the model.

Fig.11 shows the global effects obtained from FE model compared with the originals. It is found that the distribution of two cases are almost same.

By the help of the preceeding steps the FE model of the vessel under wave loads has become to a state of equilibrium. Constraints of only six degrees of freedom are enough to prevent a rigid motion because the system is in a state of equilibrium. Reaction forces at the constraint points are negligible. It means that this structural analysis does not contain any significant error and gives reliable results.

## 4.2 Simplified Application of Wave Loads

Global effects are generated by the longitudinal distribution of local loads in the rigorous application. There is an alternative method in simulating global effects not using complicated wave loads, i.e. local pressure and inertia force but using the distribution of artificial forces. The forces are calculated by applying simple equilibrium equations. The forces are suggested to be applied at the nodes of primary structures to avoid unrealistic stress concentration. In ship structure the nodes of every transverse frame are adequate for applying the artificial forces.

Special care should be taken in generating torsional moment because horizontal bending moment are closely related to torsional moment. A shear center is a reference point of the calculation of torsional moment for container vessels. Horizontal forces simulating horizontal bending moment distribution induces additional torsional moments, the values of which are determined by the distance of force applied points from a reference shear center. The loading types inducing torsional moment are shown in Fig.12. The simplified approach adopts the first two types of loading to generate torsional moment. The sum of torsional moments induced from the two types of loading should meet the original torsional moment. Therefore the value of antisymmetric vertical force depends on the position of horizontal force. To find the tendencies of the behaviors according to the position of horizontal force, three cases of 0.46*T(T:draft), 0.7*T and 1.0*T above bottom are investigated.

Fig.13 shows an example of simple approach to gernerate global effects. Vertical force components and horizontal components are generated to make global effects.

Table 1: Vertical and horizontal deflections at two typical points of the coaming top plan (unit:mm) (*Check pints are shown in Fig.15.)

| check point | direction | rigorous application | simplified applications | | |
|---|---|---|---|---|---|
| | | | 0.46*T | 0.7*T | 1.0*T |
| A | uz | 28.2 | 35.0 | 31.8 | 31.1 |
| | uy | 10.9 | 2.1 | 5.3 | 7.6 |
| B | uz | 30.0 | 36.4 | 33.2 | 32.7 |
| | uy | 10.8 | 2.2 | 5.4 | 7.8 |

Table 2: Comparison of axial stress of hatch corner on the coaming top in front of deck house (unit:N/mm2)

| position | rigorous application | simplified applications | | |
|---|---|---|---|---|
| | | 0.46*T | 0.7*T | 1.0*T |
| starboard | 215.1 | 204.0 | 223.1 | 219.1 |
| port | 216.1 | 231.1 | 224.1 | 220.1 |

### 4.3 Comparison of Results

Local effects can not be compared because the simple method does not include pressure forces and inertia forces. Only a few typical results corresponding to global behaviors are compared.

- the distribution of elongations of hatch openings
- vertical/horizontal deflections at typical points
- axial stress at the hatch corner on the coaming top in front of deck house

For the simple approach, the distribution of elongations are different case by case as shown in Fig.14, even if they simulate the same global effects. It can be concluded that the position of equivalent horizontal force has a great effects on global behaviors.

The results of the case of (1.0*T) are similar to those of the rigorous application. Noting the modified pressure distribution shown in Fig.2, resultant unbalanced horizontal force can be idealized to apply near 1.0*T of the section.

## 5 Conclusions

Practical procedure have been proposed for the application of wave loads directly obtained in wave load analysis.

Hydrodynamic pressure is combined with static pressure and modified to consider the effects of wave elevation. Self-balance beween wave loads is one of critical points for a reliable structural analysis and counter accelerations are calculated reversely for the purpose. Great efforts have been made to keep the distribution of global effects through all application steps.

In the application procedure of wave loads to the FE model, various idealization schemes of inertia forces on the cargo and the hull have been made. Lumped mass elements corresponding to ballast water are introduced in the zone of ballast tank. Hydropressure on surface hull and inertia force on hold containers are applied in the form of nodal force generated automatically. For deck container, direct modeling scheme is selected. Without interference with hull stiffness, containers are connected at the supporting points by weak spring elements. The role of hatch cover for force distribution is simulated by modelling of beam elements by which VCGs of containers are controlled. Global effects are finally recalculated with the FE model and all applied forces, and the distributions are calibrated to the originals without any loss of consistency.

The results of the proposed rigorous structural analysis are compared with those of the simple application of wave loads where only global effects are represented by artificial forces. It is shown that the proposed method is useful for the respects of reliabilty of the results.

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[2] ABS, Guide for Dynamic Based Design and Evaluation of Tanker Structures, 1993

[3] W. Fricke, "Strength and Vibration Analysis of Modern Cargo Ships Using the Finite Element Method," The North East Coast Instruction of Engineers and Shipbuilders, 1991

[4] Armin Walter Troesh, "The diffraction Forces for a Ship Moving in Oblique Seas," *Journal of Ship Research*, Vol.23, No.2, 1979

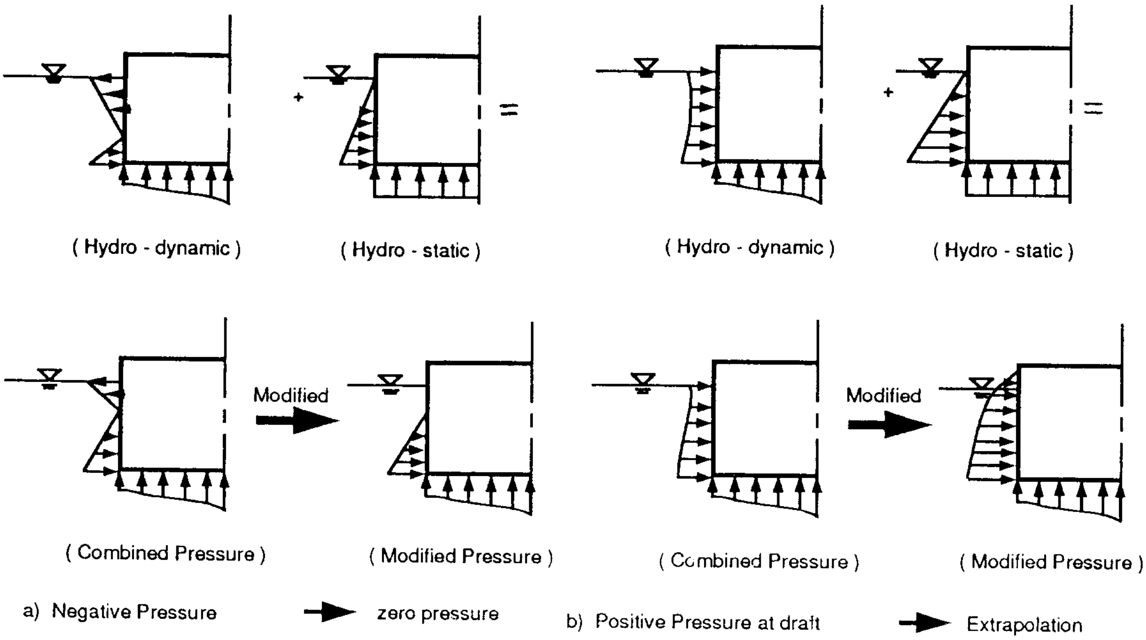



Figure 1: Pressure modification scheme for considering wave elevation

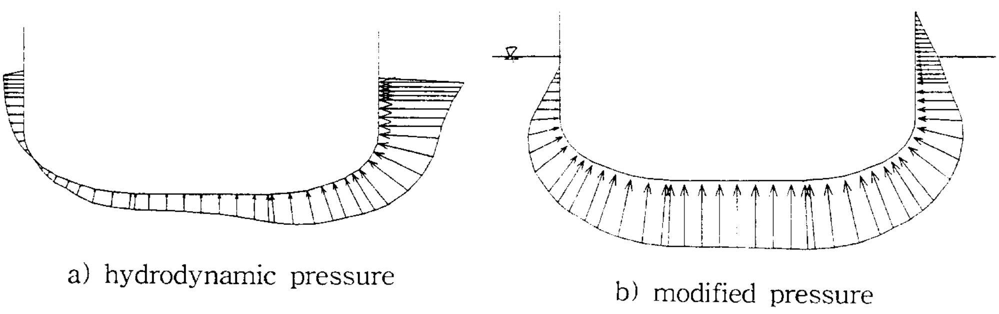



Figure 2: An example of modification of hydro-pressure

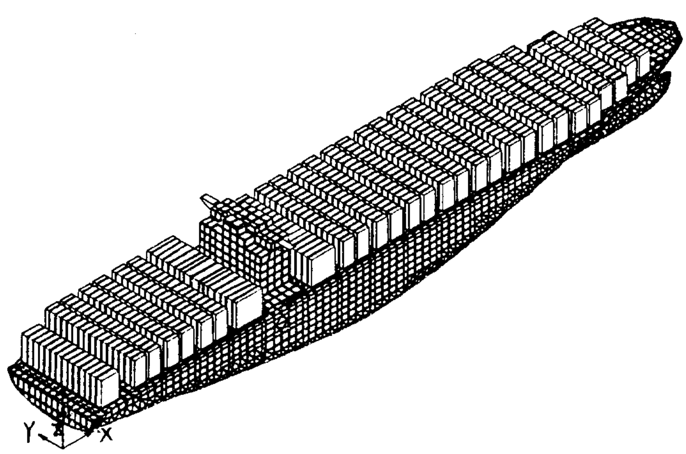



Figure 3: FE model and coordinate system

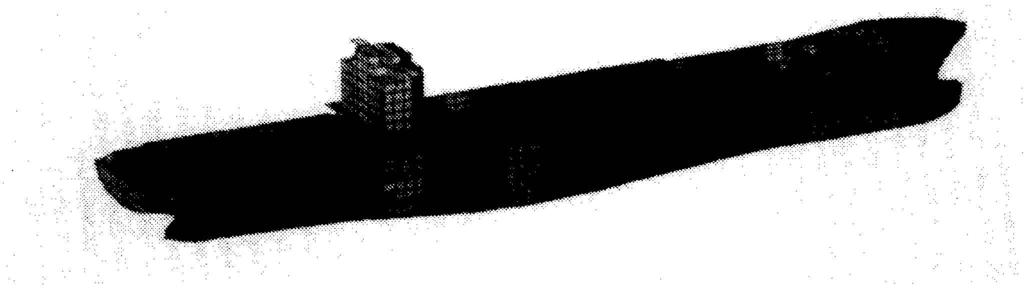


Figure 4: FE model with longitudinally different material types

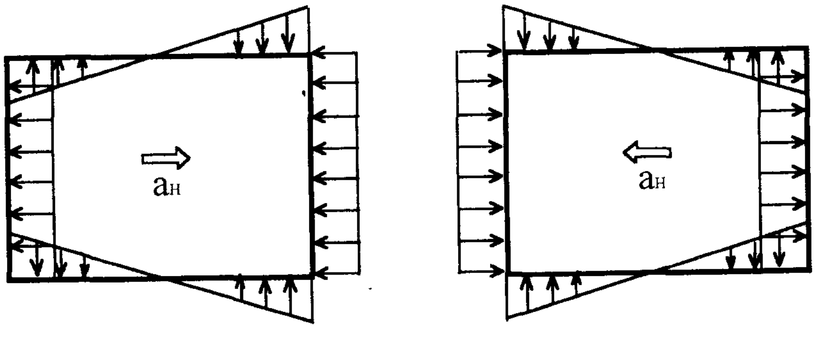



Figure 5: Internal pressure induced from liquid cargo for transverse acceleration

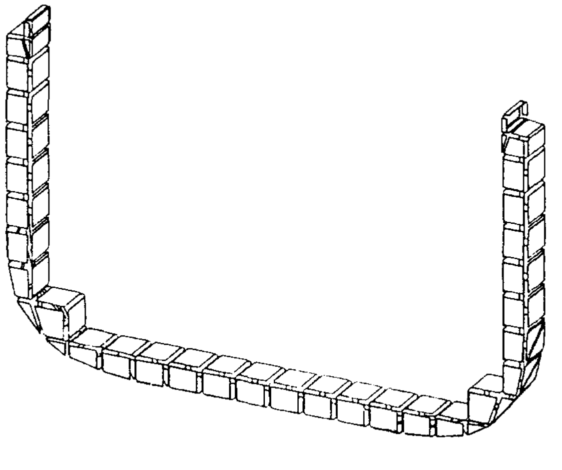


Figure 6: Typical FE model of ballast tank

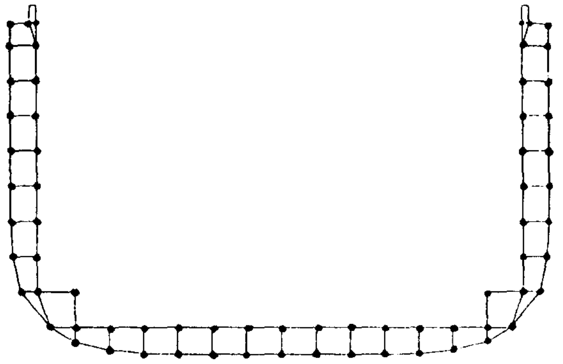


Figure 7: Idealized mass element for ballast water

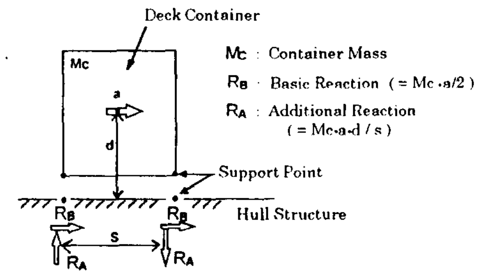



Figure 9: Additional heeling moment generated by deck container

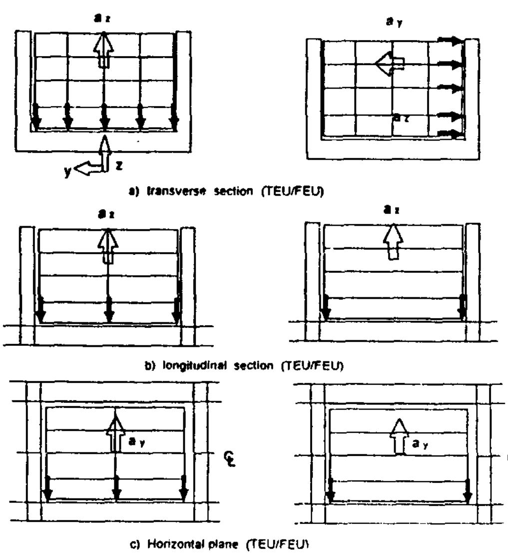



Figure 8: Idealization of inertia force generated by deck container

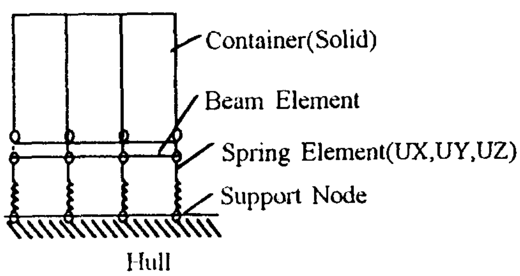



Figure 10: Diagram of idealized FE model of a deck container

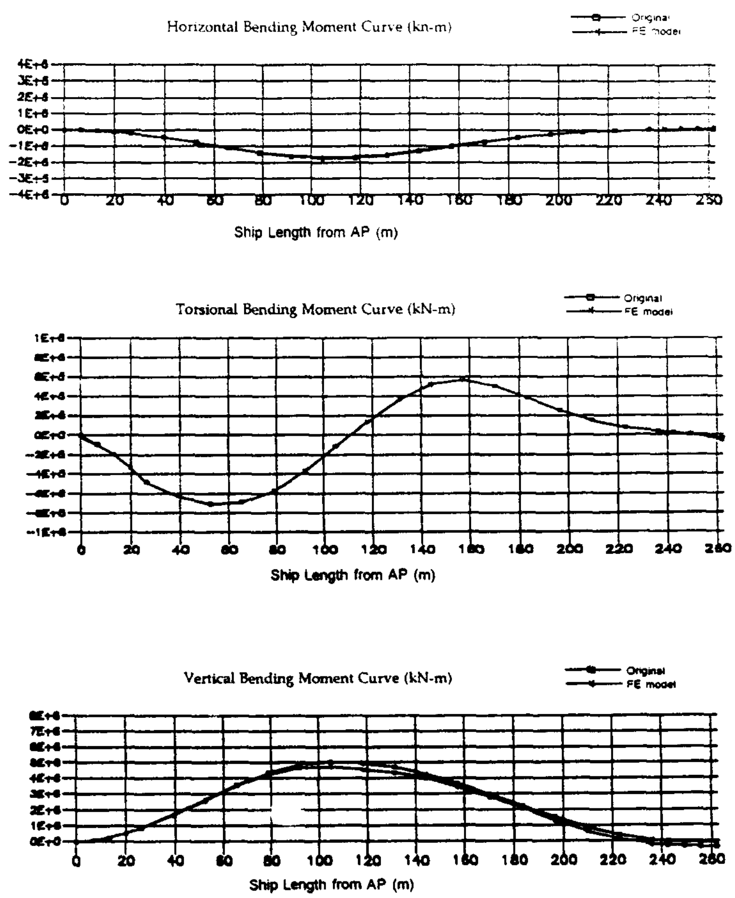



Figure 11: Comparison of global effects of FE model and the originals

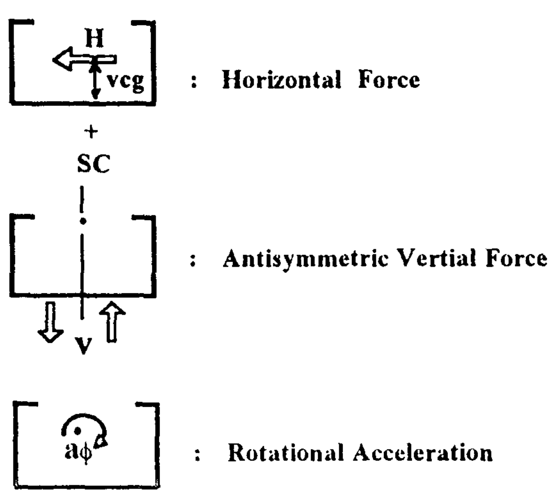
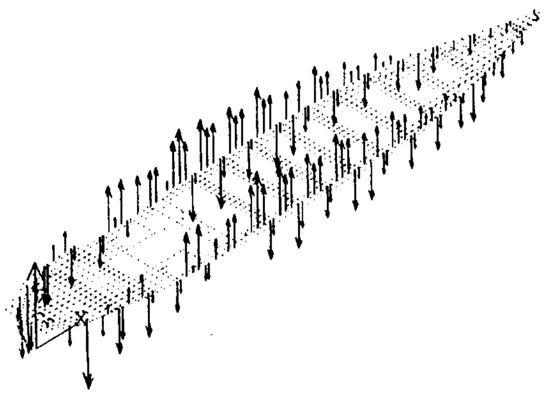
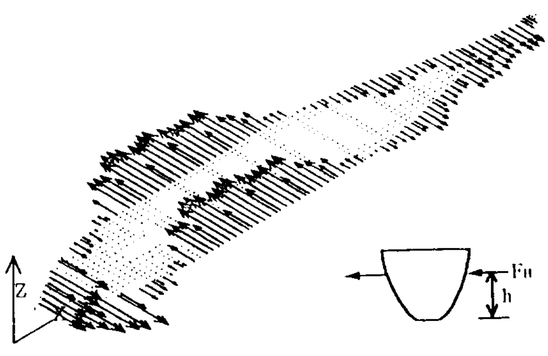



Figure 12: Three types of torsion mechanism




a) vertical forces




b) horizontal forces

Figure 13: An example of simple simulation of global effects

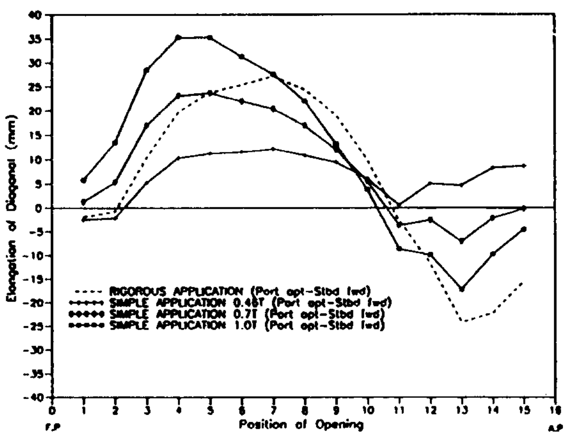



Figure 14: Longitudinal distribution of elongation of hatch openings

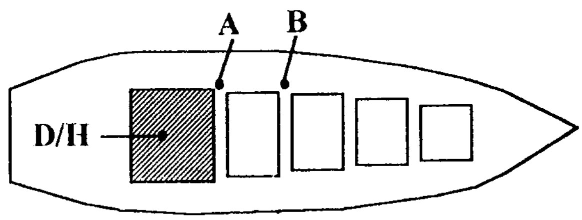



Figure 15: Two typical points for the check of deflection