SSC-178

A Survey of Some Recent British Work on the Behaviour of Warship Structures

by

J. Clarkson

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November 1966

Dear Sir:

"A Survey of Some Recent British Work on the Behaviour of Warship Structures" by J. W. Clarkson (SSC-178) reflects the excellent remarks and data the above author presented to the Ship Structure Subcommittee at its Annual New York Meeting held May 4, 1966.

The Ship Structure Committee appreciates the close cooperation and information exchange that has developed through the many years of its existence with overseas research establishments.

Sincerely yours,

JOHN B. OREN
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure
Committee

SSC-178

Special Report

A SURVEY OF SOME RECENT BRITISH WORK ON THE BEHAVIOUR OF WARSHIP STRUCTURES

by

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Washington, D.C.
U. S. Coast Guard
November 1966

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INTRODUCTION

For surface ship structures, entirely rational elastic or plastic design procedures have not yet been achieved, although, since World War II, research activity has been considerably increased. The underlying reasons for the present rather empirical methods of design are to be found in the considerable complexity of the structures and the present lack of knowledge on loadings at sea. It is interesting to observe that surface ship structures are usually far more complex than the submarine or the aircraft, and this complexity results in a requirement for appreciable ingenuity to reduce theoretical analyses to manageable proportions. On the other hand, the comparative lack of knowledge on surface ship structures is not particularly critical, since the design of structures has evolved quite slowly, being based mainly on previous experience, and the safety of the ship and personnel is seldom called into question. New developments such as the introduction of more brittle or fatigue sensitive materials, including the high-strength steels, aluminium alloys or glass-reinforced plastics, may alter this situation and lead to a more pressing requirement for rational treatment.

The present author has been working at the Naval Construction Research Establishment (N.C.R.E.) Dunfermline, Scotland, during the past 15 years, mainly in the field of surface ship structures. This period has seen considerable advances and development both in the understanding of the mechanics of ship structures and in the application of digital computers to ship problems. A number of long-term projects have been initiated to measure the strains experienced at sea. Although the work familiar to the author has been mainly concerned with warship structures, much of it is potentially applicable to surface ship structures generally. The present review is an attempt to highlight some of the more significant advances.

MEASUREMENT OF SERVICE STRESSES

There is considerable agreement that the present lack of knowledge of the loading on surface ships constitutes the largest unknown affecting the structural design of surface ships, and N.C.R.E. is now devoting quite a significant effort towards the measurement of loads at sea, using statistical strain gauges. It is widely recognized that loadings may be most conveniently measured using strain gauges placed on the ship's deck or bottom structure at positions unaffected by stress concentrations. The work at N.C.R.E. has been reviewed in a recent paper by Smith.[1]

It is considered that the measurement of service stresses should be directed towards two objectives. The first requirement is to obtain information on the extreme values of stress experienced at sea, while the second is to obtain histograms of stress reversals. It is by no means clear that the same instrument would be equally suitable for both these purposes.

More realistic information on extremes of stress is required for placing the longitudinal strength calculation on a sound basis, and Yuille[2] first proposed using a very simple maximum-reading strain gauge which has subsequently been adopted for extensive measurements by N.C.R.E. (Fig. 1). The instrument is purely mechanical in action and requires no power supply. When in operation the gauge is bolted in position by bearing against the surface of the test structure on two pairs of hardened conical studs which give an effective base length of 10 in. Any change in the separation of these bearing points is magnified by a simple lever system and is marked by a recording pen on a stationary reel of recording paper. The magnification factor is about 100, so that a line 1 in. long on the recording paper corresponds to a strain variation of about 0.001 or a stress change in steel of about 13 ton/in.^{2}. The reel of paper is moved forward manually at fixed time intervals leaving a series of lines on the paper each of which corresponds to the maximum strain variation during one interval. The gauge is designed so that by simple modification its base length can be increased to any required span. The short 10-in. base length has however proved sufficiently accurate and has in any case proved necessary because of the restricted space available for fitting of the gauges in warships.

Twenty-five maximum reading gauges have now been operated for some time, and records have been obtained from more than forty British warships of various classes including frigates, destroyers, cruisers and an aircraft carrier. An improved production version of the gauge has recently been developed, and a further fifty of these instruments are now coming into use. It is intended, ultimately, that every operative ship in the Navy should be fitted with one of these gauges. The gauges are normally positioned on the web of a longitudinal stiffener under the strength deck, well away from positions of stress concentration.

In the analysis of results, hogging and sagging stresses are separated. This is accomplished by marking still water datums immediately before and after each voyage. Low amplitude strain variations corresponding to periods of calm weather are also used, to fix intermediate datums, and these are connected

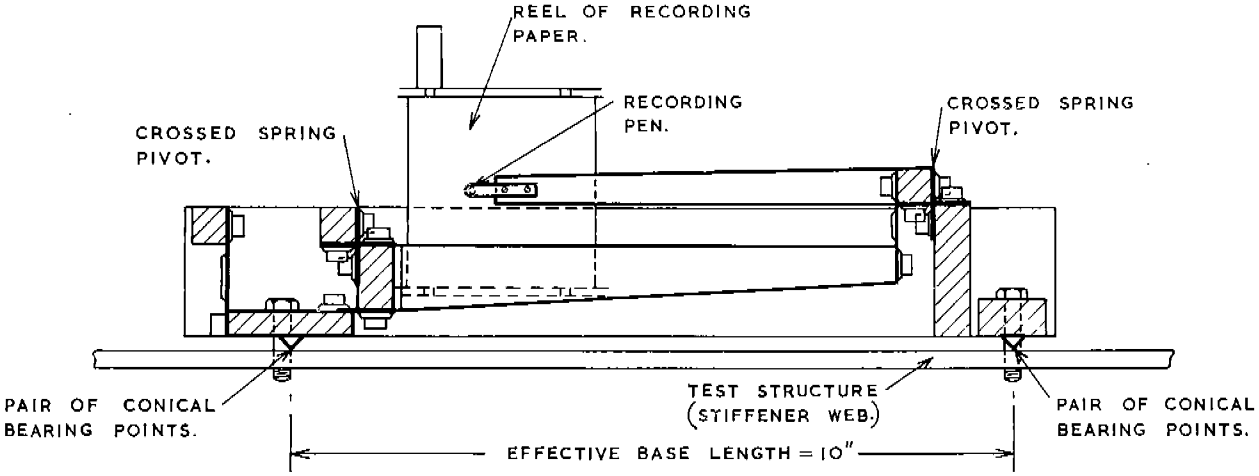


FIG. 1. N.C.R.E. MAXIMUM READING STRAIN GAUGE SHOWING LEVER SYSTEM.

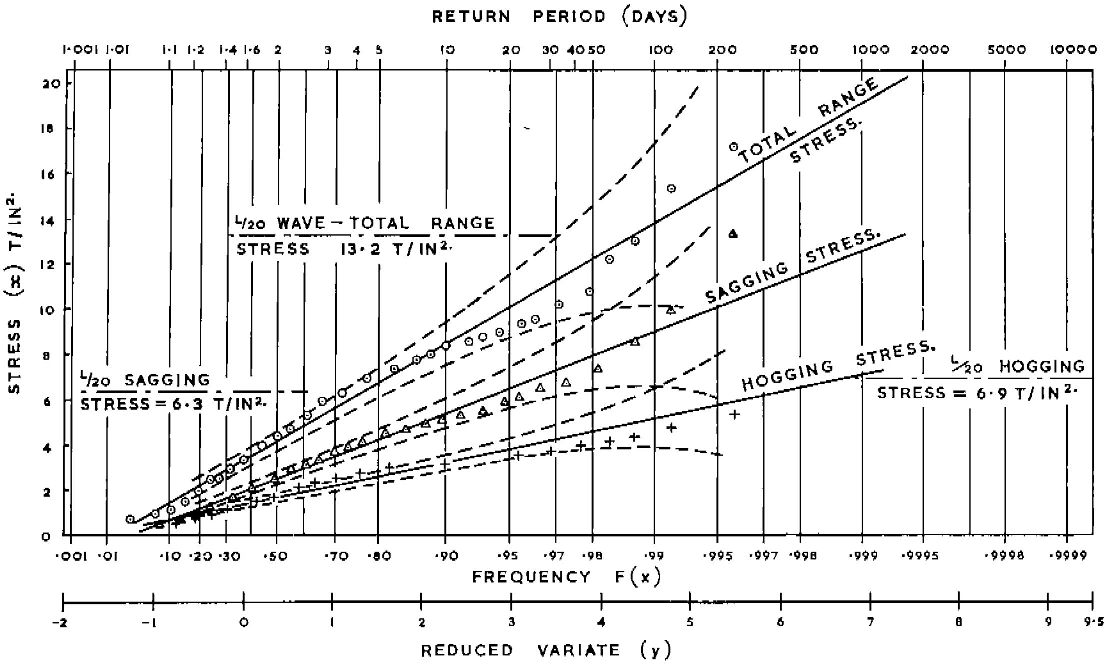
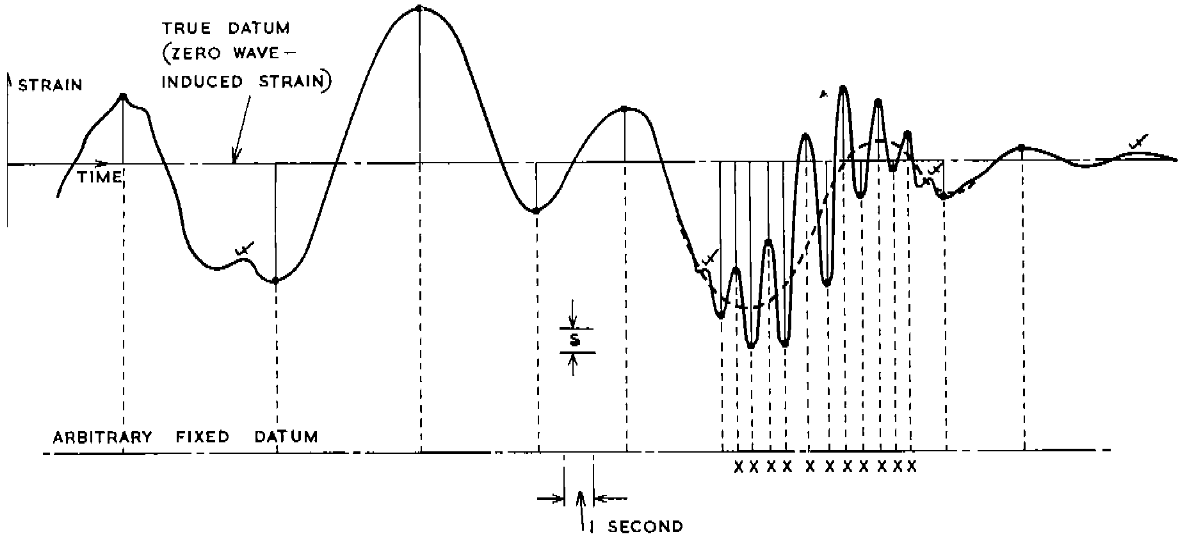


FIG. 2. TYPICAL EXTREME VALUE PROBABILITY PAPER.

by a datum line. Most of the maximum strain readings so far have corresponded to 24-hour periods at sea. With the object of representing accumulated data in a concise form, allowing interpolation between the results for ships of different types and possibly allowing extrapolation beyond the observed ranges of strain, the daily maxima have been analysed and plotted using an extreme-value statistical theory described by Gumbel.[3] In this analysis, the cumulative frequency of the observed extreme values is represented by a series of points plotted on a special probability paper. An extreme-value probability function, which appears as a straight line on the probability paper, is fitted to the observed data by a least squares method, together with control curves which define limits within which a specified proportion of the data should lie. A typical probability paper, showing the results from a group of four ships of the same class, is shown in Fig. 2. It may be seen



✓ INDICATES INSIGNIFICANT STRAIN REVERSAL.

X INDICATES NON-ZERO FREQUENCY DIGIT.

FIG. 3. SAMPLE STRAIN RECORD.

that the measured stresses bear little relation to those predicted by the standard L/20 static wave calculation, and also that the sagging stresses are appreciably higher than the hogging stresses, possibly due to the effects of slamming. It has been found that extrapolation to longer periods using the Gumbel plot produces results which are not generally confirmed by subsequent measurements. Often the extrapolation predicts extremes which are too high, and for this reason it has been decided to measure extremes for very long periods of time, possibly for ten years or more on each ship. Until more data are obtained, it will not be possible to establish any statistical pattern of the extremes.

The main reason for investigating cyclic leading as distinct from maximum leads is to provide a means of ensuring that new ships will not run unacceptable risks of fatigue failure. In existing ships, the problem of fatigue has not proved critical, and minor fatigue cracks have been troublesome rather than catastrophic. In future, the possible use of fatigue-sensitive materials such as high-yield steel, aluminium and glass-reinforced plastics, may lead to more severe fatigue problems. In mild-steel ships, any increase in the acceptable general stress level must be accompanied by improved fatigue strength of structural components. It is also possible that major structural discontinuities of an unfamiliar type may occur, inevitably causing stress concentrations and requiring an estimate of local fatigue strength.

It is considered that the existing theories of cumulative damage such as Miner's Law are not fully satisfactory, and future improvements may be expected. Equally, it is considered desirable to be able to separate vibratory stresses in order to indentify the effects of slamming and bow flare immersion. A sample of a continuous strain curve is shown in Fig. 3, and it is clear that a simple counting gauge would be rather unsuitable, the resulting histogram being dependent on the particular method of counting. At N.C.R.E., a strain-recorder design is being sponsored, which will supply the equivalent of a continuous strain record in a form suitable for interpretation and analysis by a digital computer. The instrument will record the amplitudes of maximum and minimum points on the strain curve relative to an arbitrary fixed datum which will subsequently be corrected to the still water datum. Special provision will be made to identify vibratory strains with a period of less than two seconds. Minor strain variations less than a specified amount δ will be surpressed, and δ may be adjusted in the range 0.00002 to 0.0002 (0.27 to 2.7 tons/in.^{2} for steel). The length of the digitized record will depend quite critically on the value of δ.

Two possible systems have been considered, the first based on a ship-borne slow magnetic-tape recorder in conjunction with a shore-based analogue to digital converter and data-processing unit. The second consists of a self-contained ship-borne digital recorder incorporating analogue-digital conversion and a data processing unit employing micro-logic circuits. In each case the analogue strain signal would be obtained using electrical resistance strain gauges. At the present time, the second type of system is favoured, since it reduces the effort in data processing, is more compact, and is thought to be potentially more reliable. A design has been produced by Plessey Limited, and it is likely that two prototype units will be ordered in the near future.

ELASTIC ANALYSIS

Most of the recent work in this field has been concerned with transverse strength, though, with the second generation of digital computers now becoming available, complete structural analysis including interaction between longitudinal and transverse loadings may shortly become feasible. Although transverse strength analysis has been traditionally based on treatment of a single ring frame, the subject is more correctly concerned with the analysis of flat or curved plated grillages. Until the advent of the digital computer, grillage analysis was restricted to very simple cases, and much effort was devoted to finding short cuts to the very heavy arithmetic involved. Nowadays, straightforward grillage analysis is quite commonplace. A text reviewing elastic grillage analysis applied to ship structures has recently been published by the present author.[4]

Ideally, each plate panel of a grillage should be analysed by the well-known linear plate theory equations,

$$\nabla^4\phi = 0 \qquad (1)$$

$$\nabla^4 w = q/D \qquad (2)$$

where ϕ is the Airy stress function, w is the bending deflection q is the lateral pressure and $D = Eh^3/12(1-\mu^2)$. The beams may be analysed by the usual Euler-Bernoulli theory, and the boundary conditions for equations (1) and (2) are obtained by specifying equilibrium and compatibility at each beam position. This approach was adopted by the present author to analyse a simply supported panel stiffened in one direction only, under a single concentrated load.[5] The analysis has been generalised more recently by Smith[6] to apply to a very wide variety of interconnected systems of rectangular plates and parallel beams in one direction, simply supported at the ends. Structures which can be analysed include unsymmetrical or skew stiffeners, swedged or corrugated plating, box beams or the Vee bottom region of a frigate with a rise of floor, as shown in Fig. 4. A rather similar analysis for orthogonally intersecting beam grillages was attempted about 10 years ago by Kendrick[7] who assumed that the orthogonal components of the in-plane displacement could be considered separately, the only interaction arising from the vertical shear forces at the stiffener intersections. Kendrick's work indicated that very accurate results could be obtained by treating the stiffeners alone using beam theory and including the plating as an effective flange to the longitudinal and transverse bars. The effective breadth of plating was taken in this instance as the full stiffener spacing. In practice, the plate panels of warship grillages are seldom perfectly flat, and there may be permanent set up to about a plate thickness deep caused either by welding distortions or early loadings on the structure. This has the effect of rendering the simple linear plate equations invalid, and, in view of the complexity of the problem, the practice at N.C.R.E. is to establish methods of choosing structural idealisations by comparison with experiment.

Nowadays, transverse strength and grillage analysis is based on finite element idealisations with the problems being solved numerically on a digital computer. Until recently, a comparatively small first generation computer, the Ferranti Pegasus, has been used at N.C.R.E. Initially there was a 4096 word high-speed store which has now been increased to 7168 words. General structural analysis programs have been developed for this computer, including a plane frame program[8] suitable for the traditional transverse strength calculation. This program will treat any rigid-jointed multi-connected frame up to about 20 intersections. A facility exists for treating more intersections by partitioning, and shear deflections can be included. Two programs have been written for flat grillages.[9-10] The first is very general and will treat any network of straight elements, not necessarily orthogonal, up to about 20 intersections, including both shear and torsion. The second is limited to orthogonal grillages with a rectangular boundary ignoring torsion, but it can tackle up to 72 intersections. At the present time programs are being written for the English Electric KDF 9 computer which will treat grillages with up to about 200 intersections. The plane frame and grillage programs consider the plating to be represented as an effective flange to the beam elements. A program has also been written to analyse the transverse strength of a complete midship compartment of a ship's hull.[11-12] This program includes shear panel elements, in addition to the beam elements, to allow for transfer of in-plane forces between adjacent frames. Due to the large number of unknowns and the limited size of computer, the analysis is restricted to cylindrical compartments identical though not necessarily evenly spaced frames, and longitudinals uniform along their

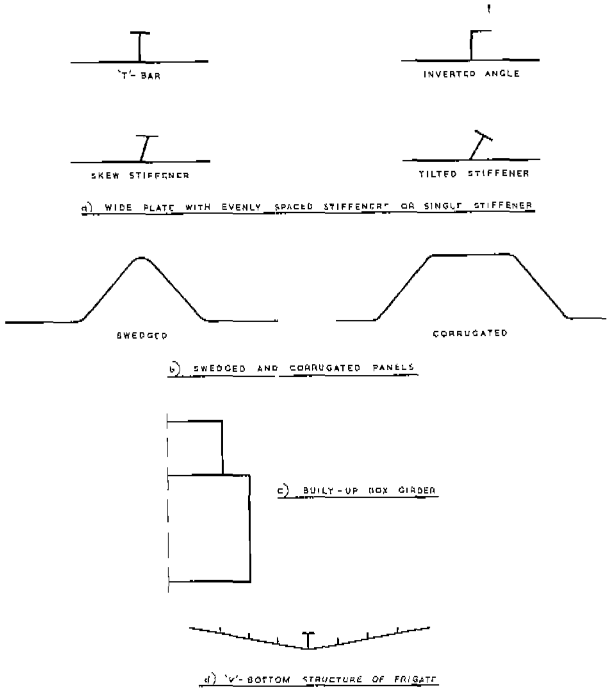


FIG. 4. TYPICAL BEAM-PLATING STRUCTURES FOR PLATE THEORY ANALYSIS.

length though not equal in size.

Throughout the grillage and transverse strength investigations, experimental work has been carried out often at full scale on typical steel structures, to assist in formulating structural idealisations, in particular, the choice of an effective breadth of plating and on effective rigidity of shear panels. The procedure has usually been to carry out calculations for a whole range of assumed values for these parameters, and choose the values giving the best agreement. Generally, for flat grillages, the assumption that effective breadth is equal to half the beam spacing gives results which are sufficiently accurate for design purposes, and some typical results for a grillage under uniform pressure are shown in Fig. 5. This graph is particularly interesting as it illustrates the pronounced effect of local bending between the intersections in a grillage having widely different longitudinal and transverse members. The choice of idealisation for transverse strength curved grillage calculations has been supported by experiments both on small-scale models in xylonite (a plastic material) and on a near full-scale steel model of a frigate section.[13] This model is illustrated in Fig. 6, and the results form some trial calculations for a load at the keel, using various effective breadths (P_L and P_T) and shear rigidities (G), are shown in Fig. 7. It was found that calculation 2, shown as the full-line curves, gave the best overall agreement with experiment.

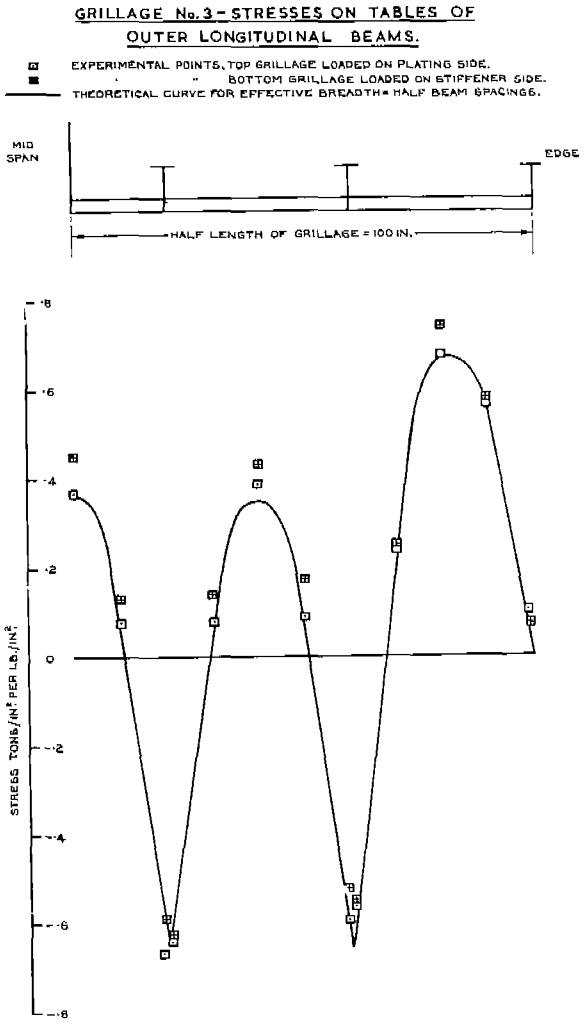


FIG. 5. STRESS MEASUREMENTS ON GRILLAGE UNDER UNIFORM PRESSURE.

The structural idealisation closely followed the shape of the frame and included all the longitudinals in the region of the applied load at the keel, but a more approximate idealisation was adequate elsewhere.

The very significant advance using grillage analysis, over the old single-ring frame calculations, can be seen in Fig. 8 for a concentrated keel load and Fig. 9 for a hydrostatic water pressure loading extending to 28 ft above the keel. These results are for a comparatively short compartment measuring 13½ ft long by 24-3/4 ft wide. The curved grillage transverse strength analysis agrees very well with the measurements in both cases, whereas the ring frame calculation is out by factors from 5 to 25, and bears little or no relation to the actual behaviour. For a longer compartment or a structure only transversely framed, the agreement using the single ring

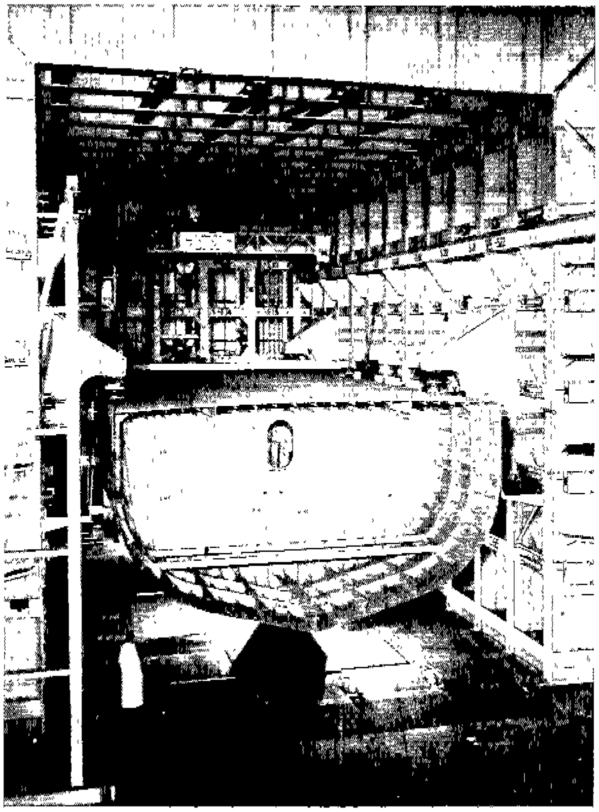


FIG. 6. FRIGATE MODEL IN LARGE TESTING FRAME.

frame calculation would, of course, be closer.

Now that considerably larger and faster computers of the second generation are becoming available, general structural analysis programs are being developed for three-dimensional structures composed of stiffened plate panels or plated grillages. One such program is being written by the English Electric Company, Ltd. at Kidsgrove, England. Using this type of program, it should be possible to examine the interaction between longitudinal and transverse loading, and also any effect due to taper of the ship section. Equally well, general structural analysis programs are applicable to problems more concerned with longitudinal strength such as the break of forecastle in destroyers and frigates, the effect of superstructures, and the analysis in way of large hatches and openings such as the side lift openings in aircraft carriers. At the present time, the English Electric (Kidsgrove) program is being evaluated at N.C.R.E. for the type of problems which arise in ship structures. As yet, it is not clear that the general analysis program referred to is ideally suited to all problems, and it is quite possible that programs for particular types of problem will still be required. In view of the considerable recent developments in the computer analysis of ship structures, particularly in regard to transverse strength, the committee of the International Ship Structures Congress dealing with stiffened

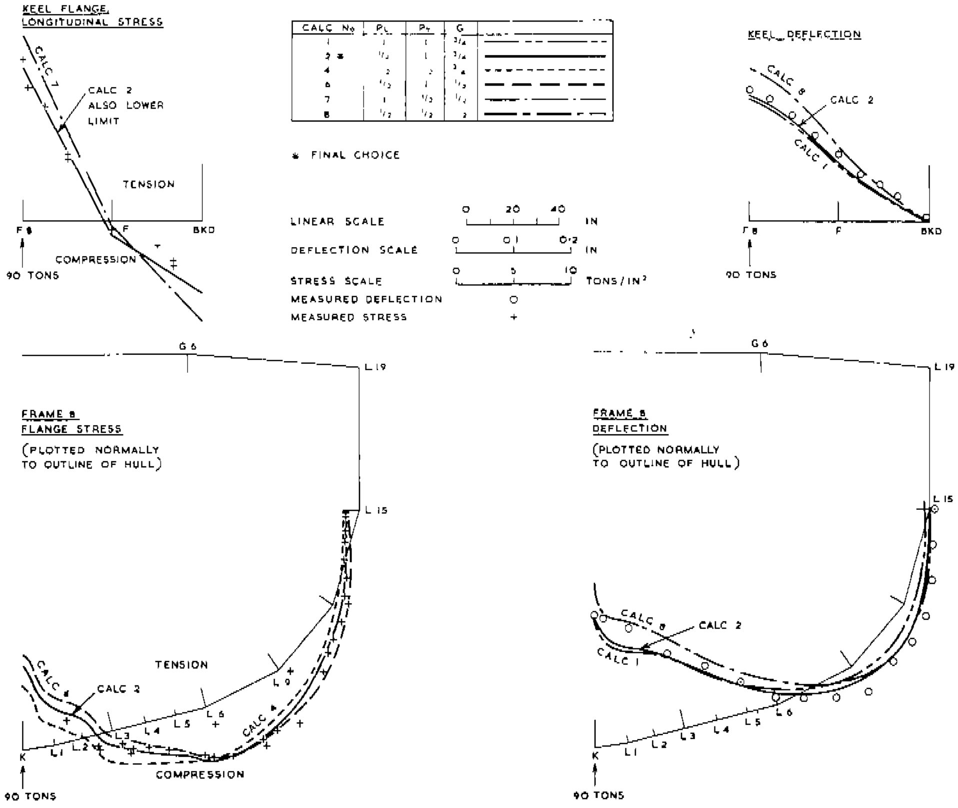


FIG. 7. THEORETICAL AND EXPERIMENTAL COMPARISONS FOR LOADING ON KEEL OF FRIGATE MODEL.

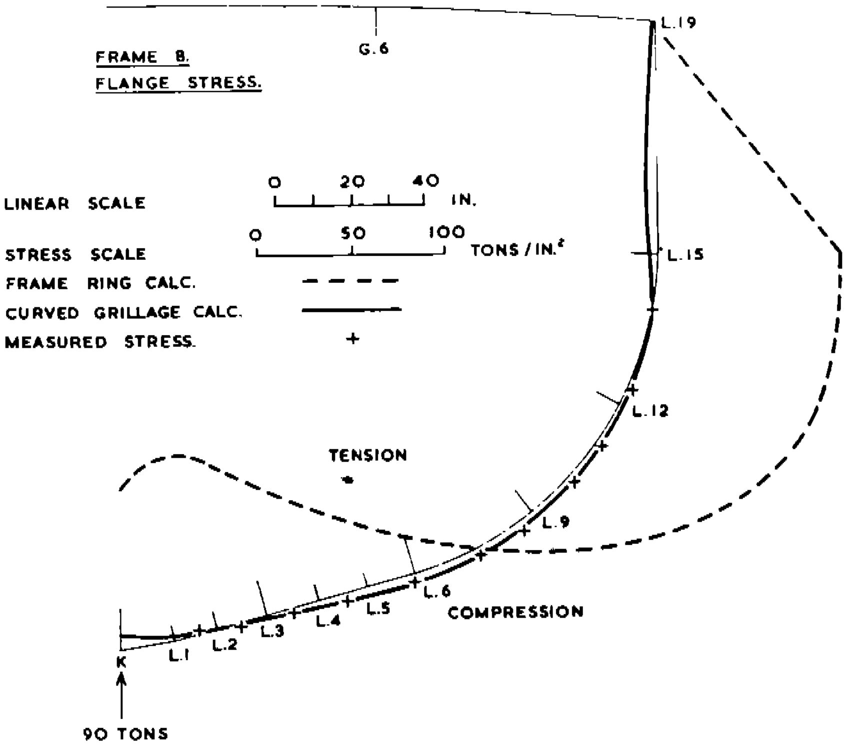


FIG. 8. COMPARISON BETWEEN CURVED GRILLAGE ANALYSIS AND RING CALCULATION FOR KEEL LOADING ON FRIGATE MODEL.

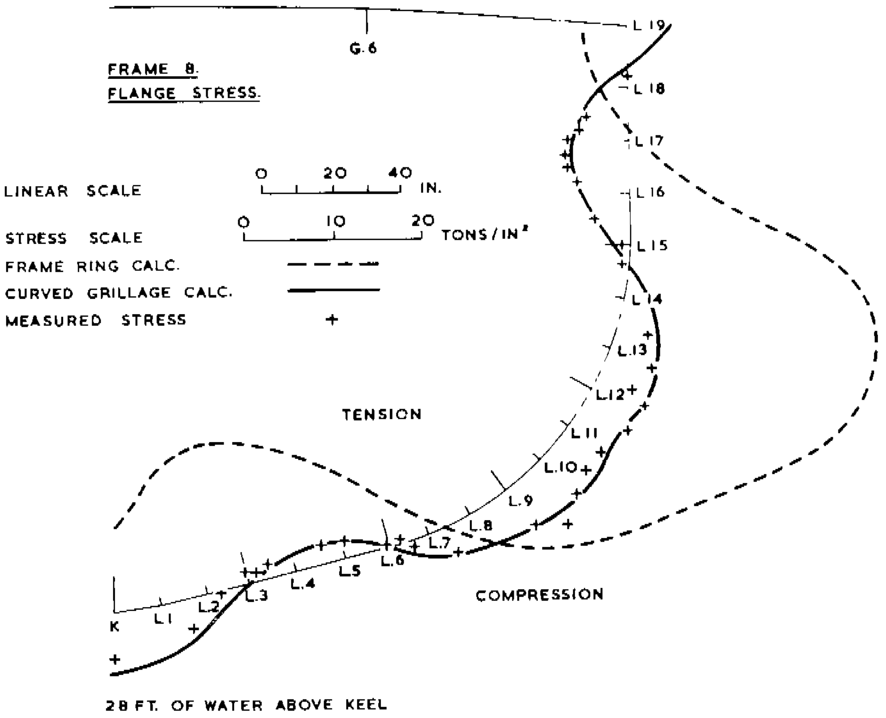


FIG. 9. COMPARISON BETWEEN CURVED GRILLAGE ANALYSIS AND RING CALCULATION FOR HYDROSTATIC LOADING ON FRIGATE MODEL.

plate panels in three-dimensional structures is sponsoring an enquiry regarding computer programs in various countries.

To conclude this section on elastic analysis, I would like to refer to the analysis of a ship in a floating dock by Vaughan.[15] In this analysis, the ship is represented as a beam consisting of a number of finite elements, each of which is reacted by a dock block regarded as an elastic spring resting on the dock floor, itself a grillage. The complete system is reacted by buoyancy forces, and initial lack of fit between the dock blocks and floor is included. This is a very useful example of a particular problem which could not be tackled using one of the standard computer programs. Nevertheless, realistic analysis could not have been accomplished at all without a computer. In a previous analysis, Amerikian[16] assumed that the floor of the dock was rigid and that the ship had uniform rigidity and was supported by uniform dock blocks, in order to be able to calculate the dock block loads. In due course, it is intended to carry out parametric numerical studies using the N.C.R.E. computer program to examine more widely the effect of lack of fit and non-uniformity of the dock blocks which are imponderables affecting the practical problem.

PLASTIC COLLAPSE

The most important potential application of plastic collapse theory to ships' structures is in longitudinal strength, where the moment to break the back of the ship is equal to the fully plastic moment of the ship's cross-section. This "strength" approach to longitudinal bending has been proposed in a recent paper by Caldwell.[17]

In almost all other ship structural problems, the methods of bending collapse analysis are not so obviously applicable. This is because a stiffened panel supported along all its edges cannot be laterally deformed without deflections which have curvature in two directions, and this in turn leads to a significant membrane stretching action, once the deflections become "large". For a single plate panel between stiffeners, "large" deflections imply a magnitude from about one plate thickness, say half an inch in the case of a warship. Membrane stretching arises even if the supporting structure at the edges cannot provide any membrane restraint, and the action inside the grillage is then one of membrane tension around the centre and tangential compression at the edges. The plating of ship grillages adds appreciably to the membrane strength of these structures. Long after the structure has exhausted its bending strength, the structure will deform as a membrane, and the final failure would usually be expected at some weak point in the details of the connections. It would be difficult to predict whether gross plastic deformation would occur before any local failures.

Although the simple collapse theory is not considered to be particularly relevant to ship structures, the present lack of knowledge on strength and collapse behaviour makes it almost mandatory to load all experimental or model structures to collapse, and this policy has been invariably followed at N.C.R.E.

Three flat grillages were tested to collapse under concentrated loads, the grillages being supported only at the corners for experimental convenience.[18] Two of the grillages failed in a simple mechanism involving only bending action, generally confirming the simple plastic theory, but the deformations of the other grillage involved membrane action. The load-deflection curve for this latter grillage is shown in Fig. 10, and it can be seen that there is no indication of any collapse around the theoretical bending theory value of 47.5 tons. Final failure occurred due to fracture of a weld at an intersection joint. Single-direction stiffened panels have also been tested to collapse under concentrated loading[19] and fairly considerable strength due to membrane action was indicated, which would be expected in the absence of any intersection joints. Some flat grillages have also been loaded to collapse under uniform pressure.[20] In one case, collapse was by plastic lateral instability of the heavy transverse beams, as shown in Fig. 11, at a load higher than the theoretical bending collapse pressure.

More recently, the large-scale steel frigate model referred to earlier has been loaded to collapse under a uniform pressure applied to the bottom structure.[13] The stress due to the applied load first reached yield locally in the longitudinals at about 20 lb./in.^{2}, but there was no sign of failure until 28 lb./in.^{2} was reached. At this stage, a number of local buckles and cracks occurred in the main longitudinals and frames. The structure was loaded several times from zero to 28 lb./in.^{2}, and the failures became successively more marked. Eventually, it was only possible to maintain a pressure of 22 lb./in.^{2}. A general view of the damage, seen from the inside of the model, in Fig. 12, shows marked shear buckling of the frame webs adjacent to the keel in way of scallop holes to take the 2-3/4 in. deep small longitudinal stiffeners. These webs were somewhat slender being 0.22 in. thick and 9½ in. deep. After the final loading, the webs were very badly buckled and fractured, as shown in Fig. 13. In assessment of the collapse test, it was concluded that these webs had failed by

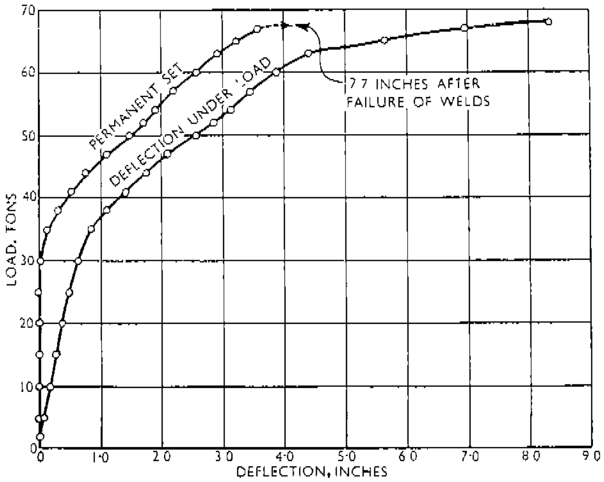


FIG. 10. LOAD-DEFLECTION CURVE FOR COLLAPSE OF GRILLAGE UNDER CONCENTRATED LOAD.

a combination of plastic instability and fracture caused by high-stress concentrations at the scallops and intermittent welds between the web and flange. Other positions of high stress were on the main logitudinal flanges adjacent to the end bulkheads. These flanges buckled plastically in way of gaps in the intermittent weld runs, as shown in Fig. 14. Similar buckles occurred in the transverse frame flanges at the bilge where there was a reduction in the section. In addition, there were a fair number of minor cracks and buckles throughout the structure.

Although the collapse of the frigate model took the form of a series of local failures, all of which occurred at approximately the same pressure, it is of interest to compare the 28 lb/in.^{2} maximum pressure attained, with the theoretical mechanism collapse pressure. The theoretical collapse pressure, in this instance, was modified to include, very approximately, the effect of in-plane displacements or membrane action. These calculations indicated that the true collapse pressure in the absence of any local instability or fractures, or failure of the supporting side structure or bulkheads, would be something like 45 lb/in.^{2}, and that the mode of collapse would differ somewhat from that observed. The theoretical collapse pressure for the observed mode would be 70 lb/in.^{2} with all members taking the full plastic moment, and without allowing for strength due to a plane action. This result emphasises that the rather low collapse pressure of the model was entirely caused by inadequate detail design.

The importance of rational design of details, particularly welded connections, has been recognized at N.C.R.E. for some time past, and Faulkner[21] has presented a review of work on the static strength of simple welded knee joints, longitudinal to bulkhead connections,

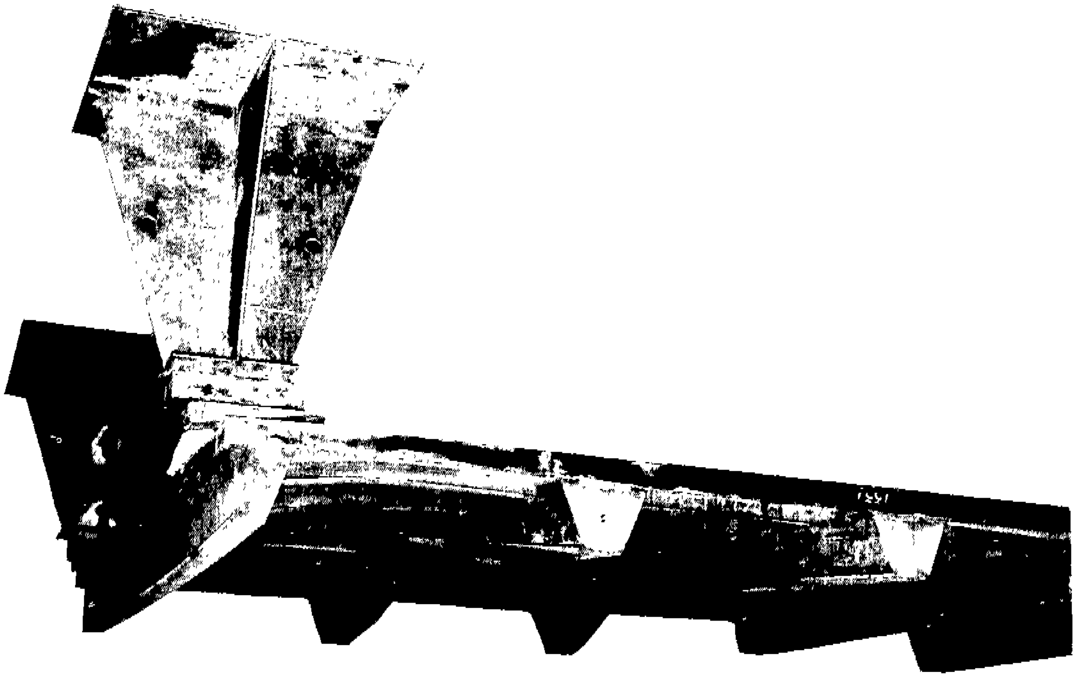


FIG. 11. PORTION OF GRILLAGE LOADED TO COLLAPSE UNDER UNIFORM PRESSURE.

and grillage intersections. The object of this work was to examine the strength of a number of simple joint designs and place them into an order of merit. As a result of this work, joints of various degrees of sophistication are now recommended for use in ship design, according to the magnitude of loading anticipated. It is appreciated that the fatigue strength of connections is also an important issue affecting surface ships and fatigue tests on a number of grillage intersection joints are planned for the near future.

FIG. 12. GENERAL VIEW OF DAMAGE TO FRIGATE MODEL AFTER COLLAPSE TEST.

STRENGTH OF BOTTOM STRUCTURES

A knowledge of the ultimate strength of the stiffened plate panels or grillages forming ship's bottom structures is required to determine the fully plastic moment to break a ship's back. This, in conjunction with a knowledge of the maximum bending moment at sea, will permit the true margin of safety or load factor against collapse to be determined. It is also necessary to understand the behaviour of the individual plate panels under simultaneously applied lateral and end load before the design of the mid-ship cross-section can be optimised.

With regard to the plating of warships, few quantitative results applicable in design have yet been obtained, despite a great deal of work at N.C.R.E. and elsewhere. The principal achievements so far have been for the case of lateral pressure alone. A concept

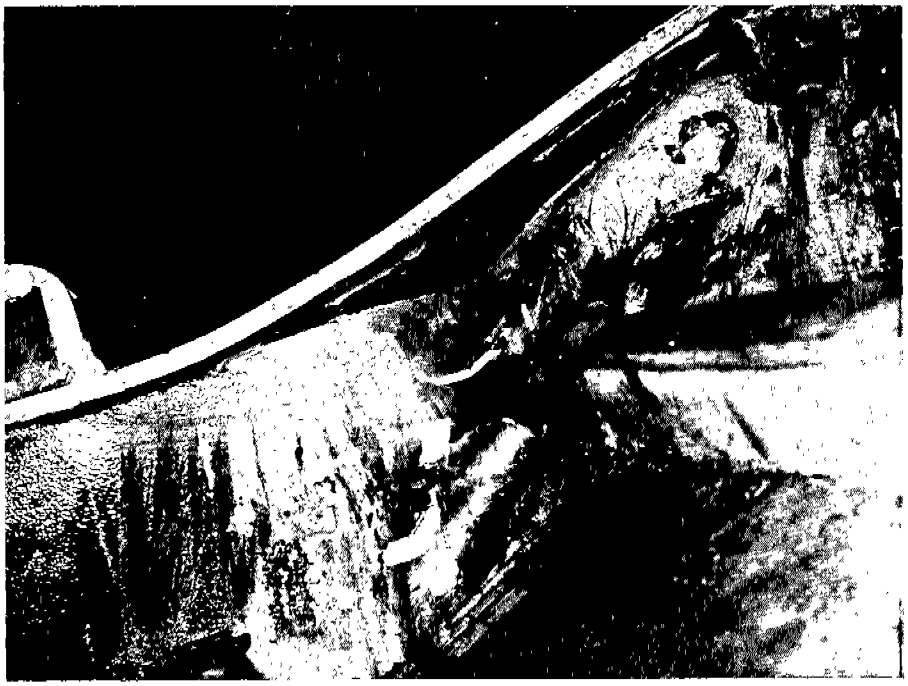


FIG. 13. DAMAGE TO FRAME WEB AFTER COLLAPSE TEST.

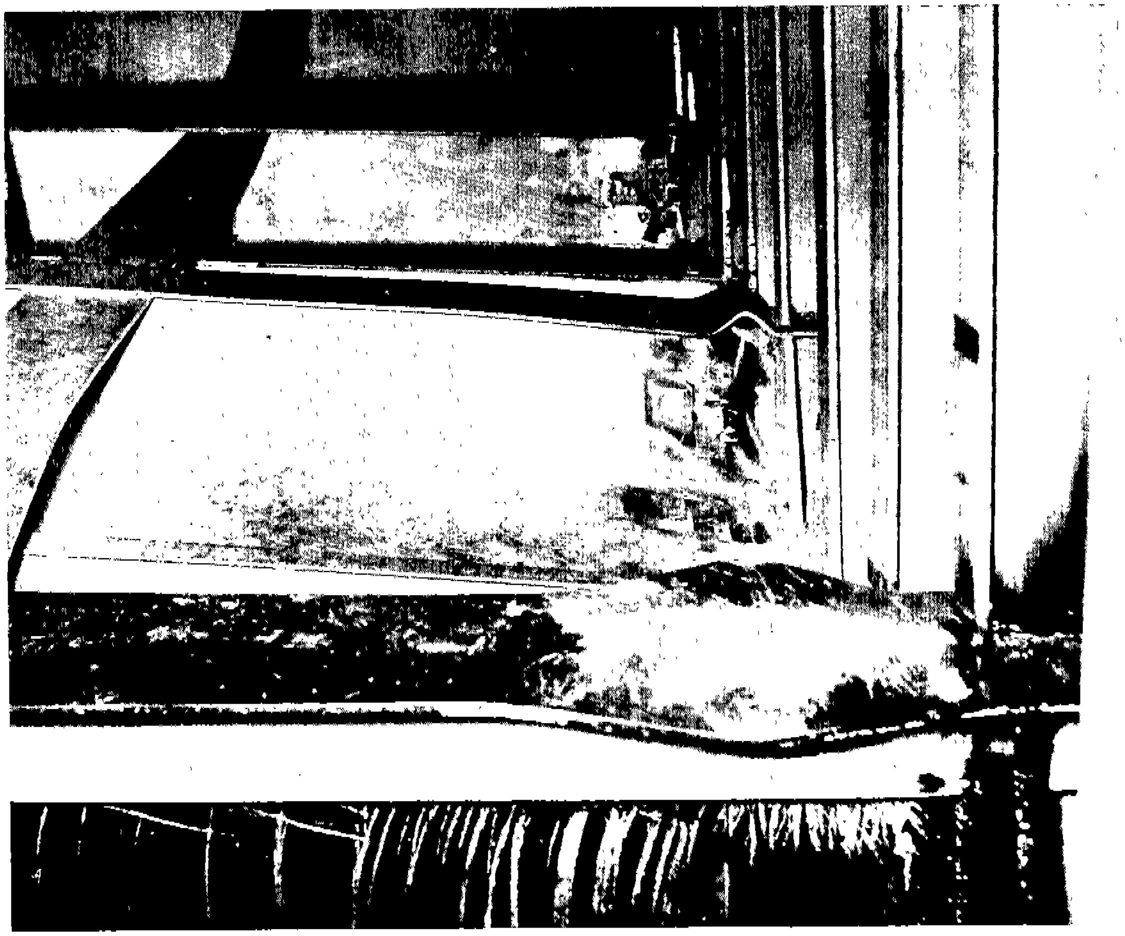


FIG. 14. BUCKLES IN KEEL AND LONGITUDINALS ADJACENT TO BULKHEAD.

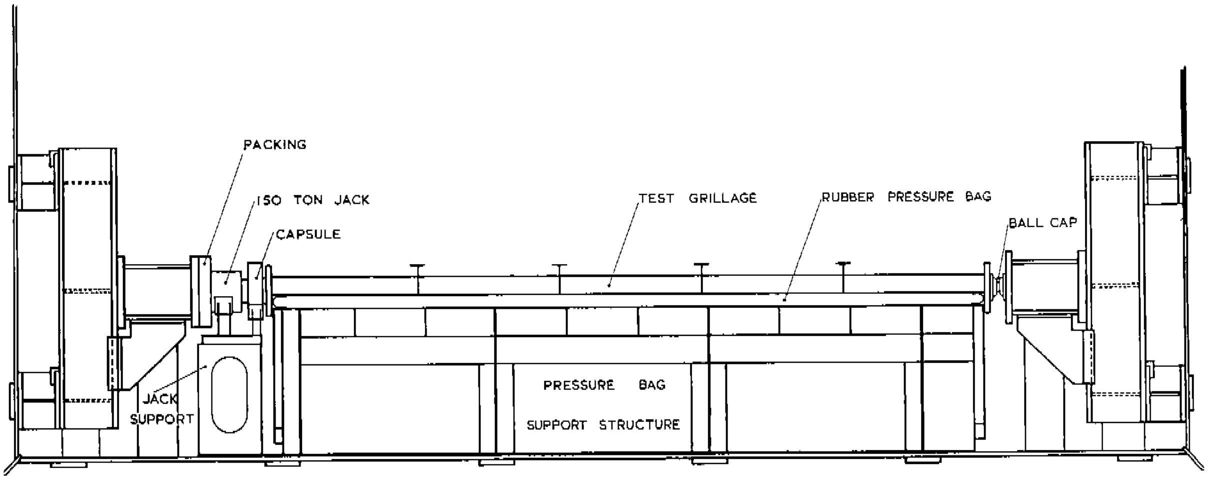


FIG. 15. TEST ARRANGEMENT FOR GRILLAGE UNDER COMBINED LATERAL AND AXIAL LOADING.

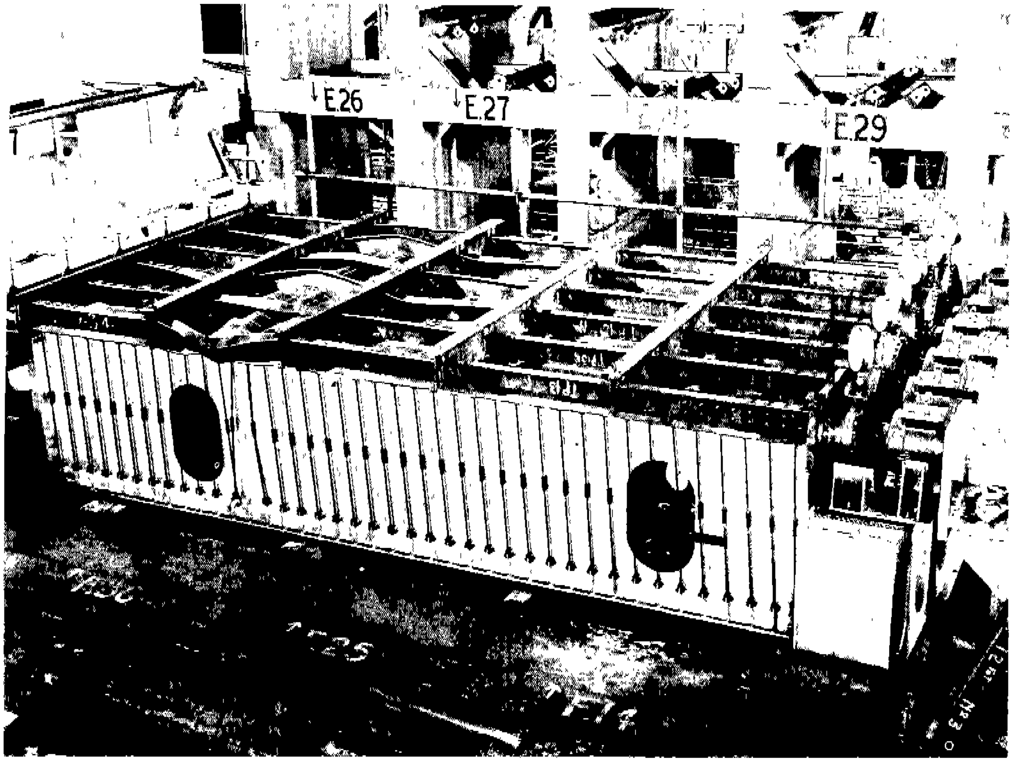


FIG. 16. FIRST GRILLAGE AFTER COLLAPSE UNDER AXIAL LOAD.

has been advanced of designing to a small but acceptable permanent set, assuming that the edges are clamped against rotation but free to slide inwards.[22] It has recently been established that there are some cases where a compressive stress field in the plating due to bending of the stiffening members may significantly affect the permanent set.[20]

Experimental work is now in hand in the Large Testing Frame at N.C.R.E. to study the behaviour of full-scale welded grillages under simultaneously applied lateral pressure and end load. Five pairs of mild-steel grillages are being tested initially, each with overall dimensions of 20 ft by 10 ft, covering a range of width to thickness ratios for plate panels between stiffeners from 40 to 100, and a range of span to radius of gyration ratios for longitudinal girders (between frames) from 20 to 60. The first grillage of each pair is being tested to collapse under end load only, while the second will be collapsed under a combination of lateral and end load. In-plane loading is applied through six 150-ton hydraulic jacks acting through load cells and ball caps; lateral load is applied by a water filled rubber bag, as shown in Fig. 15. Approximate conditions of simple support are provided by light flexure plates at the ends of each grillage and by tie-bars at the sides. The complete test assembly is shown in Fig. 16, which also illustrates the collapse of the first grillage by elasto-plastic instability between two adjacent frames. In parallel with the experimental work, numerical computer programs have been developed for the elastic analysis of grillages under combined lateral and in-plane loading, and to calculate the buckling loads and modes. Programs for Pegasus are complete, and programs for the larger KDF 9 computer are in preparation.

EXPERIMENTAL TECHNIQUES

Even with the large and high-speed digital computers now available, the complexity of ship structures is such that considerable simplification and approximation are usually required before theoretical analysis is feasible. At N.C.R.E., all the structural investigations have included experimental work to assist in formulating idealisations and to check on the accuracy of the results. Ideally, large-scale models using full-scale materials and fabrication techniques are desirable so that the details at joints and the welding distortions are typical of full-scale practice. These distortions have an important bearing on the effec-

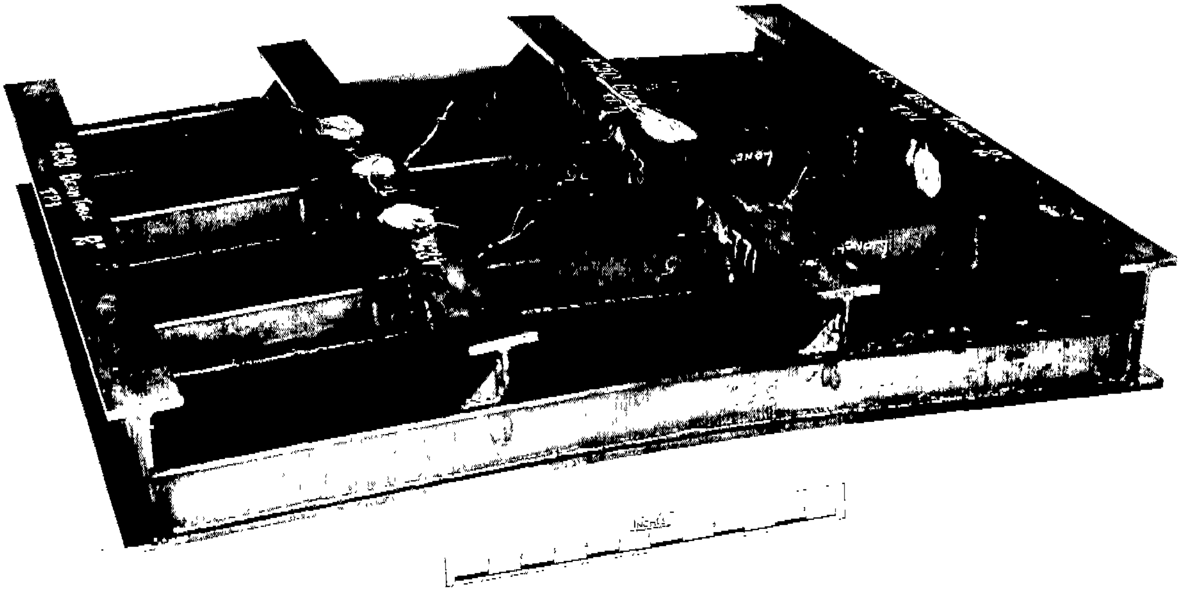


FIG. 17. SMALL-SCALE GRILLAGE MODEL AFTER COLLAPSE.

tiveness of the plating as stiffener flanges and under shear. Because of limitations on the smallest size of strain gauge available, large-scale models are also necessary to carry out detailed strain surveys. Information on collapse strength can only be obtained from realistic, preferably large-scale models.

N.C.R.E. is fortunate in having a large testing frame measuring 69 ft long by 33 ft wide by 39 ft ft high, capable of withstanding loads up to 500 tons (or 2,000 tons axially).[23] The frigate model mentioned earlier was tested in this large testing frame.

Large-scale tests have the unfortunate disadvantage of proving extremely costly and difficult to carry out due to the very large loads and test rigs required. A large number of small models can be constructed and tested for the same outlay as one large model, and small models are usually adopted by N.C.R.E. whenever it is desired to study the effects of fairly wide changes of parameters. On the other hand, small-scale welded steel models have often suffered from large and completely unacceptable welding distortions which render strain measurements in the elastic range of very limited value. Small-scale steel models may also be fabricated using silver solder techniques or by intermittent or spot welding, but these constructions are seldom sufficiently strong for tests in the plastic range. In recent years, the dip transfer gas shielded electrode method of welding has been adopted for comparatively small-scale steel models. This process produces very much smaller welding distortions than the manual processes, owing to the smaller heat input. Partly as a test on the dip transfer procedures, two small grillages have recently been constructed at N.C.R.E. using material ranging from 0.15 to 0.27 in. thick, which might be regarded as 1/3 or 1/4 of full scale.[24] The models incorporated fillet welds, butt welds in the plating, and correctly scaled details at the intersections. Only very small welding distrotions were obtained which were quite typical of good full-scale practice. The models were loaded elastically and then into the plastic range. The maximum loads applied were above the theoretical plastic collapse loads but there were no cracks or signs of failure. A view of the first model after testing is shown in Fig. 17. The presence of butt welds in the plating did not have any noticeable effect on either the behaviour of a panel between stiffeners under a localized loading or on the overall behaviour up to the maximum load applied. As a result of these developments, it is anticipated that future structural testing may tend to be carried out more on small-scale steel models.

For purely elastic measurements, small-scale models in a plastic material such as Xylonite (cellulose nitrate), celastoid (cellulose acetate), perspex (polymethyl methacrylate), or vybak (rigid polyvinyl chloride) have many advantages. Despite their nomenclature as plastic materials, the mechanical behaviour of these materials is elastic, obeying Hooke's Law up to very large strains, say 0.6 to 0.8%, provided the measurements are taken at a constant time interval after application of the load to allow for creep. Of these plastic materials,

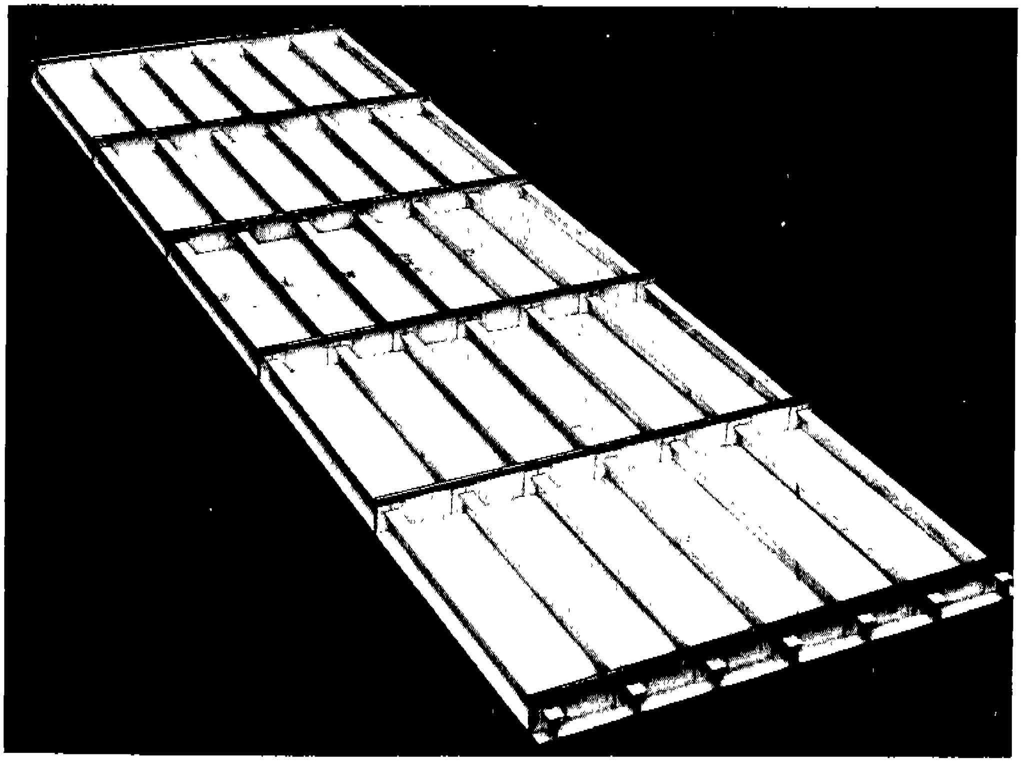


FIG. 18. GRILLAGE MODEL IN VYBAK.

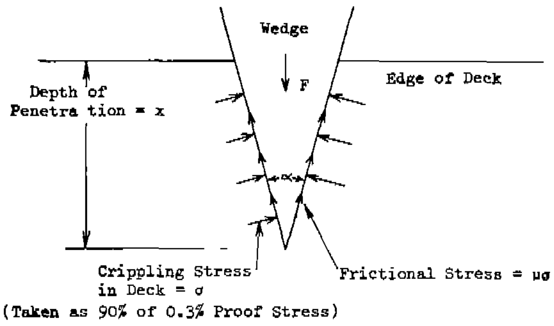
celastoid can be ruled out since it is very sensitive to humidity changes, while perspex is only available for a fairly limited number of thicknesses. Xylonite is possibly the most commonly used plastic material for models using strain gauge techniques. In common with most plastics, xylonite has the advantages of a very uniform thickness with smooth surfaces ready for cementing strain gauges, softness making it easy to cut and work, and ease of forming by moulding at about 120°C, somewhat above its softening point. The low Young's modulus, roughly 1/100 of that of steel, leads to appreciably smaller test loads and simplifies the problem of providing stiff supporting structures. Unfortunately, Xylonite has poor dimensional stability, and the material is frequently found to warp, distort and contract over periods of months. Its elastic constants at any one time are affected by temperature and humidity changes, and they also vary with the life of the sheet. Also, the bonds at connections which are made by wetting with the solvent acetone or a mixture of acetone and amyl acetate are not fully reliable and may "give" or even fail at quite low stresses. Another disadvantage of Xylonite is its inflammable nature.

At N.C.R.E., a rigid polyvinyl chloride material manufactured by Bakelite, Ltd. under the trade name "Vybak", has been adopted as a superior replacement to Xylonite. Vybak has complete dimensional stability; it is not inflammable; it's Young's modulus is more uniform than Xylonite; and it is not affected by atmospheric humidity. The rigidity of the material is affected by temperature, rather more than Xylonite, so that temperature control of the laboratory is required. Vybak can be bonded very easily using the cements Tensol No. 6 and Tensol No. 7, manufactured by the Plastics Division of Imperial Chemical Industries, Ltd. for use with perspex. Both these cements are cold setting, Tensol No. 6 is suitable for shear connections but shrinks on curing, while cement No. 7 can be used to fill gaps and will develop almost the full tensile strength of the vybak. Vybak has been successfully used at N.C.R.E. for a number of grillage and transverse strength experiments, (such as the aircraft carrier flight deck structure shown in Fig. 18) and models to investigate stress concentrations at hatch openings.

A review of model procedures for naval structures was published by the present author in 1962,[25] but this paper was written before the dip transfer welding was introduced for small-scale steel models. Another model technique, currently under development, is to use vybak models for elastic instability experiments. Due to the very large elastic range of strain for vybak, buckling analysis can be checked for realistic full-scale geometries of designs which would fail by yield when constructed in steel. In this way, the true margin of safety against buckling may be determined. Vybak is also very suitable for instability experiments because it can be bonded together with only minor distortions, even when very small thicknesses are used. This makes it possible to approach the buckling load more closely without large effects caused by magnification of initial imperfections.

PROTECTION STRUCTURES FOR MARINE NUCLEAR REACTORS

N.C.R.E. has made an important contribution to the design of collision barriers to protect the reactor of a proposed nuclear powered ship. The work has been sponsored by the Ministry of Transport Technical Committee on the Structural Protection of Marine Nuclear Reactors and the report of this committee is now being drafted. Four possible methods of providing structural protection have been considered; namely, a deck system, grillage system, membrane tension barrier and membrane compression barrier. Of these, the deck system was favoured since, by stiffening to prevent instability, the striking ship would be resisted by forces near to yield stress throughout the deck material, and the space requirements would not be too severe. The principle of the deck resisting structure is illustrated in Fig. 19, the striking wedge being resisted by a direct crippling stress in the deck, normal to the wedge, and a frictional force tangential to the wedge. The deck resistance at the leading edge of the bow, and the bending rigidity and friction from the outer shell plating were considered to be secondary terms. With these assumptions, some very simple expressions were derived for the penetrating force and work done, and these were subsequently confirmed by static tests on a series of models. In order to achieve as high as possible a value for σ, the crippling stress normal to the wedge, the breadth to thickness ratio for each plate panel between stiffeners was limited to 50, and the effective span to radius of gyration ratio for the stiffeners was limited to 40.



Penetrating Force $= 2\sigma A(\sin\frac{\alpha}{2} + \mu\cos\frac{\alpha}{2})$ for each deck

$$= 2k\sigma t(\tan\frac{\alpha}{2} + \mu)x$$

where A = effective area of contact on each side of wedge

k = (effective area of contact)/(area of plating) = A/A_p

t = thickness of plating

Work done $= \int F\,dx = k\sigma t(\tan\frac{\alpha}{2} + \mu)x^2$

Results for 54 in. penetration on Model 2:

$k = \frac{A}{Ap}$	μ	F tons	Work Done tons in.
1.0	0.2	105	2840
1.0	0.3	128	3440
1.85	0.2	--	5250
Experimental		128.5	3200

FIG. 19. PRINCIPLE OF DECK PROTECTION STRUCTURE FOR NUCLEAR REACTOR.

The possibility of carrying out dynamic tests was considered, but was ruled out due to difficulties in correctly scaling both the velocity of load application, and inertia effects. It was thought that dynamic effects would be small in a practical problem involving gross plastic deformation of many square feet of material. The tests were therefore carried out on small-scale models loaded statically in a 500-ton testing machine. Static tests also provided a continuous record of the relation between load and depth of penetration which would require a large number of models if determined by dynamic tests. The possibility of a final dynamic test at full scale was considered, but has not been followed up due to the prohibitive costs involved.

The models were based on a full-scale barrier depth of 20 ft and deep-frame spacing of 10 ft. Two designs were considered, one having a deck plating thickness of 1/2 in. and the second 1 in. The first model was a 1/8 scale model of 1/2-in. thick deck structure, constructed in mild steel using a silver solder technique. It was loaded by a rigid wedge with a 30° included angle and 3/4 in. radius nose. This test was not fully successful, due to insufficient end constraint in the test ring, and failure of some of the soldered joints. The second model was 1/4 scale of welded construction, and this model failed progressively by local crippling of the stiffened deck structure in way of the penetrating wedge. The results are compared with predictions from the simple theory, for a 54-in. penetration in Fig. 19.

The third model was similar to the second but represented a 1-in. thick deck at full scale, and the model scale was 1/8. This model was fabricated by welding using the dip transfer welding procedure. The model was loaded by a rigid wedge with a 20° rake and an included angle of 30°. In this model there was more pronounced curling of the deck as it was pushed back by the sides of the wedge, and the energy absorbed was about 70% of the value estimated for a vertical wedge, based on the test of Model 2. The fourth model was identical to the third, and was loaded by a bow representative of the actual structure in a fast car cargo ship. In this case, the bow was severely crumpled with little penetration of the barrier decks. This indicates that the types of deck structure barrier investigated would be most effective in full-scale collisions, and that the energy absorbed would be significantly greater than that derived from crippling of the collision protection structure alone. The experiments with the raked rigid bow have indicated that, at full scale, the energy which could be absorbed by the protection structure would be 32,000 tons ft (or 360,000 tons - knot^2) for each deck, and it is considered that this would be increased by at least 1/3 for any simulated actual bow structure. Bearing in mind that part of the energy of any collision will remain as kinetic energy, it is felt that a satisfactory protection structure can be based in the N.C.R.E. design using say six decks, and that this will be adequate against almost all possible collisions at sea.

CONCLUSIONS

It may be seen that significant progress has been made in the understanding of ship structures, particularly by developing methods of elastic analysis using electronic computers. Furthermore, research is in progress to obtain information on loadings at sea, with regard to both extremes and repeated cyclic loading. It is considered that the most important outstanding problem affecting surface ship structures is to formulate rational design criteria. With more information on the loading becoming available, the choice of maximum allowable design stress must be re-examined, for both the mean field stress, and locally at stress concentrations. At the present time there appears to be some inconsistency in designers' attitudes to stress concentrations. While major structural discontinuities such as the break of forecastle or major hatch openings receive careful attention, it is quite common for smaller discontinuities such as scallop holes, joints and connections either to be designed by eye or hardly to be considered at all. Our ship designers must also assess whether minimum weight design, possibly accompanied by increased manufacturing costs, is of interest. Minimum weight and costing studies are now quite feasible using electronic computers, though difficulties may be experienced in obtaining data on the breakdown of manufacturing costs.

ACKNOWLEDGEMENT

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REFERENCES

1. Smith, C. S., "Measurement of Service Stresses in Warships." Paper No. 14, Conference on Stresses in Service, Institution of Civil Engineers, March 1966.
2. Yuille, I. M., "Longitudinal Strength of Ships." Trans. R.I.N.A. Vol. 105, No. 1, January 1963, pp.1-34.
3. Gumbel, E. J., Statistics of Extremes. Columbia University Press, 1959.
4. Clarkson, J., The Elastic Analysis of Flat Grillages. Cambridge University Press, 1965.
5. Clarkson, J., "Elastic Analysis of a Beam-Plating Structure under a Single Concentrated Load." Proc. IX Int. Congr. Appl. Mech. Bruxelles 1956. pp. 176-186.
6. Smith, C. S., "Elastic Analysis of Stiffened Plating under Lateral Loading." Trans. R.I.N.A. paper for written discussion, 1965.
7. Kendrick, S., "The Analysis of Flat Plated Grillages."European Shipbuilding, Vol. 5, No. 1, 1956. pp. 4-10.
8. Kendrick, S. and McKeeman, J. L., "Pegasus Computer Specifications - Plane Frame Analysis," Report No. N.C.R.E./R484, October 1963.
9. Kendrick, S. and McKeeman, J. L, "Pegasus Computer Specifications - Plane Grillage Analysis," Report No. N.C.R.E./R481, August 1963.
10. Smith, C. S., "Pegasus Computer Specifica-

tions - Elastic Analysis of Orthogonal Grillages Excluding Torsional Effects." Report No. N.C.R.E./R520. To be issued shortly.

11. Yuille, I. M. and Wilson, L.B., "Transverse Strength of Single Hulled Ships," Trans. R.I.N.A., Vol. 102, No. 4, October 1960. pp. 579-612.

12. McKeeman, J. L., "Pegasus Computer Specifications - Curved Grillage Analysis," Report No. N.C.R.E./N145, June 1961.

13. Clarkson, J. and Wallace, G., "Transverse Strength of a Large Steel Frigate Model," Report No. N.C.R.E./R526. To be issued shortly.

14. English Electric - Lee-Marconi Computers Limited: KDF 9 Structural Analysis. 1. Elastic Frameworks. Issued by firm's Technical Services Bureau.

15. Vaughan, H., "Elastic Analysis of a Ship in a Floating Dock." Trans. R.I.N.A. paper for written discussion, 1965.

16. Amerikian, A., "Analysis and Design of Floating Dry Docks," Trans. S.N.A.M.E., Vol. 65, 1957, pp. 307-361.

17. Caldwell, J. B., "Ultimate Longitudinal Strength." Trans. R.I.N.A. Vol. 107, No. 3, July 1965, pp. 411-430.

18. Clarkson, J., "Tests of Flat Plated Grillages under Concentrated Loads." Trans. I.N.A., Vol. 101, No. 2, 1959, pp. 129-142.

19. Clarkson, J., "The Behaviour of Deck Stiffening under Concentrated Loads." Trans. R.I.N.A., Vol. 104, No. 1, 1962, pp. 57-65.

20. Clarkson, J., "Tests of Flat Plated Grillages under Uniform Pressure." Trans. R.I.N.A. Vol. 105, No. 4, 1963, pp. 467-484.

21. Faulkner, D., "Welded Connections used in Warship Structures." Trans. R.I.N.A., Vol. 106, No. 1, January 1964, pp. 39-70.

22. Clarkson, J., "Uniform Pressure Tests on Plates with Edges Free to Slide Inwards." Trans. R.I.N.A., Vol. 104, No. 1, 1962, pp. 67-80.

23. "Testing Frame for Ships' Structures." Engineering, Vol. 176, No. 4565, July 24, 1953, pp. 115-116.

24. Clarkson, J., "Small Scale Grillage Tests," Report No. N.C.R.E./R517, February 1966.

25. Clarkson, J., "Steel or Plastic? The Choice of a Material for Small Scale Models of Naval Structures." European Shipbuilding, Vol. XI, No. 4, 1962, pp. 78-89.

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Entirely rational elastic or plastic design procedures for surface ship structures have not been achieved. During the past 15 years, considerable advances and development both in the understanding of the mechanics of ship structures and in the application of digital computers to ship problems have been made. This is a report on research in progress to obtain information on loadings at sea, with regard to both extreme and repeated cyclic loading.

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SSC-171, *Micro- and Macrocrack Formation* by B. L. Averbach. October 1965. AD 473496.

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