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SANDWICH CONSTRUCTION IN GLASS REINFORCED PLASTICS
PART II - FURTHER BEAM TESTS

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Naval Construction Research Establishment
St Leonard's Hill
Dunfermline
Fife

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ABSTRACT

Parts I and II of this report are concerned with the suitability of GRP sandwich construction for deck, bottom and bulkhead structures in ships. The relevant stiffness and strength characteristics of various sandwich constructions were examined by means of tests applying lateral loads to beams manufactured to typify the various sandwich constructions considered for this purpose.

Detailed results for beams 1 to 8 are given in Part I, these featured the various speculative sandwich constructions initially considered, among which only beams 7 and 8, incorporating 'Plasticell' cores, achieved an adequate strength for consideration in ship construction. Part II continues with beam tests on sandwich constructions incorporating 'Plasticell' and BAP 'flomat' box cores; the latter proving to provide the most suitable type of sandwich, with regard to both stiffness and strength.

This investigation was carried out with regard to static loading only, and effects due to fatigue, shock and high temperatures were not considered. Interest in this type of sandwich construction for warships diminished when its poor resistance to explosive loading was revealed, and although certain advantages are offered for general ship construction, these are largely offset at present by the high manufacturing costs involved.

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Approved for Issue
for I.J. Campbell
Superintendent

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SANDWICH CONSTRUCTION IN GLASS REINFORCED PLASTICS
PART II - FURTHER BEAM TESTS

by

G. Wallace

INTRODUCTION

This report describes the continuation of an investigation into the use of sandwich construction in glass reinforced plastics (GRP) for load bearing ship structures. For these applications, the primary interest is in comparatively cheap woven cloth or woven rovings for the skins, with a variety of lightweight materials for the core.

2. The principal reason for interest in using a sandwich construction arises from the low Young's Modulus of GRP, about 3×10^6 lb/in.^{2} for woven fabric laminates. The low modulus leads to increased deflection under load and an increased susceptibility to buckling, and these problems may be overcome by increased use of stiffening, or by using a sandwich structure. In view of the problems of attaching stiffeners and making stiffener intersection connections involving high labour costs in a closely stiffened structure, it was thought that a sandwich construction with more widely spaced stiffeners might be preferable for small ship construction. At the start of the investigation, there was already successful experience using a GRP sandwich with a foam core for the hull structure of a landing craft (1)*, and there was a fair experience with sandwich construction for radomes and parts of aircraft structures.

INITIAL DESIGN STUDY FOR RECTANGULAR PANEL

3. Initially, a numerical design study was carried out to find a satisfactory structure in GRP measuring 200 in. by 100 in. to withstand a working pressure of 20 lb./in.^{2}, the edges being simply supported. This particular case was chosen to provide comparison with a mild steel grillage which had been tested at NCRE (2). The GRP calculations were based on using skins with an ultimate tensile strength of 44,000 lb./in.^{2}, the maximum stress at working load being taken as 16,000 lb./in.^{2}. Simplicity of construction could be achieved by

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*( ) = References on page 19

adopting a core with parallel GRP webs or ribs running across the shorter 100 in. width of the panel, but it was calculated that this would involve unacceptably high end bay stresses at right angles to the ribs. These high stresses could be avoided, at least theoretically, by using a triangulated core ressembling a Woven girder truss in cross section, but this solution was not pursued. Instead, a panel was conceived having orthogonal web stiffeners in GRP, bonded to the two skins of the sandwich, with equal spacing of the webs in the longitudinal and transverse directions, forming a square mesh of 'egg-box' formation. The loading dimensions, chosen to obtain a minimum weight structure for a maximum allowable stress of 16,000 lb./in.^{2} and a factor of safety of 2 on local instability, were as follows:

Skin thickness	0.30 in.
Skin spacing	5 in.
webs	0.15 in. thick, spaced every 5.55 in. in both longitudinal and transverse directions

The total weight of the GRP panel was calculated to be approximately 1120 lb. as compared with 2840 lb. for the final mild steel structure reported in Reference 3.

4. Since the investigation was started, fairly considerable experience with GRP for ship structure application has shown that a factor of safety in the range 2 to 2.75 is not large enough for primary load bearing structure. A factor of at least 4 is now considered appropriate for this type of construction, to obtain reasonable assurance against failure due to possible poor quality fabrication, and inadequate detail design at local positions of stress concentration leading to either extreme loading or fatigue failure. Underboth extreme loads or fatigue, GRP which is a brittle material bears rather poor comparison with the ductile metals. This is particularly the case when the structural components are connected using a resin bonding method. If a factor of safety of 4 were adopted for the initial GRP panel design, it might be regarded as satisfactory for a working pressure of about 10 lb./in.^{2}, but in this context the comparison with a successful steel design for 20 lb./in.^{2} has been lost.

BEAM TESTS UNDER UNIFORM PRESSURE AND CHANGE TO QUARTER POINT LOADING

5. Preliminary discussions with GRP firms indicated that the cost of manufacturing a core of orthogonal webs with an adequate shear connection to the skins would involve very expensive tooling which could not be justified in the first instance. The first phase of the investigation, fully described in Part I was therefore centred on the use of a number of commercially available alternatives including hexogonal honeycombs of GRP or impregnated paper, and various foams. To keep costs to a minimum, beam specimens were made, broadly representative of the rectangular panel at half scale, measuring 52 in. long, 8 in. broad and about 2.65 in. deep. These were tested under uniform lateral pressure with simply supported ends. In all cases, the core structure failed in shear, usually accompanied by appreciable debonding of the skins from the core, and the collapse pressure ranged from 13 to 20 lb./in.^{2}, appreciably less than the requirement (it should be appreciated that the mean density of core, ranging from 3.5 to 5.7 lb./ft.^{3} was also less than for the NCRE panel design which gave 6 lb./ft.^{3} without any allowance for shear connection to the skins.) These early tests highlighted the importance of shear strength for a uniformly loaded sandwich beam, and provided the failure is by shear, the results are equally applicable to a clamped ends boundary condition. The structures actually tested, originally envisaged as representing a section of a panel at half scale, have subsequently proved to be very similar in span and section to section between frames in a design for a 160 ft long ship in GRP now under construction, and the shear aspects of these beam tests are very relevant to this design project.

6. The test rig used to apply uniform pressure by means of an impregnated fabric pressure bag inside a steel box did not prove fully satisfactory, probably due to the bag losing contact around the edges of the GRP beam on one side as the deflections became very large, reaching 2.8 in., in one case. After collapsing the first six beams using the uniform pressure rig, the remainder were tested under combined bending and shear in a 50 ton Denison testing machine. By dividing the load through a steel beam into two equal concentrated loads applied at a quarter and three quarter of the span, the ends being

simply supported, the ratio of maximum shear force to maximum bending moment was kept the same as for the original uniform pressure loading. For convenience a span of 44 in. was used, somewhat less than the complete length of beam, and an equivalent uniform pressure p over span L, corresponding to a collapse load W with span l, may be obtained by equating the maximum shear forces for a shear type of failure:

$$\frac{pbL}{2} = \frac{W}{2} \quad \text{or} \quad p = \frac{W}{bL} \qquad \ldots\ldots\ldots\ldots (1)$$

For a failure mainly involving the skins, the equivalent uniform pressure may be obtained by equating the maximum bending moments:

$$\frac{pbL^2}{8} = \frac{W\ell}{8} \quad \text{or} \quad p = \frac{W\ell}{bL^2} \qquad \ldots\ldots\ldots\ldots (2)$$

where b is the breadth of the beam. The loading arrangement using the 50 ton Denison machine was both more precise and more convenient than the uniform pressure rig used for the earlier specimens. The tests on Beams 7 to 15, tested in this way, form the subject of the present report (Beams 7 and 8 were reported in Part I, but are described again, to obtain a tidier discussion).

DESCRIPTION OF BEAMS 7 to 15

7. Details of the beam specimens are tabulated in Table I which includes the measured thicknesses of skins and core (usually the mean of 15 readings), the percentage of glass by weight obtained from one ½ in. square specimen per skin, the measured density of core structure and a breakdown of the weight between skins, core and bonding agent. The beams fall broadly into two main groups, five having a Plasticell rigid PVC foam core, and the remaining core having a core fabricated from hollow GRP box units.

BEAM 7 PLASTICELL CORE DESIGNED AND MANUFACTURED BY MICROCELL LTD

8. The beam was designed by the firm, to withstand a working pressure of 20 lb./in.^{2} and an ultimate load of 50 lb./in.^{2}. The skins consisted of a nominal thickness of 0.375 in. very high strength glass cloth polyester resin laminate having a stated dry strength of 50,000 lb./in.^{2}. There were measured variations in thickness from 0.35 in. to 0.41 in. The core was made from Plasticell D500 rigid expanded PVC foam having

a nominal density 30 lb./cu.ft., the total thickness of 1.73 in. being made from two layers of pre-cast sheet. The components of the beam were bonded with Araldite. This beam, weighing 32.7 lb. was over twice as heavy as the previous beams 1 to 6.

BEAMS 8 to 11 PLASTICELL CORE ASSEMBLED AT NCRE

9. These beams were of similar construction to Beam 7, but incorporated either a lighter grade of Plasticell foam D300 weighing nominally 18 lb./cu.ft. or thinner skins or both. The skins were cut from grade 24/DE Permaglass laminate, a fine weave glass cloth epoxy resin material having a very uniform thickness, manufactured by Permali Ltd. The core was fabricated from two layers as previously, and the components were bonded with Araldite resin AY105 with hardener HY153F.

BEAMS 12 to 15 FLOMAT BOX CORE STRUCTURE MANUFACTURED BY BRISTOL AEROPLANE PLASTICS LTD

10. The unique feature of these beams was their novel design of core structure formed from interlocking 6 in. square hollow box units as shown in Figure 1, and the size of beam was made 48 in. long by 12 in. wide to suit the size of box. The composite core structure, formed from an assembly of boxes bonded together, might be regarded as an elegant practical procedure for producing something like an orthogonal mesh of shear webs in GRP, as envisaged in the initial design study at NCRE. The concept of the box units and their design and manufacture were contributed by Bristol Aeroplane Plastics Ltd. The mean density of core structure at 15.5 lb./cu.ft., was quite similar to the lighter grade of Plasticell, D300, used in Beams 8 and 9.

11. The skins of this group of beams were made from a comparatively coarse weave cloth with polyester resin, by hand lay-up methods. The first operation was to lay up on a flat surface and cure the first skin, denoted the 'upper' skin in Table I to correspond to the test configuration. The Flomat box core units were then assembled with their flanges downwards, and bonded to the skin at these flanges and to each other at their interlocking side flanges and grooves,

using polyester resin. Fabric tape 1 in. wide was then laid across the gaps between adjacent box covers both longitudinally and transversely, supported at the connecting side flanges. This was to avoid undue sagging of the second skin ('lower' skin, Table I) which was finally hand laid over the core.

12. The nominal skin thickness for Beams 12 and 14 was 0.13 in., and for Beams 13 and 15 was 0.19 in. In addition, there were differences in the composition of lay-up. Beams 12 and 13 incorporating a surface layer of tissue and chopped strand mat, while Beams 14 and 15 were entirely of cloth, with a somewhat higher glass to resin content. The precise thickness of the cured laminate was difficult to measure due to the fairly coarse weave material used, but the mean values in Table I were obtained from five readings over the 'hills' and five readings in the 'valleys' around the edge of each skin. Nevertheless, the range of thickness within a particular skin was small, up to 0.03 in. The overall weight of beam ranged from 25.2 to 31.6 lb., but in comparing with the other beams of the series it should be remembered that the plan size was 38½% greater. The weights are therefore very competitive by comparison with the beams having a Plasticell foam core.

13. Table I also shows the cost of precuring the beam specimens which ranged from £25 to £43 (for a 52 in. by 8 in. size), though for the beams assembled at NCRE the assembly costs are not included. The cost of the Microcell beam with a Plasticell core and the Bristol Aeroplane Plastics beams with the box core structure were fairly similar at £43 and about £35 respectively for a 52 in. by 8 in. size. Unfortunately, all these costs may be pitched rather high, due to the requirement for a very small number of specimens, and the costs for large scale production should be lower.

MECHANICAL PROPERTIES OF COMPONENTS

14. Tensile specimens of the skin materials were machined to the profiles shown in Figure 2 (a) and (b). The smaller specimen (a) with a 1.66 in. parallel length was used for Beam 8, but the larger specimen (b) with a

4.1 in. parallel length was used for all the remainder - Beams 7 and 9 to 15. In the case of the beams fabricated at NCRE, the specimens were made from offcuts of material cut adjacent to the pieces actually used for the beams, and for Beams 9 to 11, both longitudinal and transverse specimens were taken. For the beams fabricated by outside firms, for which no plane sheet material was available, the specimens were made from an undamaged portion of each skin after collapse, the adhering portion of core being machined off. For the specimens from Beams 7 to 11 Huggenberger tepic wire resistance strain gauges with a plastic base, with two superimposed orthogonal elements of gauge length 0.7 mm (type R.90 - BL/0.7) were attached to the front and back at mid-length, using Eastman 910 adhesive. For Beams 12 to 13, a similar arrangement was used with foil gauges of Japanese manufacture having two elements of length 10.5 mm (Kyowa type 2KPR-4). In each case, the mean of the readings from front and back was used to derive the Young's Modulus (E) and Poisson's ratio (U). Each specimen was loaded in increments to failure and the results are summarised in Table II. While each material was reasonably uniform within itself, there were appreciable differences in Young's modulus and ultimate strength between Beam 7 made by Microcell and the remainder of the specimens. In the burn-out test to determine the percentage content, it was found that this beam incorporated a directionally biased cloth and detailed examination showed that the proportion of longitudinal to transverse fibres by weight was $9\frac{1}{4}$. The use of this virtually unidirectional cloth of course explains the favourable properties of this beam in the longitudinal direction. A further comment on the results in Table II is that the modulus and strength for Beam 12 were noticeably lower than for the other beams of this series with nominally equal longitudinal and transverse properties, though this may be attributable to the use of a relatively smaller proportion of woven fabric (Table I).

15. For the Plasticell core material, small blocks of material, up to 3 in. long with a cross-section about $\frac{7}{8}$ in. square, were tested to failure in compression, the Youngs Modulus being obtained from caliper readings.

Poisson's ratio (U) was also measured. It was found that the length of specimen and various rates of loading from 40 to 350 lb./in.^{2} per minute had no significant effect on the results, but there was up to 25% anisotropy. The results, which were presented in Table IV of Part I (1) bore reasonable comparison with the maker's figures.

16. The Flomat box core material was tested by taking tensile specimens from the vertical sides of two specimen boxes, orientated parallel to the flanges, adjacent to these flanges and at mid-depth, on one side. In view of the very limited length of material available, these specimens had a parallel portion 1.0 in. long and 0.3 in. wide, as shown in Figure 2(c). Japanese foil strain gauges were attached longitudinally and transversely to the front and back at mid-length, the types being Kyowa KF-1-C2 and KF-1-C3 respectively, both having a 1 mm gauge length. The values obtained for Young's Modulus (E) ranged from 2.49 to 2.71 x 10^6 lb./in.^{2} with a mean 2.58 x 10^6 and the mean value of Poisson's Ratio (U) was 0.37. The collapse results were not fully satisfactory since one specimen broke within the grips, and a second could not be held within the grips, both these features arising from the limitation on overall length of specimen, but the other two broke within the parallel portion, giving strengths of 18,400 and 18,600 lb./in.^{2}.

17. Shear deflection in a GRP sandwich structure is an important consideration so it becomes essential to know the shear modulus G, for the plane of shear in the sandwich. The flomat boxes in the BAP sandwich structure were made with a composite GRP material and consequently G could not be derived from the E and U values obtained from the tension tests on flomat specimens. Experimental determinations of G were handicapped by both the material properties of flomat, which allow local crushing and distortion where high forces are applied and the limited size of specimens available from the sides of the boxes. In view of this it was decided not to attempt applying pure shear forces directly to flomat specimens, but to determine G by applying centrally concentrated loads to simply supported beam specimens with span to depth ratios designed to give significant shear deflections. A miniature beam specimen having overall dimensions 4 in. x $\frac{1}{2}$ in. x $\frac{1}{4}$ in. was fabricated from material machined from the side

walls in a box. Central deflections were measured under loads for successive support positions giving spans of 1 in., 2 in. and 3 in. The three results allowed shear deflection, bending deflection and local indentation at the positions of the 1/16 in. diameter rollers, where loads were applied and reacted, to be distinguished in the measured deflection. The shear modulus and Young's Modulus could then be derived by relating measured deflections to the beam deflection formula including shear effects; however this technique assumed a uniform amount of indentation at the rollers. In fact the results for both E and G were inconsistent and erratic, due principally to inconsistencies in the indentations at the support positions. In the course of another investigation, G was measured for a material similar to the skins in beams 12 to 15. In this case a much larger beam specimen with a similar span to depth ratio was available and in tests varying the supported spans, G was found to be within the range 4-6 x 10^5lb./in.^{2}. The larger specimen allowed the indentation at the rollers to be measured independently, leaving E and G as the only two quantities to be evaluated from the measured deflections at mid span, and the E value obtained from the beam tests agreed closely with an independent check from a tensile specimen of the same material. As the E value for this GRP material was similar to that of the flomat box core material, it seemed reasonable to assume a similar G value and a value of 5 x 10^5 lb./in.^{2} was assumed for the shear modulus in the flomat box core sandwich.

18. In the case of the beams with plasticell cores, the material properties of plasticell were even more unfavourable for experimental determinations of G, than those of flomat. However despite some slight anisotropy in this material, G values derived from the isotropic relationship between E and U gave good agreement with the G values derived from the tests on the plasticell sandwich beams. The modulus for D300 was taken at 1.4 x 10^4 lb./in.^{2} and at 2.8 x 10^4 lb./in.^{2} for D500.

19. The elastic constants determined for the skins and core materials in the sandwich beams were to be used subsequently in analyses of the beam tests for comparison with experimental results.

TESTING PROCEDURE

20. The beams were tested in a 50 ton Denison machine. The load (W) was applied through a 1 in. diameter steel ball at the mid-span of a steel beam, which in turn loaded onto the specimen through two 2 in. diameter steel rollers, 22 in. apart. The specimen was reacted from the table of the testing machine through two rollers 44in. apart (ℓ). The surface of the beam was locally reinforced at the load positions by 2 in. wide by 1/32 in. thick steel strips glued with Pliobond rubber solution. The deflection at the mid-span and load positions was measured by dial gauges mounted from the rigid table of the testing machine, and strains were measured at the mid-span using pairs of gauges placed longitudinally and transversely, at three positions across the breadth, on both top and bottom surfaces. The load was applied in increments, the size of increments being reduced towards collapse.

ELASTIC BEHAVIOUR OF BEAMS

21. The deflections and strains of 7 to 15 tested under quarter point loading were all virtually linear, apart from the effects of some initial slackness due to imperfect alignment of the loading and reaction rollers, and a slight reduction in stiffness prior to collapse. In the case of the beams with a Plasticell foam core, this reduction in stiffness became apparent beyond about two thirds of the collapse load, typical graphs being shown in Figure 9 of Part 1 (1). The strains of these beams, on the other hand, were linear right to collapse. In the case of the beams with a box core structure, the behaviour was exactly linear, up to the final increment causing collapse, as shown in Figure 3.

22. A summary of the elastic response is presented in Table IIIa. The deflection per unit load is given for the central span relative to the inner load positions, D1 minus D2, involving only bending action, and for the end spans, D2 involving both bending and shear. According to the Engineers bending theory, these deflections may be calculated from the following expressions:

$$D1 - D2 = \frac{W\ell^3}{256EI} \qquad \text{..........} \; (3)$$

$$D2 = \left(\frac{W\ell^3}{96EI}\right) + \frac{W\ell}{8GA} \qquad \text{..........} \; (4)$$

where I is the moment of inertia, A is the shear area, E is the Young's Modulus of the skins, and G is the shear modulus of the core. To a first approximation the moment of inertia may be calculated neglecting the rigidity of the core and the local bending rigidity of the skins.

$$I = \frac{btd^2}{2} \qquad \text{..........} \; (5)$$

$$\left.\begin{aligned} A &= b(d-t) - \text{ for plasticell cores} \\ &= 4b'd' - \text{ for BAP box cores} \end{aligned}\right) \qquad \text{..........} \; (6)$$

where b = breadth of beam
t = skin thickness
d = distance between mid-depth of skins in sandwich
b' = thickness of walls in flomat boxes
d' = length of sides in flomat boxes under shear

Skin stresses and shear stress in the core may be calculated using

$$Z = btd \text{ (section modulus)} \qquad \text{..........} \; (7)$$

$$\text{and } \tau = W/_{2A} \text{ (shear stress)} \qquad \text{..........} \; (8)$$

23. More accurate alternatives to expressions (5) (6) (7) and (8) are provided by considering the flexural rigidity B, and the shear stress distribution in the composite sandwich structure as a whole, which gives:

$$B = \int E_i z^2 b \, dz \qquad \text{..........} \; (9)$$

and

$$A = \frac{F}{\tau_o} \qquad \text{..........} \; (10)$$

where

$$\tau_o = \frac{F}{b_o B} \int_{z_o}^{z_s} E_i \, b_z \, d_z \qquad \text{..........} \; (11)$$

and τ_o = Maximum shear stress
z_o = Position of N.A.
z = Distance from z_o
z_s = Position of skin surface
b_o = Width of material at z_o
b = Width of material at z
E_i = Young's Modulus of material at z

24. These expressions neglect local effects on the stress pattern at load application points, which might incur a slight inaccuracy in predicting shear deflection and shear stress in the rather short side spans.

25. There is an additional effect concerning the relationship between the span, the shear stiffness in the core and the local bending stiffnesses of the skins; in some sandwich designs the skins may have sufficient independent bending stiffness in relation to the shear stiffness of the core, to modify the deflection. (3). Including this effect would lead to a modification of equation (4) as follows:

$$D2 = \frac{W\ell^3}{96EI} + \frac{W\ell}{8GA}\left\{1 - \frac{EIs}{EI}\right\}^2 \psi$$

where EI_s = flexural stiffness of skins
EI = flexural stiffness of sandwich,

the general expression for ψ is given in the appendix to reference (3).

26. In the series of sandwich beams dealt with in this report, Microcell beam No 7 had the stiffest skins in relation to the shear stiffness of the core, and including this effect would reduce the calculated deflection by about 15%. The effect on the other beams would be reductions less than 10%. The effect was then considered negligible for this range of sandwich designs.

27. In Table III results calculated using both sets of expressions are given. The calculated deflections and skin stresses are compared with measured values from the 4 point loading tests on the beams. Comparison shows that the calculations using the more sophisticated impressions (9) (10) and (11) give closer agreement with the measured deflections and stresses, however the calculations using the simpler expressions (5) (6) (7) and (8) give an adequate estimate of the measured results.

28. Results dealing with the elastic response of the sandwich beams are detailed in Table III. With the exception of beams 7 and 12, the deflection results indicate that the BAP box core sandwich beams are more than twice as stiff as those with plasticell cores. The microcell beam 7 was the single example where a plasticell core sandwich supplied a stiffness comparable

to the BAP box core beams, but this beam had a heavier construction throughout with virtually unidirectional glass cloth stiffening along the length of the skins. Beam No. 12 was the only BAP box core beam where the deflection at the centre of the middle span exceeded the prediction by the calculations using expressions (9) and (10); also unlike the other beams, the measured skin stresses were significantly less than those predicted; both these considerations imply that the physical skin to core connections were less than completely efficient in this beam.

29. Deflection in the side spans carrying shear force (D_2) in the BAP box core sandwich beams indicate that over the spans considered, shear action contributes about 25% of the total deflection which is also more or less true for the sandwich beams with plasticell cores.

COLLAPSE BEHAVIOUR

30. The collapse loads and deflections together with measured and calculated skin stresses, including calculated shear stresses in the core and at the core to skin connections at collapse, are detailed in part (b) of Table III for each beam in the series.

31. The sandwich beams failed initially near the inner loading point in the side spans carrying shear force, see Figure 4. The highest collapse load was achieved by Microcell beam No 7, where the D500 Plasticell core material failed in shear at a calculated shear stress of 1220 lb./in.^{2}. Neither NCRE beam (10 and 11) with the same core material achieved a comparable collapse load, both suffering earlier shear failures at the skin to core connections similar to that shown in Figure 4 for Beam 9; they were not, in fact, effectively stronger than NCRE beams 8 and 9, which had D300 plasticell cores with lower potential shear strength, but which also failed at the core to skin connections.

32. The BAP box core beams all suffered shear failures in the box cores except beam no 12, where failure resulted in delamination of the upper skin in the central span of the beam where it was put in compression,see Figure 5a. Unlike the other three BAP box core beams, beam No 12 was tested with the upper skin bonded to the bottom of the boxes in the core; however, although

the bonding areas provided at the top and bottom surfaces of the boxes are not identical, see Figure 1, it is unlikely that this circumstance influenced this particular result, since the failure occurred at the skin to box connection with the larger bonded area. Although the elastic results indicated that the physical connections between skin and core in beam No 12 were not completely efficient, the shear stresses in the core and at the skin to core connection at collapse were approaching the values where shear failure had occurred in beams, 13, 14, and 15. In GRP materials surface bearing stresses, can usually be related to ultimate stress values, and the ultimate stress for the skin material in beam 12 was significantly less than the ultimate values for the skins in other beams (see Table II); although the measured skin stress in the centre span away from the load position was far short of the ultimate value when the beam failed, it is very likely that the failure leading to delamination of the upper skin originated at the inner loading point where the high shear stress at the skin to core connection was combined with the severe local crushing stress on the upper skin face. In this case the four point loading system employed in these beam tests may have produced an earlier failure than would have been experienced with a lateral pressure loading condition, but the shear stresses at failure indicate only a marginal difference. In the broader context of ship hull construction this result is of minimum importance, since the sandwich skins on this beam were more flimsy than any skin likely to be used in practice. The shear failure in the box core structure, typical of the failures in the other three box core beams, is shown in Figure 5b. The calculated shear stresses causing failure in the box cores of these beams ranged from 4,830 to 6,350 lb./in.^{2}, comparing with a specified shear strength of 8,000 lb./in.^{2} for these boxes, however the calculated values ignore the possible stress concentration effects in the box core structure at the loading position.

33. Failures in beams 8 to 12 all seemed to originate in the skin to core connections at calculated shear stresses in the range 310 to 470 lb./in.^{2}. Efficient bonds using polyester or epoxy resin systems should withstand shear stresses of the order 600 to 800 lb./in.^{2}, however in practical situations

bond strengths are critically influenced by gaps which can cause local shear stresses in excess of the calculated values. The best bond achieved in this series of beams was by the epoxy system used in Microcell beam No 7, where a calculated shear stress of 1200 lb./in.^{2} was acting between skin and core when shear failure occurred in the core which immediately resulted in delamination of the upper skin, this result is shown in Figure 10 in Part I of the report.

34. The maximum stresses recorded in the skins when failure of the beams occurred, can be compared with the ultimate stresses longitudinally for the various skins given in Table II. In every beam the skin stresses at failure were less than the ultimate stress values, and in the case of the BAP box core beams the maximum skin stresses were less than half of their ultimate stress values. There was therefore no question of failure by rupture of the skins in any of the beams tested, failure being dictated by shear behaviour in every case ie possibly including beam 12 where the bond failure may also have been influenced by local crushing in the skin.

35. The ultimate interest in the various sandwich constructions centres round their stiffness and weight in relation to the pressure loadings they can endure, and the four point loading tests actually performed on the beam specimens were only an experimental expediency. A shear type failure was experienced in all the beams tested, equivalent failure pressures (related to spans of 52 in.) could be derived using expression (1), and these are also detailed for every beam in Part (b) of Table III. If a FOS of 4 on a working pressure of 10 lb./in.^{2} is taken as the criterion, thus Microcell beam 7 would give a FOS greater than 10, so that it is much stronger than is necessary. The safety factors achieved in the BAP box core beams and the other plasticell core beams range from 3 to 4.6, indicating that all are in the vicinity of the strength requirements; however since the BAP box core sandwich and the Microcell plasticell D500 sandwich proved to be more than twice as stiff as the other plasticell core sandwiches, and the Microcell D500 sandwich offers no weight advantage over a steel structure while the BAP box core sandwich does, the net result favours the use of the BAP box core sandwich in ship hull design.

COMPARISON BETWEEN ALTERNATIVE DESIGNS IN GRP STEEL AND ALUMINIUM

36. GRP sandwich is under investigation to find a strength and stiffness for ship hull design comparable to a conventional steel design, including a significant saving in weight. It is also hoped to accomplish this without entailing prohibitive production costs. The strength requirements have been represented in this investigation by considering a FOS of 4 on static failure in a 52 in. long, 8 in. wide and approximately 2.65 in. deep panel, simply supported at its ends under a lateral pressure of 10 lb./in.^{2}. Tests have been carried out to determine the behaviour of different GRP sandwich designs in these panels. To judge their general suitability for naval structures, it is instructive to compare some characteristics of the GRP panels with panels of similar span in aluminium and steel, designed for the same working load.

37. A suitable mild steel panel was regarded as having uniform plating thickness and equally spaced Tee-bar stiffeners. The panels were designed to withstand lateral pressure of 10 lb/in.^{2}, allowing onset of yield in the plating (4) and one half yield stress in the flanges of the stiffeners. This led to the plating thickness and Tee bar dimensions specified in Table IV with 18 in. spacing between stiffeners. A panel in aluminium alloy was designed from similar considerations, 0.1% proof stress being taken in place of the yield stress in mild steel. One stiffener with an 18 in. width of plating was then taken as a basis for comparison with the GRP sandwich designs, data for the 8 in. widths used in the GRP sandwich investigation being adjusted to suit.

38. The yield stress of mild steel was taken as 15 ton/in.^{2} and the 0.1% proof stress of aluminium alloy as 10 ton/in.^{2}, mild steel having a density 0.28 lb./in.^{3} and aluminium alloy 0.096 lb./in.^{3}. The 'fabricated' cost of mild steel was taken at £700 per ton, being roughly based on frigate type construction, while the 'fabricated' cost of aluminium was taken at £1800 per ton.

39. The comparison between GRP sandwich, mild steel and aluminium alloy is presented in Table IV. Although large scale production might to some extent reduce the cost of GRP sandwich quoted in this table, nevertheless its use

in ship hull construction would clearly produce much higher costs than the use of the more conventional metals, and while a considerable saving in weight would be achieved compared with the steel construction, a similar effect at a reduced cost would be accomplished using aluminium alloy.

CONCLUSIONS

40. The results from the tests on this series of selected sandwich designs enabled their static strengths to be related to their weights, but insufficient samples of each design were tested to assess the possible scatter in failure loads. Nevertheless these tests furnished sufficient results to demonstrate that GRP sandwiches with BAP box cores offered the best static strength to weight characteristic of the various designs considered, and that these sandwiches were a practical proposition for use in ship hulls with regard to static strength.

41. The test results also demonstrated that shear strength is the most important single consideration for sandwich designs under static loading. For the actual beam project chosen lower quality skins would have been adequate as shear strength in the cores and at the core to skin connections did not match the strength of the skins.

42. This series of sandwich designs showed linear behaviour over most of the range to failure, those with BAP box cores having a linear response as far as failure. The elastic response of all these sandwiches was predicted quite adequately using the approximate Engineer's formulae; possibly the greatest difficulty in analysis is in obtaining information on the elastic constants of the structural components.

43. In GRP sandwich designs, the FOS of 4 on static failure which is considered a reasonable criterion for ship design, represents a higher FOS than that usually adopted in the design of metal structures. This is because stress concentrations create a greater hazard in brittle materials such as GRP. These stress concentrations result not only from geometrical arrangements in the sandwich, but may also result from critical gaps in the resin bonds caused by difficulties in quality control during large scale fabrication.

44. Fatigue behaviour is an important consideration in the choice of the FOS. In an investigation into the fatigue behaviour of specimens representing structural connections in a ship hull of GRP sandwich with the BAP box core, the fatigue performance under service loads based on a FOS of 4 was found to be acceptable for ship construction (5).

45. A further aspect not previously considered in this report is the behaviour under explosive loading. Results from a separate investigation concerning explosive loading tests on GRP sandwich panels with the BAP box core showed that the resin bonds at the core to skin connections were quite inadequate to resist the tension forces developed by the impact of quite small pressure waves normal to the skin. This in fact was revealed as the crucial weakness of resin bonded sandwich designs for warship hulls.

46. The major advantage of sandwich design in GRP structures is its contribution to stiffness; however it is felt that the drawbacks outweigh this advantage. As far as warship design with GRP is concerned, single skin hulls with stiffeners attached using both resin bonds and high tensile bolts offer a sounder proposition.

47. GRP sandwich remains a practical proposition for ships not likely to be subjected to explosive loading. It offers a saving in weight and maintenance costs compared with steel designs. Production costs are very much higher however, and in cases where weight saving is attractive, this can be accomplished more economically with aluminium alloy.

ACKNOWLEDGEMENT

The work described in this report was supervised by the late Mr J Clarkson. The present author was responsible for completing an analysis of the results, and for revising and completing an early draft of the report by Mr Clarkson.

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TABLE I

DETAILS OF SANDWICH BEAMS 7 TO 15

Beam No.		7	8	9	10	11	12	13	14	15
ufacturer (1)		Microcell	N.C.R.E.	N.C.R.E.	N.C.R.E.	N.C.R.E.	B.A.P.	B.A.P.	B.A.P.	B.A.P.
mensions	Length in.	52	52	52	52	52	48	48	46	48
	Breadth in.	8	8	8	8	8	12	12	12	12
	Depth in.	2.51	2.65	2.50	2.57	2.45	3.26	3.34	3.27	3.39
ces or Skins	Material	glass cloth polyester	Permaglass 24/BE epoxy	Permaglass 24/BE epoxy	Permaglass 24/BE epoxy	Permaglass 24/BE epoxy	1 lam. tissue 1 lam. mat 1 lam. cloth polyester	1 lam. tissue 1 lam. mat 3 lams. cloth polyester	4 lams cloth polyester	6 lams. cloth polyester
Thickness	Upper Skin or Mean	0.39	0.13	0.189	0.185	0.126	0.129	0.177	0.131	0.197
	Lower Skin in.						0.130	0.160	0.135	0.193
	Percentage glass by Wt.	62	57	53	56	58	45	49	57	55
ore	Material	← Plasticell expanded P.V.C. foam →					← 6 in. square "flomat" box units →			
		D500	D300	D300	D500	D500				
	Density (2) lb./ft.^{3}	32	17.4	17.4	32	32	15.5	15.5	15.5	15.5
	Thickness in.	1.73	2.39	2.125	2.2	2.2	3.0	3.0	3.0	3.0
ght lb.	Skins	19.5	6.6	9.6	9.5	6.7	8.1	10.7	8.7	13.1
	Core	12.7	10.5	8.9	16.8	17.2	15.5	15.5	15.5	15.5
	Bonding Agent	0.5	0.8	1.1	1.2	0.7	1.6	2.8	2.9	3.0
	Total	32.7	17.9	19.6	27.5	24.6	25.2	29.0	27.1	31.6
st	Skins (3)	break-down not available	£13.12s.	£16	£16	£10.10s.	← break-down not available →			
	Core		£16. 0s.	£12	£14	£14. 0s.				
	Bonding Agent		£ 0.10s.	£ 1	£ 1	£ 0.10s.				
	Total (4)	£42.17s.	£30. 2s.	£29	£31	£25	← total cost of 4 beams £195 →			

Notes: (1) Manufacturers: NCRE = Naval Construction Research Establishment, BAP = Bristol Aeroplane Plastics Ltd.
(2) Density of BAP box core taken as total weight of core divided by volume occupied by core.
(3) Cost of skins where separately shown includes off-cuts for tensile specimens.
(4) Total cost of beams made by NCRE is for components only, not assembly.

TABLE II

TENSILE PROPERTIES OF SKINS OF BEAM SPECIMENS

Beam No.		7	8	9 10	11	12	13	14	15
Manufacturer		Microcell	N.C.R.E.	N.C.R.E. N.C.R.E.	N.C.R.E.	B.A.P.	B.A.P.	B.A.P.	B.A.P.
Longitudinal E lb./in.^{2}	(1)	4.67×10^6	2.77×10^6	2.61×10^6	2.86×10^6	2.13×10^6	3.08×10^6	2.65×10^5	2.80×10^6
	(2)	4.57×10^6	2.69×10^6	2.60×10^6	2.72×10^6	2.37×10^6	2.73×10^6	2.60×10^6	2.66×10^6
	(mean)	4.62×10^6	2.73×10^6	2.60×10^6	2.79×10^6	2.25×10^6	2.91×10^6	2.63×10^6	2.73×10^6
Poisson's Ratio	(1)	0.26	0.16	0.13	0.14	0.27	0.25	0.15	0.14
	(2)	0.25	0.16	0.13	0.13	0.24	0.22	0.12	0.13
	(mean)	0.26	0.16	0.13	0.14	0.25	0.24	0.13	0.13
Ultimate stress lb./in.^{2}	(1)	67,000	41,500	41,900	41,400	20,500	37,700	34,500	36,600
	(2)	61,600	39,900	39,900	42,700	23,900	37,500	42,000	40,600
	(mean)	64,300	40,700	40,900	42,000	22,200	37,600	38,200	38,600
Transverse E lb./in.^{2}	(1)	not measured	not measured	2.24×10^6	2.50×10^6	not measured	not measured	not measured	not measured
	(2)			2.28×10^6	2.45×10^6				
	(mean)			2.26×10^6	2.48×10^6				
Poisson's Ratio	(1)			0.12	0.12				
	(2)			0.12	0.12				
	(mean)			0.12	0.12				
Ultimate stress lb./in.^{2}	(1)			37,000	43,100				
	(2)			39,200	40,400				
	(mean)			38,100	41,700				

TABLE III

COMPARISON OF MEASURED AND CALCULATED RESULTS FOR SERIES OF SANDWICH BEAMS UNDER 4 PT. LOADING

Beam No. Manufacturer Core Material		7	8	9	10	11	12	13	14	15
		Microcell	N.C.R.E.	N.C.R.E.	N.C.R.E.	N.C.R.E.	B.A.P.	B.A.P.	B.A.P.	B.A.P.
		←		Plasticell	→		← square "float" box units			→
Skin Thickness		0.390	0.130	0.189	0.185	0.126	0.129	0.169	0.133	0.195
(a) Elastic Response										
Deflection of Mid Span relative to Load Position $D_1 - D_2$ (Fig. 4) in./ton	measured	0.023	0.070	0.060	0.057	0.076	0.045	0.019	0.035	0.017
	calculated (1)	0.023	0.083	0.071	0.068	0.098	0.043	0.025	0.036	0.023
	calculated (2)	0.021	0.080	0.069	0.065	0.092	0.028	0.019	0.025	0.018
Deflection of End Spans D_2 (Fig. 4) in./ton	measured	0.077	0.230	0.196	0.172	0.230	0.105	0.076	0.087	0.062
calculated (1)	bending	0.061	0.224	0.189	0.182	0.261	0.116	0.067	0.097	0.061
	Shear	0.032	0.048	0.054	0.025	0.025	0.018	0.018	0.018	0.018
	total	0.093	0.269	0.243	0.207	0.286	0.123	0.094	0.105	0.080
calculated (2)	bending	0.057	0.213	0.185	0.173	0.245	0.075	0.051	0.067	0.047
	shear	0.024	0.046	0.050	0.024	0.025	0.017	0.017	0.017	0.016
	total	0.081	0.259	0.235	0.197	0.270	0.092	0.068	0.084	0.063
Maximum Skin Stress (Mid Span) lb./in.^{2} per ton										
Upper and Lower Skins (mean of 6 values)	measured	2140	4270	3420	3230	4730				
	calculated (1)	2200	4940	3810	3760	5530				
	calculated (2)	2030	4780	3720	3550	5190				
Upper Skin (mean of 3 values)	measured						1120	1760	1730	1330
	calculated (1)						2630	2020	2570	2100
	calculated (2)						1570	1630	1940	1440
Lower Skin (mean of 3 values)	measured						1450	1300	1610	1130
	calculated (1)						2630	2020	2570	2100
	calculated (2)						1800	1420	1600	1260
(b) Collapse										
Collapse Load Tons		19.80	6.25	8.02	7.84	5.52	6.00	8.50	7.50	6.50
Equivalent Uniform Pressure lbs./in.^{2}		107	34	43	42	30	32	46	40	35
Maximum Shear Stress in Core at Collapse lb./in.^{2}	calculated (1)	1600	370	530	500	350	4850	6870	6060	5260
	calculated (2)	1220	350	490	470	340	4570	6350	5760	4830
Shear Stress at Core to Skin Bond at collapse lb./in.^{2}	calculated (2)	1200	340	470	440	310	440	760	600	580
Maximum Skin Stress at Collapse lb./in.^{2}	measured (3)	14,500	31,400	27,700	25,900	27,300	8,030	14,950	14,360	-6,590
Maximum Deflection at Collapse in.	measured	2.30	2.00	2.20	1.90	1.80	0.90	0.82	0.83	0.51

Notes:- (1) Calculated values based on approximate expressions, $I = btd^2/2$, $Z = btd^2/(d + t)$, $A = b(d - t)$

(2) Calculated values based on I and Z including terms from core; shear deflection from shear strain at neutral axis;

shear stress from $= \frac{F}{bB}\int_{z}^{e_1} E\, bz\, dz$

(3) Measured value mean of 6 positions for beams 7 to 11; mean of 3 positions for each flange for beams 12 to 15, sign of value (tensile or compressive) indicates flange giving larger stress.

TABLE IV

COMPARISON BETWEEN ALTERNATIVE DESIGNS IN G.R.P. STEEL AND ALUMINIUM

Span of Panels between Simple Supports = 52 in.
Maximum Working Pressure = 10 lb./in.^{2}

Material and Design	G.R.P. Sandwich No. 9	G.R.P. Sandwich No. 14	Steel	Aluminium
Thickness of Each Skin or Plating, in.	0.189	0.133	0.213 (8.5 lb.)	0.3
Core Material	Plasticell D300	"Flomat" box units	-	-
Thickness of Core, in.	2.125	3.0	-	-
Stiffener Size	-	-	1¾" x 3½" T(1)	5" x 4" x 0.375" T(2)
Stiffener Spacing, in.	-	-	18	18
Weight per 18 in width, lb.	44	44	77	43
Cost per 18 in width, £	65	73	23	35
Maximum Deflection at 10 lb./in.^{2}, in.	0.48	0.21	0.15	0.20

(1) Admiralty Welding Tee bar, flange 1.75" x 0.375", web 4.125" x 0.2"
(2) BS 1161: AT14, flange 5" x 0.375", web 3.625" x 0.375"

6" SQUARE FLOMAT BOX CORE UNIT

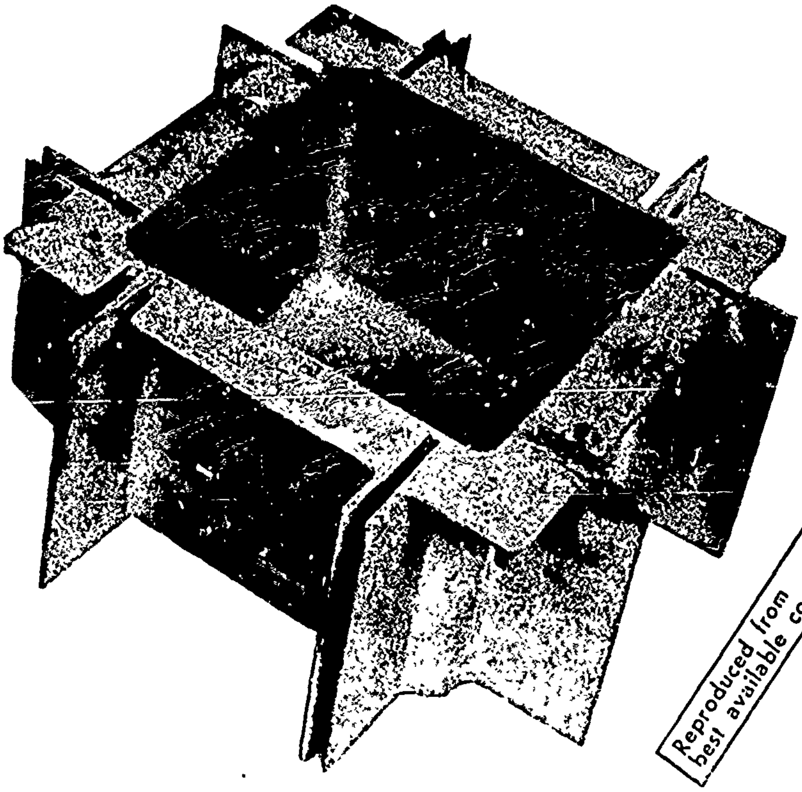

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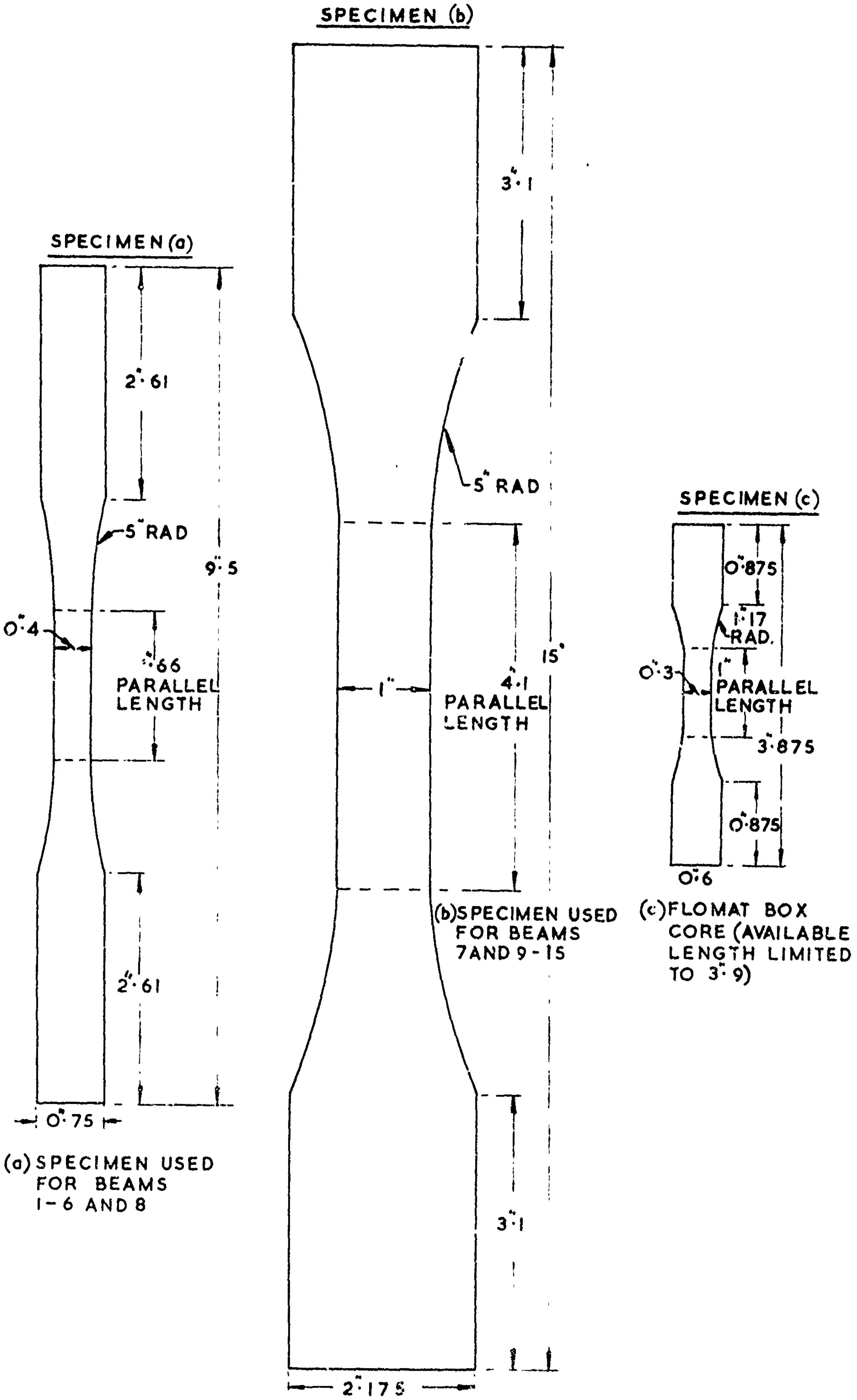
FIGURE 1

TENSILE SPECIMENS



(a) SPECIMEN USED FOR BEAMS 1-6 AND 8

(b) SPECIMEN USED FOR BEAMS 7AND 9-15

(c) FLOMAT BOX CORE (AVAILABLE LENGTH LIMITED TO 3"·9)

FIGURE 2

MID - SPAN DEFLECTION OF BEAMS WITH FLOMAT BOX CORE STRUCTURE

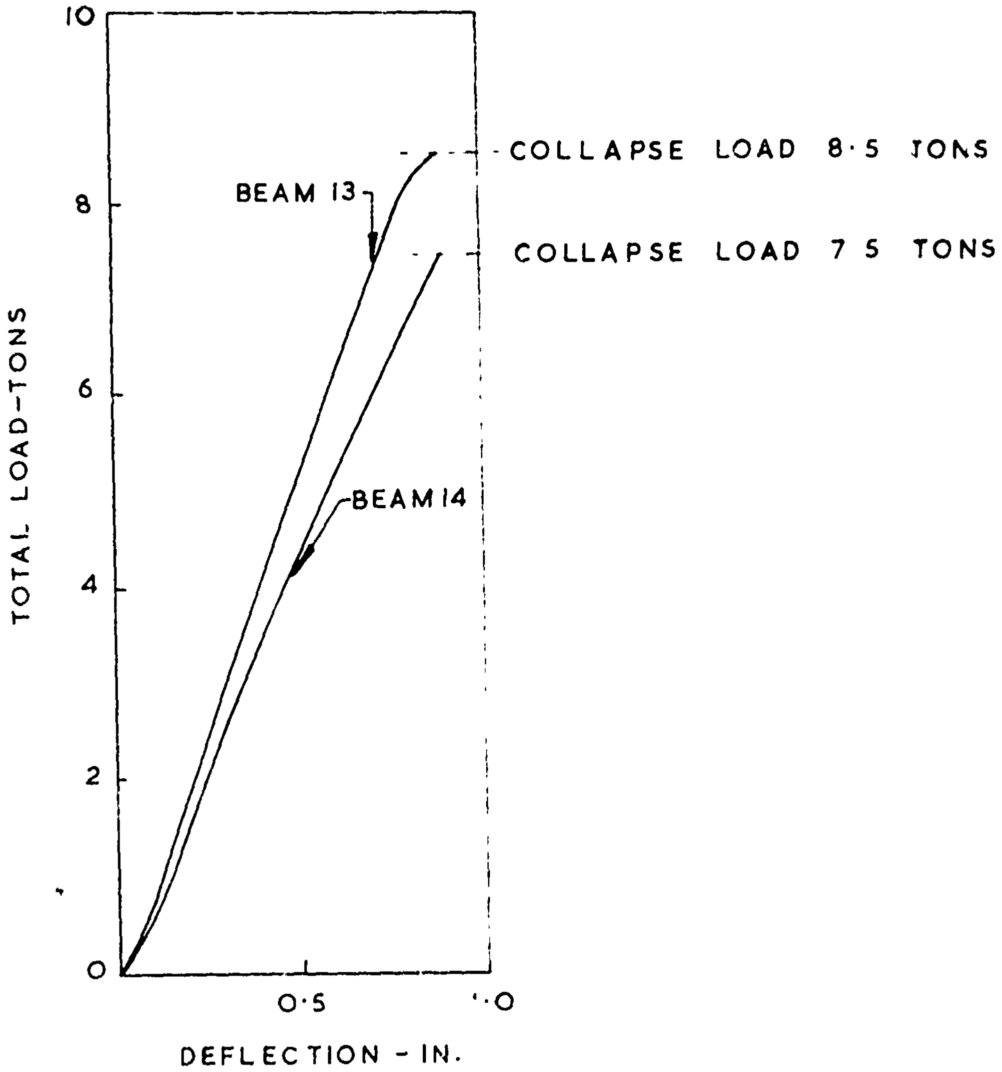
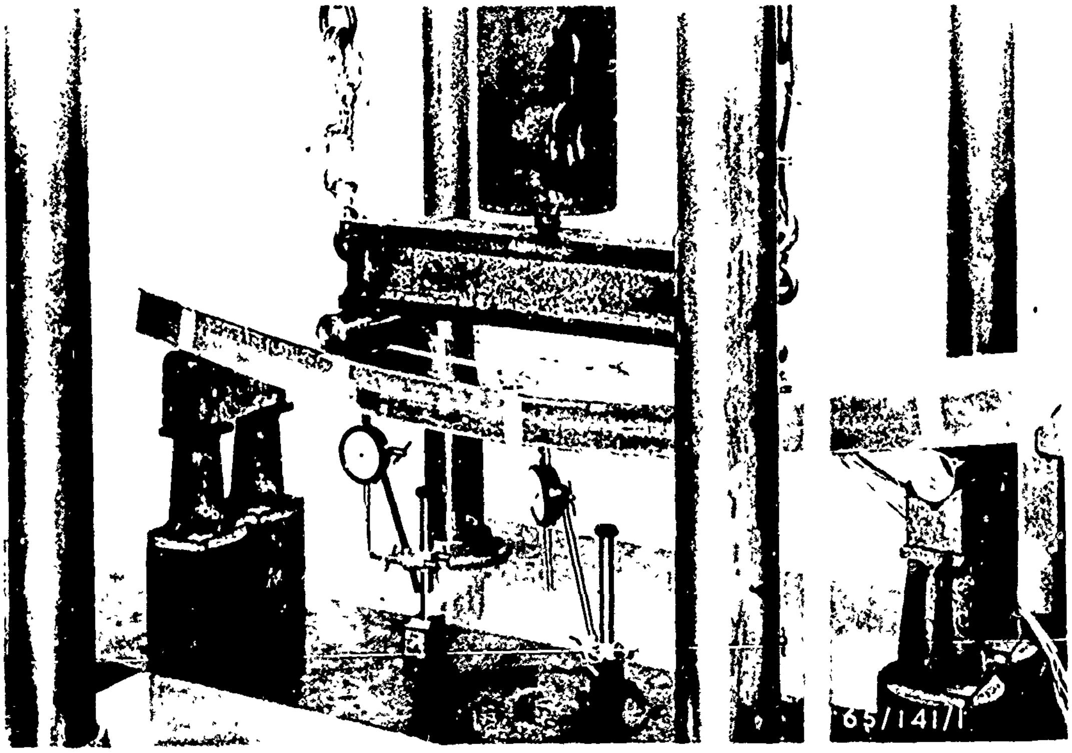


FIGURE 3

FAILURE OF BEAM No. 9 WITH PLASTICELL CORE

(a) BEAM IN TESTING M/C IMMEDIATELY AFTER COLLAPSE



(b) DETAIL OF FAILURE AT SKIN TO CORE CONNECTION

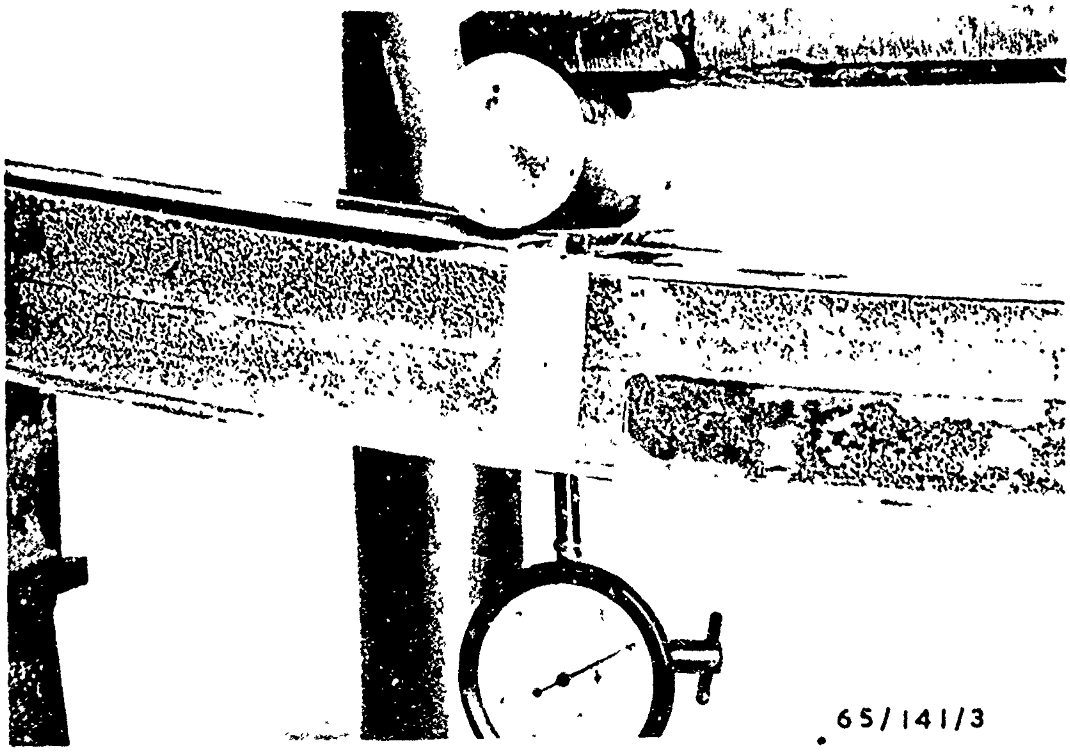


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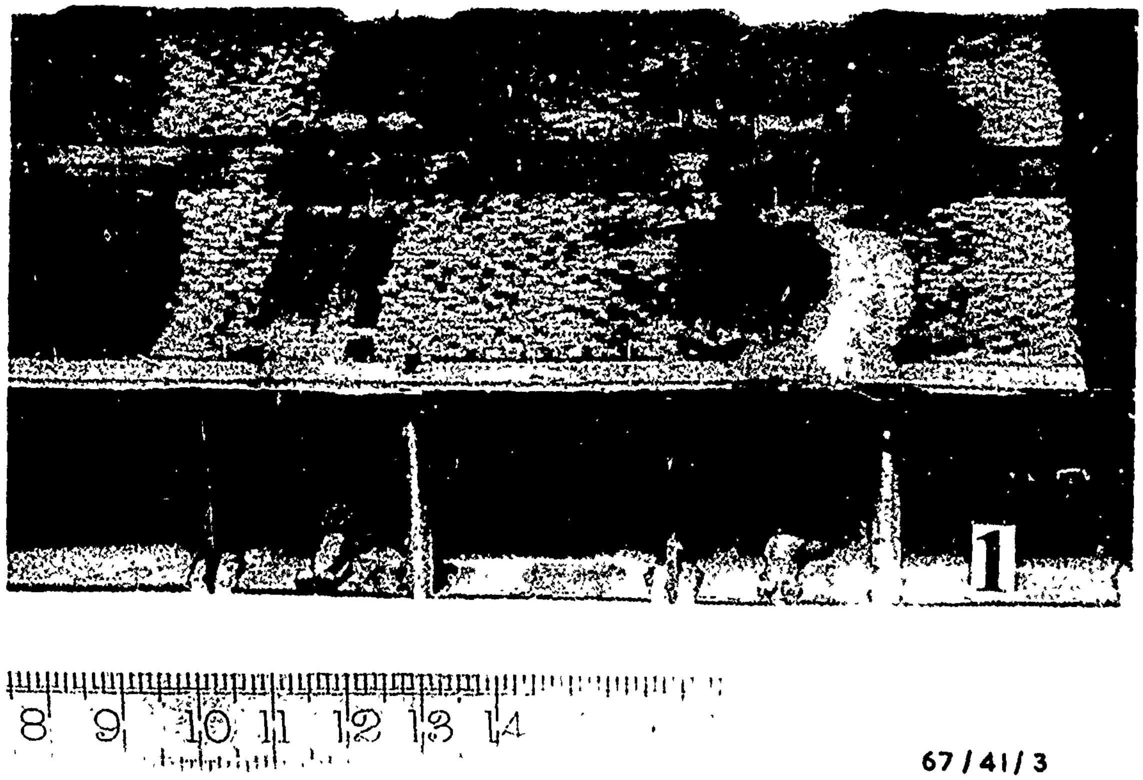
FIGURE 4

FAILURE OF BEAMS WITH FLOMAT BOX CORE STRUCTURE

(a) FAILURE ON COMPRESSION FLANGE OF BEAM No.12



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(b) DETAIL OF SHEAR FAILURE OF BEAM No.14

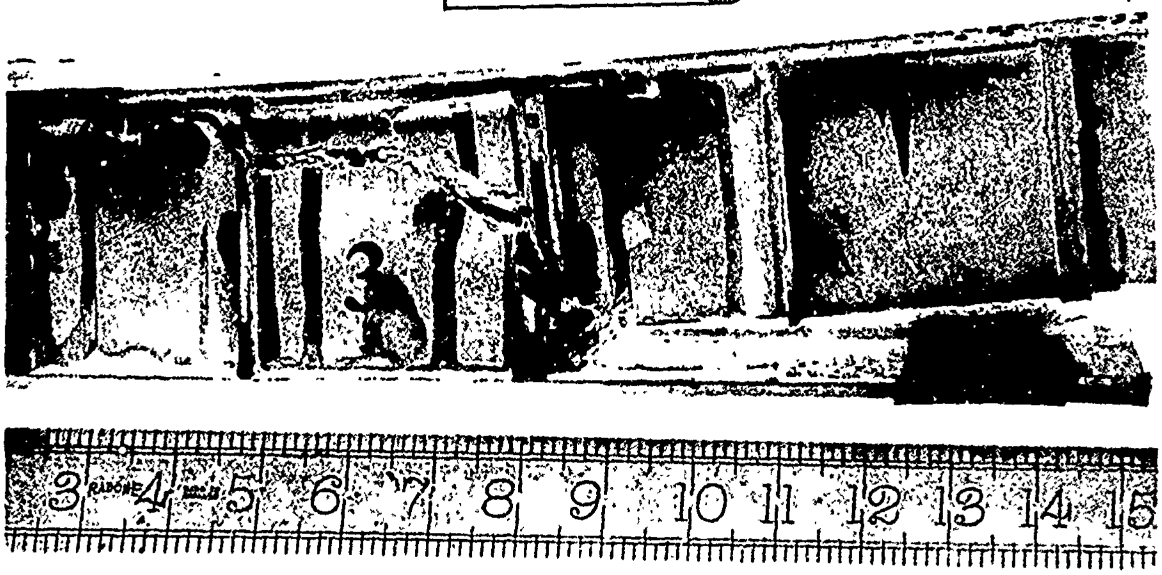

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FIGURE 5