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Classification Aspects of Ship Flexibility [and Discussion]

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Classification aspects of ship flexibility

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The main bending stresses in a ship's hull result from weight, buoyancy and hydrodynamic forces and are normally calculated satisfactorily assuming the ship does not vibrate. However, the ship will vibrate when it impacts with waves or if excited by waves of frequencies close to its natural frequencies. The calculation of these generally smaller vibratory stresses is much more demanding.

The paper discusses all the mechanisms which can cause a ship to flex and the analysis techniques for evaluating the resulting lifetime stress effects. By comparing these with statistics from service experience or full-scale measurements, simple rules are devised and validated to ensure that ships can withstand a lifetime of bending, vibration, or both, without failure.

Introduction

The functions of a classification society such as Lloyd's Register include the setting of standards for the design, construction and maintenance of ship's hulls to ensure adequate safety throughout their service lives (Lloyd's Register of Shipping 1989*a*). The fact that a ship is constantly bending throughout its life is one of the many effects that have to be considered when setting such standards.

Depending upon the imposed loading, a ship will, throughout its normal life, bend as a non-uniform elastic beam in three distinct frequency régimes: ultra low frequency, low frequency and high frequency. The ultra low frequency, often regarded as static, will occur in still water primarily by virtue of a differential distribution of weight and buoyancy forces. Other bending which is independent of sea state, due to diurnal temperature changes, effect of ship generated waves and variations in the loading condition during voyages, will also be at a very low frequency. Low-frequency bending, at frequencies associated with the natural heaving and pitching periods, will occur all the time the ship is in waves. This bending is influenced by the time-dependent differential distribution of weight and buoyancy and hydrodynamic effects. High-frequency bending is in fact vibration and will occur most strongly if any of the natural modes of vibration are excited either continuously by high-energy waves of similar frequencies or by wave impacts.

In the majority of ships, low-frequency bending is the most important effect in both absolute terms and in accounting for the majority of stress reversals during a ships life, with still-water bending coming next in absolute terms. High-frequency bending will invariably produce the lowest stress magnitudes of the three types but can have a profound effect on the number of stress reversals encountered.

Figure 1 is taken from a continuously recording stress monitoring system on a 'Great Laker' form bulk carrier operating on the Eastern Seaboard of North America. It clearly shows three types of bending stress response in two of the frequency régimes, namely low-frequency bending due to high-energy low-frequency

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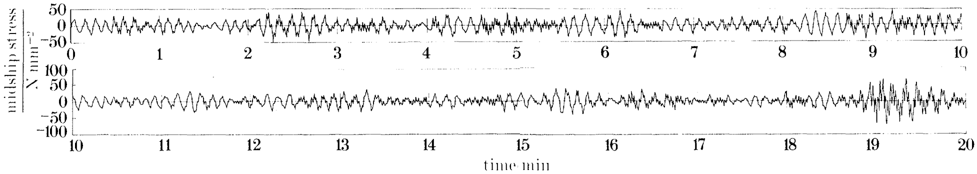

Figure 1. Output from stress monitoring system aboard a strengthened Great Lakes bulk carrier. Ship N, maximum stress plot, month May 1988. Maximum stress occurred during hour 10 of day 28. Nearest raw data stress stored watch 3 of day 28.

waves, and two types of high-frequency bending, namely, steady-state bending or springing (at the 2-node mode) and transient bending (also at the 2-node mode). The springing results from constant encounter with medium energy high-frequency waves and the transient bending, which is infrequent in this case, results from a significant ship wave impact.

The task, from a classification point of view, is to devise practicable rules that take proper account of all these still-water and wave effects. In particular, the Rules should provide adequate strength to prevent ultimate collapse in either tension or compression due to the absolute maximum load formed by the addition of still-water, low-frequency and high-frequency bending effects. They also have to prevent the possibility of a significant fatigue failure in a primary strength member due to lifetime stress cycles.

Clearly, when other factors such as corrosion, three-dimensional structural geometry and local strength are considered, the provision of simple Rule criteria for safe flexing becomes quite demanding. In general, the problem is tackled in three parts by the estimation and control of still-water effects, the estimation and control of wave effects and the overall control of the combined effects. Criteria for all three are defined in our Rules and are based on theoretical estimation of the response to the various loads, with calibration of the techniques coming from service experience (class records of defects) or from model or full-scale measurements.

Analysis methods

Bending in still water

This elastic bending is a relatively simple computation based only upon the hull girder properties, the light weight distribution plus consumables and cargo, and the buoyancy distribution. Although a straightforward calculation, it is extremely important because the resultant bending moment and shear stresses account for over 40% of the total allowed by the normal rules.

Calculations (Lloyd's Register of Shipping 1989*b*) to confirm that still-water bending moments and shear forces from all normal loaded and ballast conditions do not exceed Rule limits are carried out for defined departure and arrival conditions to allow for consumption of fuel, oil and fresh water and are described in a 'loading booklet'.

Bending in waves

For convenience of calculation, and to be able to take account of the probabilistic nature of ship response in waves, the evaluation of wave bending effects is split into low frequency, high frequency, that is, bending where higher modes are excited, and combined low- and high-frequency effects.

Low-frequency wave-induced bending

This type of bending occurs throughout a ship's life, in fact all the time that a ship is in waves. Because it constitutes something like 50% of the maximum combined stress allowed by Rules, naval architects have always used 'state of the art' techniques for its evaluation.

Before the early 1970s, an 'effective' wave approach was used and moments and shear forces were simply calculated by the algebraic summation of buoyancy and weight with their appropriate levers.

Such a procedure did not take account of the composition of the sea, the variety of sea states likely to be encountered, or the inertial, added mass and damping effects. Although the work to take these effects into account started in the 1950s, practical techniques were not developed until the early 1970s when a reasonable computing power became available to link the various components of sea description, response to regular waves (Longuet-Higgins 1952; St Denis & Pierson 1953; Korvin-Krowkovsky & Jacobs 1957) and response to long-term irregular sea states (Pierson & Moskowitz 1963; Bennet 1966; Goodman 1970). Response to regular waves was provided originally by model experiments but subsequently by strip theory (Blixell 1972; Raff 1972). When combined with a spectral description of the sea, taking frequency of encounter due to ship speed into account, the corresponding response variance m_0, as described by Goodman (1970), for a particular ship to wave heading α is given by

$$m_0 = \int_{-\pi}^{+\pi} \int_0^{\infty} S(\omega_e, \theta) \frac{R^2(\omega_e, \alpha)}{\zeta^2} \, d\omega_e \, d\theta,$$

where $S(\omega_e, \theta)$ is the encountered wave energy spectrum for each wave heading and $R(\omega_e, \alpha)/\zeta$ is the response transfer function. Then, if the ship response is assumed to vary linearly with wave amplitude and the distribution of crest to trough wave height follows a Rayleigh distribution (Longuet-Higgins 1952) then so do the peak-to-peak ship responses. This assumption is then used to predict either short-term response estimates for particular sea states or long-term predictions taking the lifetime wave climate into account.

The Lloyd's Register direct calculation procedure is best illustrated by the expressions used in the programs LRS2 (Robinson 1972*a*) and LR257X (Robinson 1972*b*) which evaluate short-term and long-term predictions of wave induced responses:

$$P(X) = \sum_{T_{\min}}^{T_{\max}} p(T) \left[\sum_{H_{\min}}^{H_{\max}} p(H/T) \exp(-X^2/2m_0) \, \Delta H \right] \Delta T,$$

where $P(X)$ is the long-term probability of a response X, $p(T)$ is the probability density function of wave period (from wave data analysis), $p(H/T)$ is the probability density function of wave height for a given wave period (from wave data analysis), $\exp(-X^2/2m_0)$ is the short-term probability (Rayleigh distribution) of obtaining a response amplitude of X for a given response variance of m_0 (a function of H and T).

One of the disadvantages of the statistical derivation of low-frequency bending stress using the linear strip theory approach is that the method naturally predicts equal positive and negative bending. In reality, due mainly to hull form, the process is nonlinear which leads to higher sagging than hogging wave bending moment and shear stresses. Frequency and time domain methods of dealing with these nonlinear steady state effects have been produced within Lloyd's Register (Dawkins 1985*a*, *b*) and work is in progress to calibrate such methods.

High-frequency wave-induced bending

Vibration excitation, that is excitation of the 2-node mode or higher modes, can be from a number of sources. We do not consider machinery induced (engine or propeller) excitation which can produce local and in some cases global vibration but concentrates on the wave-induced effects.

Before the ability to measure in detail the structural response of ships, to know whether high-frequency response was a problem or not, mariners were able to see vibration of the 2-node mode on Great Lakes type bulk carriers. Such ships are long, have very high breadth to depth ratios, and are designed with only about 50 % of the hull girder modulus of vessels for unrestricted navigation. Such flexibility leads to a very low natural frequency (or long period) of vibration of around 1.5 s with large deflections for a given bending moment. When excited by waves of similar frequencies, a steady state 2-node mode vibration is set up. This has become known as 'springing'.

Because there was, in the mid-1960s, a desire to build longer Lake bound vessels which could be excited by longer and therefore higher-energy waves, studies were carried out to quantify the resulting stresses (SNAME 1965; Mathews 1967; Goodman 1971).

Steady-state high-frequency bending (springing)

A method of treating the non-transient high-frequency response was devised by Goodman (1971) which assumes that the wave excited vibration originates from the synchronization of the ship's 2-node natural frequency with a region of the wave energy spectrum which has a significant energy content. This is illustrated in figure 2 which clearly demonstrates the susceptibility of Great Lakes bulk carriers to steady-state vibration due to their low natural frequency.

Higher modes of vibration are ignored due to a lack of energy in the particular sea spectra at such frequencies to initiate and sustain vibration. Moreover, because of the relatively short period of length of waves, it was further assumed that rigid body pitching and heaving motions would be small.

Knowing the natural frequency and non-dimensional deflection profile of the 2-node mode of vibration from standard calculations (Sole 1975) and assuming that damping is proportional to velocity, an estimate of the deflection at any point along the hull due to an arbitrary distribution of exciting forces can be found (Biggs 1965).

The wave excitation forces are determined using strip theory (Blixell 1972) with added mass according to Frank (1967). Hydrodynamic damping was estimated originally using coefficients by Vugts (1968) with later modifications by Betts *et al.* (1977) and with structural damping coefficients derived from measurements on existing ships (Johnson & Ayling 1961/62).

From the amplitude of deflection, the amidships bending moment amplitude per unit wave height was estimated from

$$M = \int_{-L/2}^{0} \{m_{\mathrm{w}}^{1}\, z_{\mathrm{b}}(x_{\mathrm{b}}) - F_{\mathrm{w}}^{1}\}\, x_{\mathrm{b}}\, \mathrm{d}x_{\mathrm{b}},$$

where $z(x_{\mathrm{b}}) = \bar{z}(-\tfrac{1}{2}L) \times (x_{\mathrm{b}}) \cos(\omega_{\mathrm{e}} t + \epsilon_1)$. The result of the calculation is a springing bending moment transfer function which can be used to determine short-term or long-term estimates of springing bending moment, or stress, in a similar way to that described for low-frequency responses.

Transient high-frequency bending (whipping)

This type of response, analogous to a beam being struck, is invariably due to wave–ship impacts of one sort or another and has the potential of exciting all modes of vibration from the 2-node upwards. It may be caused by bottom slamming (fore or aft), impacts on the flare (or bow) or impacts due to the shipping of green water on the foredeck.

Because both the exciting forces and resulting response are time dependent, and cannot be reduced to a steady-state process, the exact solution to the problem of deriving the response–time relationship, for any position along the hull, is very difficult. Notwithstanding the problems, general solutions to the process, if not the statistics, have been found. In 1974, McCallum used a simple 20-beam element finite-element method to model the ship and its flexural properties to examine the problem of loads on fast dry cargo ships with high flare.

Here, the additional bending moments applied to the hull girder by a transient force was estimated from the solution via NASTRAN of the equation

$$M\ddot{x}+N\dot{x}+Tx = F(t),$$

where x, $\dot{x}$ and $\ddot{x}$ are the displacement, first and second derivative of the displacement respectively. M is the mass matrix, N is the damping matrix, T is the stiffness matrix, $F(t)$ is the time-dependent force vector. The mass matrix was built up from the lightweight, deadweight and added mass with the added mass and hydrodynamic damping being calculated using the Frank method (Frank 1967). Bending and shear stiffness was included in the stiffness matrix and the force function shape based on full-scale measurements but with an impact pressure based on work by Ochi (1967).

Since 1974 the above method has been improved by the combination of the so-called rigid body motions and flexible response, with the ship being represented by up to 50 elements, and with hydrodynamic added mass wave damping and excitation force (low frequency) coming from strip theory (Salveson *et al.* 1970). Recent work has streamlined the procedures to a near automatic process (Kavanagh 1988*a*, *b*), but the method is still only considered suitable for examining either the relative effect of parametric variations or predictions for particular sea states due to the sensitivity of the magnitude of response to impact load and damping assumptions. Typical output from this procedure is shown in figure 3. Although the output looks ‘realistic’ when compared qualitatively with measurement records, considerable efforts are now needed to calibrate the method with full-scale measurements before proceeding to its use in design studies.

An alternative hydroelastic approach, which has been the subject of numerous notable papers and a text book has been advanced by Bishop & Price with associated authors (Bishop *et al.* 1977, 1978, 1980; Bishop & Price 1979). A similar approach, albeit with different assumptions of beam and load modelling, has been used by Yamamoto *et al.* (1983).

Combined low- and high-frequency bending

The ‘hydroelastic’ techniques mentioned have been used to model ship behaviour and response in a short-term sea state, to estimate the overall response to steady-

Figure 2

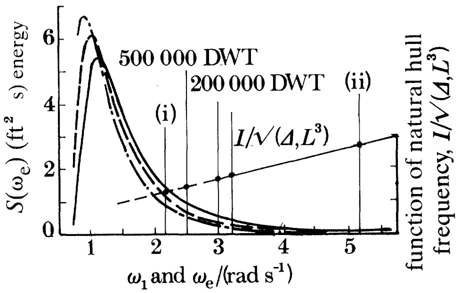

Figure 4

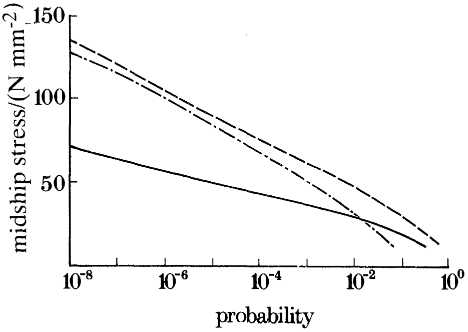

Figure 2. Wave energy density and natural frequency of 2-node mode of vibration. 1964 ISSC wave spectrum formulation: $H_{\frac{1}{3}} = 3$ m, ship speed = 16 knots. ——, $\bar{T} = 6.0$ s; ----, $\bar{T} = 6.5$ s; —·—, $\bar{T} = 7.0$ s. (i) 1000 ft Laker; (ii) 700 ft Laker.

Figure 4. Uncorrelated long-term predictions of low- and high-frequency bending stresses. ----, Combined; -·-·-, wave bending; ——, springing.

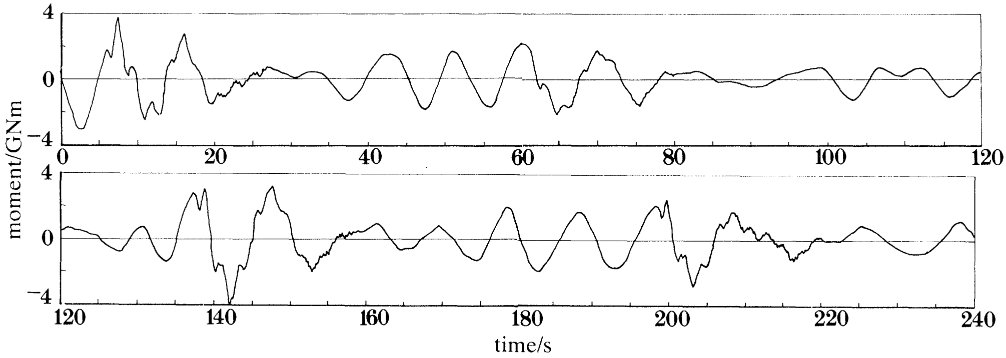

Figure 3. Vertical bending moment amidships using LR flexible ship theory for a bulk carrier in extreme seas.

state and transient excitations. However, due to the difficulty of calibrating either individual aspects of the mathematical model or the overall model, it is extremely difficult to progress authoritatively to the long-term or lifetime extreme combined response.

Looking again at figure 1 or any other representation of full-scale measurements where low- and high-frequency responses are present together, it has proved easier to describe statistically something which is relatively steady state compared with something which only happens occasionally, even in the same sea state. In the short term, the Rayleigh distribution has been shown to describe the peak-to-peak distribution of low-frequency bending stresses and also steady-state high-frequency bending stresses provided they are examined separately (Cartwright & Longuet-Higgins 1956). Both responses have a narrow bandwidth spectrum and the Rayleigh distribution can therefore be used to predict short-term probabilities of individual response levels. The bending moment (or stress) spectrum of a combined low- and high-frequency response is not of narrow bandwidth and so the Rayleigh distribution is inappropriate to predict the peaks of the combined response.

Where it can be assumed that the low-frequency bending and springing responses are independent, the distribution of the peaks of the combined record can be

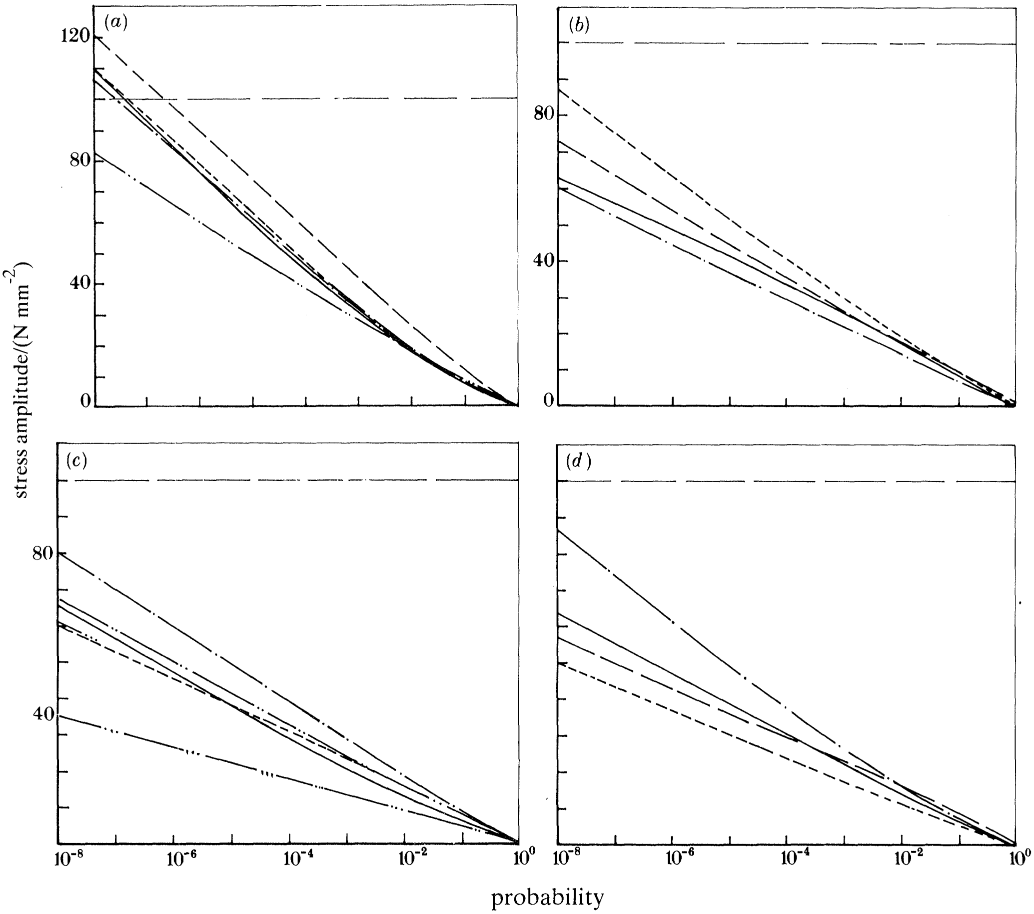

Figure 5. Long-term measured stress data. (*a*) Tankers: ——, ships 6 and 41; ----, ship 18; —·—, ship 23; ——, ship 35; —··—, ship 43. (*b*) Bulk carriers: ——. ship 16; ----, ship 17; —·—, ship 34; ——, ship 36. (*c*) Dry cargo ships: ——, ship 2; ----, ship 3; —·—, ship 4; ——, ship 5; —··—, ship 10; —···—, ship 11. (*d*) Passenger ships: ——, ship 30; ----, ship 31; —·—, ship 21; ——, ship 22. (*a*)–(*d*) Horizontal dashed line is the rule wave bending stress, σ_w. (From Ward 1970.)

predicted by the use of a formula given by Rice (1944). Examination of full-scale data where springing was present showed that springing and wave bending stresses were mutually independent but both dependent on sea state. Accordingly, Miles (1971) used the Rice approach to define the short-term peak distribution of combined low-frequency and springing stresses. This method has been used by Lloyd's Register for many years to study the importance of springing and its affect in the long-term on the combined low- and high-frequency bending stresses (Morris & Brunet 1977). Figure 4 taken from the output of program LRPIM15 (Morris & Brunet 1977) shows the magnitude of the springing stresses for a Great Lakes bulk carrier operating continuously in the Lakes and its affect on the total or combined response.

Service experience and full-scale measurements

Theoretical models of hull flexure in waves must be verified by both service experience and full-scale measurements. Model experiments are also helpful to verify certain aspects. Long-term service experience will show the accumulative consequences of flexure, and full-scale measurements will provide detailed confirmation of predicted responses in particular sea states. Such data are used extensively by the classification societies to calibrate theoretical design methods and Rule criteria.

Service experience

Systematic accumulation of service experience has always been fundamental to the process of classification as a means of determining success or failure of components, local structure or overall design and hence confirmation or otherwise of the current 'Rule' requirements.

The retention of surveyors' reports for the life of the ship (and beyond) has long been normal practice. However, the examination of such reports to establish damage incidence rates was a very time-consuming process and so in the late sixties it was decided to computerize the damage records database. It then became easier to establish the frequency of any type of damage, whether it was peculiar to a particular ship type or length range or to a particular design detail, or both. Obvious indicators of damage caused by ship flexing are fatigue cracks, brittle fracture and buckling of plating and/or supporting stiffeners. Repeated examination of the database has, with one exception failed to reveal any incidences of failure in primary strength members in any ship type attributable to hull flexure in heavy seas at any frequency range. Had it been otherwise, the Rule margins against all such occurrences would have been increased immediately.

The exception occurred in the mid-seventies when a new breed of fast refrigerated cargo ships was developed. To keep the deck relatively dry, the ships had what was then regarded as very pronounced bow flare which brought about increased low-frequency sagging wave bending moments. This, coupled with flare impact loads, gave rise to deck and side shell buckling in heavy weather. In this dramatic instance, we did not have to wait for the statistics to tell us that there was a problem and that Rule amendments were necessary.

Failures, mostly in secondary structure due to high stress concentration factors have, however, been identified. Such failures were primarily due to poor detail design and solutions have been found to prevent their reoccurrence. An example of such damage was cracking of bracket connections in tankers in the seventies and once the problem had been highlighted, changes were introduced so that these failures are, in the main, a thing of the past.

Although the database can, with an assumed model of the loading, help to set criteria to prevent local or global damage, it cannot be used in the converse sense to quantify dynamic loads to any degree. This is due to the lack of information regarding the time of damage and the associated ship and environmental conditions. On the other hand, evidence of some types of damage could almost certainly indicate the likelihood of high dynamic responses.

Therefore, although the accumulation and analysis of surveyors reports is invaluable in the setting of standards to prevent local damage, it is of marginal value if more detail is required of the loading/response process as a function of time. When such information is required one must resort to some form of physical measurement.

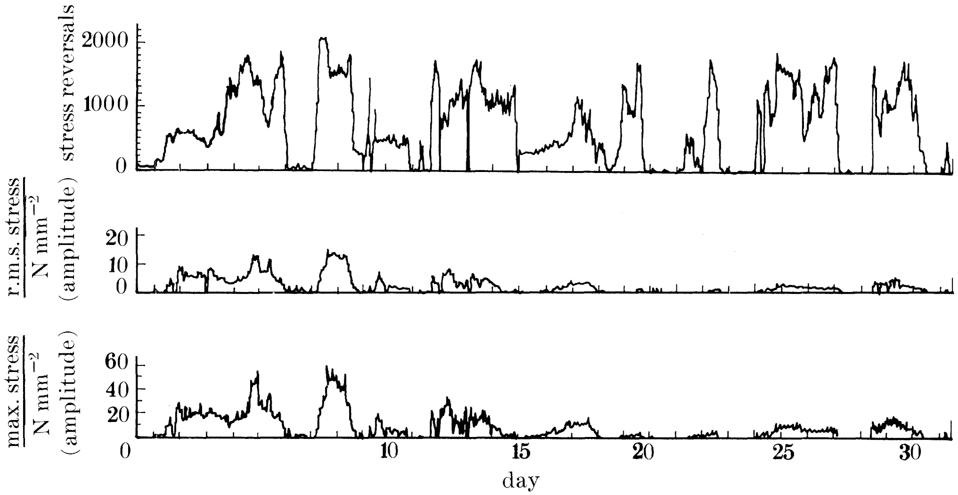

Figure 6. Hourly bending stress summary from stress monitoring system. Ship N hourly stress summary, month: October 1988.

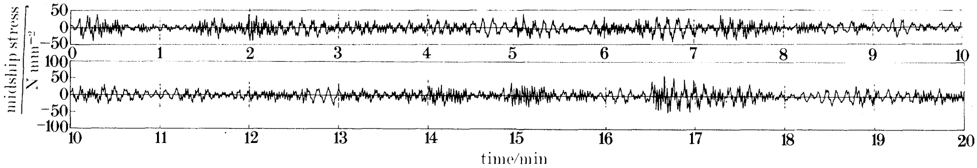

Figure 7. Measured data from watch containing maximum stress. Ship N maximum stress plot, month: October 1988. Maximum stress occurred during hour 8 of day 8. Nearest raw data stress stored watch 2 of day 8.

The value of model experiments in calibrating theoretical models of both loading and structural capability should not be underemphasized as they have been used extensively by Lloyd's Register and other classification societies, particularly for the low-frequency wave response régime. However, model techniques for investigating the vibratory response of ships are still in their infancy, which is in direct contrast to the methods available in the full scale, where it is now relatively simple to carry out detailed environmental loading and structural response measurements.

Full-scale measurements

Measurement of the structural effects of ships bending and vibrating in waves has taken place over a number of decades. With progressive improvement in sensors, recording storage capacity and computing power, it is now possible to continuously examine the structural response in minute detail. Early work on Great Lakes bulk carriers (Mathews 1967) highlighted the importance of 'springing' and systematic strain gauging by the British Ship Research Association (BSRA) of numerous ships (Ward 1970) added greatly to our knowledge of the level and frequency of total wave induced bending stresses. In both cases the measurements were used to formulate and calibrate strength standards even though they were relatively crude by today's standards. Figure 5 is a compilation of some of the BSRA stress data.

The type of electromechanical stress range counting device used at that time for the systematic measurements was capable of measuring instantaneous total absolute stress ranges but gave insufficient detail to differentiate between high- and low-

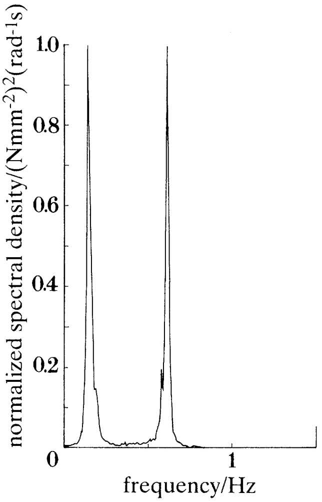

Figure 8. Spectral analysis of bending stress data from stress monitoring system. Scale factor to convert spectral density to engineering units = 371.81. Ship N, month: October 1988.

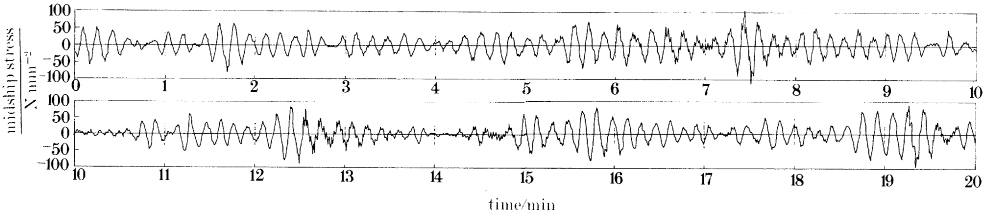

Figure 9. Measured data from stress monitoring system. Ship A maximum stress plot, month: December 1989. Maximum stress occurred during hour 21 of day 17. Nearest raw data stress stored watch 5 of day 17.

frequency responses. Current measuring and recording devices can so differentiate and figures 6 and 7 show the response amidships, with time, as monitored by a system fitted on a Great Lakes type bulk carrier. The ship was specifically designed to operate both inside and outside the Lakes. Figure 8 shows the corresponding spectral analysis of the data. Although not as ‘flexible’ as a pure Great Laker, it is clear that the frequency of the 2-node mode is low enough to be almost continuously excited by low to medium sea states. Figure 9 was taken by the same system on a sistership in a very high sea state and shows no steady-state vibration but some transient response due to bottom slamming. This picture is typical and very important when setting criteria that are to cover the steady-state and transient responses.

Because of the importance, in terms of magnitudes, of the low-frequency bending responses, most full-scale stress measurements on merchant ships in the past have concentrated on the midships region. However, in view of the fact that impact loading will give rise to modes of vibration which could produce a maximum response at locations other than amidships, recent measurement systems installed by Lloyd’s Register have incorporated strain gauges forward in addition to those at amidships. Figure 10 is taken from the output from a voyage data recorder installed on a 100 m containership and show the type and level of analysis that is now possible on a continuous basis. The low- and high-frequency responses can be separated by analysis and are shown in the second and third traces respectively in this figure.

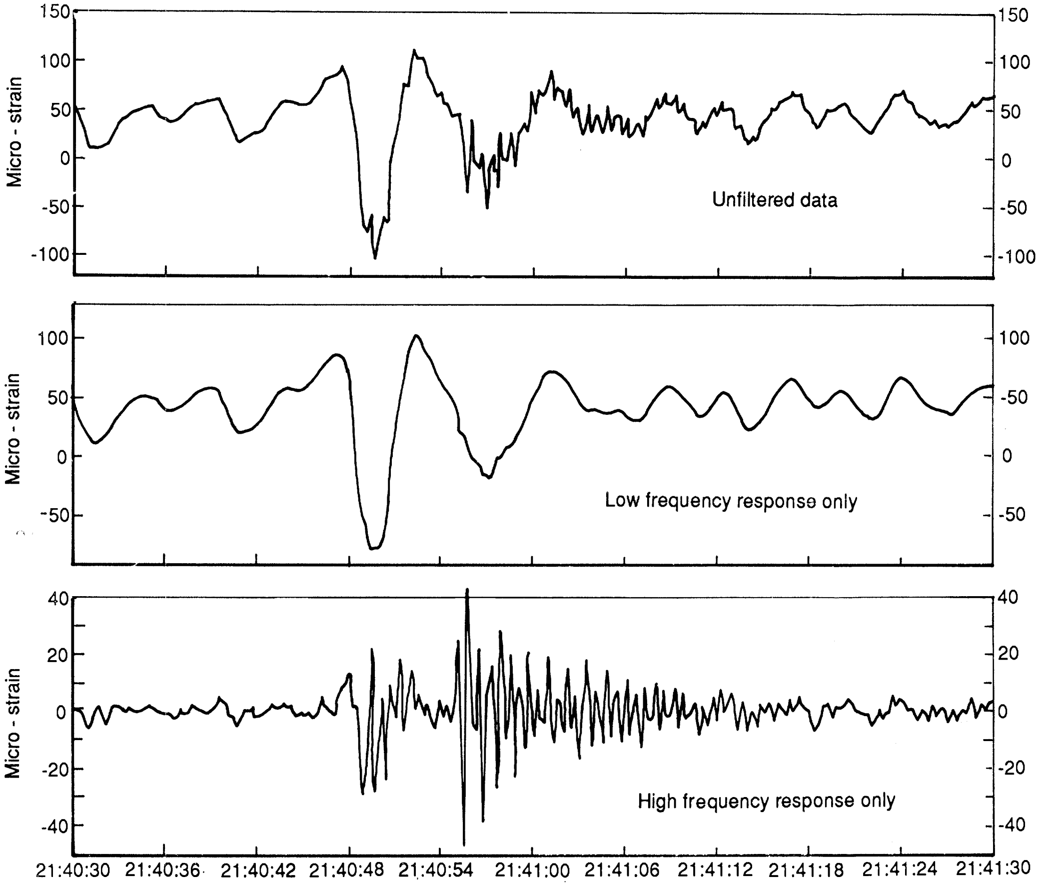

Figure 10. Amidships bending strain output from a voyage data recorder on a 100 m container ship. M.V. *City of Plymouth*: analysis of 'accident data recorder' channel no. 12 midship strain; from 21:40:30 to 21:44:30. (*a*) Unfiltered data, (*b*) low-frequency response only, (*c*) high-frequency response only.

Clearly, we are now able to determine the maximum wave induced stresses and their composition, that is, whether low- and high-frequency components are involved and their frequency of occurrence. We can also display such information to the ships officers so that measures may be taken to reduce stress levels in service should this be considered necessary.

Setting criteria for safe hull girder flexing

The concept of treating the hull as a Bernoulli beam and allowing estimated total bending and shear stresses to attain a fixed proportion of yield is fundamental, in our opinion, in the practical assessment of the strength of a ship. The other important global ultimate failure mode considered is hull girder buckling.

In addition to the global checks, most classification societies require detailed structural analysis to cater both for the important three-dimensional effects of the real ship (rather than a two-dimensional beam) under the assumed loads, and to prevent local areas of high stresses which could give rise to local failures. During the structural appraisal of any particular ship, fatigue studies to ensure adequate fatigue lives due to lifetime stress variations are not yet normal practice except for certain details on liquefied gas carriers. There is almost complete reliance on service experience to confirm that structural details perform satisfactorily and in fact, where fatigue studies are carried out, the service database is extremely important in calibrating the calculation method.

In general, primary consideration is given to hull girder bending and, because the resulting associated shear force is resisted, in the main, by different structural components, separate checks are carried out to limit both shear stresses and prevent shear buckling. Accordingly the process of setting criteria for vertical bending of the hull will now be addressed in the context of its various components.

Still-water bending

Rule levels of permissible still-water bending moments and associated stress limits have been developed taking into account the cargo weight distribution necessary for the function of various ship types and the need to limit the resulting stresses to a certain proportion of the total stress which includes all wave-induced stress effects leaving a reasonable margin or factor of safety against yield. The precise proportion of the still-water bending stress at present varies somewhat between classification societies, but is around 40% of the combined stress.

Control of still-water bending is achieved either by reference to an approved loading booklet in which all conceivable conditions have been assessed, or, by use of a loading instrument on board to directly calculate, in advance, the bending moments and shear forces for any desired loading pattern so that permissible levels will not be exceeded.

Where specific designs and trading patterns require higher still-water bending moments than the maximum values envisaged in the Rules, these are permitted provided that appropriate additional strengthening is fitted.

Wave-induced bending in conventional ships

In the Rule approach for conventional ships, the three effects of low-frequency, steady-state high-frequency and transient high-frequency bending are treated as additive and control is exercised on the total value.

Since 1974, our Rules have included a simple formulation for the estimation of the total wave bending moment.

$$M_{\mathrm{w}} = \sigma_{\mathrm{w}} C_1 L^2 B (C_{\mathrm{B}} + 0.7) \times 10^{-3}\ \mathrm{kN\ m}.$$

This is merely an expression of total wave-bending moment in terms of an allowed wave-bending stress and the prevailing required hull girder modulus. For such an approach to be reasonable, the modulus requirement must be proved sufficient to prevent ‘failure’ due to hull girder flexing and the assumed stress level must be representative of the lifetime maximum.

Naturally the damage database was examined to prove that prevailing modulus requirements were satisfactory, and extensive analyses of full-scale stress measurements and direct calculations were performed to verify the adopted stress level.

The full-scale measurements and their analyses were particularly important as they provided the calibration factor to take account of all operational conditions such as speed, loading condition, route and likely environmental conditions to be met.

Figure 5 shows the measured maximum combined low- and high-frequency wave-induced bending stress amidships against probability of exceedance for a whole range of ship types and sizes. As the stress data were available for a number of years, it was only necessary to extrapolate to a very small extent to an assumed lifetime probability of 10^{-8}.

It is clearly shown that the level of wave-bending stress adopted by the Rules is on the conservative side, so that when combined with the maximum permissible still-water bending stress, which may not occur at the same time as the maximum wave effect, it produces a safe criterion on which to judge the adequacy of the ship's longitudinal strength.

Wave bending in Great Lakes bulk carriers

The criteria for the longitudinal strength standard adopted by Lloyd's Register for these very flexible ships are those set by the Ottawa Strength Standard 1968 (Mathews 1971) which assumes a significant amount of springing, the level of which was confirmed by full-scale measurements (Mathews 1967).

As illustrated in figure 4 for these ships, which is typical, the absolute increase in the long-term combined stress level over and above low-frequency considerations is relatively small. However, the increase in the frequency of occurrence of low to medium stress levels can be seen to be significant. This, of course, has an important bearing on fatigue life considerations, but the service history of these ships in this respect has been excellent with very few fatigue failures reported.

The Ottawa Strength Standard applies only to ships intended to operate in the Great Lakes and the St Lawrence Seaway. Where service in extended areas is required, such ships have to be strengthened after consideration of the likely springing, low-frequency and combined stresses and the effect on fatigue life (Robinson *et al.* 1978).

Other considerations

Principal stresses

Recent work (Bishop *et al.* 1989), has confirmed that at or near the ends of any ship, the bending moments of any frequency category are each proportional to, and in phase with, their associated shearing forces. Moreover, the associated principal stresses at points in these end regions do not fluctuate in direction. The region where this occurs will vary in length although it is suggested that its extent will be reduced when modes of higher order are significantly excited.

The phenomenon is, of course, present on all ships and the separate consideration in the Rules for bending and shear has caused no known problems, primarily, because different parts of the three-dimensional ship resist bending and shear.

Buckling

Hull girder flexing is equally about tension and compression, and although tensile tearing is often assumed to be the dominant potential failure mode, this may not always be the case. It is therefore important to verify the buckling capability against the total compressive stresses in deck and bottom due to the still-water and wave bending.

Although such verification is normally considered to be a check on local strength, ultimate hull girder failures due to buckling have occurred in very special circumstances due to static overloading and, in one probable case, due to dynamic overloading (Yamamoto *et al.* 1983).

Fatigue

The complete elimination of relatively high levels of stress concentration in secondary structure due to compromises in detail design or to some degree of constructional misalignment is virtually impossible, and some fatigue cracks do occur in service. Because of the semi-redundant nature of the three-dimensional ship structure, they rarely progress to primary structure and the effects of any such progression are inhibited by the selection of appropriate quality steel in key parts of the structure. Their incidence can serve as useful indicators of fatigue loading. They are kept to an absolute minimum by the use of detailed finite-element structural analysis and good surveying practice during construction. Where high tensile steels are used for primary structure, factors are incorporated which effectively lowers the total permissible stress to offset the fatigue effects of bending at higher stress ranges.

Brittle fracture

Brittle fractures are never purely the result of ship bending. They normally occur under a certain combination of circumstances, such as the presence of large defects in non-notch tough steels in cold temperatures in association with a high strain rate rather than high strain. High strain rates are likely when ships slam, but this failure mode is prevented by the incorporation of notch tough steels in the hull girder and by the prevention of serious defects during construction or during any repair situation thereafter.

Concluding remarks

Classification Societies have always used state-of-the-art techniques for assessing the effects of ship flexibility and have used this knowledge when setting the relatively simple strength criteria which have been extremely effective in preventing failures. Success in this respect has not given rise to complacency. Close cooperation with other research bodies both inside and outside of the International Association of Classification Societies (IACS), will ensure that appropriate refinements to the classification rules are made as soon as this can be done authoritatively.

The greatest possible use is presently made of direct calculation methods, but only when they have been calibrated either against physical measurements, or against service experience. New techniques are becoming available for potentially more rigorous theoretical assessment of ship flexibility and these will undoubtedly be used more frequently when they are calibrated. At present they may be used for assessing the relative, rather than the absolute merits, of design alternatives.

For the majority of ships, low-frequency bending and still-water bending effects dominate the total applied stresses. High-frequency effects are only explicitly catered for in Rules for Great Lakes bulk carriers, but, where such effects are considered important, direct calculations are carried out to assess the likely effect on the total stress and on the fatigue life.

Analysis of full-scale stress data has confirmed that springing can be treated separately from transient effects as the sea states which maximize the two phenomena rarely occur together.

In most cases the low-frequency response dominates any fatigue assessment, with steady-state high-frequency response coming second and transient response, due to its infrequent nature, coming last.

We have come a long way since the naval architect first poised his proposed hull design on a wave to confirm its adequacy to withstand wave-induced responses. Considerably more is now known about the vibratory response of ships and the future looks even more promising. Moreover, it is now inexpensive and simple to fit reliable and continuous hull girder monitoring systems on board for the use of the master which will enable him to make more effective navigational judgements in adverse sea states. Such monitoring will also provide us with further means of calibrating the new theoretical techniques.

The continuous refinement of the classification rules for hull structure will go on, and this, together with the continued vigilance of the field surveyors during construction and service, will ensure that ships are as safe as they practicably can be.

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Discussion

D. B. Foy (*FNI MRIN, London, U.K.*). It seems clear that the work done by Lloyd's Register will make a significant contribution to the science of naval architecture. I am concerned about the amount of information withheld from the practising naval architect by the classification societies, and by flat state administrations. I am qualified as a mariner, not as a naval architect, and as a mariner have taken a close interest in the foundering at sea of loaded bulk carriers. On 9 March 1987 Lloyd's List gave the names of 38 bulkers which had foundered or disappeared. It worked out at between five and six per year, many of them old ships. Absence of distress calls or survivors is evidence that the ships broke in two and sank suddenly. This presumption is supported by the case of the *Singa Sea*. She was a 26586 deadweight tonnes bulker loaded with mineral sand which disappeared west of Australia in July 1988. A month after communication with the ship ceased six survivors, including the master, were spotted in a ship's lifeboat which had been torn free, not launched. The survivors reported that the *Singa Sea* broke in two and sank in five minutes. She was only twelve years old.

To arrive at a conclusion on the likely cause of the disappearance of a loaded bulker a naval architect would need access to the most recent survey report of the classification society which accepted her and information from any classification society which refused to accept her. The naval architect would also wish to know how stress was controlled during the high-speed loading and deballasting and of course the way the cargo was distributed in the vessel and the qualifications and experience in the bulker trade of the ship's master. None of this information is likely to be released. The classification society will not release its survey report and all the other information will be unobtainable unless a formal inquiry is held by the flag state. Liberia holds formal inquiries but Panama and many other states do not. Lest anyone think the problem is of the past I will mention two recent cases included in the March 1990 Casualty Return published by the Institute of London Underwriters, 49 Leadenhall St, London EC3A 2BE. The 23-year-old 54566 gross ton *Alexandre P* (Ex. *Acacia*) was last heard from on 14 March, 25 in crew, cargo iron ore, presumed sunk off north coast of West Australia. The 20-year-old 44276 gross ton *Azalea*, loaded with iron ore pellets, developed a crack on 22 March when off the coast of Norway. She was taken in tow by two tugs but capsized the same day. Two salvors dead, one missing. Losses continue and should not be dismissed as cause unknown when the cause is most likely sitting in the confidential files of the classification societies. These losses should not be listed as 'cause unknown' or blamed on the weather – they probably account for about 150 widows a year – mostly Philippine.

To conclude I must say that I am not alone in blaming the classification society system for the continuance 'in class' and thus in service of unseaworthy ships – ships unfit to carry the cargo loaded through the weather to be expected. The ability of owners to shop around for a society that suits them and the delegation of society decision making to local committees all seems to result worldwide in a very permissive system.

Professor Price and the late Professor Bishop are the originators of a challenging approach to the problem of structural failure in large bulk carriers. May I put forward another approach to the problem – ban all badly wasted bulkers from the ore terminals of the major consumer states – create a situation in which aged vessels are not 'run to death' but run to where they belong, the scrapyards of Taiwan.

J. G. Beaumont. The main points that Captain Foy makes concern the condition of ships as they increase in age, and the availability or non-availability of information stating their condition. It must be said that Lloyd's Register and other responsible classification societies have very stringent Rules that dictate survey requirements and corrective measures which strive to maintain ships in a safe condition. Should such Rules and procedures be found wanting, changes are suggested immediately to rectify the situation. To illustrate our genuine concern, Lloyd's Register was recently at the forefront in proposing to the International Association of Classification Societies (IACS), more stringent survey requirements for ballast spaces of bulk carriers and oil tankers where accelerated corrosion might occur. Having said that, we recognize that substandard ships do exist, mainly as a result of poor maintenance and that availability of surveyors reports, providing they are reliable, ought to improve matters. Contrary to what one might expect, the information contained in the surveyors reports is proprietary and can normally only be made available if the current owner agrees or, as Captain Foy points out, it is required for a Public Inquiry. Notwithstanding the restricted nature of the information, it should also be stated that should such information indicate that the condition of certain aspects of a ship fall below our standards, corrective action would be required for the ships to remain in class, irrespective of owner.

Regarding the specific losses referred to, it is our opinion that the true explanation of the sequence of events and mode of failure can only come from voyage data recorders. Although the universal fitting of such recorders, analogous to the aircraft 'blackbox', is probably a long way off, Lloyd's Register has spent considerable time and effort in promoting such technology. This included the development of prototypes and production systems and presenting our thoughts on the subject to the International Maritime Organization and to the shipping industry at large through a number of technical papers.

Finally the idea behind Captain Foy's banning of all badly wasted bulkers, or any ship for that matter, is also the very situation which we hope to create by the rigorous application of our Rules.

D. W. CHALMERS (*HMS Saker*, *BFPO* 2, *U.K.*). A figure was presented illustrating rule bending moment for four types of ship and comparing them with statistical distributions of bending moment derived from strain measurements. The values of rule bending moment were fairly well justified but not entirely so. Is it intended to modify the rule bending moment formulation so as to give it a consistent probability of exceedance?

J. G. BEAUMONT. One of the main causes of differences between measurements and Rule values of wave bending moments, highlighted by Dr Chalmers, is the difference between the wave climate assumed for the Rule approach compared with that experienced in reality. When the measurements shown in figure 5 were taking place, it was assumed for approval purposes that the ships would be for unrestricted service and this could entail service to and fro across the North Atlantic. Clearly this is not always, or nowadays, even seldom true but such service remains the conservative yardstick.

Since 1986 the Rules permit the wave bending moment to be modified by a ship service factor which takes into account the ship response to the anticipated wave climate for a specific service. In this respect, we have already modified the Rules to give a more consistent probability of exceedance.

It should also be pointed out that for some ship designs the Rule requirements for local strength components, for the relevant modes of failure, may result in 'excess' modulus from the global strength point of view. This will also produce an apparent inconsistency between measured and Rule global stresses.

G. VICTORY (*Surrey*, *U.K.*). If Mr Beaumont has heard the proceedings of this meeting he would be aware that the need to consider vibrational and wave forces on the ship's structure during the design is of vital importance. Professor Ralph's discourse on the importance of selecting materials which can accept dynamic loading and fatigue and the faults in construction which are inevitable in the standards of acceptable welding and lack of continuity of strength members all too often found after a casualty implies that the present methods of ship design leave much to be desired. It seems that the forces due to dynamic loading and wind and wave impacts are underestimated in the classification societies rules!

Yet Mr Beaumont states that the hull bending moments are calculated on the assumption that 'the ship does not vibrate', and that vibratory stresses are 'generally smaller'. But they are additive, and it was the 'straw which broke the camel's back'.

Without stating how it is done, but admitting that the calculation of vibratory stresses are 'much more demanding', save that they take account of statistical experience and full-scale measurements (I wonder how many stress measurements are taken on a given ship). Mr Beaumont concludes that 'simple rules are devised and validated to ensure that ships can withstand a lifetime of bending, vibration or both without failure'.

Statistics showing that too many ships do not 'withstand a lifetime of bending, vibration or both without failure' appear to indicate that such is not the case and that classification societies should examine means by which structural failures might be reduced by increasing scantlings, i.e. by reducing the still water bending moments and sheer forces allowed by their Rules and perhaps making an addition to their corrosion allowances!

J. G. BEAUMONT. Mr Victory makes a number of pertinent points and it is hoped that the written paper goes a long way to answering them. The paper explains the lengths to which a classification society will go and details the methods used to calculate the response when vibration is particularly important. Vibration is never ignored, but a true understanding of the phenomena does allow us, with the aid of numerous measurement trials, to use rather simpler direct calculation methods to set criteria which accommodates the additions due to vibratory stresses. There is also constant examination of damage statistics, survey procedures and research which result in Rule modifications to ensure that the ships are as structurally safe as they practically can be.