SHIPS' SUPERSTRUCTURES IN FIBRE REINFORCED PLASTIC

BY

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Introduction

Following the extensive experience gained by the Navy in the use of glass reinforced plastic (GRP) in the MCMV programme, consideration is now being given to where the material could be used to advantage in other areas. The idea has been floated* that improvements could be made in the design of surface ship superstructures by incorporating fibre reinforced plastics (FRP). Potential advantages are:

(*a*) Virtual elimination of fatigue cracking associated with hull/superstructure interaction, because of the low stiffness of FRP.

(*b*) Weight substantially lower than that of steel and comparable with that of light alloy construction.

(*c*) Better fire resistance than is provided by aluminium structure.

(*d*) Better ballistic protection for a given weight than is provided by steel or aluminium.

(*e*) Cost is likely to be less than for aluminium and through-life cost may be comparable with using steel.

The purpose of this article is therefore to present what may appear to be a revolutionary idea to a wider naval audience, and the following crown copyright text is largely reproduced from the Royal Institution of Naval Architects paper*. Comments based on operators' or maintainers' experience would be welcomed, and should be addressed to Sea Systems Controllerate Section NA123, Block F, Foxhill, Bath.

Research into the use of FRP for superstructures is being pursued as a collaborative project by the U.S.A., Canada, and the U.K., and includes full scale air blast trials on a panel representing a deckhouse side in the U.S.A. in 1987. It is intended that this research will lead to an alternative design in FRP for one of the superstructure blocks of the NATO frigate (NFR 90), and the technology could also be used to design and fit an experimental FRP deckhouse on one of the later Type 23 frigates.

Superstructure Design

At some stage in a ship's design a decision must be made on whether the superstructure is required to contribute significantly to longitudinal stiffness and strength of the hull girder. If it is, then the following principles should be observed as far as possible:

(*a*) The superstructure should be as long as possible.

(*b*) It should be continuous, with a minimum of discontinuities in profile and planform including openings in decks and sides.

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*Smith, C. S., and Chalmers, D. W.: Design of ship superstructures in fibre-reinforced plastic; Royal Institution of Naval Architects, spring meeting 1986, paper no. 3.

(*c*) It should extend the full width of the ship.
(*d*) It should be rigidly attached to the main hull.
(*e*) It should be of welded steel construction with longitudinal stiffening.

If the superstructure is not intended to contribute to hull strength and rigidity, its structural role reduces to that of withstanding lateral loads including green seas, static and inertial forces from 'own weight' and massive items of equipment and, in the case of warships, airblast, ballistic attack, missile launch forces and possibly helicopter landing loads. Inevitably, however, deformations of a superstructure will be induced by bending of a ship's hull tending, especially in the case of welded aluminium construction, to cause fatigue cracks which may propagate downwards towards primary hull structure. A rigid deckhouse also tends to impose severe local loads, particularly at its ends, on the main hull structure: in some existing ships persistent fatigue failures induced by such loads have curtailed the effective ship life.

Various methods may be employed to reduce hull/superstructure interaction, principally using expansion joints. An expansion joint is effective in reducing stress levels in the upper part of a deckhouse adjacent to the joint but is likely to transfer the problem downward, tending to cause stress concentrations and cracking in the deckhouse sides; more significantly high stresses and susceptibility to cracking may be induced in the primary hull structure immediately below an expansion joint.

An alternative means of avoiding unwanted hull/superstructure interaction is use of a low-modulus material in the superstructure. One such material is glass-fibre reinforced plastic (GRP), which offers tensile and compressive strengths of the same order as the yield strength of mild steel with a Young's modulus less than 10% that of steel. The purpose of the present article is to examine the feasibility of using GRP in ship superstructures. Consideration is given to some alternative combinations of materials and forms of construction with reference to strength, stiffness, weight, cost, fire-resistance and other factors affecting performance. Comparisons are made in each case with conventional steel and aluminium construction.

Choice of Materials

The materials most likely to be used in a GRP superstructure are polyester resin reinforced by E-glass fibres in the form of woven rovings or similar fabric. S-glass reinforcement, employed extensively in the U.S. aerospace industry (or its European equivalent, R-glass), which has a strength about 30% higher than E-glass at a cost 5 to 10 times greater, might be justified in a weight-critical design or to obtain increased ballistic resistance. Aramid (Kevlar 49) fibres, offering very high specific tensile strength (43% higher than E-glass) but having a low compressive strength, at a cost 10 to 15 times higher than that of E-glass, might be employed in areas of a weight-critical superstructure requiring a high level of ballistic protection.

Despite its marginally higher cost, isophthalic polyester resin, as used in most high-performance marine construction including GRP minesweepers[1,2], is probably preferable, because of its superior water resistance, to orthophthalic polyester as used commonly in lower-performance boat hulls. Vinylester resin offers an alternative to polyester, having a higher heat-distortion temperature, better water resistance and slightly better mechanical properties[3,4] at a cost 1.5 to 2 times greater. Phenolic resin, now available in cold-curing form suitable for hand lay-up[5,6], is a further alternative; its main attraction is very good fire resistance but its performance in a wet environment is suspect, suggesting an application only in internal (dry) bulkheads.

Laminates based on thermoplastic resins such as PES (polyethersulphone) and PEI (polyetherimide) have considerable promise for high performance applications, providing high thermal stability, good fire resistance and hot-formability, but their cost is likely to be many times that of polyester-based GRP.

Sandwich panels formed by GRP skins with foam, balsa or honeycomb cores offer an alternative form of construction. Rigid PVC foam, which is employed in the sandwich structure of Swedish[7] and Australian[8] minesweeper hulls, has been rejected as a superstructure material by British naval designers because of concern about the toxic fume (hydrochloric acid) hazard under fire conditions. Alternatives include phenolic foam, with good fire resistance but poor mechanical properties, and thermoplastic (e.g. PES and PEI) foams which promise high strength and fire resistance but are not yet available commercially in large quantities. Sandwich panels with aluminium, stainless steel or GRP honeycomb cores offer very good mechanical performance but at a cost only likely to be justifiable in the most weight-critical applications.

Mechanical properties of candidate materials for ship superstructures are summarized in TABLE I. Properties of FRP laminates are more variable than those of steels and aluminium alloys.

TABLE I—*Properties of Candidate Superstructure Materials, mean and (minimum) values*

Material	*Specific Gravity*	*Young's Modulus* GPa	*Shear Modulus* GPa	*Tensile Strength* MPa	*Compressive Strength* MPa	*Shear Strength* MPa
Steel (B-quality or BS 4360 Grade 50D)	7·8	207	80	390(325)	390(325)	225(188)
Steel HY80	7·8	207	80	617(552)	617(552)	356(319)
Aluminium N8 (5083)	2·8	69	26	200(130)	200(130)	115(75)
Aluminium H30 (6082)	2·8	69	26	(250)	(250)	(144)
GRP (hand lay-up, balanced E-glass woven rovings, polyester resin, fibre wt fraction = 0·55)	1·7	18(15)	4(3·2)	260(200)	210(152)	110(100)
GRP (hot-pressed, balanced E-glass woven rovings, polyester resin, fibre wt fraction = 0·75)	2·0	25(20)	6(5)	325(250)	270	130

Note: Strengths of steel and aluminium refer to σ_y and $\sigma_{0\cdot 2}$ respectively

These figures are derived from published sources[9,10,11] and unpublished MOD test data representative of materials used in MCMV construction.

Possible Forms of FRP Construction

The two forms of construction which seem most feasible are:

(*a*) integral moulded GRP, laid up by hand in a female mould following normal boat-building practice as employed in current MCMV designs.

(*b*) assembly of prefabricated flat GRP panels by bolting and/or bonding or screwing on to transverse frames in steel, aluminium or pultruded GRP (pultrusion is the reverse of extrusion, i.e. the material is pulled through the die).

In either case sandwich construction might be employed, i.e. GRP inner and outer skins with foam, end-grain balsa or possibly honeycomb core. An integral sandwich superstructure would probably be most economically achieved by adopting the procedure developed by the Swedish navy for

MCMV hull construction[7], in which fabrication is started by assembly of core material on a wooden framework, followed by hand lay-up of the outer GRP skin, after which the unit has sufficient rigidity to be turned over for completion by hand lay-up of the inner GRP skin.

The second form of construction identified above (assembly of prefabricated flat panels) appears to offer the most potential for optimized, low-cost hybrid construction in which, for example, steel or aluminium transverse bulkheads might be combined with GRP deckhouse sides and GRP or metallic decks. Some such superstructure configurations are compared below with integral GRP designs and with standard aluminium and steel designs.

Strength and Stiffness under Lateral Load

As a basis for comparison a reference design in light alloy has been considered, corresponding to a light, vertically stiffened deckhouse side of height 2·3 m, or similar transversely stiffened superstructure deck panel of the same width supported at its edges by the deckhouse side and a longitudinal girder or minor bulkhead. Loading was assumed to comprise green-sea pressure of 25 kN/m^2 (0·25 bar), which is typical of warship design and intermediate between the requirement of Lloyds Register and the more stringent requirement of the Japanese Classification Society NKK[12]. A substantially higher design pressure is applicable in the case of transverse panels forming superstructure ends.

Details of the aluminium reference design and of equivalent stiffened panels in other materials are shown in FIG. 1. Assumed material properties are given in TABLE I, and more details of the designs and design criteria are contained in the original paper. GRP moduli and strengths are lower-bound values reduced by 15% to allow for long-term degradation in a wet environment. Permissible strains rather than stresses are specified for GRP, equivalent to 30% of the initial ultimate strengths in accordance with current design practice for short-duration loads. A limit of 30% UTS is adopted for normal working loads because of the occurrence of initial damage (microscopic resin cracking and initial debonding of fibres lying across the line of tensile load) at about this strain level in glass-fabric based laminates: substantially higher permissible strains are appropriate in the case of exceptional loads (e.g. air blast).

A comparison of the alternative designs is made in TABLE II. Deflections (w), stresses and strains were estimated using composite beam theory with appropriate reductions in assumed effective breadth for slender metallic and GRP panels. In the case of Designs C, D, E1, E2 and F, folded-plate analysis[13] was employed to account for the unequal span 'continuous beam' behaviour of the plating and the effects of coupled bending and twisting of asymmetric stiffeners. Shear stresses in stiffener webs were examined and found to be well below buckling and material failure levels. In the case of GRP and hybrid sections the average shear stress (τ_{ave}) across the bondline between stiffeners and plating was estimated using the composite beam formula

$$\tau_{ave} = \frac{S E_x b_e t z'}{b_a EI}$$

where S: shear force
E_x: Young's modulus of the GRP panel in the stiffener direction
b_e: effective breadth of the GRP panel assumed to act with the stiffener in bending
t: the panel thickness
z′: the distance from the neutral axis of the section to the mid-thickness plane of the GRP panel
b_a: total breadth of bondline
EI: flexurable rigidity of the composite section

Shear stresses estimated in this way were substantially lower than the nominal bond shear strength (for cold-setting epoxy adhesive) of 27 MPa.

TABLE II lists overall and local maximum stresses and displacements normalized with respect to permissible levels, together with weight per unit length W normalized with respect to that of the reference design (A). Although somewhat different scantlings would be required in more severely loaded superstructure ends and more lightly loaded internal bulkheads, the comparison of performance provided by Designs A to H is believed to be reasonably representative.

Weights achieved in the all-GRP designs (C, F, G) are in all cases lower than in the aluminium reference design; hybrid designs (D, E1, E2) have weights similar to or slightly greater than Design A. Maximum stresses in the GRP and hybrid designs are in most cases smaller fractions of permissible stress, while deformations are in all cases larger fractions of permissible levels, than in the reference design. It proved difficult to identify a satisfactory unstiffened PVC core sandwich configuration: Design H1 fails to meet permissible stress and deformation requirements and Design H2, while almost meeting these requirements, is very thick and probaby not practical.

Cost Evaluation

TABLE II includes a comparison of estimated overall cost, normalized with respect to that of Design A. Cost estimates include the material and labour to construct a simple panel representing a deckhouse side and include an allowance for electro-magnetic screening of each of the non-metallic options. Costs of attachment between panels and to the steel main deck are not included because of the many possibilities and lack of data. However it is possible to rank attachment methods in order of cost, commencing with the cheapest:

(*a*) Welded connection—steel to steel
—aluminium to aluminium
—aluminium to steel using explosive bonded strip

(*b*) Bonded connection—appropriate to all composite configurations

(*c*) Bolted or riveted connections.

The cost of fire protection has been considered, as has that of thermal insulation. It is evident that all the panel designs except G, H1 and H2 will require insulation, and for naval purposes thermal insulation also provides adequate fire-retardant properties. Thus all the single skin options would need thermal insulation, and the three sandwich options would require fire protection because of their very thin skins. Consequently the cost of insulation does not bear directly on the cost comparisons but adds the same absolute value to each. A complication arises from the need to insulate the underside of the steel main deck below the deckhouse to prevent conduction of heat from a fire below melting or burning the deckhouse attachment. This gives rise to an additional cost for all materials other than steel which has been included in the estimates given in TABLE II.

For merchant vessels the policy is to contain fires within fire-retardant boundaries for a prescribed time depending on the level of risk[14]. Although the insulation or fire retardant materials to meet these regulations may be different from those used in warships, the overall requirement is likely to be similar for each structural material option and will not affect the first order cost comparisons. It is clear from RN experience[15] that any of the Safety of Life at Sea (SOLAS) regulations of the International Maritime Organization can be met by providing an adequate thickness of GRP, but the thickness required structurally in any of the configurations would be insufficient to withstand a severe fire for more than 15 minutes or so without protection.

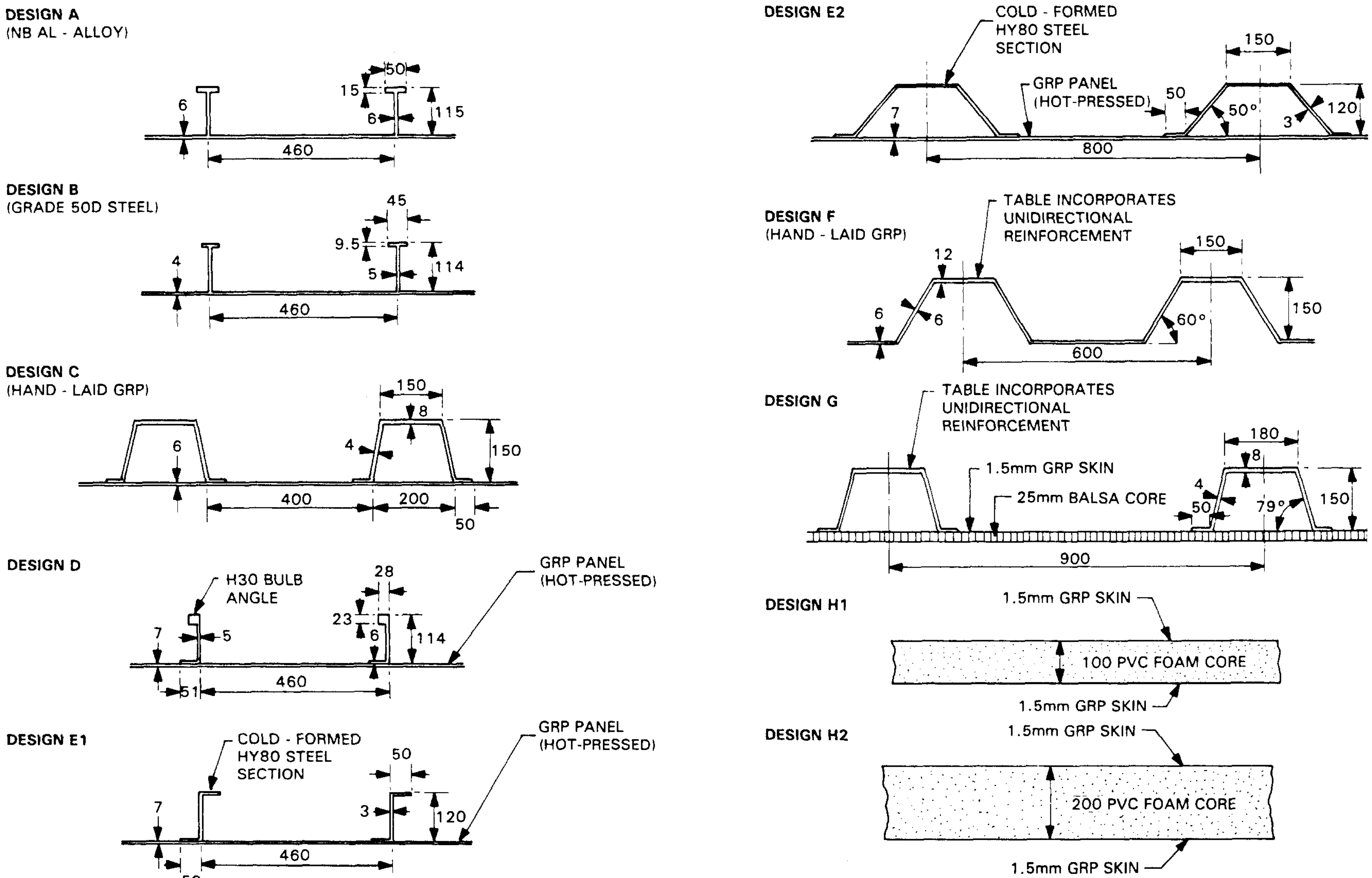
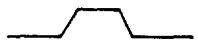


FIG. 1—ALTERNATIVE METALLIC, GRP AND HYBRID STIFFENED PANEL DESIGNS

TABLE II—*Comparison of Alternative Stiffened Panel Designs*

Design Particulars	*Overall Bending*		*Local Panel Bending*		*Relative Weight* W/W$_A$	*Overall Relative Cost* £/£$_A$
	σ_{max}/σ_p	w_{max}/w_p	σ_{max}/σ_p	w_{max}/w_p		
Design A (Reference Design: N8 Alloy) 	0·91	0·39	0·75	0·21	1·0	1·0
Design B (Grade 50D Steel) 	0·63	0·20	0·76	0·24	1·98	0·35
Design C (All GRP (Hand-laid)) 	0·68	0·72	0·64	0·89	0·87	0·85
Design D (H30 Alloy Bulb angle on hot-pressed GRP) 	0·65	0·56	0·91	0·42	1·00	0·74
Design E1 (Cold-formed HY80 Z-section on hot-pressed GRP) 	0·78	0·40	0·68	0·41	1·11	0·54
Design E2 (Cold-formed HY80 hat-section on hot-pressed GRP 	0·51	0·30	0·68	0·54	1·23	0·59
Design F (Hand-laid corrugated GRP) 	0·67	0·74	0·49	0·26	0·74	0·71
Design G (Hat-section GRP stiffener on Balsa-core GRP sandwich) 	0·84	0·99	0·87	0·64	0·71	0·75
Design H1 (Unstiffened PVC foam-core sandwich: 100 mm core) 	2·12	3·84	—	—	0·56	0·76
Design H2 (as H1 but with 200 mm core) 	1·05	1·04	—	—	0·88	1·00

Permissible deflection: w_p (overall bending) = 25 mm
w_p (local panel bending) = 10 mm

It has been shown that the balsa-core sandwich (Design G) is marginally the most attractive material if weight is the critical parameter. However, for minimum cost after steel it can be seen that the options E1 and E2 of single skin GRP stiffened by cold-formed steel sections are preferable. As a good compromise between cost and weight, option F (hand laid-up corrugated GRP) also looks attractive. At this stage it is not possible to estimate the reduction in through-life cost due to the elimination of fatigue problems around the superstructure, nor to assess the cost benefits of much greater flexibility in layout of the superstructure which would result from the use of the composite construction. Nevertheless, it is likely that much of the cost difference between steel and the cheapest composite option would be eliminated by through-life cost savings.

Analysis of Hull/Superstructure Interaction

One of the principal reasons for using low modulus materials for superstructures is to reduce or eliminate stress concentrations at the interface to the main deck. This region is structurally complex and the only way of estimating the effect of structural changes on stress concentrations is to analyse the structure using finite elements. The critical loading condition for the interface stresses is primary longitudinal bending. Ideally a length of hull should be modelled including the superstructure end region, the bending moment then being applied to the ends by means of forces or displacements on the end nodes. However, such a model is much larger than the area of interest, and as the need is to estimate the relative effect on stresses due to changes in superstructure material properties a much simpler model is acceptable (FIG. 2). The model is scaled from an existing ship, and the

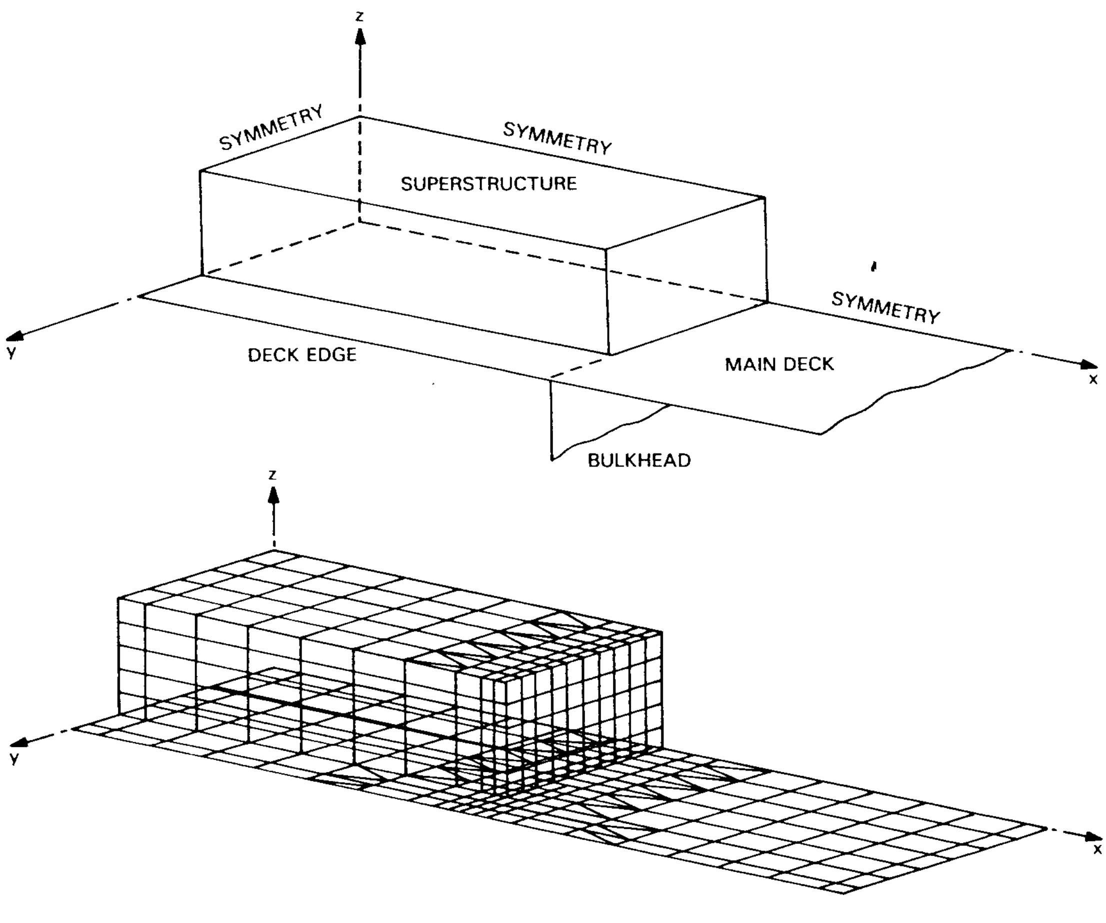


FIG. 2—FINITE ELEMENT MODEL OF HULL/SUPERSTRUCTURE INTERACTION

bending moment resulting from a standard load condition, in this case static balance on a wave of height $0{\cdot}6\sqrt{L}$, is calculated along its length.

By scaling the second moment of area (I) and position of neutral axis from the type ship, the deck edge deflection due to the bending moment distribution can easily be calculated and input to the model as nodal displacements in the x and z directions. If the superstructure is first assumed either 100% or 0% efficient for the estimation of I, then from the first run of the model the actual superstructure efficiency can be estimated from the derived stress, a new distribution of I calculated, new deflections deduced and the model run again. It has been found in all cases from a check on superstructure efficiency after the second run that the applied deflections are sufficiently accurate and no further iteration is needed.

Four superstructure configurations have been investigated in this way, corresponding approximately to the designs of FIG. 1, combined in each case with a steel hull:

(*a*) Aluminium (Design A).
(*b*) Steel (Design B).
(*c*) GRP with steel stiffeners (Design E1).
(*d*) GRP sides (Design E1) with steel top and ends.

Analysis was carried out at Foxhill, Bath, using NASTRAN with CQUAD4 and CTRIA3 shell elements and appropriate beam elements. Two planes of symmetry have been used to define boundary conditions, as shown in FIG. 2; the assumption that the superstructure is symmetrical about the centre-plane and midships does not invalidate the comparative stresses at the superstructure end.

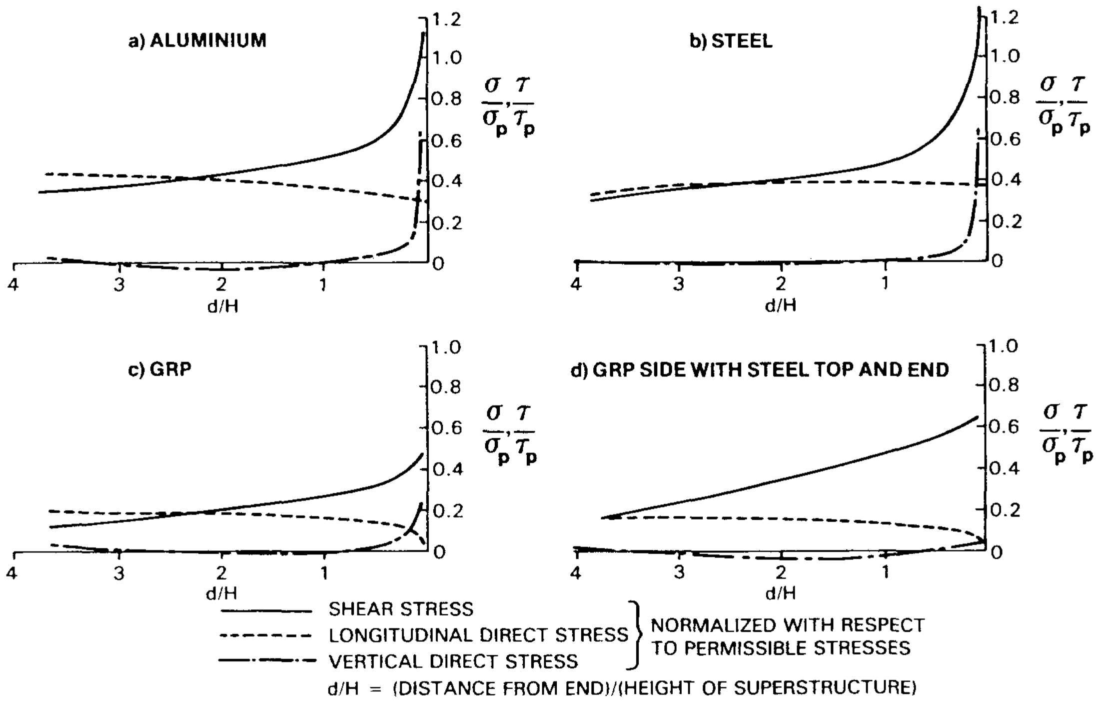


FIG. 3—DISTRIBUTION OF STRESSES AT BASE OF SUPERSTRUCTURE SIDE

Results of the analyses are shown in FIG. 3 in the form of distributions of direct longitudinal and vertical stresses σ_x and σ_z and other shear stress τ_{xz} along the base of the deckhouse side. These are plotted as ratios of calculated stress to maximum permissible stress for the material as defined above for panel designs A, B and E1. It will be noted that changing the material does not change the general pattern of the stresses: σ_x is fairly low and uniform with a fall-off towards the superstructure end; σ_z and τ_{xz} both increase towards the end, but with σ_z rising suddenly from a very low value, while τ_{xz} is higher overall but with a slightly less rapid rise at the end. The effect of the lower allowable stresses for aluminium compared with steel is that there is little absolute difference between the two sets of curves, both exhibiting shear stresses at the extreme end which are greater than the allowable stress. For both GRP models, however, the stresses are markedly lower, reflecting the much higher ratio of allowable stress to stiffness for GRP. Shear stress is higher in the model with a steel top as the strain at the top is very small and virtually all the superstructure deformation occurs in the low stiffness sides.

Analysis has been carried out both including and excluding a stiff transverse bulkhead (represented by a rigid beam) under the superstructure end. Where no supporting bulkhead is present, results indicate that vertical forces at the end of a rigid superstructure cause severe local bending of the deck structure which under cyclic loading would be likely to cause fatigue failure unless local strengthening were introduced; substitution of GRP, either throughout the superstructure or in the deckhouse sides alone, results in a dramatic reduction in vertical forces and hence in deck bending. Where a bulkhead is present, local deck bending is virtually eliminated but large vertical forces at the ends of a rigid deckhouse must be transmitted through the deck into the bulkhead and in view of inevitable misalignments of plating and stiffeners in this region, fatigue failure is again likely; use of GRP, even where confined to the deckhouse sides, is again found to reduce vertical forces substantially.

Design of Connections

Design of connections, both between components of a superstructure and between the superstructure and main hull, is obviously a critical aspect of the overall design problem. A clear understanding is needed of the nature of magnitude of forces and moments to be transmitted, including particularly those induced by primary hull bending, green seas and air blast. Connections may be considered to fall into the two categories discussed below.

Stiffener to Panel Joints

Joints must be able to transmit shear forces associated with panel bending together with peeling loads which will tend to arise particularly at the ends of snaped stiffeners (i.e. stiffeners with tapered ends) or under concentrated masses.

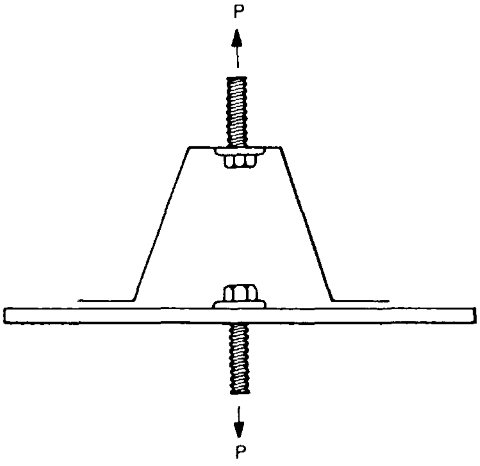


FIG. 4—PULL-OFF TEST

Stiffener to panel joints in GRP or hybrid panels (Designs C to G as shown in FIG. 1) may be achieved either by mechanical fastening (bolts or rivets) or by adhesive bonding or by some combination of these methods. An effective and economical means of attaching metallic stiffeners to GRP panels, currently under active investigation at ARE, Dunfermline, is believed to be adhesive bonding supplemented by a small number of bolts serving as peel-arresters, e.g. at the ends of snaped stiffeners and adjacent to concentrated masses. Intermittent bolting is also desirable as a means of maintaining stiffener attachment under fire conditions.

A series of 'pull-off' tests as illustrated schematically in FIG. 4, has been carried out to evaluate the peel strength of steel stiffener/GRP panel attachment: the following provisional findings may be noted.

(*a*) Cold-curing, gap-filling epoxy adhesive appears to be the most effective bonding agent. Consideration has been limited to cold-curing adhesives for reasons of fabrication economy. A gap-filling capability is needed in order to accommodate surface irregularities in the GRP laminate. Of the adhesives investigated the two front-runners, with little difference in performance, were Ciba-Geigy Araldite 2005 and Permabond E32.

(*b*) Simple and effective surface preparations for bond zones are as follows. On GRP panels: surface wipe using styrene or acetone (for hand lay-up of GRP stiffener or attachment of steel stiffener); on steel stiffeners: de-grease using trichlorethane, grit blast, then de-grease again.

(*c*) Variation of gap-size in the range 0–2 mm was found (surprisingly) to have little effect on peel strength. A standard gap of 1 mm, controlled by use of spacer wires, has been adopted provisionally. Curing was carried out for 24 hours under light compression at a 'room temperature' of $20 \pm 3°C$.

(*d*) The pull-off load for hat-section stiffeners as shown in FIG. 4, characterized as a peel load $q = P/2L$ where L is specimen length, was found to have a mean value of 0·41 kN/cm with cov (coefficient of variation) of 0·24.

Further tests are being carried out on beam specimens under three-point loading in order to evaluate overall bending behaviour, shear and peel strength of bonded stiffener attachment and strength of end connections.

Panel to Panel Joints

These must be able to transmit bending moments and direct and shear forces. At butt connections, any of the joints shown in FIG. 5 may be employed, with adhesive bonding supplemented as necessary by bolts or rivets. Guidance on the design of bonded and bolted joints of this type may be found in references 16 to 18. Metallic extrusions or GRP pultrusions, as illustrated in FIG. 5, might also be employed at butt joints. At corner joints two possibilities arise, with significantly differing implications for the

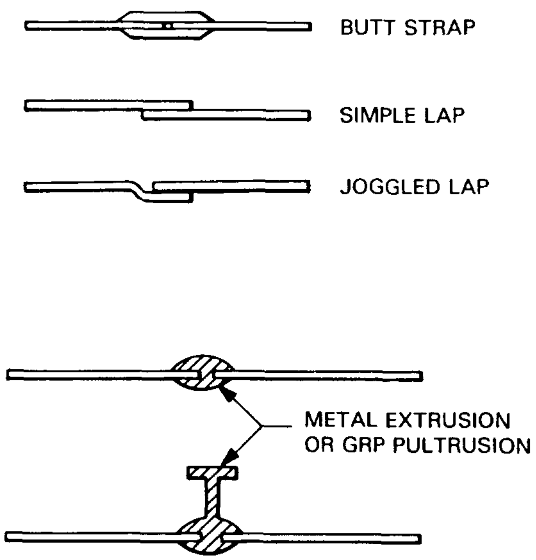


FIG. 5—BUTT JOINTS BETWEEN GRP PANELS

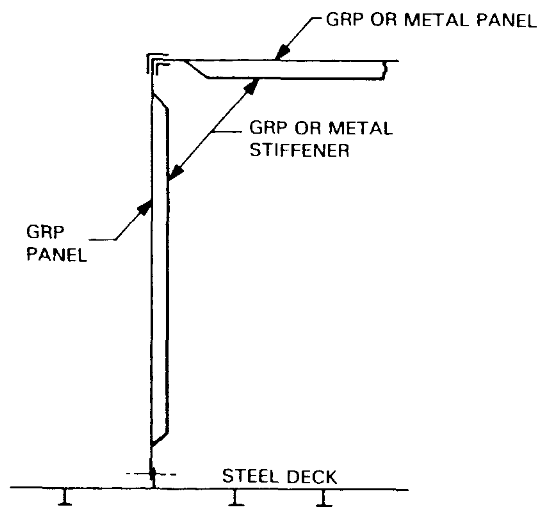


FIG. 6—'PIN-JOINTED' PANELS

fabrication process. In the first case rigid joints are employed, aimed at providing full transmission of bending moments: this approach is feasible where stiffeners are all metallic, in which case they may be prefabricated in the form of portal frames, welded directly to the main deck, with GRP panels added *in situ*. In the second case a quasi 'pin-jointed' connection is sought as illustrated in FIG. 6, stiffeners being snaped off just short of panel intersections: this form of joint, which has been used extensively in MCMV construction[19], avoids the awkward problem of joining GRP and metallic stiffeners and is also appropriate for attaching corrugated panels (Design F). Edges may be completed as shown in FIG. 7. Simply supported panels must be designed to transmit lateral loads into membrane stress resultants in the supporting structure, overall strength and stiffness of the superstructure being provided by in-plane direct and shear rigidity of the superstructure decks, sides and bulkheads.

Careful proportioning of local geometry at the edges of 'pin-jointed' panels is necessary to control deformations and stresses round the ends of snaped stiffeners. Approximate analysis may be carried out using a non-uniform beam or frame model[20]. More accurate analysis requires finite element treatment, as shown in FIG. 8; a study of selected designs from FIG. 1, aimed at optimizing joint geometry, is being carried out using a sub-structured FE idealization in which the complex edge zone is modelled using shell elements while the central region of the panel is represented by beam elements.

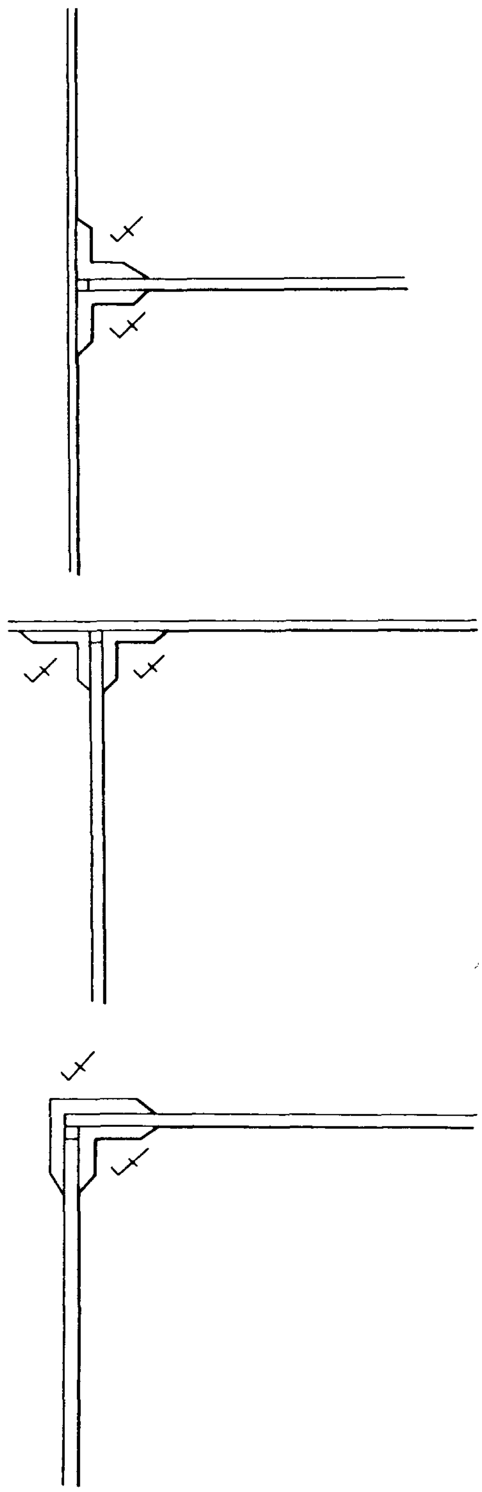


FIG. 7—CORNER JOINTS BETWEEN GRP PANELS
⨯ corner angle hand-laid or pultruded GRP or metal extrusion

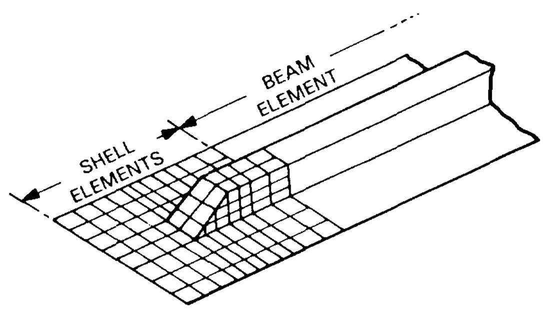


FIG. 8—STRESS ANALYSIS OF 'PIN POINT' AT SNAPED STIFFENER ENDING

Air blast Resistance

A warship superstructure may be required to withstand air blast caused by nuclear explosions. The literature on this subject is largely classified, but a useful account of the mechanics of nuclear blast and structural response is available[21].

A vertical deckhouse side directly exposed to incident overpressure p_i from a large (say megaton) explosion will experience a virtually instantaneous rise of pressure to the reflected level $p_r(>2p_i)$; as the blast wave diffracts round the structure the load drops rapidly over a period t_1 to the stagnation pressure $p_s = p_i + p_d$, where p_d is a dynamic pressure caused by air flow; finally the stagnation pressure decays slowly over a period t_2 which may extend to several seconds. A typical pressure-time history for moderate blast exposure is shown in FIG. 9.

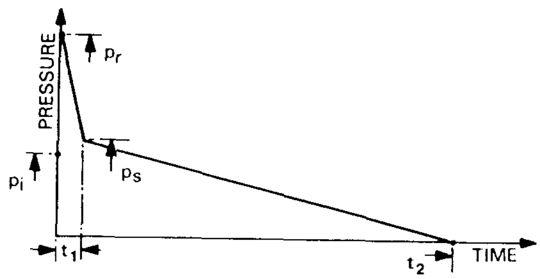


FIG. 9—TYPICAL AIR-BLAST LOADING TIME HISTORY

$p_i = 0.25$ bar
$p_r = 0.6$ bar
$p_s = 0.29$ bar
$t_1 = 0.015$ sec
$t_2 = 2$ sec

Air blast may be regarded as an 'exceptional' load for which substantial relaxations can reasonably be made in margins of safety against damage and failure. In the case of metallic structures, elastic design is generally regarded as too conservative; fairly large inelastic deformations, as illustrated in FIG. 10, are permissible provided that the superstructure maintains its protection of internal systems.

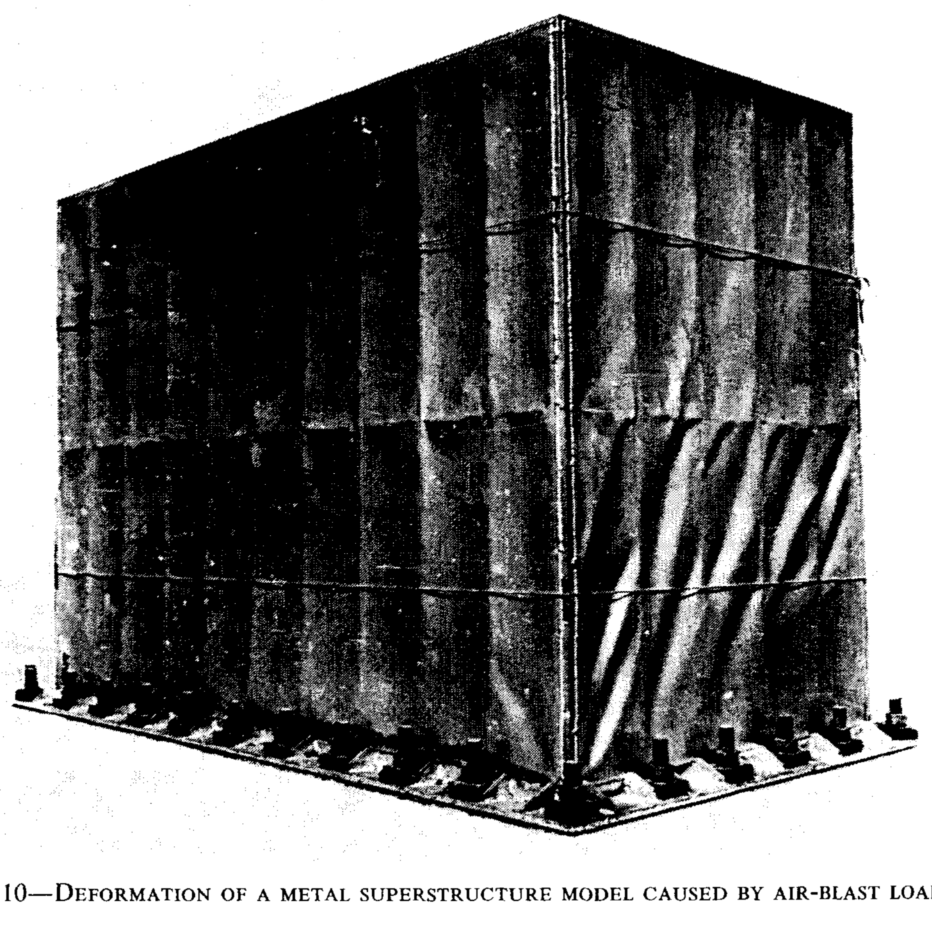


FIG. 10—DEFORMATION OF A METAL SUPERSTRUCTURE MODEL CAUSED BY AIR-BLAST LOADING

Evaluation of air-blast resistance requires consideration of:
(*a*) Local response of plate panels between stiffeners.
(*b*) Local response of stiffened panels between supporting bulkheads and or decks.
(*c*) Overall response of the complete superstructure.

Since the length of a stiffened panel or plate element is commonly large compared with its width in the other direction, items (*a*) and (*b*) above may usually be examined using a two-dimensional model. Considering, for example, deckhouse sides corresponding to designs A and C (FIG. 1), undamped dynamic responses (mid-span lateral displacements plotted on a time base) computed using lumped-mass beam models of the stiffened panels are shown in FIG. 11 for the air-blast loading defined in FIG. 9. Analysis was carried out using special-purpose computer codes developed at ARE[22, 23].

The linear elastic response of Design A is shown as a dashed line in FIG. 11: displacements evidently exceed by a factor of about 4 those caused by static application of the pressure p_i (see TABLE II), indicating that yield would occur and that linear analysis is inadequate. Nonlinear response accounting for large displacements, yielding and buckling of plating is shown as a full line, indicating a permanent set of about 5·2 cm.

Response of the GRP panel (Design C), which remains essentially linear, is shown in FIG. 11: displacements again exceed those associated with application of a static pressure p_i by a factor of about 4 but because of the large

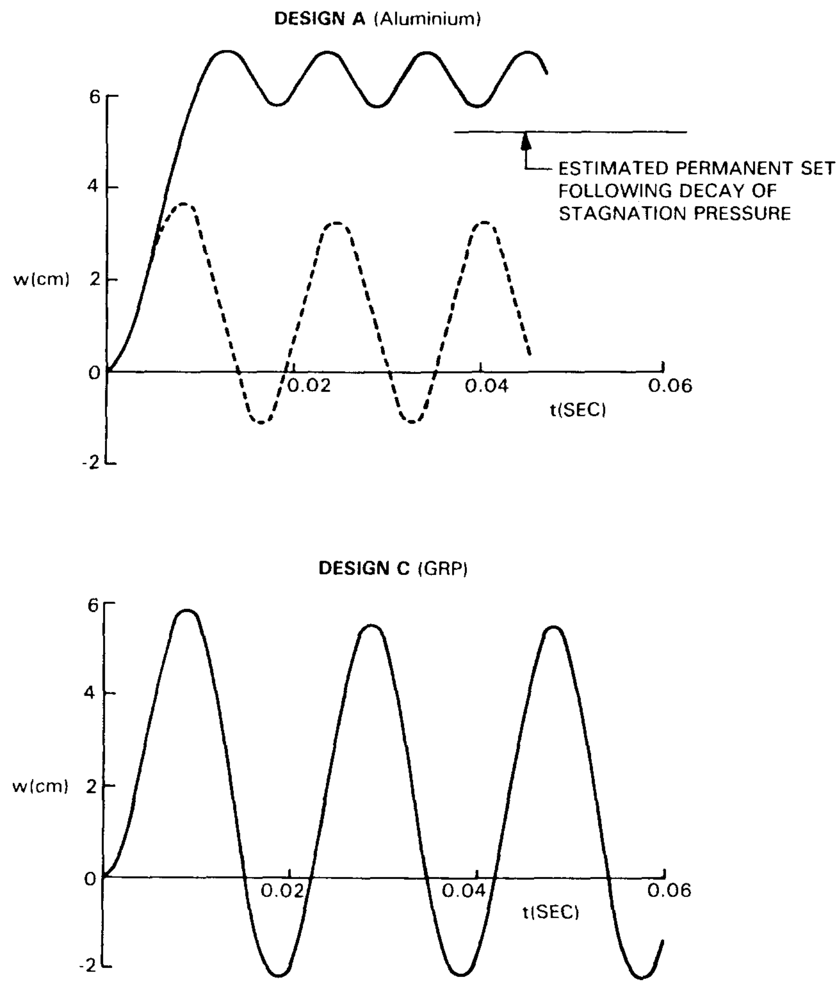


FIG. 11—UNDAMPED DYNAMIC RESPONSE OF STIFFENED PANELS UNDER AIR-BLAST LOADING

margin against outer-fibre material failure adopted in the static design, the panel remains virtually undamaged. Evaluation of local plating response under the loading shown in Fig. 9 yielded similar results: a small permanent set of about 1 mm was found to occur in the plating of Design A while Design C remained virtually undamaged. Analysis of the type described above also provides an estimate of dynamic forces at panel boundaries which in the case of GRP panels require particularly careful consideration.

The likely behaviour of GRP and metallic panels may be summarized comparatively, as follows:

(*a*) under low incident pressures insufficient to cause yielding, neither metallic nor GRP structure will experience any damage.

(*b*) Over an intermediate range of pressure above the level which causes yield, metallic panels will undergo permanent deformations while GRP structure remains undamaged apart from unimportant localized resin cracking.

(*c*) At pressures which cause laminate ultimate strains to be exceeded, a GRP panel is likely to suffer serious fractures while a metallic panel, provided weld failure does not occur, may undergo large ductile deformations without losing its ability to protect internal systems.

A GRP panel should clearly be designed to fall into the second of these ranges.

The overall response of a superstructure depends mainly on the in-plane (in particular shear) rigidity of panels lying in the direction of applied load, i.e. decks and transverse bulkheads in the case of blast pressure acting on a ship's side. Provided that the static shear post-buckling load-deformation relationship of such panels can be established, overall dynamic response of the superstructure can be computed approximately for a simplified lumped-parameter model containing one or a few degrees of freedom. In view of the possible 'brittleness' of GRP panels in undergoing large post-buckling deformations and in transmitting edge loads, it may be that, in designs for which air-blast resistance is a dominant requirement, use of GRP should be confined to deckhouse sides and longitudinal bulkheads, incorporating metallic stiffeners as in Designs D and E, with transverse bulkheads and superstructure decks of all-metallic construction: this option represents a minimal use of GRP but one which should fulfil the aim of eliminating unwanted hull-superstructure interaction under conditions of primary hull bending.

Ballistic Protection

Design of a warship's superstructure requires consideration of resistance to high-velocity projectiles including fragments from missile burst, small-arms fire, larger calibre cannon shells, and debris from incoming anti-ship missiles destroyed by close-range gunfire or similar countermeasures. Ballistic resistance provided by FRP laminates against high-velocity fragments and small-arms attack is very good. For example it has been found[24] that GRP laminates of thickness 5·5 mm, 13 mm and 26 mm are sufficient to stop, respectively:

(*a*) a fragment simulator of mass 1·1 g with a velocity of 460 m/s;

(*b*) a M1 carbine round of mass 7·2 g with a velocity of 570 m/s;

(*c*) an Armalite bullet of mass 3·6 g with a velocity of 976 m/s.

In each case equal-weight mild steel or N8 aluminium plating would be likely to experience penetration or spalling.

The primary mechanism of ballistic resistance in FRP laminates or fibrous fabrics[25,26] is energy absorption by transmission of tensile stress-waves along

TABLE III—*Fire-related Properties of Metallic and FRP Materials*

Material	*Melting Temp.* °C	*Thermal Conductivity* W/(m.°C)	*Heat Distortion Temp.* °C (BS2782)	*Self-Ignition Temp.* °C	*Flash-Ignition Temp.* °C	*Oxygen Index* % (ASTM D2863)	*Smoke Density* Dm (ASTM E662)
Aluminium	660	240	—	—	—	—	—
Steel	1 430	50	—	—	—	—	—
E-Glass	840	1·0	—	—	—	—	—
Polyester Resin	—	0·2	70	—	—	20–30	—
Phenolic Resin	—	0·2	120	—	—	35–60	—
GRP (polyester-based)	—	0·4	120	480	370	25–35	750
GRP (phenolic-based)	—	0·4	200	570	530	45–80	75

fibres and transfer of momentum into intersecting fibres by friction. This process is to some extent inhibited in a laminate by the presence of the resin matrix: optimum ballistic resistance appears to be offered (provided no other structural role is required) by unimpregnated curtains of woven or knitted fabric, as have been back-fitted in some existing ship superstructures to provide enhanced protection. In designing a new ship, however, it will be desirable to combine the structural and ballistic-resistance roles, which can be achieved effectively by use of GRP laminate.

An even higher level of ballistic protection can be obtained by use of aramid (Kevlar 49) fibres[26], whose main attribute is very high specific tensile strength. The cost of Kevlar fibres is however about 15 times that of glass while its ballistic performance in laminate form is about 1·2 to 1·5 times that of glass[27]: this suggests that its use is only justifiable in weight-critical applications. The use of Kevlar for general structural purposes is also undermined by its low compressive stress (about 25% of tensile strength in laminate form). Where a very high level of ballistic protection is required, e.g. in magazines or control rooms, the extra cost of ceramic-composite armour[28] may be justified; in this case externally bonded tiles of very hard (aluminium oxide or boron carbide) ceramic are provided to cause break-up of projectiles, the resulting debris being caught by back-up plies of GRP laminate.

Fire Resistance

Fires in a ship's superstructure may be caused by electrical faults, spillage and ignition of hydraulic or fuel oil, welding and flame-cutting operations during construction or refit and, in warships, by weapon effects. Requirements of a structure under such conditions are:

(*a*) prevention of spread of flames to adjoining compartments;

(*b*) limitation of temperature and hence damage in adjacent compartments;

(*c*) preservation of strength and stiffness for prescribed periods of time until a fire is extinguished;

(*d*) minimization of smoke and toxic fumes.

In addition to normal manned fire-extinguishing procedures, countermeasures are likely to include automatic water sprinkling and/or halon gas drenching.

Some of the fire-related characteristics of contending structural materials are summarized in TABLE III. In the case of plastics, data are derived mainly from Reference 29. Because of its low melting point and high conductivity, aluminium is deficient in requirements (*a*), (*b*) and (*c*) above. Polyester-based GRP burns slowly in air with copious emission of black smoke, but flames are readily extinguished by water sprinkling or oxygen exclusion. Phenolic resin GRP has substantially higher self-ignition temperature and oxygen index with very much lower smoke emission and should for these reasons probably be preferred to polyester-based GRP for internal superstructure bulkheads and decks. Because of its very low thermal conductivity, GRP is particularly effective in meeting requirement (*b*). In the recent instance of a major oil-fed fire in the engine room of a HUNT Class MCMV[15], which lasted for four hours (following partial failure of the countermeasures system) with temperatures sufficient to melt aluminium fittings and to cause severe charring of laminate to a depth of several millimetres, the remaining thickness of shell and bulkhead laminate was found to have virtually unimpaired mechanical properties and paint on the reverse side was not even discoloured.

Presently available fire-retardant polyester resins are not regarded as effective because of inferior mechanical properties and wet-durability and greater fume toxicity. Worthwhile protection can however be provided by intumescent and other fire resistant coatings. Provided that normal insulation is employed, that protective coatings are applied where appropriate and especially if phenolic resin is used in internal panels, the overall fire resistance of GRP structure is judged to be superior to that of aluminium although not as good as that of steel.

EM Characteristics

The transparency of GRP laminates to electromagnetic emissions from within and outside a ship may lead to problems of interference in electronic equipment and control systems. Such interference is minimized in a steel or aluminium structure by the EM opacity of decks, shell and bulkheads. Effective EM screening of a GRP laminate can be provided, where necessary, by a sprayed or bonded metallic coating and/or by incorporation of some metallic fibre into the laminate.

A thorough study of EM screening requirements for GRP structure has been carried out by the British Aerospace Dynamics Group under contract to ARE[30]. Quantitative screening targets were established relating to EMC (compatibility), EMP (pulse caused by a nuclear burst) and TEMPEST (crypto-security); alternative screening methods were assessed including use of bonded aluminium foil, conducting fibres and inherently conducting polymers and paints as well as metal spraying. The study included durability tests on panels under conditions of flexural deformation and culminated in assessment of a full-scale prototype compartment. The most efficient solution was found to be a simplified arc-spraying process involving deposition of a thin layer of zinc. Costs associated with this process, included in the figures given in TABLE II, were found to contribute no more than 7% towards the total cost of GRP panels.

It might be thought that the EM transparency of FRP would lead to a beneficial reduction of radar profile in warship superstructure and in certain components, e.g. masts and funnels, this may be the case. It is probable, however, that the internal clutter of sharp-angled metallic objects within a superstructure would give rise to enhanced radar reflection and for this reason it is likely that most external GRP panels in a warship would have to be screened, presenting a smooth, inclined reflective surface. It may be noted that in this respect corrugated construction (Design F in FIG. 1) probably would not be acceptable in the deckhouse sides of a warship because of the reflective characteristic of its re-entrant corners, although this scheme remains a front-runner for internal bulkheads and for use in merchant ships.

Conclusions

Use of GRP in a ship's superstructure, either on its own or as part of a hybrid form of construction possibly including metallic framing, transverse bulkheads and decks, offers a means of eliminating the problem of fatigue cracking caused by hull superstructure interaction. Improved ballistic protection may be achieved, together with better fire-resistance than is provided by aluminium. Effective and economical screening methods are now available for dealing with the problem of EM transparency of GRP laminate. The weight of a GRP or hybrid superstructure is likely to be of the same order as, or less than, that of welded aluminium and to be about 50% that of steel. It should be possible to achieve first costs (materials plus labour) less than that of welded aluminium construction and 1·6 to 2 times that of steel. Differences between the first costs of steel and GRP superstructures are likely to be offset entirely or in part by whole-life savings in maintenance and repair costs.

The most economical form of construction for GRP or hybrid superstructures appears to be assembly of flat prefabricated stiffened panels, employing 'pin-jointed' edges at panel intersections to avoid the awkward problem of rigid connection between stiffeners in different materials with different sectional shapes. Panels of hot-pressed GRP laminate, which have a higher fibre content than hand-laid laminate and offer superior mechanical properties and ballistic and fire resistance, are at present only available in limited sizes (typically $1{\cdot}2 \times 2{\cdot}4$ m): such panels would require a large number of butt connections of the type shown in FIG. 5 and for this reason do not appear to be economically viable. The preferred method of laminate production is good-quality hand lay-up, using isophthalic polyester resin and E-glass woven rovings (giving 0·5 to 0·6 fibre content by weight), with cold-setting phenolic resin substituted for polyester in internal panels. A complete deckhouse side could, for example, be fabricated in this way as a single unit incorporating any necessary steps in profile or planform, openings and variations in thickness. Any of the configurations represented in Designs C, D, E1, E2, F and G (FIG. 1) appear to be feasible, with the proviso that the simple corrugated section (Design F), while in other respects very effective, probably would not be acceptable in the external structure of a warship for reasons relating to radar reflection.

In the particular case of frigates, destroyers and other large warships the problem of air-blast response requires special attention. While GRP panels can be designed with adequate local blast resistance, the overall response of an all-GRP structure is uncertain because of possible 'brittleness' of GRP panels in undergoing large post-buckling deformations and in transmitting associated edge loads. Further theoretical and experimental investigation of this problem is needed. In the meantime it may be preferable, where a high level of blast resistance is required, to confine the use of GRP to deckhouse sides and longitudinal bulkheads with metallic construction of decks, transverse bulkheads and deckhouse ends.

While scope clearly exists for further R&D aimed at optimization of GRP and hybrid supestructures, sufficient design data and fabrication expertise already exist to allow incorporation of GRP superstructure into ships of most types. This is evidenced by the successful use of GRP deckhouses on steel, aluminium, GRP and wooden hulls in many existing classes of MCMV and patrol boat. In the author's opinion, designers should give serious consideration to improvements in performance and whole-life cost savings which might be obtained by application of GRP in superstructures of larger ships.

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