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VOLUME 3

COMMITTEE II.1

QUASI-STATIC RESPONSE

COMMITTEE MANDATE

Concern for the quasi-static response of ship and offshore structures, as required for safety and serviceability assessments. Attention shall be given to uncertainty of calculation models for use in reliability methods, and to consider both exact and approximate methods for the determination of stresses appropriate for different acceptance criteria.

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1 DISCUSSION

1.1 Official Discussion by Toichi Fukasawa

1.1.1 Preface

First of all, the discusser expresses his sincere appreciation to the committee members for their extensive research works on the Quasi-Static Responses. The quasi-static response is the fundamental bridge between the load and response of ships and offshore structures, and is directly linked to the actual structural design. With the progress of computers and the development of soft wares, nonlinearities of loads acting on ships and offshore structures are estimated in detail recently, and even the large scale dynamic stress analyses are getting to be possible in the structural analysis. In the structural design stage, however, it is still usual to adopt the quasi-static response analysis, rather than the dynamic response analysis, particularly in the early design stage. Mainly because the dynamic structural response analysis is quite time-consuming, it would be preferable to use such a method as the quasi-static response analysis in the structural design stage of ships and offshore structures.

In employing the quasi-static response analysis in appropriate way, it is firstly important to recognise the discrepancy between dynamic and quasi-static analyses, in particular the hypothesis in the simplification of the processes. It is then necessary to figure out the accuracy of approximation in the response calculations using a structural analysis technique with various loads acting on the structure. The individual topics with respect to the quasi-static responses are explained in detail in the committee report, including uncertainties associated with reliability assessment. The discusser therefore would like to make comprehensive comments on the report from the viewpoint of the application of quasi-static response analysis to the structural design of ships and offshore structures.

1.1.2 Quasi-Static Modelling of a Dynamic Problem

As a ship is sailing in waves and an offshore structure is used in waves, the behaviours of these structures are essentially time dependent and the structural responses should be analysed taking account of dynamic effects in a precise sense. The equation of motion of the structural response of such structures can be written in the following form in general.

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{f\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass matrix, the damping matrix and the stiffness matrix respectively, which can be obtained by means of structural modelling technique such as FEM. $\{f\}$ is the displacement vector in generalised coordinate. $\{q\}$ is the force vector comprised of several types of loads of different amplitudes, phase angles and frequencies. As the loads acting on the structure are mostly nonlinear, to be exact, Eq.(1) should be solved in time domain taking account of various nonlinearities of the loads; however, it is usual to reduce the dynamic problem to a quasi-static problem particularly in the ship structural design stage because enormous time and efforts are required to solve the dynamic problem strictly.

To reduce the dynamic problem to a quasi-static problem, the time variation of structural response is usually assumed to be a sinusoidal variation or its superposition; that is, the displacement vector is assumed to be

$$\{q\} = \{\overline{q}\}e^{i\Omega t} \tag{2}$$

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where $\{\overline{q}\}$ is the response amplitude and Ω is the response frequency. Substituting Eq.(2) into Eq.(1), and ignoring the force vector, we have

$$\left([K] + i\Omega[C] - \Omega^2[M]\right)\{\overline{q}\} = 0 \tag{3}$$

Eq.(3) is an eigenvalue problem. The eigenfrequency of the structure can be obtained assuming the proportional damping for the damping matrix, or simply ignoring the damping matrix. With the use of the eigenfrequency ω, Eq.(1) can be reduced to

$$\left(1 - \frac{\omega^2}{\Omega^2}\right)[K]\{\overline{q}\}e^{i\omega t} = \{\overline{f}\}e^{i\omega t} \tag{4}$$

where the force acting on the ship is considered to vary in time with the frequency ω and the amplitude $\{\overline{f}\}$. In the case where the eigenfrequency of the structure is much higher than that of the external force, Eq.(4) can be approximated to be

$$[K]\{\overline{q}\} = \{\overline{f}\} \tag{5}$$

This is the basic idea of the quasi-static response analysis. The idea is sometimes extended to a general form as

$$[K]\{q\} = \{f\} \tag{6}$$

Eq.(6) will be solved in the quasi-static analysis. Different from the pure static analysis, the loads are mostly dynamic and sometimes nonlinear, and the load components which constitute the force vector in Eq.(6) have different phase angles in general as well as the different amplitudes and the frequencies.

It should be noted here that the basic assumption "the eigenfrequency of the structure is much higher than that of the external load" should be still kept in Eq.(6). In terms of this assumption, special attentions should be paid in the case where slamming, sloshing and other impulsive load are applied to the structure, because the duration of impulsive loads are very short in most cases comparing with the natural period of fundamental vibration of the structure. There are a number of research works on the impulsive loads as shown in the committee report, but the noteworthy point would be the practical treatment of impulsive loads, such as slamming, sloshing etc. in the quasi-static structural response and the effect of such treatment of the impulsive loads on the structural responses.

1.1.3 Load Characteristics and Structural Analysis

In the structural design stage of ships and offshore structures, the buckling strength, the ultimate strength, the fatigue strength and so on are evaluated mainly by means of the quasi-static response calculation. In these evaluations, the maximum or the minimum stress is usually needed for the design purpose. In order to obtain the maximum or the minimum stress by the quasi-static response analysis, to begin with, it is convenient if the moment when the stress becomes maximum or minimum in time domain is known. With the development of load estimation procedures recently, time variation of pressure or load acting on the ships and offshore structures can be calculated and it is possible to know the moment when the pressure at a certain point becomes maximum or minimum in time domain; however, the peak stress at a point of the structure does not necessarily occur at the same time as the peak load in general. One of the most obvious examples is the wave-induced pressure at a certain point and the resulting stress at other points. Thus, the moment when the stress

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at a certain point becomes maximum or minimum in time domain cannot be known without structural analysis a priori from the load information in general. This means that the structural analysis is inevitable to obtain the maximum or minimum stress in time domain; however, the structural analysis sometimes needs much time and effort. In this context, the number of structural analysis is the key in ship structural design from the viewpoint of efficiency.

As the number of structural analyses depends on the load type, the load component acting on ship's hull is firstly categorised. The load type would be categorised in the following 3 types, that is,

- Load Type I: A load corresponds one-to-one with stress in time domain, such as hull girder bending moment.
- Load Type II: A load of which distribution profile does not change in time but the magnitude changes, such as internal liquid pressure.
- Load Type III: A load of which distribution profile and magnitude both change in time, such as external pressure caused by waves.

It is easy to estimate the moment when the stress becomes maximum or minimum in time for the Load Type I, because the load and the stress correspond one-to-one in time domain; for example, stress due to hull girder bending can be calculated by dividing the bending moment by the section modulus of the ship. FEM analysis is not necessary in this case unless stress concentration is concerned.

Liquid cargo or ballast water of a ship acts on the ship structure as internal pressure. The internal pressure of a fully-filled tank can be treated as the inertia force of the liquid mass caused by the acceleration due to ship motions as shown in Figure1. It is well accepted that the grain or coal can also be treated in the similar manner, although the shearing stress component is to be added. The internal pressure is caused by the acceleration of cargo or ballast water, and the acceleration can be separated into x-, y-, and z-components. In each acceleration component, the pressure distribution profile does not change in time, but only the magnitude of the profile is varying time to time according to the accelerations. FE analysis is necessary to calculate the stress caused by internal pressure; however, the calculation effort is not so heavy, that is, the structural analysis is only necessary for 3 acceleration components assuming the load-stress linearity, and the pressures due to unit amplitude of each acceleration component can be used in the FE analysis. The amplitude and phase lag of the stress due to internal pressure can be determined by superposing the calculated stress components taking account of the phase angle of each acceleration component.

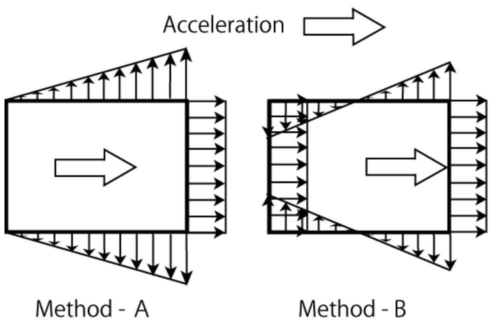

Figure 1: Internal pressure distributions

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On the other hand, in the case of external pressures in waves, not only the pressure magnitude but also the pressure distribution profile vary in time according to the wave profile as shown in Figure 2. It is easy to know when the pressure becomes maximum or minimum at a certain pressure point in this case; however, it is not possible to know the moment when the stress at a certain point becomes maximum or minimum without structural analysis. There are phase lags between external pressure of each pressure point in general, particularly in shorter wavelength cases. This means that so-called "maximum pressure distribution" or "minimum pressure distribution" cannot necessarily be defined to be exact.

In the case of external pressure in waves, moreover, the wave surface relatively moves up and down along the ship's side shell in a seaway as shown in Figure 2. As the relative magnitude of the wave surface movement could be the same order of the wave height, the wave elevation along the ship's side shell cannot be ignored in the estimation of the stresses caused by the external pressure in waves. The pressure at a certain point near the still water surface is positive when the point is submerged under the wave surface, while it is zero when the point comes out over the wave surface. This is known as the "pressure nonlinearity", and the distribution profile of non-dimensional pressure cannot be the same in time, different from the internal pressure case. The ordinary linear superposition technique cannot be used in this case.

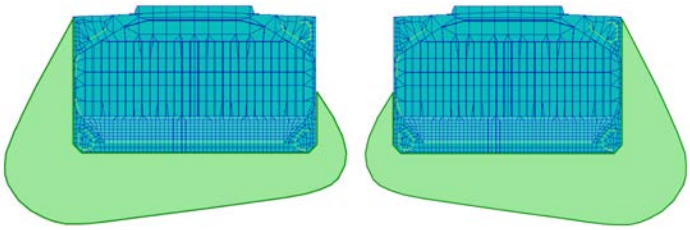

Figure 2: External pressure distributions

Strictly speaking, time domain structural analyses are necessary to obtain the stress amplitude and phase lag due to the external pressures in waves because of the "pressure nonlinearity". If the quasi-static analysis is adopted, rather than the dynamic analysis, the approximation would be as follows in this case. Assuming the response in regular waves for simplicity, the wave encounter period is divided into various points in time. The quasi-static structural analyses are conducted at given times applying the external pressure in waves at each instant. As the stresses are obtained at given times, the magnitude and the phase angle of the stress are calculated by interpolating the obtained stresses as a sinusoidal function in time. This procedure is rather strict and the pressure nonlinearity can be taken into account, but this would require too many stress analyses for the structural design purpose.

In order to simplify the above method, some assumptions are necessary. If the pressure nonlinearity is assumed to be insignificant, the wetted area on the ship surface can be considered to be unchanged. And also, if the external loads vary in sinusoidal manner in time, the pressure can be decomposed into sine and cosine components, and Eq.(6) can be written as

$$[K]\{q\} = \{f_c\}\cos\omega t + \{f_s\}\sin\omega t \tag{7}$$

Assuming that the structural response is in simple harmonic,

$$\{q\} = \{q_c\}\cos\omega t + \{q_s\}\sin\omega t \tag{8}$$

the response amplitude can be obtained by solving the following equations.

$$[K]\{q_c\} = \{f_c\} \tag{9}$$

$$[K]\{q_s\} = \{f_s\} \tag{10}$$

This means that the structural analysis is only necessary for Eqs.(9) and (10), even if the phase angles of external pressure in waves are different from each other.

Another alternative way would be as follows. In the case where the structural response can be considered to be linear, a linear superposition method is available to calculate the stress amplitudes. Dividing the surface of ship's hull into a number of panels upon which the external pressure in waves is applied, the load-stress influence matrix is calculated at a certain stress point by applying the unit load on each panel one by one by means of stress analyses. Superimposing the load-stress influence matrix according to the distribution profile of the external pressure in waves, the stress due to any kind of pressure distributions can be calculated. This method is known as DISAM (DIScrete Analysis Method, see Kuramoto *et al.* (1991)).

The different approach would be that to approximate the "maximum pressure distribution" or the "minimum pressure distribution". As was shown before, the "maximum pressure distribution" or the "minimum pressure distribution" cannot be defined strictly, because the pressure at each point varies in time with different phase lags. In the approximation, the pressure distribution when the pressure at a representative point becomes maximum or minimum is assumed to be the "maximum pressure distribution" or the "minimum pressure distribution". An example of this method would be the design load provided by the classification societies' rule.

In any cases described above, the compromise between the accuracy and the number of structural analysis would be the key in the structural design stage of ships and offshore structures. Even in the quasi-static response analysis, FE analysis is necessary to be conducted to some extent. It would be important to know the merit and the demerit of each approximate procedure to obtain the maximum or minimum stress due to various loads, bearing in mind of the recent development of computers and soft wares.

1.1.4 Internal Load and Load Combination

The ISSC committee II.1 have reported on the various loads including ice loads, slam loads and accidental loads. These reviewed loads are mainly related to the external loads, that is, the loads acting on the ship structure from outside. In the ship structure, however, another important load, the internal load, is acting on the ship from inside. For example, the oil pressure is acting on tankers, the ore or coal pressure is acting on bulk carriers, and the container load is acting on container ships, as well as the ballast water pressure. The magnitude of the internal pressure is not small, but is comparable to the external pressure caused in waves. If the internal and the external pressures are acting on the ship in the same phase from each side of the ship's hull, the pressures are cancelled out and any stress may not be induced. On the other hand, the internal and external pressures are acting on the ship in the opposite phase from each side of the ship's hull, the magnitude of the pressure acting on the hull will be doubled. Because of this, the internal loads are very important in the ship structural design.

When the tank or cargo hold of a ship is partially filled with liquid, well-known sloshing phenomenon may occur, of which pressure can be estimated by numerical simulations or other formulae based on the experiment as was shown in the committee report.

On the other hand, if the tank is fully-filled with the liquid, only the pressure due to the gravitational acceleration and the acceleration of ship motions occurs. In order to estimate these pressures, it is necessary to determine the "reference point" of the internal pressure, which is defined as the point where the pressure is always zero such as the free surface in a partially filled tank case; however, it is known that the reference point cannot be determines theoretically under the incompressible fluid assumption. Several methods to predict the reference point of pressure have been examined based on the experimental results (e.g. Ship Research Panel 228 (1999)); however, the results were not unique. In fact, the reference point is different, case by case, in the common structural rules for bulk carriers and double hull oil tankers. The internal pressure of the dry bulk cargo is also provided in the Common Structural Rules for bulk carriers. It is possible to treat the pressure of bulk cargo in a similar way as the liquid pressure except for the shearing stress. There seems to be a room to investigate further the pressure distribution of internal liquid cargo in a fully-filled tank particularly in a ballast tank of complicated shape and the behaviour of bulk cargos in a hold in detail.

As for the actual ship in a sea way, stresses of a certain structural member are resulted by multiple loads, for example, due to hull girder bending, internal pressure of cargo or ballast water, external sea pressure caused in waves, and so on. It is, therefore, necessary to superpose the stresses caused by such plural load component to obtain the total stress acting on a certain structural member of a ship. General superposition procedure of stresses due to several load components is shown in the followings.

Let the dynamic stress components caused by hull girder bending, internal pressure and external pressure be denoted as , and , and the static stress be. The superposed total stress can be given by

$$\sigma_t = \sigma_i + \sigma_e + \sigma_b + \overline{\sigma}_s \tag{11}$$

As the dynamic stresses have phase difference each other, the stress components in regular wave are given by

$$\sigma_b = \overline{\sigma}_b \cos(\omega t - \varepsilon_b) \tag{12}$$

$$\sigma_i = \overline{\sigma}_i \cos(\omega t - \varepsilon_i) \tag{13}$$

$$\sigma_e = \overline{\sigma}_e \cos(\omega t - \varepsilon_e) \tag{14}$$

where is the encounter frequency of the ship and wave. Substituting Eqs.(12), (13), (14) into Eq.(11), we have

$$\sigma_t = \overline{\sigma}_s + \overline{\sigma}_d \cos(\omega t - \varepsilon_d) \tag{15}$$

where

$$\overline{\sigma}_d = \sqrt{\overline{\sigma}_b^2 + \overline{\sigma}_i^2 + \overline{\sigma}_e^2 + 2\overline{\sigma}_b\overline{\sigma}_i \cos(\varepsilon_b - \varepsilon_i) + 2\overline{\sigma}_i\overline{\sigma}_e \cos(\varepsilon_i - \varepsilon_e) + 2\overline{\sigma}_e\overline{\sigma}_b \cos(\varepsilon_e - \varepsilon_b)} \tag{16}$$

$$\varepsilon_d = \tan^{-1}\left(\frac{\overline{\sigma}_b \sin\varepsilon_b + \overline{\sigma}_i \sin\varepsilon_i + \overline{\sigma}_e \sin\varepsilon_e}{\overline{\sigma}_b \cos\varepsilon_b + \overline{\sigma}_i \cos\varepsilon_i + \overline{\sigma}_e \cos\varepsilon_e}\right) \tag{17}$$

Eqs.(16) and (17) represent the amplitude and the phase angle of the total stress caused by the plural stress components. It should be noted here that not only the amplitude but also the phase angle of each stress component are necessary to estimate the stress amplitude of total stress. As was mentioned before, it is not easy to calculate the phase angle of the stress caused by the external pressure in waves. It may be necessary to adopt some practical techniques to superpose the multiple stress components in the ship structural design.

1.1.5 Buckling and Ultimate Strength

One of the most important strength of ships and offshore structures is the buckling and the ultimate strength. The quasi-static response analysis is often applied to these problems because the dynamic effects can be disregarded in most cases. In the assessment of the buckling strength and particularly the ultimate strength of a ship, it is basically necessary to obtain the maximum load. In the case where a single load component is applied to the structure, a "design wave" concept is often adopted to estimate the extreme ship response. A regular wave train is usually adopted as the design wave and is properly calibrated by a stochastic analysis; the wave height and wavelength of the design wave are chosen so that the maximum load and resulting maximum stress are expected to occur. In the case where multiple load components are applied to the structure, however, it is not easy to define a single design wave because each load component has different phase angle generally. Maximum stress occurs in a certain structural member in the design wave for a certain load component, but this design wave may not cause the maximum stress for the other load component. It would be a practical way to use several design waves in this case according to each load component, although how to superpose the maximum stresses due to each load component may arise a new problem. In any cases, it may be possible to know the maximum "load" in the design wave method, but this does not directly lead to the estimation of the maximum "stress" as was mentioned before. The phase information of load and response is indispensable particularly in the above mentioned Load Type III or the multiple load case to estimate the maximum stress.

In conjunction with the buckling and ultimate strength of a ship, it is getting to be common to take account of the uncertainties associated with reliability based quasi-static response assessment as is shown in the committee report. In the reliability analysis, not only the magnitude of stress but also the statistical properties such as the variance of stress are needed. The exceeding values of ship response in her life can be calculated by a frequency domain analysis, or a spectral method, where statistical values of linear ship response in a short-term sea state are calculated based on the wave spectrum and the transfer function of ship response. The tail parts of the long-term prediction of the stress can also be estimated by using the statistics of extreme value, and recently the First Order Reliability Method (FORM) is also adopted extensively. Most of these researches, however, are carried out on the external loads or at most the stress caused by the above mentioned Load Type I such as bending moment of ship hull girder. As was mentioned before, the maximum load does not necessarily give the maximum stress in some load types. In this aspect, the important point in the quasi-static response analysis would be how to convert the useful information obtained in the "load" to the "stress". Future works may be necessary focusing on the reliability-based structural analysis technique to estimate the global and local stresses caused by multiple loads.

1.1.6 Fatigue Strength

In contrast to the buckling and the ultimate strength, the problem is more complicated in the fatigue strength. In the ship structural design, the fatigue strength is usually evaluated by the crack initiation: Adopting the linear cumulative damage law such as Miner's rule, the cumulative fatigue damage factor is calculated and is used for the judgement of crack initiation. According to the probabilistic approach, the stress transfer function is firstly calculated, and the short-term and the long-term prediction of the stress are carried out with the use of the wave spectrum and the wave scatter diagram. On the other hand, the fatigue strength is sometimes evaluated by means of the crack growth analysis according to Paris law. The reason is that the order of stress occurrence affects the crack propagation considerably, and such nonlinearity is one of the important factors in actual fatigue damages. Miner's rule may be unsatisfactory from this point of view. Crack propagation is to be simulated with the use of stress time histories of a certain structural member of the ship in waves. Although there might be several ways to estimate the stress time histories, a practical and simple way is to utilise a stress transfer function. Time-varying stress histories can be generated from the stress spectrum calculated by the stress transfer function and the wave spectrum.

In this way, the stress transfer function is actually useful in the estimation of fatigue strength of ships and offshore structures; however, it is not easy to obtain the stress transfer function caused by various load components. The stress transfer function represents the amplitude and the phase angle of stress as a function of wave length and wave direction. As several load components, such as hull girder bending, internal pressure of cargo or ballast water, external pressure in waves, are acting on the ship structure, enormous numbers of FE analysis would be necessary in general to obtain the stress transfer function exactly, as was already mentioned in the previous section. There are several research works to approximate the stress transfer function with the use of the load transfer functions, but it may be necessary to develop some ideas to boost efficiency with regards to the structural analysis in the assessment of the fatigue strength of ships and offshore structures.

1.1.7 Design Trends

The Committee II.1 have also reviewed the design trend of ships and offshore structures. The effects of global warming, the utilisation of renewable energy, the ballast water treatment and so on would be the key issues in the future design of ships, and there will appear several new types of ships in near future. The Committee II.1 concluded that "nowadays whenever a problem or question arises, the standard procedure is to either seek an answer from existing quasi-static references or to use any one of the many available finite element programs". The discusser thinks that it is inevitable to use a finite element program to design a new type of ship, and the key question is not "how is the function of the program" but "how to utilise the program" in the design stage. A lot of computational tools are now readily available even for the nonlinear dynamic response analysis, and the designers are being required to choose these tools efficiently and adequately in the structural design stage.

1.1.8 Summary of Discussions

In an actual ship sailing in a sea way, various external and internal loads are acting on the ship structure and the loads result in stress fluctuations in structural members. In the ship structural design stage, it is required to estimate the stresses attributed to such time-varying various loads. At present, it is usual to rely on the quasi-static response analysis, rather than the dynamic response analysis, to estimate the responses of the structure because of the convenience and the good prospect of the calculated results. In the quasi-static response analysis, the basic assumption is that the frequency of external loads is sufficiently lower than the eigenfrequency of the structure. The discusser would like to know the practical treatment of impulsive loads, such as slamming, sloshing and so on, in the quasi-static structural response and the effect of such treatment of the impulsive loads on the structural responses.

In the ship structure, not only the external pressure in waves but also various internal loads are acting on. The internal loads, such as the ballast water pressure, the oil

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pressure, the ore or coal pressure, the container load, are very important in the ship structural design. In the internal pressure of the liquid in a fully-filled tank, there is a problem of the "reference point. The discusser would like to know the recent trend in the estimation of internal pressures due to the ballast water, the liquid cargo and the bulk cargo from the viewpoint of quasi-static response analysis.

In the structural analysis using FEM, which is commonly used in the quasi-static response analysis, the number of FE analysis depends on the characteristics of the loads. The compromise between the accuracy and the number of structural analysis would be the key in the structural design stage. In the multiple load case, since each load component has each phase lag, the phase difference between load components and resulting stresses should be taken into account in the estimation of the total stress. In this respect, the discusser would like to have a comment from the committee on the practical structural analysis procedure using FEM to obtain the maximum or minimum stress due to various load components and on the superposition technique of the stresses due to each load component taking account of the recent development of computers and soft wares.

The maximum load does not necessarily give the maximum stress in some load types. With respect to the buckling strength, the ultimate strength, the fatigue strength, and the associated reliability assessment, it is important how to convert the useful information obtained in the "load" to the "stress" in the quasi-static response analysis. In the statistical approach, it might be easy to calculate the transfer function of a load, but it is rather difficult to calculate the stress transfer function from the viewpoint of time and effort of the structural analysis. The discusser would like to have a comment and a suggestion from the committee on the reliability based approach to the assessment of the buckling strength, the ultimate strength, and the fatigue strength of ships and offshore structures from the viewpoint of the quasi-static structural analysis.

As for the structural design of ships and offshore structures, there exists the classification societies' rule as a guideline, and someone may advocate that extra response analysis is not necessary beyond the rule; however, some kind of structural analysis would still be necessary in order to design a new type ship, to determine the details of scantling, to verify the structural integrity, to re-analyse damaged parts, and also, to improve the classification societies' rule. The quasi-static response analysis may be used sometimes, and the dynamic response analysis may be necessary in some cases. In such structural analyses, it is inevitable to use a finite element program nowadays, and a lot of computational tools are now readily available even for the nonlinear dynamic response analysis. In this circumstance, the discusser would like to have a comment of the Committee II.1 on the orientation and the role of the quasi-static response analysis in regard to the structural design of ships and offshore structures.

1.1.9 References

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1.2 Floor and Written Discussions

1.2.1 Bart Boon

The Committee Chairman stressed in his presentation that FEA requires efficient and effective modelling (e.g. shape of elements) and correct loading of the model. This discusser is of the opinion that optimal results of a FEA for structural design require in addition:

1. a good interpretation of the FEA results, and
2. special techniques (temporary modifications of the FE model) in order to understand correctly the cause of undesirable results of the analysis and to be able to optimise the structural concept and design.

Discusser feels that not sufficient attention is given to these points in literature. What is the opinion of the committee (chairman)?

1.2.2 Ahmad Zakky

In your final recommendations, you have some points which should review in future. One from the points is reliability based inspection and maintenance and life-cycle design concept.

My question: Could you explain, what do you mean about reliability based inspection and maintenance and life-cycle design concept in quasi-static point of view?

1.2.3 Adrian Constantinescu

First of all, I would like to say that it is a real pleasure to participate in this conference. The report of the 'Quasi-Static Response' committee was very interesting and, in this way, I congratulate all members of this committee.

My comments and questions concern the slamming phenomena. Firstly, I observed that the majority of researchers try to model and to validate the bottom slamming. But, the literature presents four main types of slamming. The first one is the bottom slamming, the second is the bow flare (lateral impact), the third is the bow-stem (frontal impact) and the last is the wet-deck slamming. The last is critical to the catamarans. In my opinion, it will be interesting to analyse more the other three types of slamming.

Secondly, I would like to add a comment on the vibration of the structures during slamming phenomena. According to the work of J. Paik, the report indicates that a quasi-static response is characterised by peak pressure duration greater than 3 times the fundamental period of vibration. I would like to know what you understand by 'peak pressure duration', because in slamming phenomena the peak pressure is characterised by very short duration.

More than that, we have to add another limitation of the quasi-static domain. Thus, this last involves the velocity of the peak pressure, i.e. of the wet surface, along the length of the structure, e.g. the generatrix of a wedge body, and the distance between the apex of the body (keel for ships) and the position of the antinode of the vibration mode.

The first question is: How can we estimate the loads, and then the quasi-static response, in case of flat bottoms knowing that simple theories (Wagner, von Karman) are not adapted due to air trapping complex phenomena?

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The second question concerns the classification societies' rules. Why is in these rules the term 'quasi-static' not mentioned? And why are there no explanations to indicate that the rules are used to obtain quasi-static responses?

1.2.4 Bart Boon

In his presentation, the Committee Chairman stated that greening of ships has little effect on the structural design other than allowing for instance an adaptation of the hull shape based upon hydrodynamic considerations.

This discusser is of the opinion that greening of ships (life cycle minimisation of negative effects for the environment) may have at least two direct influences on structural design:

1. The choice of material may be influenced by the footprint for the environment on a life cycle basis. For instance, aluminium may get a better position relative to steel because of its less energy requiring recyclability (without suggesting that aluminium already at this moment may oust steel).
2. Lightweight materials reduce fuel consumption of the ship and thus may get more important as a result of greening of ships.

What is the opinion of the Committee?

2 REPLY BY THE COMMITTEE

2.1 Reply to Official Discussion

Professor Fukasawa provided comprehensive mathematical definition to the quasi static problem and discussed the simplifications and their accuracy. The Committee members are very appreciative of comprehensive comments provided by Prof Fukasawa. The committee members recommend that future committee is to consider, i.e. pay attention to the Equations 4 and 5 when reviewing the papers.

The superposition of stresses presented in Equations 11-17 is true, but extremely challenging task when different limit states are to be assessed (buckling, fatigue). Challenge is due to the fact that numerous simplifications are made. First of all, it can be that the analyses for different load components are done with different FE-meshes one modelling the global response, other secondary structures and yet another detail such as welds. Combining the stresses of these analyses has problems due to differences in scales of numerical models as well as making sure how the loads are actually occurring between these. Theoretically, it is an easy, but in practice is difficult task. Perhaps, the link between primary to tertiary local loads/response should be addressed better in future committee work. There are papers discussing on this effect both at naval architecture as well as solid mechanics (multi-scale modelling, homogenisation).

The Committee II.1 would like to respond to Prof Fukasawa's question on the practical treatment of impulsive loads, such as slamming, sloshing and so on, in the quasi-static structural response and the effect of such treatment of the impulsive loads on the structural responses by way of example of GL's simple procedure for consideration of slamming loads for container ships. GL addressed this with a relative simple procedure for consideration of slamming loads in a global strength analysis with an entire FE-model of the ship, Germanischer Lloyd (2011).

The procedure requires the generation of load cases from rule-based slamming pressures p_e - Structural Rules for a specific ship type, say container vessels, for bow and

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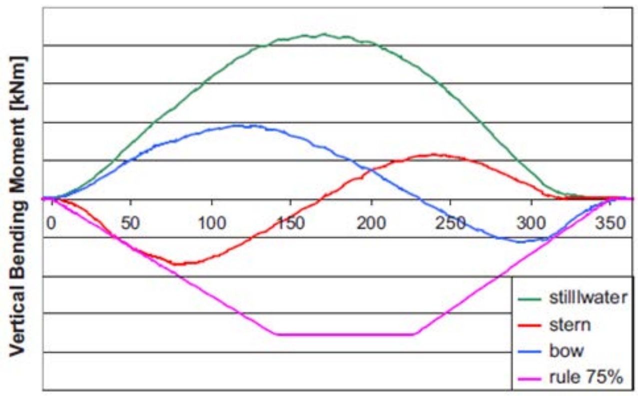

Figure 3: Vertical bending moments with and without inclusion of slamming load as per GL rules, Germanischer Lloyd (2011)

stern areas, respectively. Pressures p_e on bow and stern areas are applied in a way that, in combination with hydrostatic and weight loads, the resulting vertical bending moment (including stillwater loads) does not exceed the rule wave sagging bending moment (without stillwater loads). This restriction is imposed between 10% and 90% of the ship's length. Each slamming load case results from the combination of pressures p_e, hydrostatic loads, and weight loads. These loads are balanced by adjusting the acceleration factors for the weight loads. The evaluation is limited to permissible stresses and buckling strength only. The fatigue criteria are ignored for slamming load cases.

When discussing estimation of the internal pressure of the liquid in a fully-filled tank, Prof Fukasawa points out that there is a problem of the "reference point". He then requests the committee's view on the recent trends in the estimation of internal pressures due to the ballast water, the liquid cargo and the bulk cargo from the viewpoint of quasi-static response analysis.

In response, the committee II.1 would like to provide from ICAS (2012) the Common Structural Rules for Bulk Carrier and Oil Tanker which are published in July 2012 for external review as reference. Here the reference point is to be determined in respect of a maximum response, see Figure 4.

Under the assumptions that the tank or compartment of any type is fully filled with the homogeneous liquid of unique density, and the tank wall is rigid, the dynamic liquid pressure can be determined as a function of usage factors representing the difference between the tank pressure at 98% tank filling and 100% tank filling at the tank sides and the acceleration components that are measured at the centre of the tank. The reference point is defined as the point with the highest value of V_j. The technical background of IACS (2012) provides some possible examples for determining the reference point.

The discusser states that, in the multiple load case, since each load component has each phase lag, the phase difference between load components and resulting stresses should be taken into account in the estimation of the total stress. In this respect, the discusser would like to have a comment from the committee on the practical structural analysis procedure using FEM to obtain the maximum or minimum stress due to various load components and on the superposition technique of the stresses due

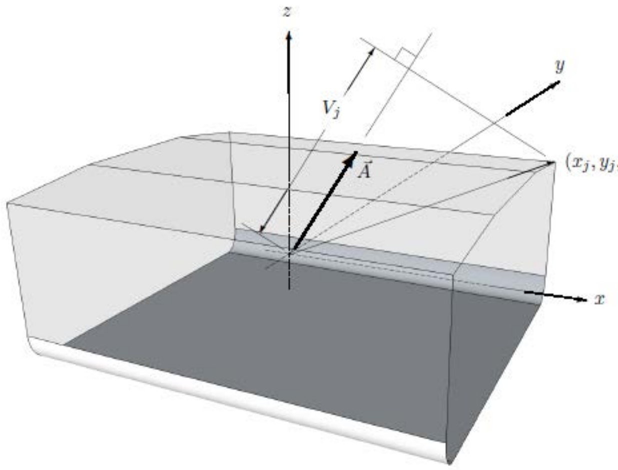

Figure 4: Definition of reference point, IACS (2012)

to each load component taking account of the recent development of computers and soft wares."

The application of the design wave load concept (see previous committee report Aksu *et al.* (2009) Section 3.1.2) by the class societies is to provide assurance of correct superposition of the different global load parts (Shear forces, torsion, horizontal- and vertical bending) and also with the local effects induced by the pressures. Therefore the maximum and minimum conditions can be selected directly by the stress response.

Prof Fukasawa requests for a comment and a suggestion from the committee on the reliability based approach to the assessment of the buckling strength, the ultimate strength, and the fatigue strength of ships and offshore structures from the viewpoint of the quasi-static structural analysis. There exist advanced numerical hydrodynamic tools, which do take into account highly nonlinear dynamic loads such as slamming. Application of such tools will provide pressures on hydrodynamic panels of the vessel. These pressures may then be transferred to a FE model at selected time steps. From the FE analysis, deflections and stresses can be determined and checked against failure criteria. Reliability analysis is carried out by considering statistical variation in pressures and the response. For example, the process may be repeated for a number of samples to have sufficient statistical representation, say, using Monte Carlo simulations. Importance sampling methods, such as response surface approach could be used to reduce the number of FE runs to a reasonable level. Even though the above mentioned procedure is primarily used to determine the deflections and stresses, a number of commercially available FE packages offer additional modules, which enable subsequent analyses and checks for adequacy of the structure against buckling, ultimate strength and fatigue.

Prof Fukasawa requests for a comment from the Committee II.1 on the orientation and the role of the quasi-static response analysis in regards to the structural design of ships and offshore structures. The Committee II.1 fully agrees with the comment that the problem nowadays is not the capability of different numerical tools, but rather how they are used efficiently during the design process. The role of quasi-static modelling is changing towards preliminary design where the scantlings are defined for example using optimisation; this is the way for example MAESTRO works. As the design progresses

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to change the main scantlings become more difficult, since the analyses may become non-linear as the discusser points out. To change the plate thicknesses, stiffeners, even the mesh is then practically unacceptable in large scale since the modelling and solution time, involving in worst-case optimisation or reliability analysis, increases too much. It is recommended that this topic is to be covered by the future Quasi-static Response Committee.

In conclusion, the ISSC Technical Committee II-1 members would like to thank, the official discusser, Prof. Toichi Fukasawa, for his comprehensive review and valuable comments and suggestions.

2.2 Reply to Floor and Written Discussions

2.2.1 Bart Boon

The committee fully agrees with Professor Boon's comment that the interpretation and the use of FEA results should be included as one of the key issues of the Finite Element Analysis. Williams (2004) supports Prof Boon's viewpoint and discusses a need for powerful and flexible tools for the FEA software to examine results and assess designs quickly, thoroughly, and accurately. Moreover, they advanced to levels providing structural optimisation automatically. The committee notes that over the years, commercially available FE packages have improved their post processing tools, which allow the FEA user to display and check the results easier than previously. However it is absolutely critical that the FEA user must be equipped with the necessary knowledge of structural analysis so that appropriate interpretation of the FEA results, and hence design modifications can be made.

2.2.2 Ahmad Zakky

The committee members would like to thank to Mr Ahmad Zakky for his question on risk-based inspection and maintenance and its relevance to quasi-static response. Maintenance, inspection, and repair are key aspects of managing the structural integrity of ship systems in a life cycle framework. The life cycle framework, in this context, refers to activities and resources associated with all stages of an asset from design, construction, operation and scrapping.

The traditional inspection and maintenance requirements by the classification societies and national and international regulatory bodies can be categorised as compliance-based or rule-based strategy, which is often translated to prescriptive time-based inspection and maintenance planning. Inspection plans derived from such a strategy have generally been developed based on years of experience gained from inspection and maintenance of many commercial ships. They tend to provide a minimum standard and proactive owners and operators may introduce additional or more frequent inspections.

The condition-based or performance-based inspection strategy is a step improvement from the rule-based approach. In condition-based strategy, the usage and degradation are forecast from the predictive models and input from subsequent inspections. This is then used to predict the condition of the structure. When the condition is estimated to reach a predefined threshold, inspections are conducted. The condition-based inspection approach is concerned with the occurrence of the structural degradation but is not explicitly concerned with the associated consequences of the structural degradation.

The risk-based inspection (RBI) and reliability centred maintenance (RCM) methods – a step progression from the performance-based strategy – are concerned with both

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the estimation of likelihood and the consequences of the structures degradation and potential failure Serratella *et al.* (2007). In this way, these methods potentially offer the optimisation of resources by identifying and focusing on towards inspecting those items, which have a greater risk. The implementation of these risk- and reliability-based techniques into the development of a plan provides an alternative to prescriptive time-based inspection and maintenance planning.

Both the performance-based and the risk-based inspection methods require predictive models in estimating the likelihood and the consequences of structural degradation. These predictive models are naturally linked with the quasi-static response.

RBI for hull structures has been widely used within the offshore oil and gas industry (API, 2002). Even though application of risk-based maintenance approaches in shipping industry is not widely accepted, there are few recent activities. Serratella *et al.* (2007) argue that proactive marine operators feel that significant benefits could be achieved in developing RBI plans that are tailored to their assets and started employing them. European Commission provided funding to the project RISPECT (Risk-Based Expert System for Through Life Ship Structural Inspection and Maintenance and New Build Ship Structural Design) within Framework 7 programme (RISPECT, 2008, Hifi and Barltrop, 2012). RISPECT project aims to bring the traditional rule-based approach based on long term experience and the risk-based approach based on first principles together and to develop and demonstrate an improved decision making method, based on a combination of experience-based and first-principles, statistical analysis, for safe, cost-effective structural inspection, repair and design rule improvement of existing ships. Bharadwaj and Wintle (2010) demonstrated a methodology using information generated by class inspection and/or historical operational data to optimise inspection such that the combination of the risk of failure of a structure and the cost of such inspection is minimised or reduced to an acceptable limit. The authors discussed the risk based optimisation of inspections with a two steps model. First step is a technique to prioritise sub-structures within the ship hull based on measures of risk, capturing risk profile information based on the likelihood of occurrence of failure, its severity and the effectiveness of current measures to mitigate the failure and/or its consequence. Second step of the model is optimising inspection actions, given the risk based order of priority established in previous step and the financial resource available.

2.2.3 Adrian Constantinescu

First of all, the committee members would like to thank Dr-Eng Constantinescu for his comments on the terminology and types of slamming. In regards to his first question on the issue of air entrapment for slamming of flat bottomed ships. The committee acknowledges that it is a difficult task to estimate the slamming pressures on flat bottomed ships. Kim *et al.* (2008) presented consideration of slamming impact design loads on large high speed naval craft by the classification societies' rules.

The classification rules contain certain level of conservatism to account for uncertainties in the loading and strength of the designed vessel. Quasi-static analysis often means a simplified approach with consideration of worst case loading scenarios (e.g. hogging and sagging conditions). It is in that sense fits well with classification society rule set development that quasi-static analysis provides a relatively quick and conservative approach.

Like other processes involving natural seaways, slamming is a strongly non-linear three-dimensional process, sensitive to relative motion and contact angle between body and

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water surface. Characterised by highly peaked local pressures of short duration, slamming peak pressures cannot be applied on larger areas to estimate structural response to slamming impacts. Moreover, the influence of hydroelasticity, compressibility of water and air pockets may have to be accounted for as well.

Classical approaches predict slamming peak impact pressures reasonably well (von Karman 1929; Wagner 1932), albeit only for two-dimensional sections without a flat bottom or large dead rise. Thus, these classical theories are hardly applicable for real ship geometries. Shortcomings of this method are the simplified treatment of three-dimensional effects, ship motions and wave steepness. Methods that directly solve the Reynolds-averaged Navier-Stokes (RANS) equations, including the two-phase flow of water and air, are better able to describe the physics associated with slamming. However, the computational effort for a three-dimensional RANS solver to simulate motions and loads on a ship at small, successive instances of time over a long-time period appears beyond current computational capabilities.

Payer and Schellin (2012) propose a method, which combines a fast potential flow seakeeping code with an accurate RANS solver. This has been found to be practical to obtain spatial mean slamming pressures suitable for design purposes of ships subject to slamming, El Moctar *et al.* (2004); Schellin and El Moctar (2007). The procedure consists of the following steps:

1. A linear, frequency domain code computes ship response in unit amplitude regular waves. Wave frequency and wave heading are systematically varied to cover all possible combinations that are likely to cause slamming. Results are linearly extrapolated to obtain responses in wave heights that represent severe conditions, here characterised by steep waves close to breaking.
2. Regular design waves are selected on the basis of maximum magnitudes of relative normal velocity between ship critical areas and wave, averaged over these critical areas.
3. RANS computations determine ship motions and wave loads for the identified critical parameter combinations.

The obtained average slamming pressures are applied as equivalent static design loads used to specify scantlings of the ship structure. This multi-stage procedure represents a compromise between attainable accuracy and computational effort.

2.2.4 Bart Boon

The committee II.1 agrees with Professor Boon's first point that if the use of different materials is encouraged / mandated by international regulations in future, this will have significant implications into the structural design of ships. Taking a ship hull as an example, a total life cycle analysis involves from the mining of the raw materials used in its construction, through to its operations, possible re-use of the material or recycling, and its eventual disposal. In this respect, a number of studies, Belair (2012), Burman *et al.* (2008) suggest that total cost of ownership of aluminium is lower than steel.

The committee II.1 notes that lightweight aluminium superstructures have been used in naval ships in order to manage the growth margin by lowering the vertical centre of gravity as well as reducing the overall weight of the structure, Lamb *et al.* (2011). In recent years, there has been significant interest in the application of steel sandwich panels with reduced weight to passenger vessel designs. The committee II.1 has provided a comprehensive review on this development.

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