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INVESTIGATION OF ADVANCED LIGHTWEIGHT SANDWICH STRUCTURAL CONCEPT

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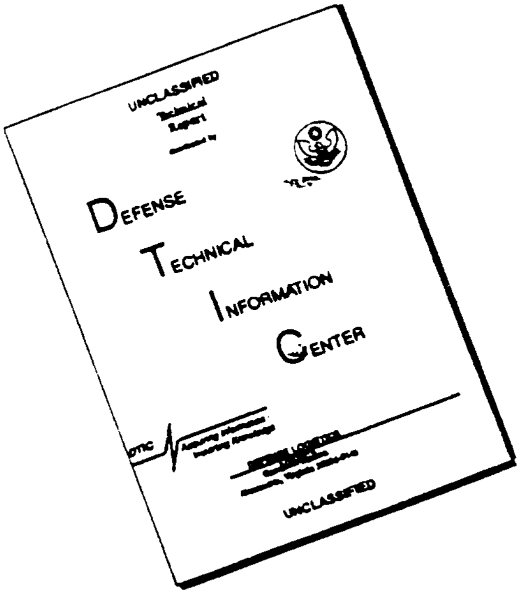

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Although the sandwich panels fabricated of honeycomb core bonded between two face-sheets are very weight-efficient, their application causes many problems such as moisture retention, extensive corrosion, ineffective edge seals, unbonding of face-sheets, and time consuming and expensive repair. In an attempt to eliminate these detrimental factors, new sandwich structural concepts are introduced. These structural concepts include bidirectionally-corrugated, lattice-core, offset-corrugated, and cross-corrugated sandwich. They are variations of corrugated sandwich.

The new features of all the sandwich are the provision of passsageways from cell to cell for moisture drainage to reduce corrosion. The lattice-core, offset-corrugated, and cross-corrugated sandwich can be fabricated of fiber-reinforced composite materials in single cure operation without any secondary bonding.

Sample specimens of lattice-core and offset-corrrugated sandwich panels have been fabricated and tested to obtain their flexural and transverse shear stiffnesses. The predicted flexural and transverse shear stiffnesses of lattice-core and cross-corrugated sandwich panels are comparable to that of honeycomb sandwich panels.

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FOREWORD

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LIST OF SYMBOLS AND ABREVIATIONS

b	Width
c	Length in a beam (Fig. A3)
d	Overhang in a beam (Fig. A3)
h	Height
p	One half of the pitch of a corrugated sandwich panel
q	Load per unit length (Fig. 1)
w	Deflection of the middle surface of the beam, measured in z-direction
D	Flexural stiffness
D_Q	Transverse shear stiffness
E	Young's modulus
G	Transverse shear modulus
L	Span of a beam
M	Bending moment per unit length, Couple (Fig. B3).
P	Load
Q	Shear force per unit length
Q_1, Q_2	Shear forces (Fig. B1)
R	Radius of curvature
X	Horizontal force (Fig. B1)
γ	Shear angle measured in the $x-z$ plane (Eq. 2a), Averange shear strain (Eq. B1).
δ_x, δ_z	Deformations in a unit cell of the corrugated sandwich (Fig. B1)
in	Inch
lb	Pound
IR	Independent Research
IED	Independent Exploratory Development
NADC	Naval Air Development Center
NAWCADWAR	Naval Air Warfare Center, Aircraft Division, Warminster

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1. INTRODUCTION

In airplane design the necessity for weight efficiency and aerodynamically smooth surfaces under high stress levels have motivated the use of sandwich construction as a possible substitute for sheet-stringer construction [1]. In spite of superior weight-efficiency of sandwich construction, their application lagged behind theoretical development primarily because of the lack of desirable properties of core materials and bonding of core to face-sheets [2]. Among the various core materials, honeycomb cores are considered most weight efficient. But retention of moisture in sandwich construction with honeycomb core degrades the structural integrity leading to premature failure of the component. A summary of service experience related to honeycomb sandwich construction applied in Navy and Air Force aircraft is reported in Reference 3. In that summary it was reported that up to 90% of repair frequency was due to problems in honeycomb sandwich construction such as moisture retention, extensive corrosion, ineffective edge seals, and unbonding of face-sheets. The repairs were very time consuming and expensive, such as $50M per year for A-6 and $20M per year for F-14 airplanes.

In an attempt to eliminate these detrimental factors, new sandwich structural concepts are introduced. These include bidirectionally-corrugated, lattice-core, offset-corrugated, and cross-corrugated sandwich construction. All of these sandwich structures are variations of corrugated sandwich construction. In these new sandwich panels, the bending and shear stiffnesses can be controlled in both directions along the plane of the sandwich. In honeycomb core, because of the very nature of its geometry, the shear stiffness in the direction perpendicular to the ribbon is usually half as great as that in the ribbon direction [4]. In addition, in the proposed sandwich structures, unlike honeycomb, the cells of the cores are open. These designs allow the panels to dissipate moisture, which minimizes or eliminates corrosion and premature failure of the component. Other advantages of these designs include elimination or reduction of the tendency of unbonding of face-sheets from the core due to formation of steam during the repair process. The damage tolerance is expected to improve due to flexibility and discontinuity of the core.

The proposed bidirectional corrugated sandwich construction can be fabricated of fiber reinforced composite materials with cocuring the two face-sheets and the corresponding corrugations producing two halves. The two halves can be adhesively bonded to obtain the final form of the sandwich. The lattice-core, offset-corrugated, and cross-corrugated sandwich have the added advantage of being constructed by cocuring without any secondary bonding. In all the designs, cores are formed by wrapping materials around mandrels which maintain the shapes of the core.

In designing sandwich plates for strength, it is necessary to determine and optimize seven physical constants: two flexural stiffnesses, one twisting stiffness, two transverse shear stiffnesses, and two Poisson ratios. A major difference between ordinary plates and sandwich plates is the consideration of transverse shear stiffness. In ordinary plates, the transverse shear stiffnesses are neglected for most applications. But in the sandwich plates, because of cores with relatively low stiffnesses, the transverse shear stiffnesses are required to be included in the theory and analysis. Since the transverse shear stiffness and bending stiffness are among the important factors in designing sandwich plates for their strength, in this report a preliminary investigation has been performed on these stiffness properties for the new sandwich structural concepts.

2. DEFINITION OF FLEXURAL AND TRANSVERSE SHEAR STIFFNESSES

The forces acting on a differential element dx of a beam of height h are shown in Figure 1. The flexural stiffness D is defined as the negative of the ratio of moment to curvature

$$D = -M \Bigg/ \frac{d^2w}{dx^2}, \tag{1}$$

where M is the bending moment per unit width (dimension in y-direction), and w is the deflecton of the middle surface of the beam, measured in z-direction. The negative sign is introduced in order to make D a positive quantity (with respect to the coordinate system, curvature d^2w/dx^2 is negative).

The transverse shear stiffness D_Q is defined as the ratio of shear force to shear angle

$$D_Q = Q/\gamma, \tag{2a}$$

where Q is the shear force per unit width, and γ is the shear angle measured in the xz-plane. The shear modulus G is related to the shear stiffness D_Q by

$$G = D_Q/h. \tag{2b}$$

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3. BIDIRECTIONALLY-CORRUGATED SANDWICH

The models of bidirectionally-corrugated sandwich are shown in Figures 2 and 3. The proposed bidirectionally-corrugated sandwich can be fabricated of fiber-reinforced composite materials by cocuring the two face-sheets and corresponding corrugations, producing two halves. The halves then can be adhesively bonded together to obtain the final form of the sandwich. The discontinuous strips of corrugations in the core of the sandwich are formed by wrapping materials around mandrels which maintain the shape of the core. These sandwiches have passageways from cell to cell for moisture drainage. The damage tolerance is expected to improve due to the presence of flexibility and discontinuity in the core. But the main detrimental feature of the sandwich is that it requires bonding which promotes unbonding of face-sheets during service usage and repair.

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4. LATTICE-CORE SANDWICH

Figures 4 and 5 show the models of lattice-core sandwich made of plastic sheets and tapes. Figure 6 is another model of lattice-core sandwich made of one-ply graphite fabric prepreg. Three different views of a prototype lattice-core sandwich of nominal size 38.4 in × 6.3 in × 0.95 in are shown in Figures 7, 8, and 9. The face-sheets have ten plies of graphite fabric cloth, and the corrugations have three, six, and twelve plies depending on the locations. In both cases graphite fabric prepreg Hercules AW193-P/3501-6 is used.

The present method of fabricating the lattice core sandwich consists of wrapping appropriate materials around the mandrels (Figure 10) which are then placed in contact with each other (Figure 11). Then face-sheets are placed at the top and bottom of the set of mandrels (Figure 11). The mandrels maintain the lattice shape during attachment to the face-sheets and are removed after the curing process. The sandwich can be constructed of fiber reinforced composite materials in one cocuring operation without any secondary bonding. The wrapping of material around the mandrels should be such that sufficient passageways (Figures 4 and 5) are provided at the sides of the mandrels. The nature of wrapping and the shape of the mandrel will also influence the structural strength and integrity of the sandwich.

The advantages of the lattice-core sandwich are as follows: (a) fabrication of the sandwich by one cocuring operation without any secondary bonding will eliminate problems related to secondary bonding such as unbonding of face-sheets from the core, (b) passageways from cell to cell in the core allow moisture to be drained from the sandwich, (c) the damage tolerance is expected to improve due to the presence of flexibility and discontinuity in the lattice core, (d) the presence of passageways and cocuring without any secondary bonding will eliminate or reduce the tendency of unbonding of face-sheets from the core due to formation of steam during the repair process.

In order to assess the strength and applicability of the lattice-core sandwich, the following analytical and experimental work has been performed, and the results are compared with the representative honeycomb sandwich used in Navy's F/A-18 airplane. The material property of aluminum is used for the purpose of analytical comparison of lattice-core and honeycomb sandwich. This is a reasonable choice because in many cases the fiber-reinforced composite laminates for application have Young's modulus at least as great as that of aluminum.

The partial cross section of a lattice-core sandwich is shown in Figure 12. In this diagram the thickness of the face-sheets is 0.075 inch, and the material used to form the core has cross sectional dimensions of $0.1\,\text{in} \times 0.075\,\text{in}$. Other dimensions for the core material considered are $0.25\,\text{in} \times 0.075\,\text{in}$, and $0.3\,\text{in} \times 0.075\,\text{in}$. A relatively heavier sandwich with face-sheet thickness of 0.15 in and a core material dimension of $0.15\,\text{in} \times 0.15\,\text{in}$ is also considered. The dimensions of the lattice core sandwich with their weight densities are shown in Table 1.

The flexural stiffness and transverse shear modulus are determined computationally by the method described in Appendix A. The general purpose finite element program ABAQUS [5] is used to obtain the deflections of the sandwich beams subject to three-point loadings. The deflections at midspan for various values of spans for the sandwich listed in Table 1 are shown in Table 2. The deflections of a point in the face-sheet, just opposite to the support, range from 0.13% (for span 24 inch) to 1.1% (for span 12 inch) of the deflection at midspan. The differences in the deflections of midspan of both face-sheets range from 0.27% (for span 24 inch) to 2.7% (for span 12 inch) of the maximum deflections. As expected the distortions are larger in sandwich with smaller span.

The quantities $w/(PL^3)$ versus $1/L^2$ are plotted in Figure 13. From these plots the flexural stiffness and transverse shear modulus are calculated and compared with that of honeycomb sandwich (Table 3). The dimensions of the honeycomb sandwich are shown in Table 4. The honeycomb sandwich construction used in the Navy's F/A-18 airplane has aluminum honeycomb and composite face-sheets. Since the density of honeycomb core used in the F/A-18 ranges to 4.5 lb/ft^3 [6], only those sandwiches whose stiffnesses are comparable to this range are selected.

For illustration, lattice-core sandwich number 1 (Table 1) is compared with honeycomb sandwich number 1 (Table 4). The calculated flexural stiffness D and transverse shear modulus G of the lattice-core sandwich are 470,858 lb.in and 12,155 lb/in^2, respectively. The required thickness t of the face-sheets (fabricated of the same material as that of lattice-core sandwich) of a honeycomb sandwich with thickness $h = 0.9$ inch, and flexural stiffness $D = 470{,}858\,\text{lb.in}$ is 0.11 inch. Aluminum honeycomb with core density of 1.6 lb/ft^3 has a transverse shear modulus $G = 11{,}000\,\text{lb/in}^2$, which is closest to 12,155 lb/in^2, according to manufacturer's catalog [Ref. 7]. Therefore, the honeycomb sandwich fabricated with core of density 1.6 lb/ft^3 and face-sheets of thickness 0.11 inch has the flexural stiffness $D = 470{,}858\,\text{lb.in}$ and transverse shear modulus $G = 11{,}000\,\text{lb/in}^2$, and weight density (weight of the sandwich per unit volume of space occupied) 39.2 lb/ft^3. Table 3 indicates that the flexural and shear stiffnesses of lattice-core sandwich are comparable to that of honeycomb sandwich with respect to their weights per unit volume occupied. The stiffnesses considered in both the honeycomb and new sandwich are in the weakest direction (x-direction). The stiffnesses in the stronger direction (y-direction) will be calculated at a later date.

The comparison of analytical and experimental results of the prototype lattice-core sandwich, determined by the methods described in Appendices A and B, is shown in Table 5. There is considerable discrepancy between the analytical and experimental results. The primary reason for this discrepancy was that solid mandrels of uniform size were not used. Consequently it was only possible to apply the required pressure on the sides of the panel during curing in the autoclave without sufficient pressure on top of the panel. As a result there was not enough compaction at the joints of the lattice-core sandwich, thus producing significant amount of voids (dark regions in the photomicrograph, Figure 14). The lower values of stiffness of the sandwich was probably due to the presence of these voids in the joints. Use of proper tooling would eliminate this discrepancy as evidenced by the presence of much less voids at the joints of the unidirectionally-corrugated sandwich (Figure 15) where proper tooling was used (see section 5).

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5. OFFSET-CORRUGATED SANDWICH

The offset-corrugated sandwich panels consist of strips of corrugations, offset by half a wave with respect to their adjacent strips, contained between two face-sheets (Figures 16 and 17). The sandwich can be constructed of fiber-reinforced composite materials in one cocuring operation without any secondary bonding. The design allows passageways for moisture drainage. This sandwich concept has all the advantages of the lattice-core sandwich described in section 4. The offset-corrugated sandwich shown in the Figures 16 and 17 (nominal size 17.5 in × 1.0 in × 1.0 in) was made of perforated annealed aluminum, and the corrugated strips were attached to the two face-sheets by nuts and bolts for convenience. The comparison of experimental results of the offset-corrugated and unidirectionally-corrugated sandwich (without any offset in the corrugations) made of annealed aluminum is shown in Table 6. Using the method described in Appendix A, the experimental values of the flexural stiffness of the offset-corrugated sandwich is 56,306 lb·in per unit width of the beam, and the transverse shear modulus 1,468 lb/in^2. The experimental values of the flexural stiffness of the sandwich with all three strips of corrugations placed in-phase (here it is called unidirectionally-corrugated sandwich, no figure shown) is 67,204 lb·in per unit width of the beam, and the transverse shear modulus 941 lb/in^2. The flexural stiffness is expected to be practically the same in both cases. The transverse shear modulus of the offset-corrugated test piece is 56% greater than that with all the corrugated strips in-phase (unidirectionally-corrugated). In this demonstration, no attempt was made to optimize the strength of the new sandwich.

Figures 18, 19, and 20 show the offset-corrugated sandwich (nominal size 22.0 in × 2.7 in × 0.9 in) fabricated of graphite fabric prepreg. The material used to form the offset-corrugated core is wrapped around a set of mandrels as shown in Figure 21. The mandrels maintain the shape during attachment to the face-sheets and are removed after the curing process. For comparison purpose, a unidirectionally-corrugated sandwich (nominal size 22.0 in × 1.93 in × 0.9 in) has also been fabricated of graphite fabric prepreg (Figures 22 and 23). In both sandwiches the face-sheets have ten plies of fabric, and the corrugations are five plies thick.

The analytical and experimental values of the flexural stiffness and transverse shear modulus of the two sandwiches have been determined by utilizing the methods described in Appendices A and B. Although the nominal size of the two sandwiches per unit width is the same, they use different amounts of material to fabricate. The offset-corrugated sandwich uses a little less material compared to the unidirectionally-corrugated sandwich because in the offset-corrugated sandwich each strip of corrugation is separated by a small distance from its adjacent strip of corrugation. Therefore, all the stiffness values have been divided by the respective weight density of the sandwich. The weight density is defined as the weight of the sandwich per unit volume of space occupied by the sandwich. Table 7 shows the analytical and experimental comparison of the offset-corrugated and unidirectionally-corrugated sandwich. Reasonably close agreement between the analytical and experimental results is observed for each sandwich. The flexural stiffness is expected to remain practically the same in both constructions. The analytical value of the transverse shear modulus per unit weight density for the offset-corrugated sandwich is seen to be 96% higher than that for the unidirectionally-corrugated sandwich, but the experimental value is only 43% higher. The low value of the experimental transverse shear modulus for the offset-corrugated sandwich is probably due to the damaged corrugations developed from being pinched by the hexagonal mandrels' edges during curing process. Similar damage is not noticed in the unidirectionally-corrugated sandwich. Proper tooling will eliminate this problem.

In these demonstrations no attempt was made to optimize the new sandwich. An illustration will be very instructive in this regard. If the thickness of each of the face-sheets and corrugations of the offset-corrugated sandwich (Figure 18) is increased by 0.005 in (about one ply), the weight of the sandwich increases by 7.7%, but its transverse shear modulus increases by 14.7% (Table 8).

The improvement in the transverse shear stiffness of the offset-corrugated sandwich results from the oppositely directed deformation patterns of the face-sheets located along the two consecutive strips of corrugations. When the sandwich is subjected to shearing forces in the plane of corrugations, its deformation pattern is shown by the solid line in the plane of a strip of corrugation (Figure 24). The deformation pattern in the plane of the adjacent strip of corrugation is shown by broken line. It is seen that the deformations of the face-sheet along the two consecutive strips of corrugation are oppositely directed. This situation reduces the overall deformation of the face-sheets; thus reducing the shear deformation resulting in the increase of the shear stiffness of the sandwich.

6. CROSS-CORRUGATED SANDWICH

This sandwich concept incorporates the features of offset-corrugated sandwich in two directions along a plane. Figure 25 shows a paper model of the cross-corugated sandwich with one face-sheet removed to show the corrugations in the sandwich. The sandwich has all the advantages of either the lattice-core sandwich or offset-corrugated sandwich. Additionally, because of the presence of corrugatoins in two directions, the cross-corrugated sandwich has higher transverse shear stiffness compared to that of either lattice-core or offset-core sandwich, and is comparable to honeycomb sandwich. To illustrate the superiority of the cross-corrugated sandwich, a short analytical study is shown in Table 9. Here the transverse shear stiffnesss per unit weight density of the cross-corrugated sandwich is compared with that of unidirectionally-corrugated sandwich and honeycomb sandwich. The nominal size of the sandwich is the same in all three cases. The transverse shear stiffness per unit weight density of the cross-corrugated sandwich is 173% and 16.5% higher than that of the unidirectionally-corrugated sandwich and honeycomb sandwich, respectively. In this comparison no attempt is made to optimize any sandwich.

A concept of fabricating the cross-corrugated sandwich with prepregs of fiber-reinforced composites is described. The strips of corrugations made from prepregs are placed around the mandrels (or molds) to form the cross-corrugations (Figure 26). After arranging the strips of corrugations as shown in Figure 26, two face-sheets are placed above and below the corrugations (not shown in the figure), and the entire assembly is then cured in an autoclave. Each mandrel (or mold) has one face octagonal (Figure 26), the opposite face quadrilateral, and the side surfaces alternately triangular and quadrilateral (Figure 27c). The mandrels (or molds) are cut into small pieces (Figure 27b) to facilitate their removal after curing the sandwich in the autoclave.

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7. CONCLUSIONS

(1) The lattice-core, offset-corrugated, and cross-corrugated sandwich can be fabricated of fiber-reinforced composite materials in single cure operation without any secondary bonding.

(2) The new designs provide passageways from cell to cell for moisture drainage to reduce corrosion.

(3) The damage tolerance is expected to improve due to the presence of flexibility and discontinuity in the lattice core.

(4) The presence of passageways and curing without any secondary bonding will eliminate or reduce the tendency of unbonding of face-sheets from the core due to formation of steam during the repair process.

(5) The predicted flexural and transverse shear stiffnesses of lattice-core, and cross-corrugated sandwich panels are comparable to that of honeycomb sandwich panels.

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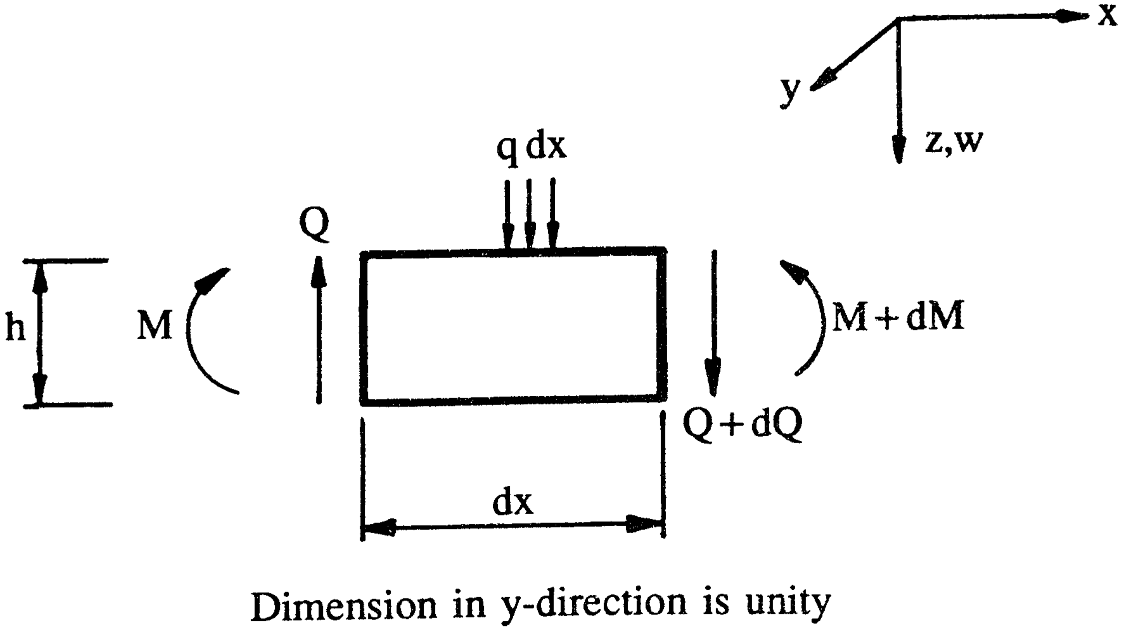


Figure 1. Forces acting on differential element *dx*.

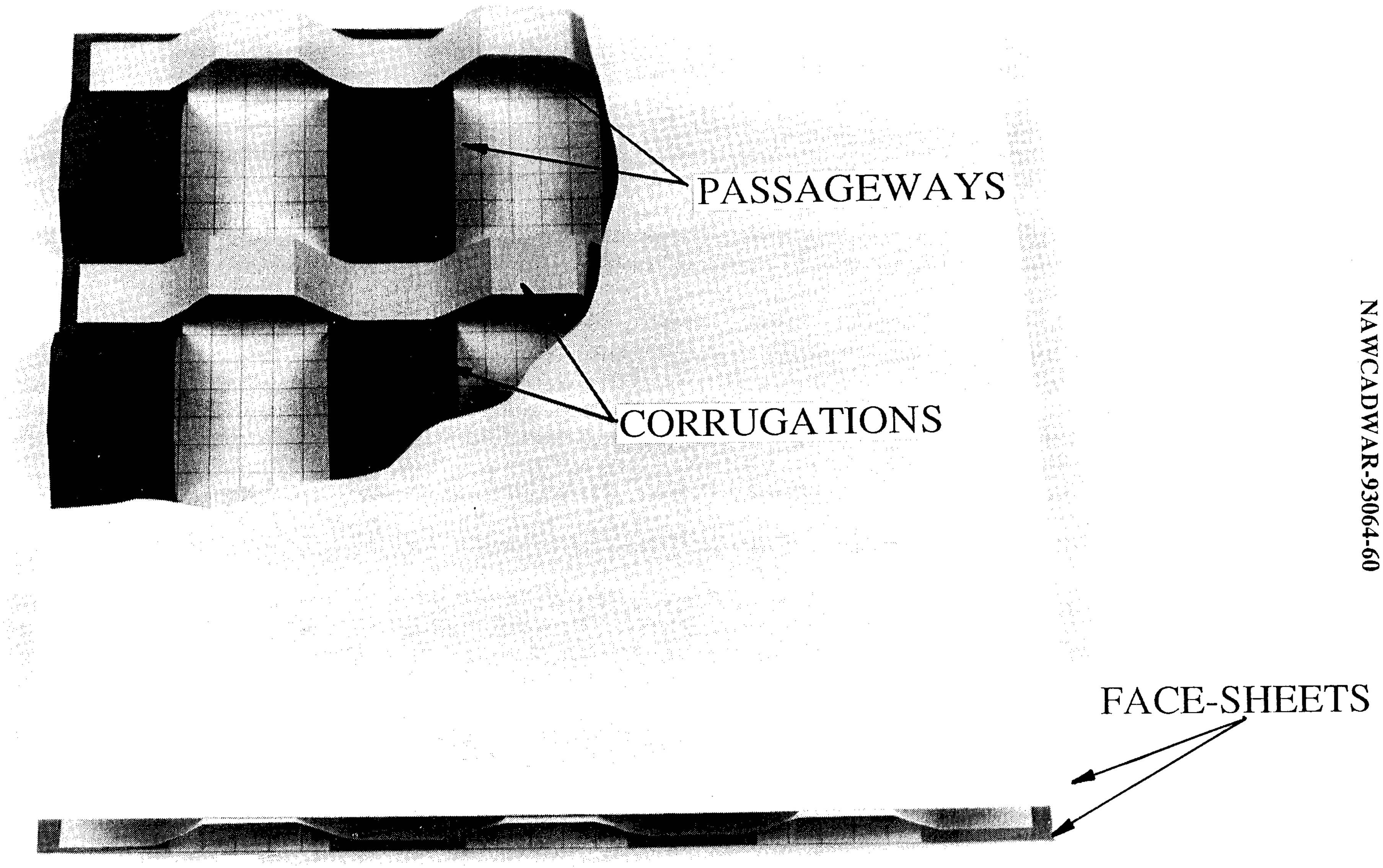


Figure 2. Bidirectionally-corrugated Sandwich (one face-sheet partially removed). [The 7.5 in × 7.5 in × 0.5 in model is made of papers.]

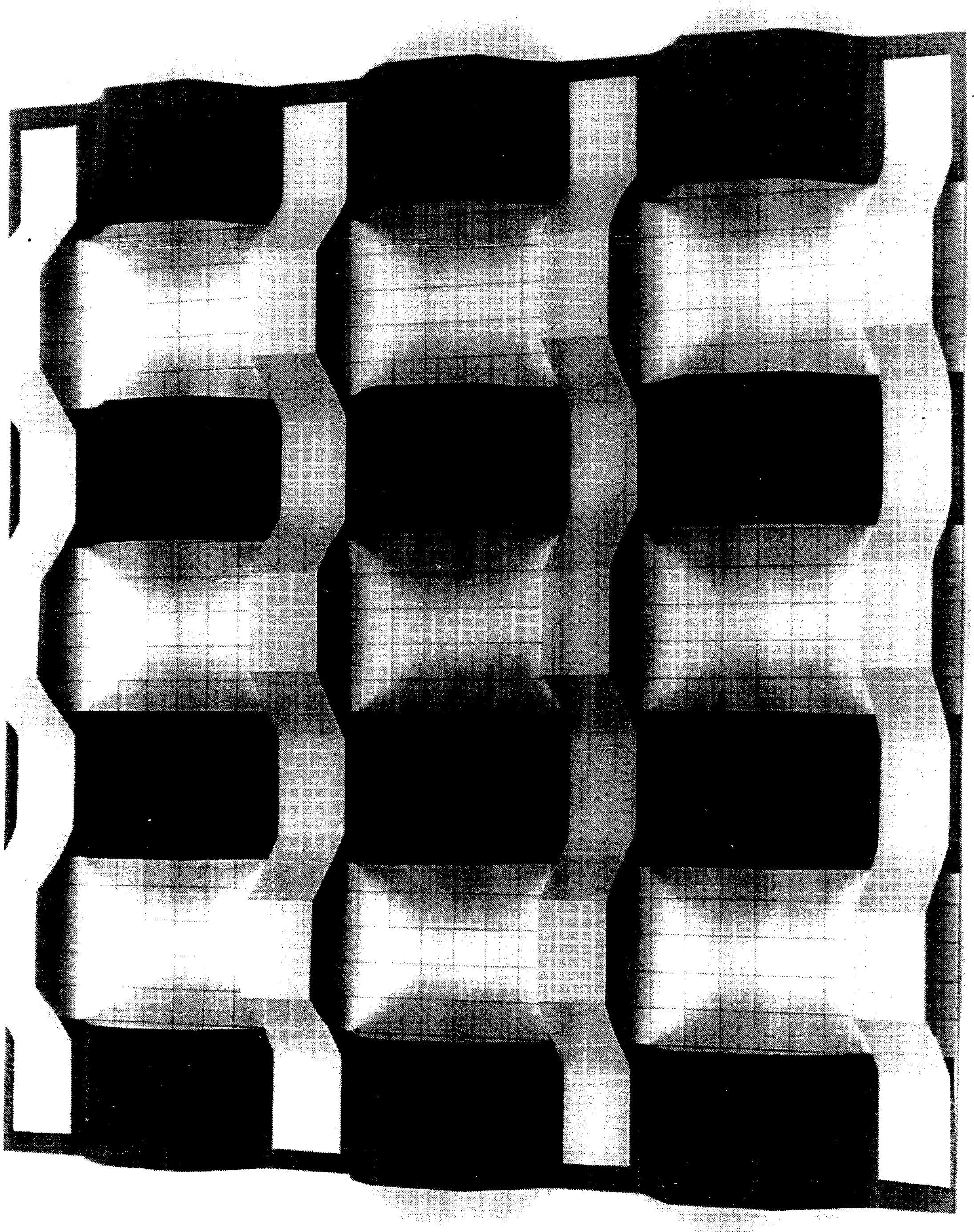


Figure 3. Bidirectionally-corrugated Sandwich (one face-sheet removed). [The 7.5 in × 7.5 in × 0.5 in model is made of papers.]

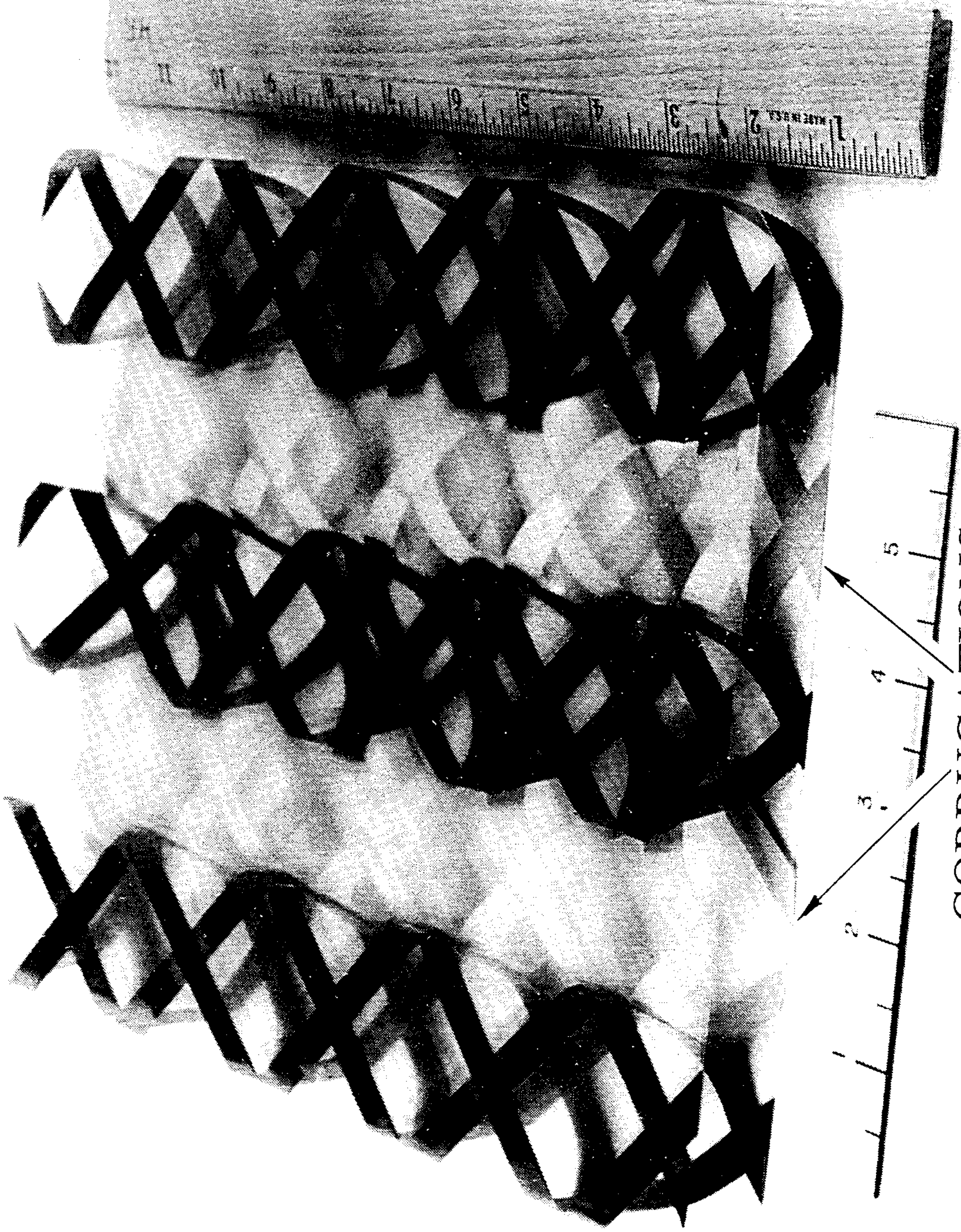


Figure 4. Lattice-core sandwich. [The 10.0 in × 8.0 in × 0.75 in model is made of plastic sheets and tapes.]

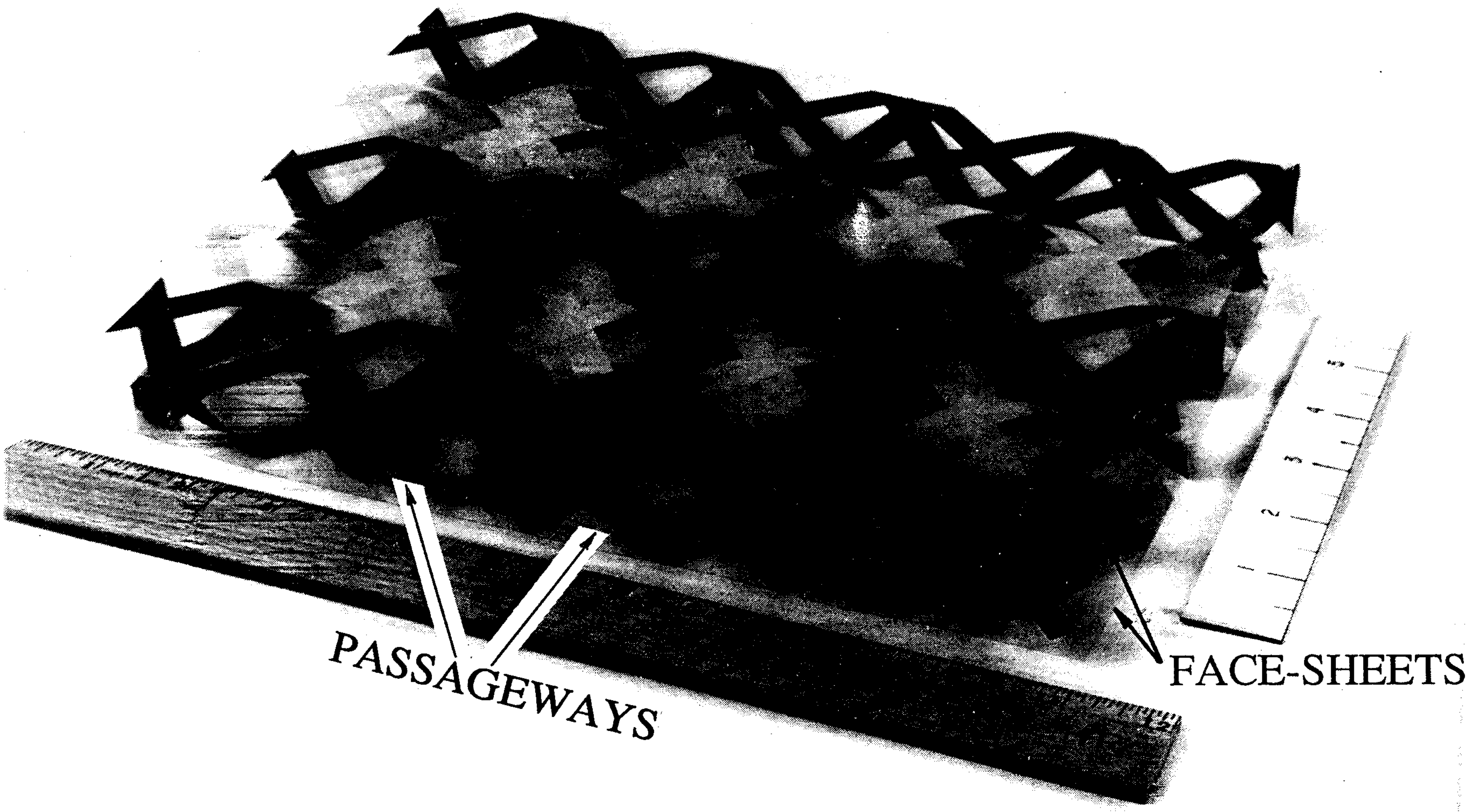


Figure 5. Lattice-core sandwich. [The 10.0 in × 8.0 in × 0.75 in model is made of plastic sheets and tapes.]

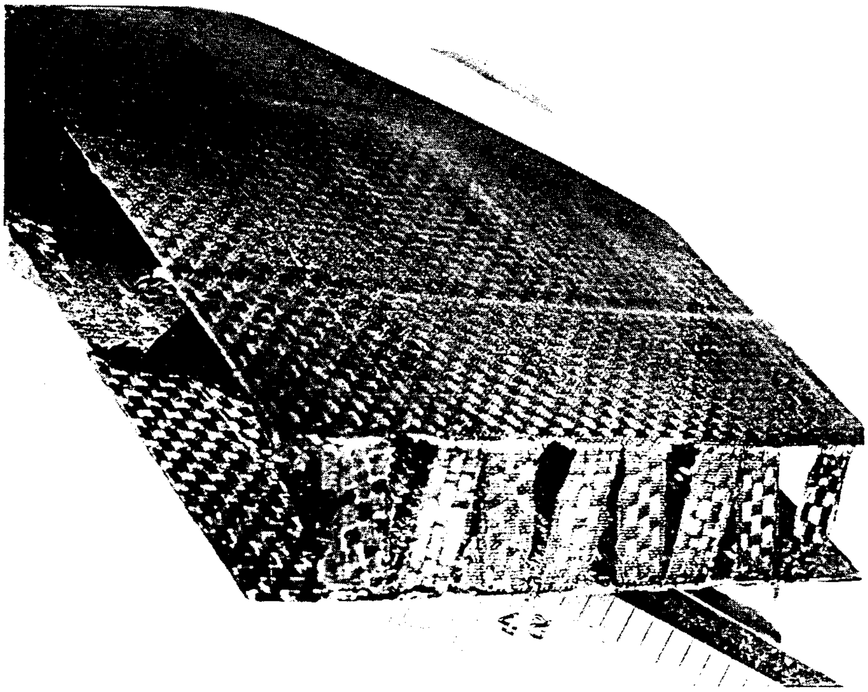


Figure 6. Lattice-core sandwich. [The 4.5 in × 4.5 in × 0.75 in model is made of one-ply graphite fabric prepreg.]

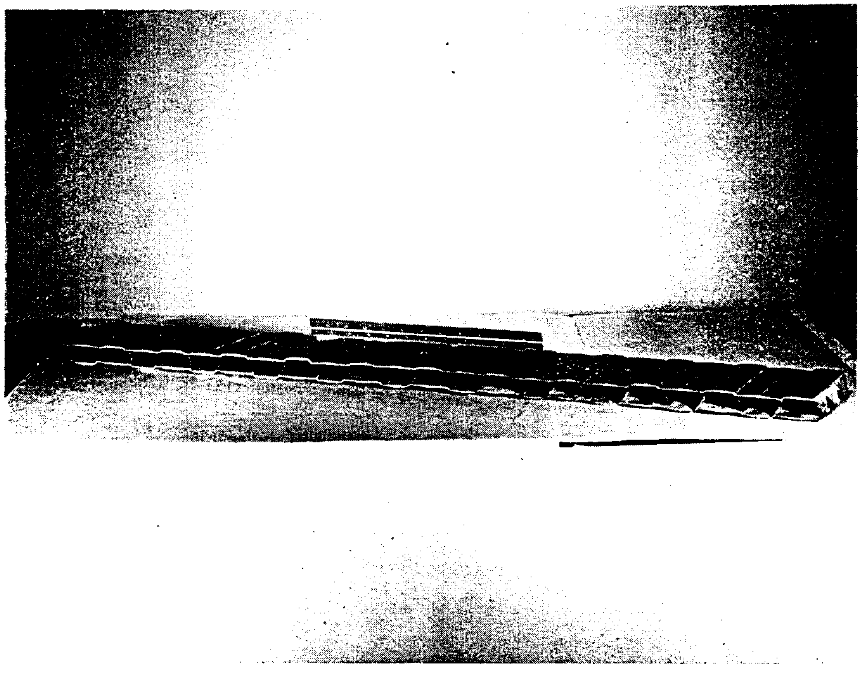


Figure 7. Lattice-core sandwich fabricated of graphite fabric prepreg (complete view).

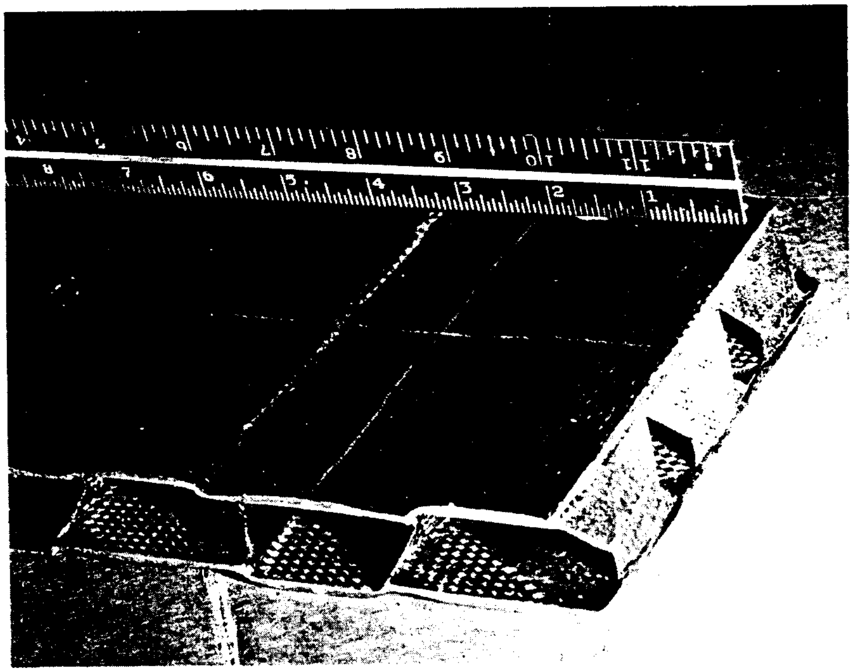


Figure 8. Lattice-core sandwich fabricated of graphite fabric prepreg (view showing a side and the front).

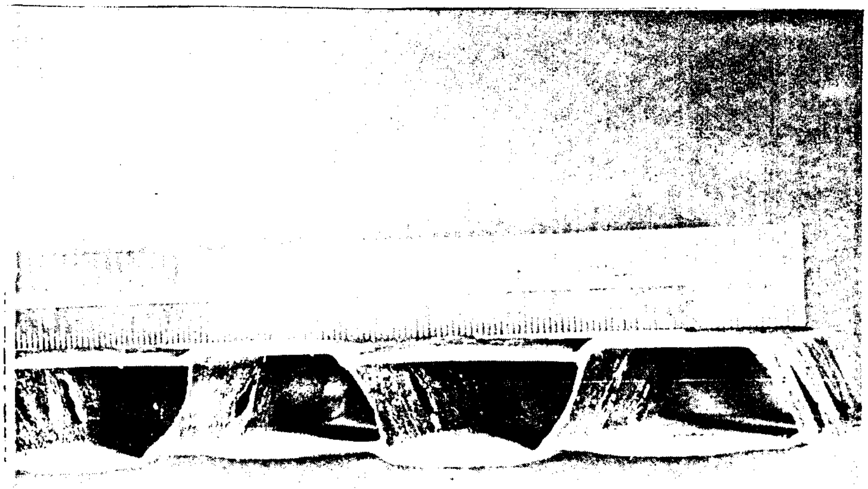


Figure 9. Lattice-core sandwich fabricated of graphite fabric prepreg (view showing the front).

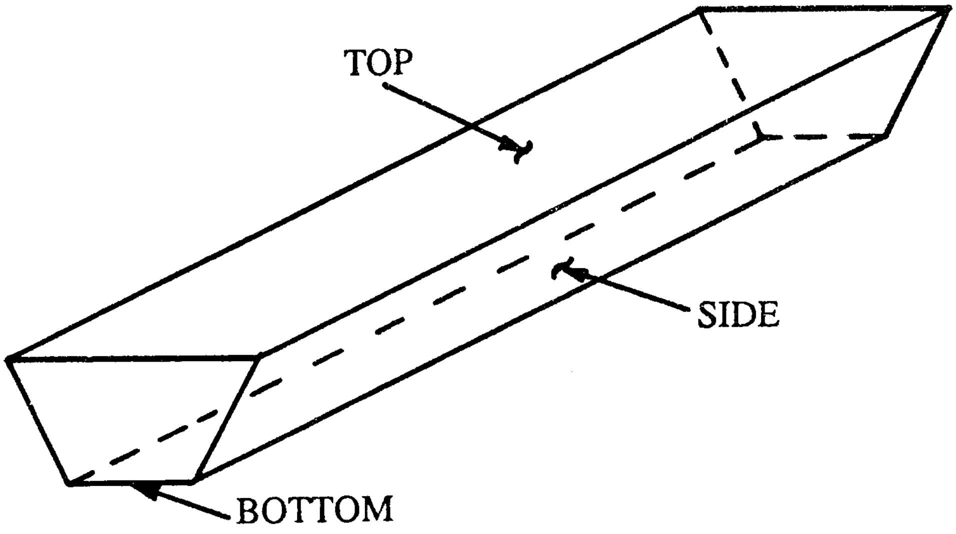


Figure 10. Diagram of a representative mandrel with trapezoidal cross-section.

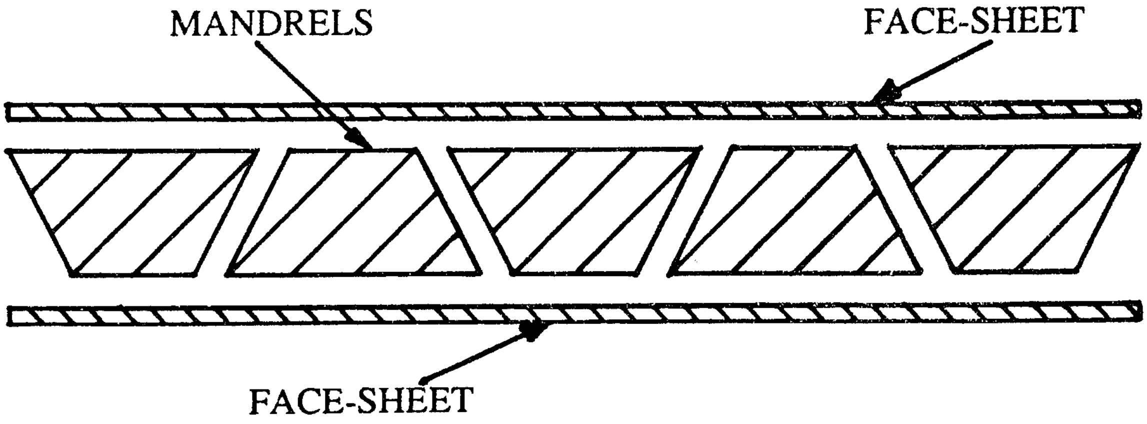
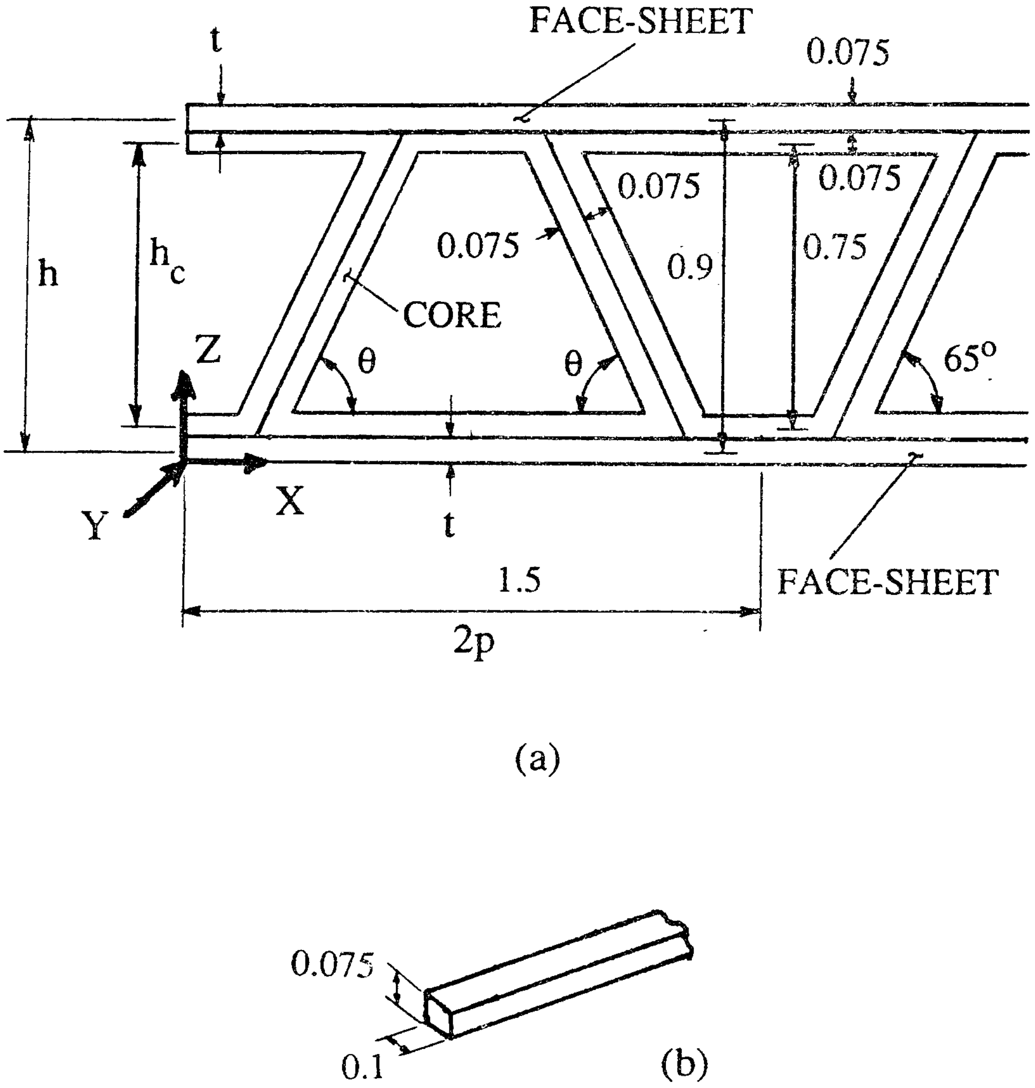


Figure 11. Arrangement of mandrels and face-sheets for fabricating a lattice-core sandwich. [Materials to be wrapped around the mandrels are not shown.]



(All dimensions in inches)

Figure 12. (a) Cross section of the lattice-core sandwich in $x-z$ plane.
(b) A strip of core material.

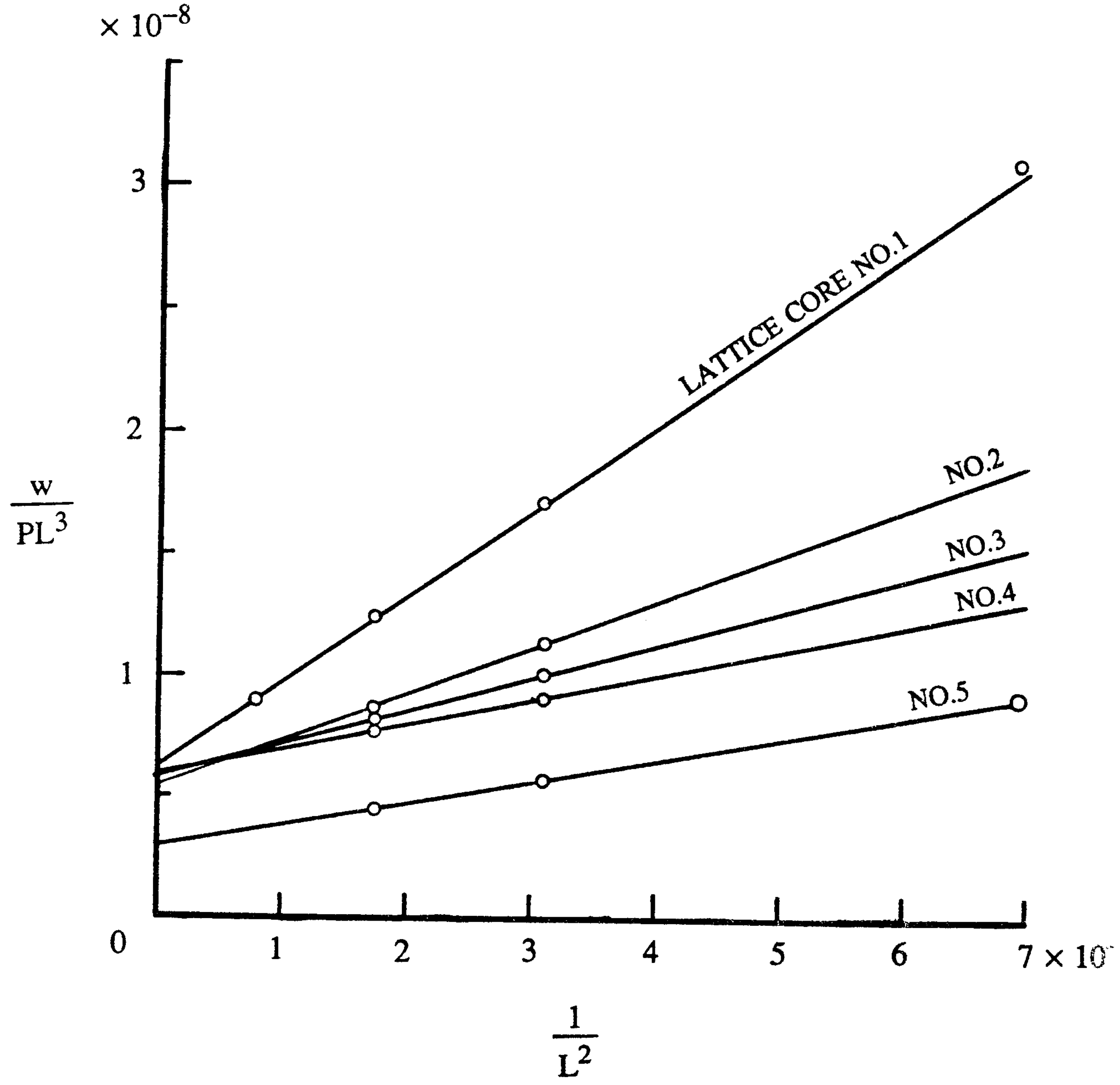


Figure 13. Plots of $w/(PL^3)$ versus $1/L^2$ for the lattice core sandwich (Table 1) subject to three-point loading.

Figure 14. Voids in lattice-core sandwich of figure 7, 50X.

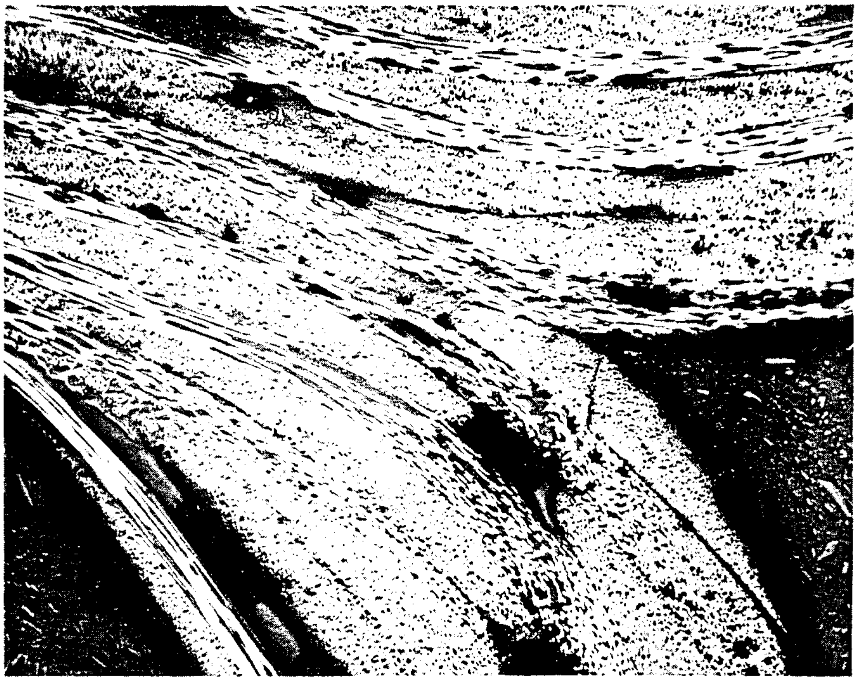


Figure 15. Voids in unidirectionally-core sandwich of figure 23, 50X.

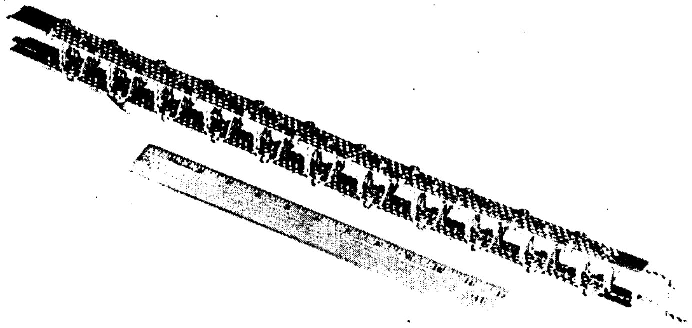


Figure 16. Complete view of the offset-corrugated sandwich made of aluminum.

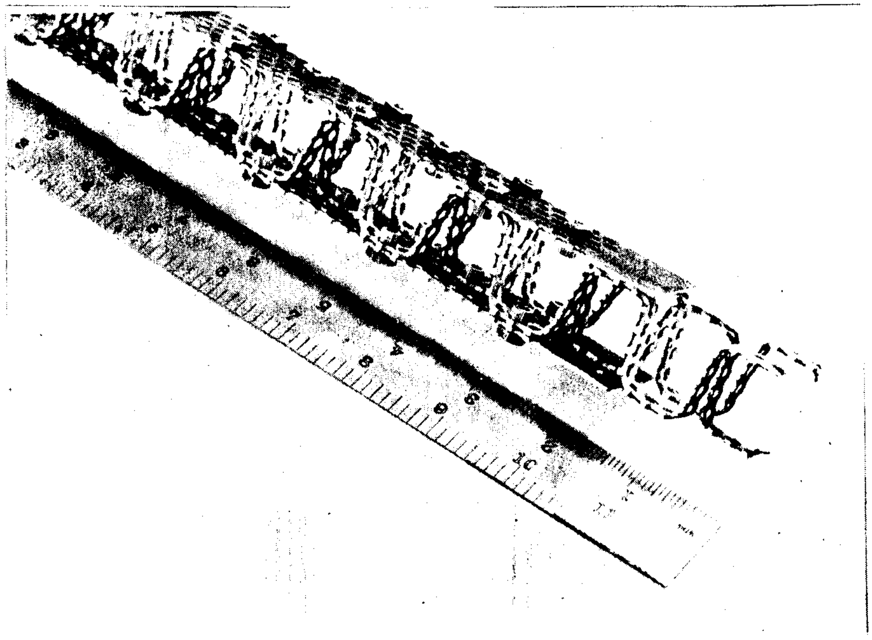


Figure 17. Partial view of the aluminum offset-corrugated sandwich with face-sheets partly removed.

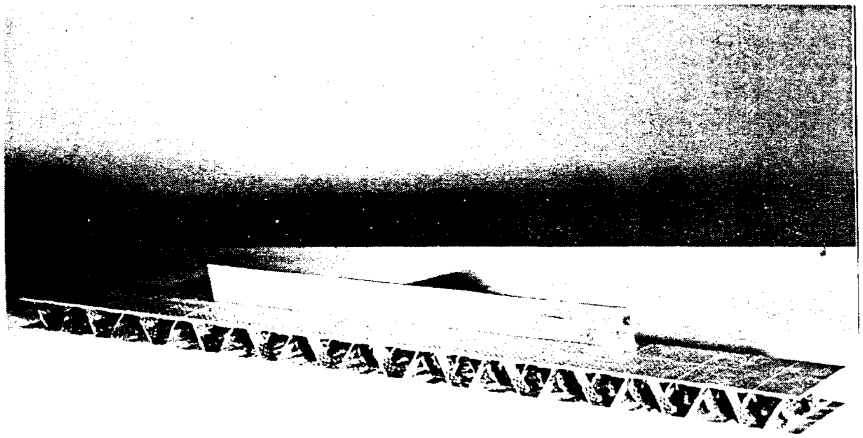


Figure 18. Complete view of the offset-corrugated sandwich fabricated of graphite fabric prepreg.

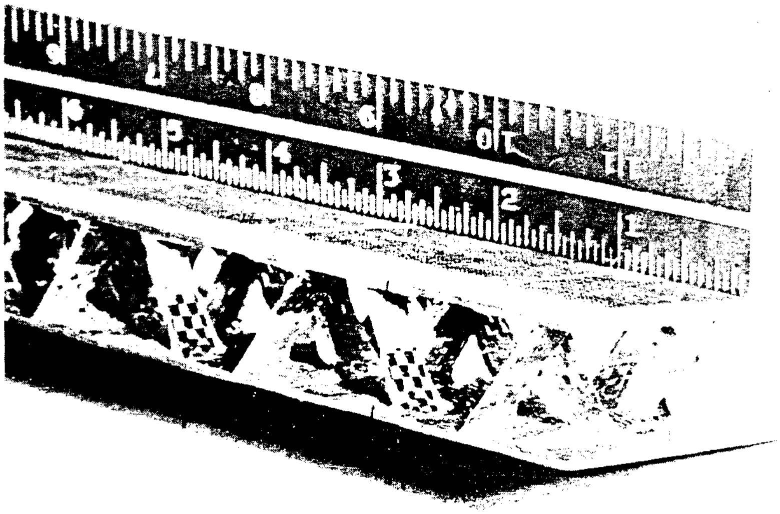


Figure 19. Partial view of the composite offset-corrugated sandwich showing a side and the front.

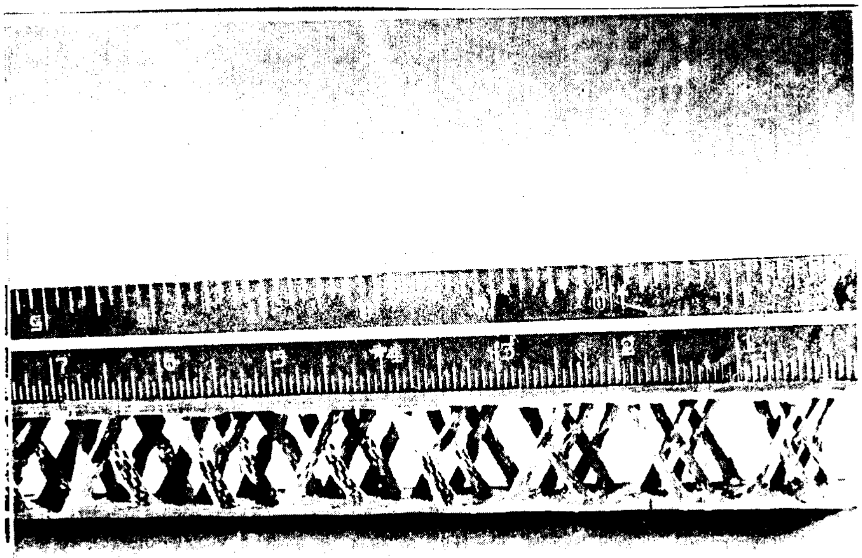


Figure 20. Partial view of the composite offset-corrugated sandwich showing front.

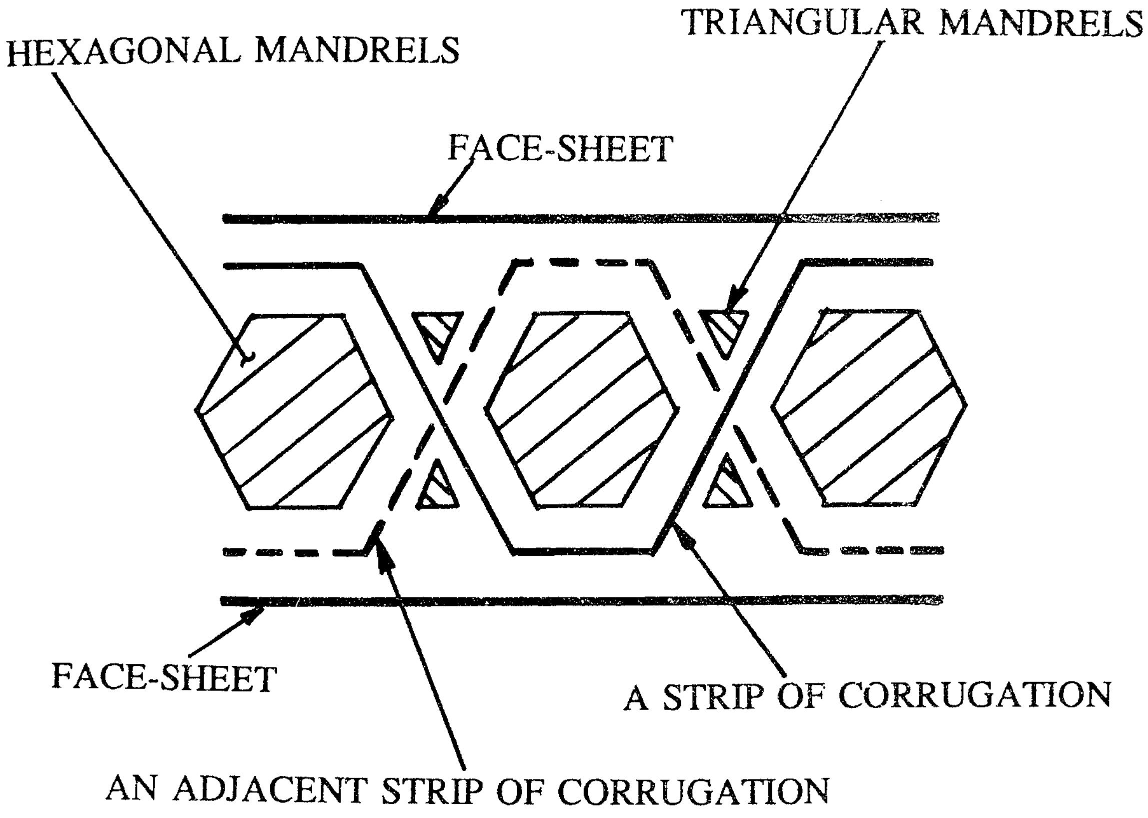


Figure 21. Arrangement showing mandrels, corrugations, and face-sheets for the offset-corrugated sandwich.

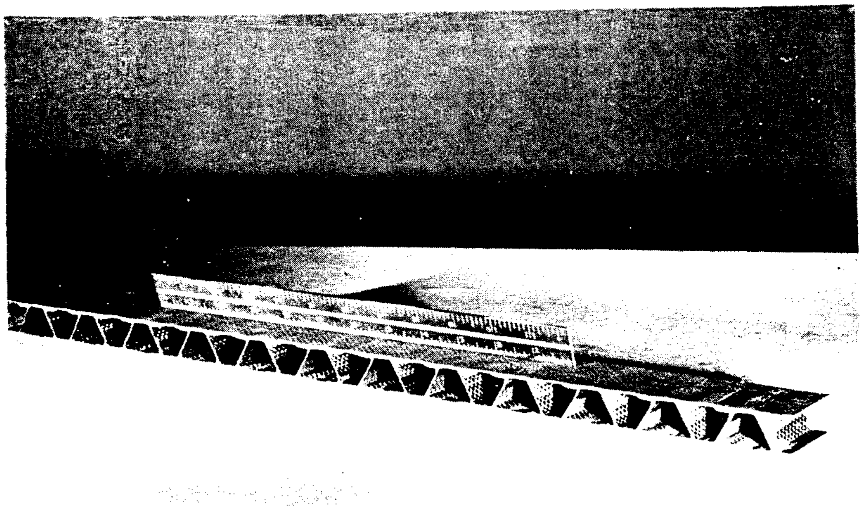


Figure 22. Complete view of the unidirectionally-corrugated sandwich fabricated of graphite fabric prepreg.

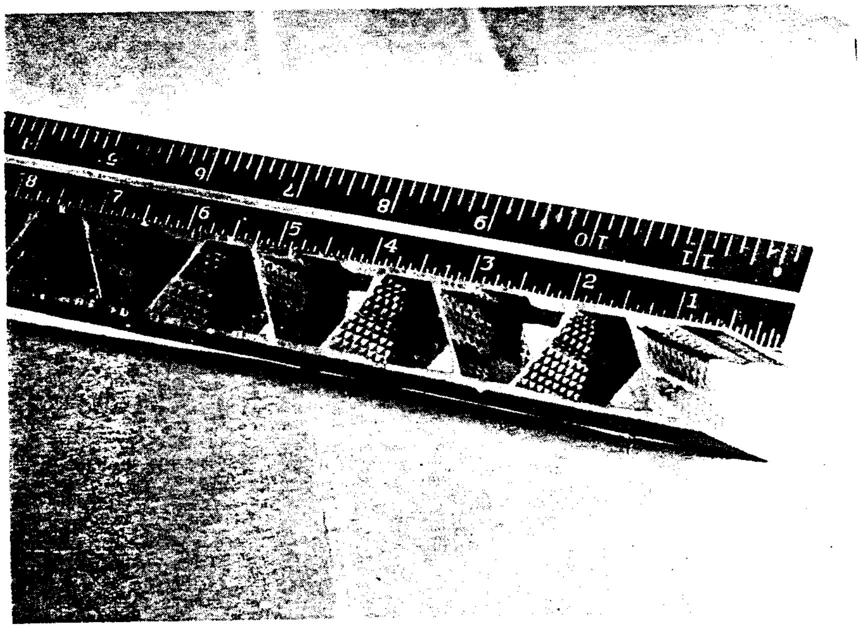


Figure 23. Partial view of the unidirectionally-corrugated sandwich fabricated of graphite fabric prepreg.

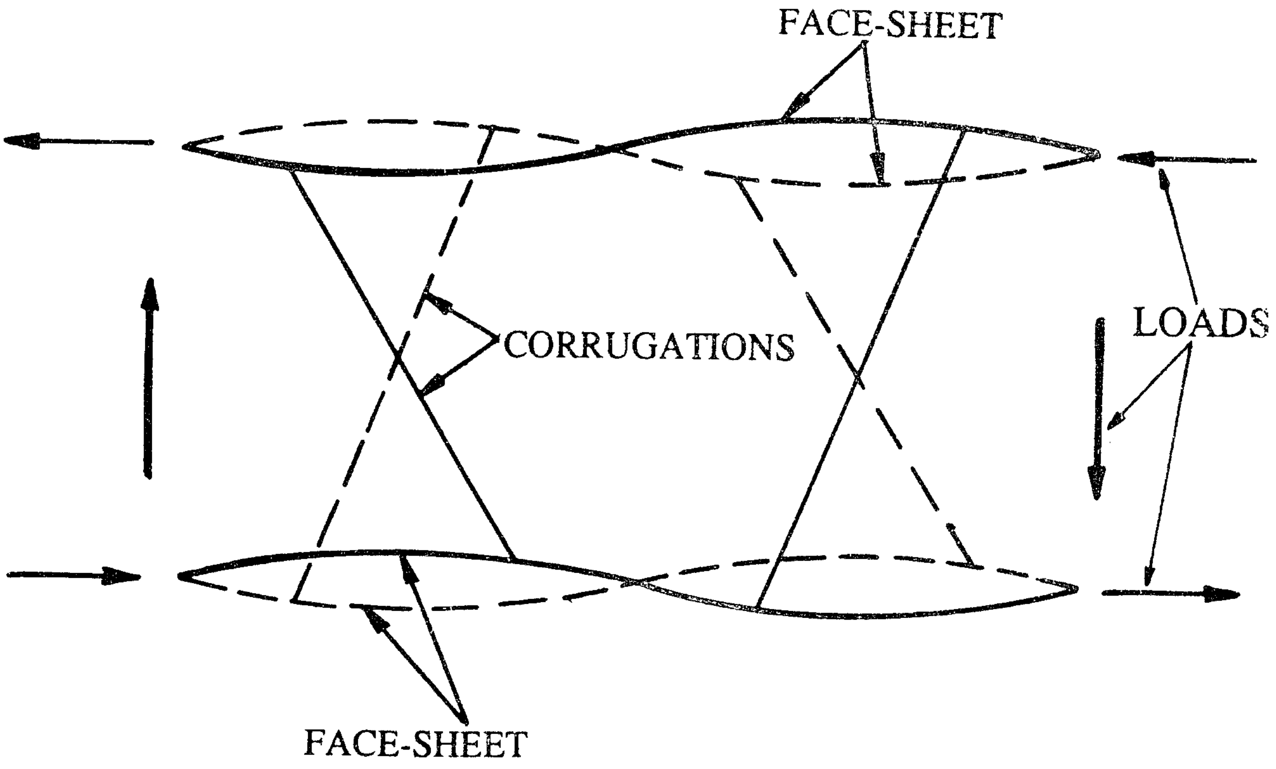


Figure 24. The deformation pattern of a unit cell of the offset-corrugated sandwich. [Two consecutive corrugations are shown.]

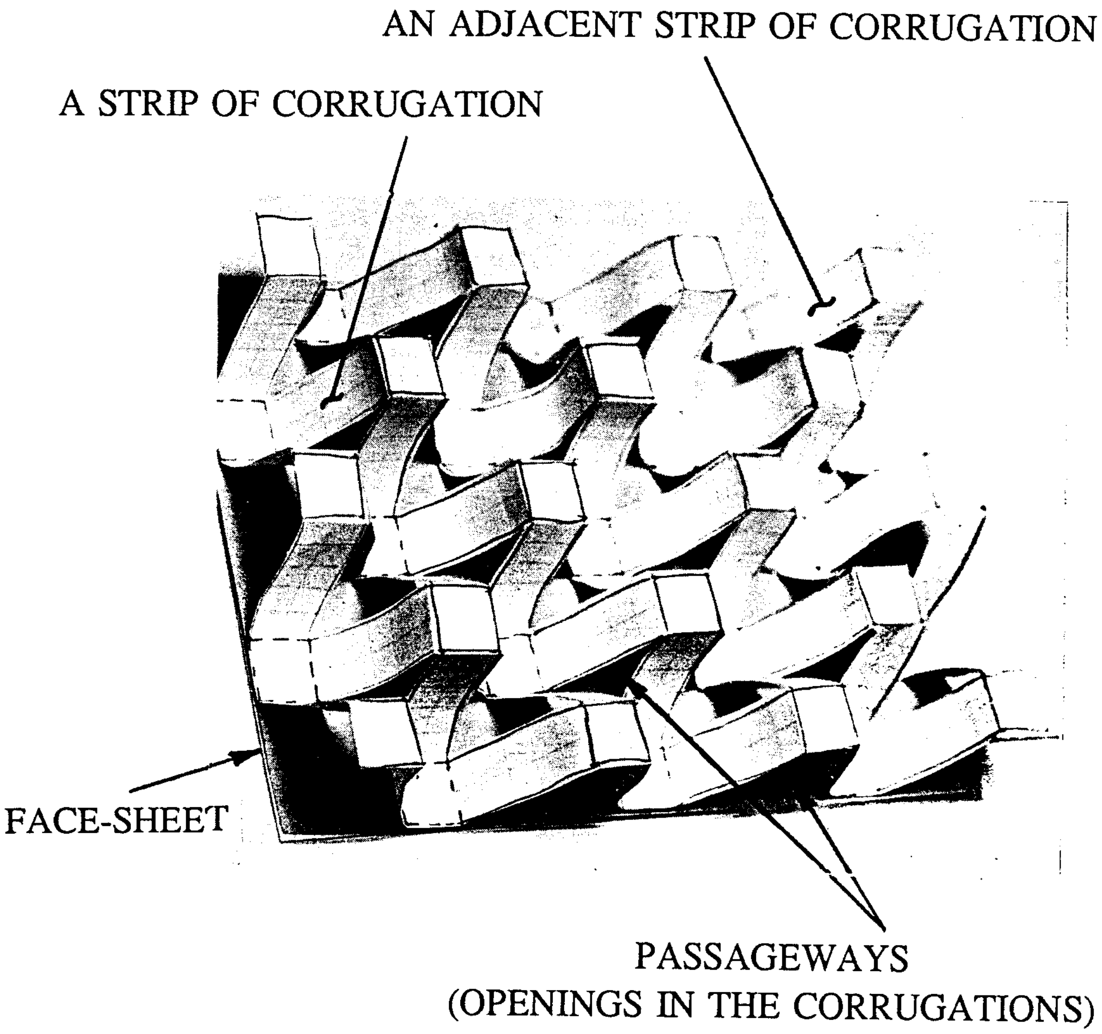


Figure 25. A paper model of the cross-corrugated sandwich with one face-sheet removed.

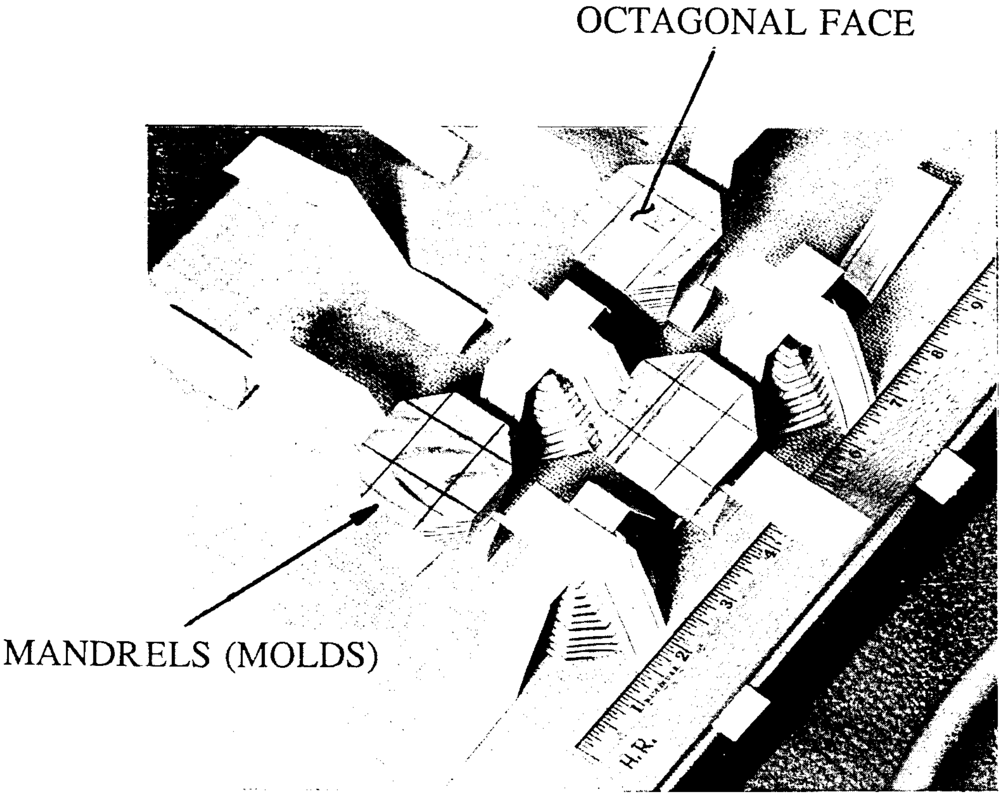


Figure 26. The strips of corrugations are placed around the mandrels (or molds) to form the cross-corrugations.

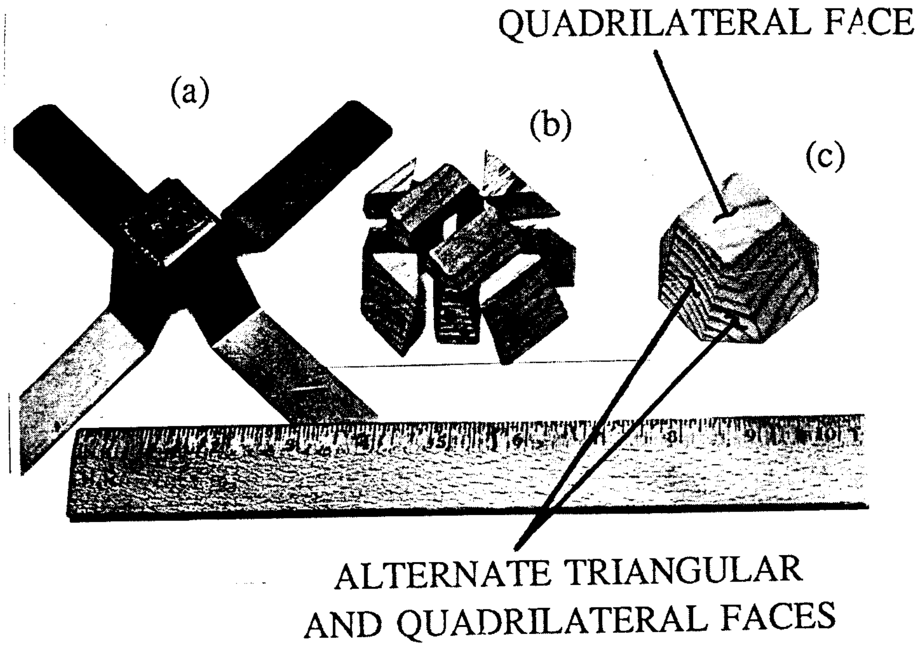
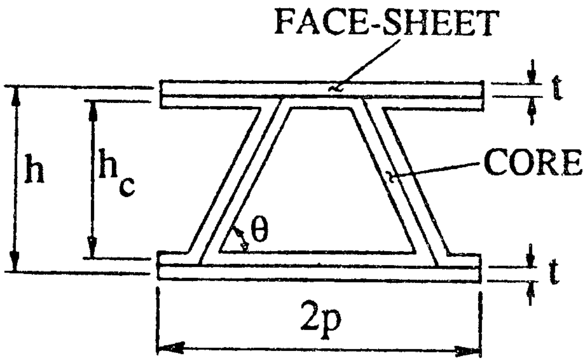


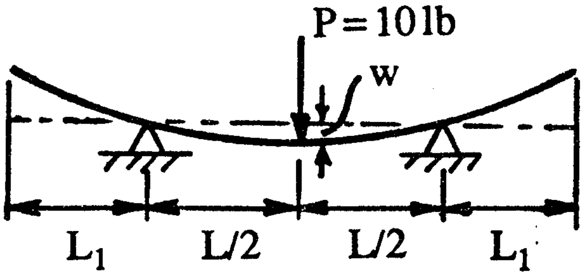
Figure 27. (a) A unit cell of the cross-corrugations. (b) The cut-pieces of a mandrel (or mold). (c) A mandrel (or mold) before it is cut to pieces.

Table 1. Dimensions of the lattice-core sandwich and their weight densities.



Sandwich No.	h (in)	2p (in)	θ (deg)	t (in)	Cross section of core material. (in × in)	Weight of sandwich per unit volume occupied. (lb / ft^3)
1	0.9	1.5	65	0.075	0.10 × 0.075	34
2	0.9	1.5	65	0.075	0.20 × 0.075	41
3	0.9	1.5	65	0.075	0.25 × 0.075	44
4	0.9	1.5	65	0.075	0.30 × 0.075	48
5	0.9	1.5	65	0.150	0.15 × 0.15	69

Table 2. The deflections at midspan for the sandwich listed in table 1 subject to three-point loading.

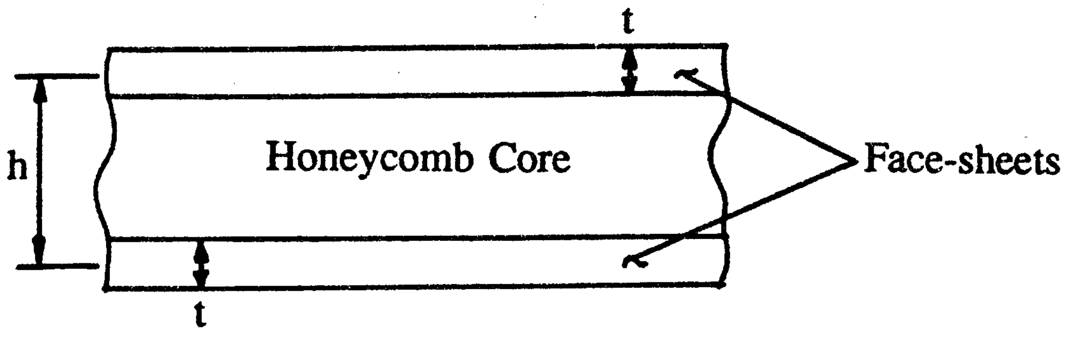


Sandwich Number	Span L (in)	Overhang L_1 (in)	Deflection w (in)	$\frac{w}{PL^3}$ ($lb^{-1} \cdot in^{-2}$)	$\frac{1}{L^2}$ (in^{-2})
1	36	0	4.20×10^{-3}	0.90×10^{-8}	0.77×10^{-3}
	24	6	1.70×10^{-3}	1.23×10^{-8}	1.74×10^{-3}
	18	9	1.00×10^{-3}	1.70×10^{-8}	3.09×10^{-3}
	12	12	5.00×10^{-4}	3.10×10^{-8}	6.94×10^{-3}
2	24	6	1.24×10^{-3}	0.89×10^{-8}	1.74×10^{-3}
	18	9	6.65×10^{-4}	1.14×10^{-8}	3.09×10^{-3}
3	24	6	1.13×10^{-3}	0.82×10^{-8}	1.74×10^{-3}
	18	9	5.91×10^{-4}	1.01×10^{-8}	3.09×10^{-3}
4	24	6	1.06×10^{-3}	0.77×10^{-8}	1.74×10^{-3}
	18	9	5.39×10^{-4}	0.92×10^{-8}	3.09×10^{-3}
5	24	6	6.26×10^{-4}	0.45×10^{-8}	1.74×10^{-3}
	18	9	3.33×10^{-4}	0.57×10^{-8}	3.09×10^{-3}
	12	12	1.55×10^{-4}	0.90×10^{-8}	6.94×10^{-3}

Table 3. Analytical comparison of flexural stiffness and transverse shear modulus in sandwich with lattice-core and honeycomb core.

Quantity	Lattice -Core No.1	Honey-comb Core No.1	Lattice -Core No.2	Honey-comb Core No.2	Lattice -Core No.3	Honey-comb Core No.3
Weight of sandwich per unit volume occupied, (lb/ft^3).	34	39	41	47	44	45
Flexural stiffness, D, (lb·in).	470,858	470,858	566,773	566,773	527,685	527,685
Transverse shear modulus, G, (lb/in^2).	12,155	11,000	21,004	21,200	29,756	30,000
Weight density of honeycomb core, (lb/ft^3).	-	1.6	-	3.0	-	4.4

Table 4. Dimensions of the honeycomb sandwich and their weight densities.



Sandwich Number	h (in)	t (in)	Core density (lb/ft^3)	Transverse Shear modulus perpendicular to ribbon dir., G, (lb/in^2)	Weight of sandwich per unit volume occupied. (lb/ft^3)
1	0.9	0.111	1.6	11,000	39
2	0.9	0.133	3.0	21,200	47
3	0.9	0.124	4.4	30,000	45

Table 5. Comparison of analytical and experimental results of the lattice-core sandwich.

Quantity	Analytical	Experimental
Flexural stiffness, D, (lb·in).	278,689	73,179
Transverse shear modulus, G, (lb/in^2).	1,371	1,179

Table 6. Comparison of experimental results of offset-corrugated and unidirectionally-corrugated sandwich made of annealed aluminum.

Quantity	Offset-Corrugated	Unidirectionally-Corrugated
Flexural stiffness, D, (lb·in).	56,306	67,204
Transverse shear modulus, G, (lb/in^2).	1,468	941

Table 7. Comparison of offset-corrugated and unidirectionally-corrugated sandwich made of graphite fabric prepreg.

Quantity	Offset-Corrugated		Unidirectionally-Corrugated	
	Analytical	Experimental	Analytical	Experimental
Flexural stiffness per unit weight density, D/ρ, $\frac{\text{lb·in}}{\text{lb/ft}^3}$.	12,043	11,488	10,717	12,159
Transverse shear modulus per unit weight density, G/ρ, $\frac{\text{lb/in}^2}{\text{lb/ft}^3}$.	645	472	329	330

Table 8. Analytical study of thickness change on transverse shear modulus for the offset-corrugated sandwich.

Quantity	Weight density, ρ, lb/ft^3	
	18.2	19.6
Transverse shear modulus per unit weight density, G/ρ, $\frac{\text{lb/in}^2}{\text{lb/ft}^3}$.	645	740

Table 9. Analytical comparison of transverse shear modulus of the cross-corrugated, unidirectionally-corrugated, and honeycomb sandwich.

Quantity	Cross-corrugated	Unidirectionally-corrugated	Honeycomb
Transverse shear modulus per unit weight density, G/ρ, $\frac{\text{lb/in}^2}{\text{lb/ft}^3}$.	1,600	586	1,373

APPENDIX A

EXPERIMENTAL METHOD OF DETERMINING FLEXURAL AND TRANSVERSE SHEAR STIFFNESSES.

The deflection w at the center of a simply supported beam of span L and width b subjected to a concentrated load P at midspan is

$$w = \frac{PL^3}{48bD} + \frac{PL}{4bD_Q}, \tag{A1}$$

where D is the flexural stiffness, and D_Q is the transverse shear stiffness per unit width b of the beam. The first term is the deflection due to bending and the second term is the contribution due to shear by using simple beam theory.

The Eq.(A1) can be expressed in the following forms

$$\frac{w}{PL} = \frac{L^2}{48bD} + \frac{1}{4bD_Q}, \tag{A2}$$

$$\frac{w}{PL^3} = \frac{1}{48bD} + \frac{1}{4bD_Q}\frac{1}{L^2}. \tag{A3}$$

Equation (A2) can be represented by a straight line in a plot of w/PL versus L^2 (solid line in Figure A1), while the Equation (A3) can be represented by a straight line in a plot of w/PL^3 versus $1/L^2$ (solid line in Figure A2). If the deflection w is known for a number of different spans, the straight lines in Figures A1 and A2 may be plotted and the flexural stiffness D and shear stiffness D_Q can be obtained from the slopes of the lines and intercepts of the lines with the vertical axes.

This method provides good results except for sandwiches with thick face-sheets and cores with low shear stiffness [8, 9]. In those cases the plotted results follow the curves indicated by broken lines in Figure A1. Test results confirm the predictions of the more rigorous theory by Allen [8, 9]. The elementary beam theory is adequate provided that the ratio of beam span to core depth exceeds a certain limiting value.

The flexural stiffness D of a sandwich beam can also be obtained from four-point loading illustrated in Figure A3. The region BF of the beam is subjected to a uniform bending moment Pd. As a result the region BF bends in an arc of a circle of radius R and curvature $1/R = (Pd)/D$. If the deflection w of the point M is measured with respect to the line CE, it can be shown that for small deflections,

$$D = \frac{Pdc^2}{2bw}. \tag{A4}$$

Rigorous analysis [9] shows that this method gives good results for flexural stiffness D of sandwich beams provided the cores have high transverse shear stiffness G, and the specimens have very large overhang d (Figure A3). The accuracy of the results also depends on the ratio of core shear stiffness to the local bending stiffness of the face-sheets. A practical method for simulating very large overhang in the specimen is bonding rigid inserts into the short overhanging parts, in place of the core. The methods described above can also be used to compute the flexural and transverse shear stiffnesses by finite element method.

APPENDIX B

COMPUTATIONAL METHOD OF DETERMINING FLEXURAL AND TRANSVERSE SHEAR STIFFNESSES.

The method of determining transverse shear stiffness is based on the procedure shown in reference [10]. The element of a corrugated-core sandwich, shown in Figure B1, has width b perpendicular to the page and is in equilibrium under the action of shear forces Q_1, Q_2, and horizontal forces X of magnitude $(Q_1 + Q_2)p/h$. For small values of the applied forces, the deformations of the element are proportional to the forces. The deformed shape of the element is shown in Figure B2. An average shear strain γ can be taken as

$$\gamma = \frac{\delta_x}{h} - \frac{\delta_z}{p}. \tag{B1}$$

The transverse shear stiffness D_Q is then given by the ratio of the shear force per unit width b to the shear strain [see Equation (2), Section 2],

$$D_Q = \frac{(Q_1 + Q_2)}{b\gamma}, \tag{B2}$$

and the approximate value of the transverse shear modulus G is

$$G = \frac{(Q_1 + Q_2)}{hb\gamma}. \tag{B3}$$

For certain values of the shear forces Q_1 and Q_2, such that their sum $(Q_1 + Q_2)$ (taking into account proper signs) remains fixed, the deformations δ_x and δ_z can be determined by finite element method. The values of Q_1 and Q_2 need to be determined by iterations such that the deformations δ_x and δ_z of the points B, E, F, J are obtained as shown in Figure B2. Because of symmetry it is sufficient to consider the portion ACFH of the sandwich element. Having determined the values of the deformations δ_x and δ_z, the transverse shear stiffness and modulus can be determined by utilizing Equations (B2) and (B3).

The method of determining flexural stiffness is based on the load-deflection relation of a thin, prismatic, elastic cantilever beam subject to a couple M applied at the free end. Noticing the rigorous analysis of a sandwich beam subjected to four-point loading [9], it can be concluded that the simple load-deflection relation of a cantilever beam subject to a couple M at the free end can be used to determine the flexural stiffness of a sandwich beam provided the beam is infinitely long (see Figure B3). The effect of a very large cantilever beam can be simulated by bonding a rigid insert at the free end of a short beam, in place of the core. In Figure B3 if the member AF is much stiffer than the remaining members, it will function as a rigid insert. The deflections (in z-direction) of the points such as A, B, C, F, G, H can be used to obtain the average flexural stiffness of a corrugated sandwich beam. Since the deformations near the joints such as B, D, G, I will be highly distorted, their consideration will not provide a good estimate of the flexural stiffness. A better estimate of the flexural stiffness can be obtained by considering several unit-cells of the corrugated sandwich, and using the deflections of the least distorted points such as C and H that are located far from both the fixed and free ends of the beam. In this report the values of deformations needed to obtain the required flexural and transverse shear stiffnesses have been computed by the SAP IV finite element program [11].

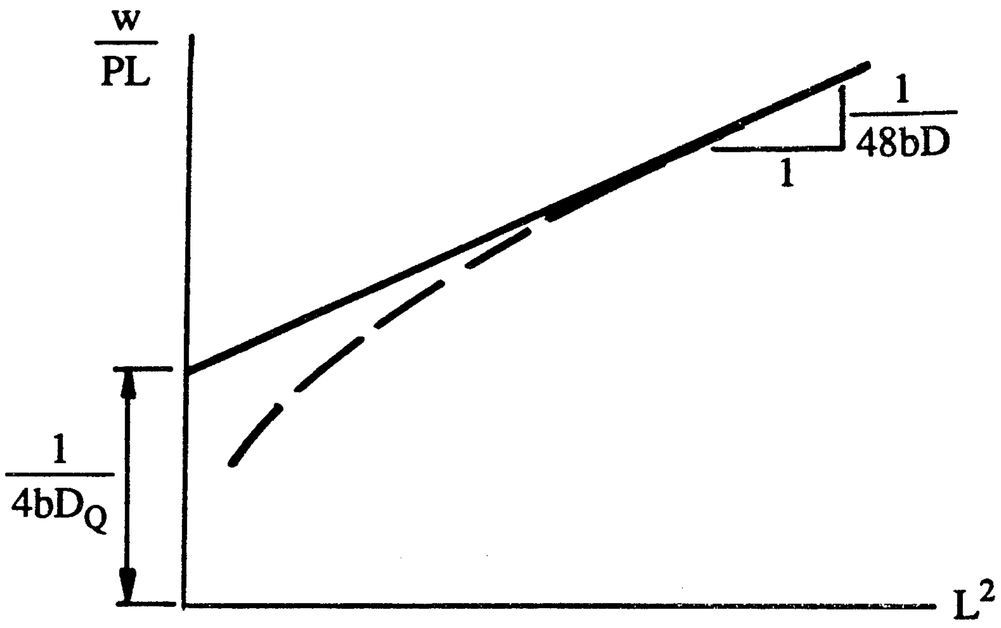


Figure A1. Plot of equation (A2).

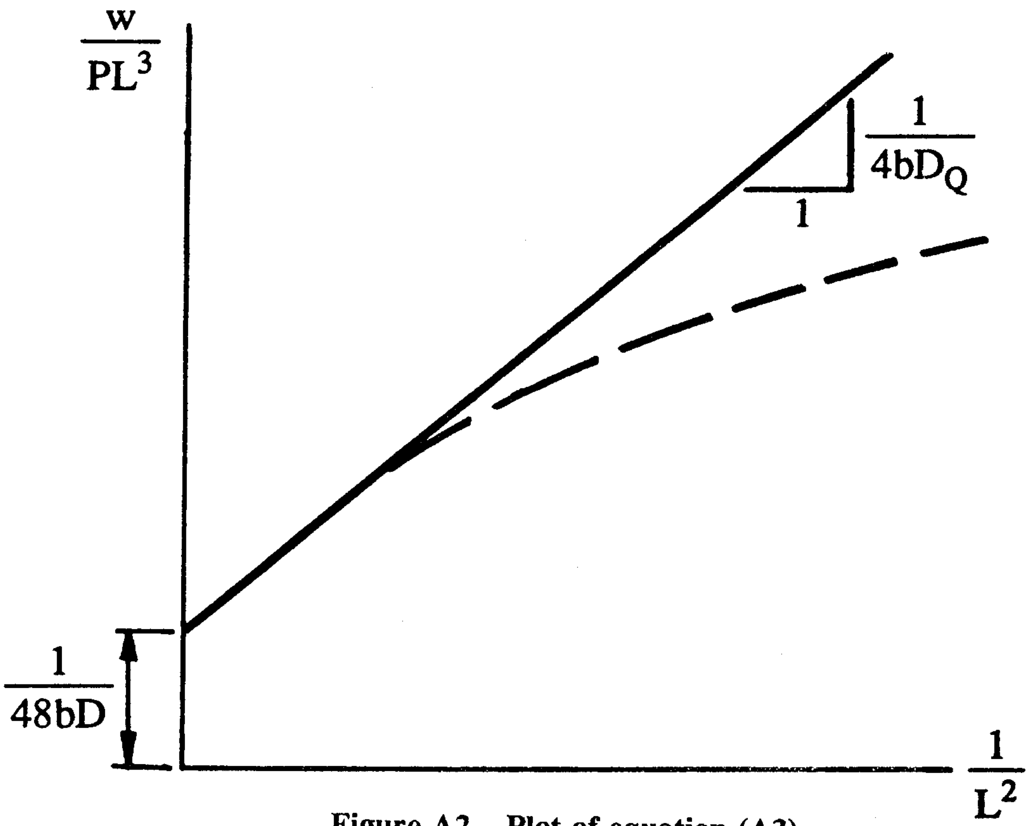


Figure A2. Plot of equation (A3).

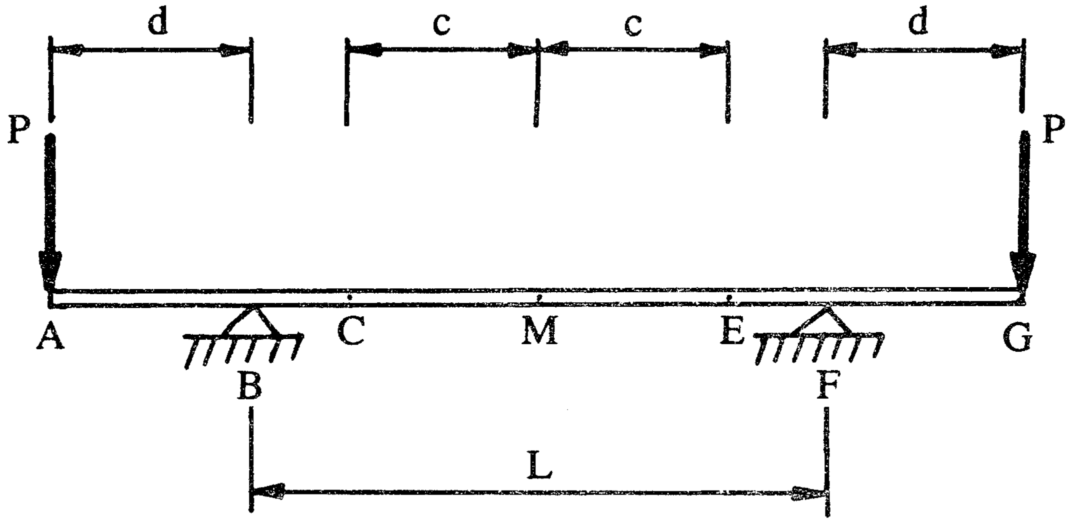


Figure A3. Four-point loading of a beam.

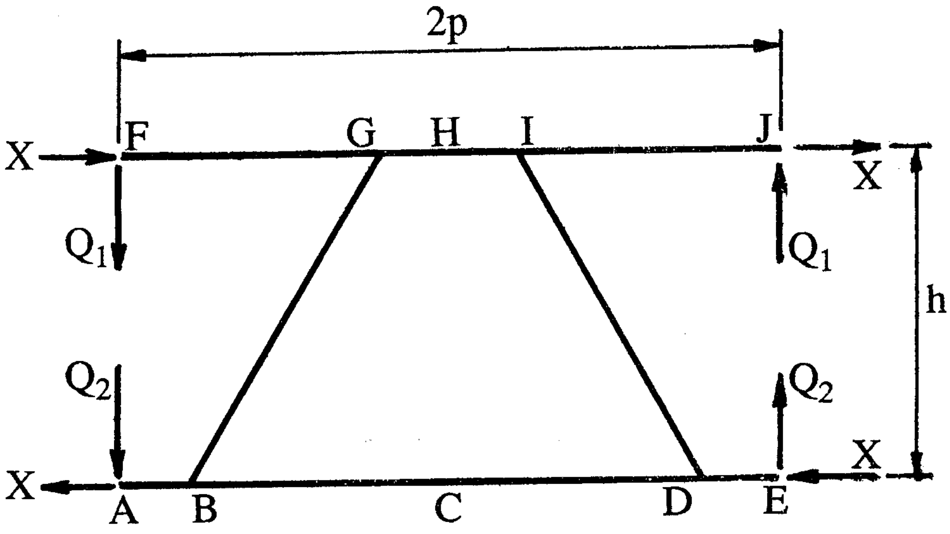


Figure B1. The element of a corrugated-core sandwich subject to shear forces.

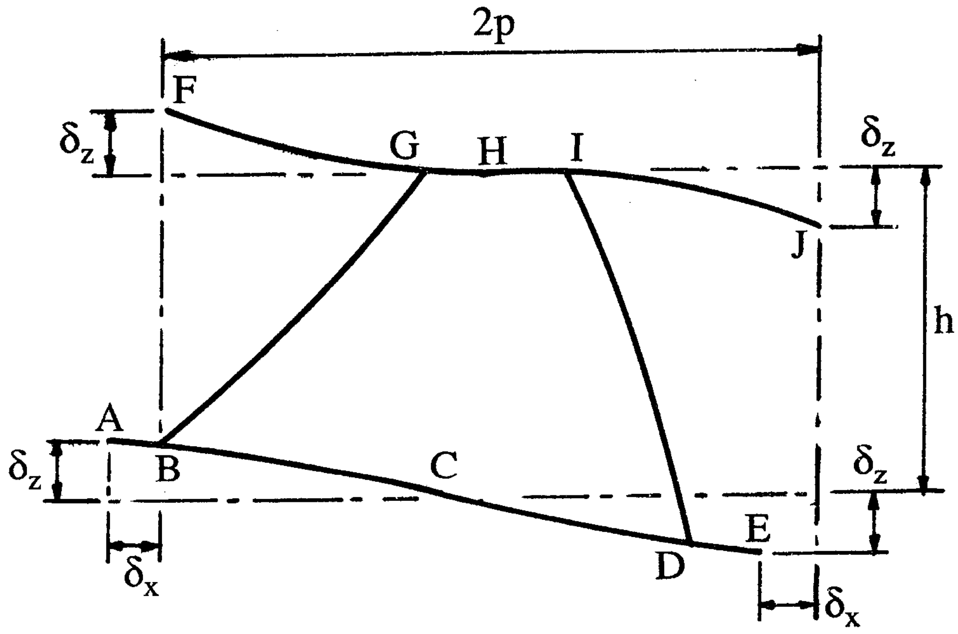


Figure B2. The deformed shape of the element of a corrugated-core sandwich subject to shear forces.

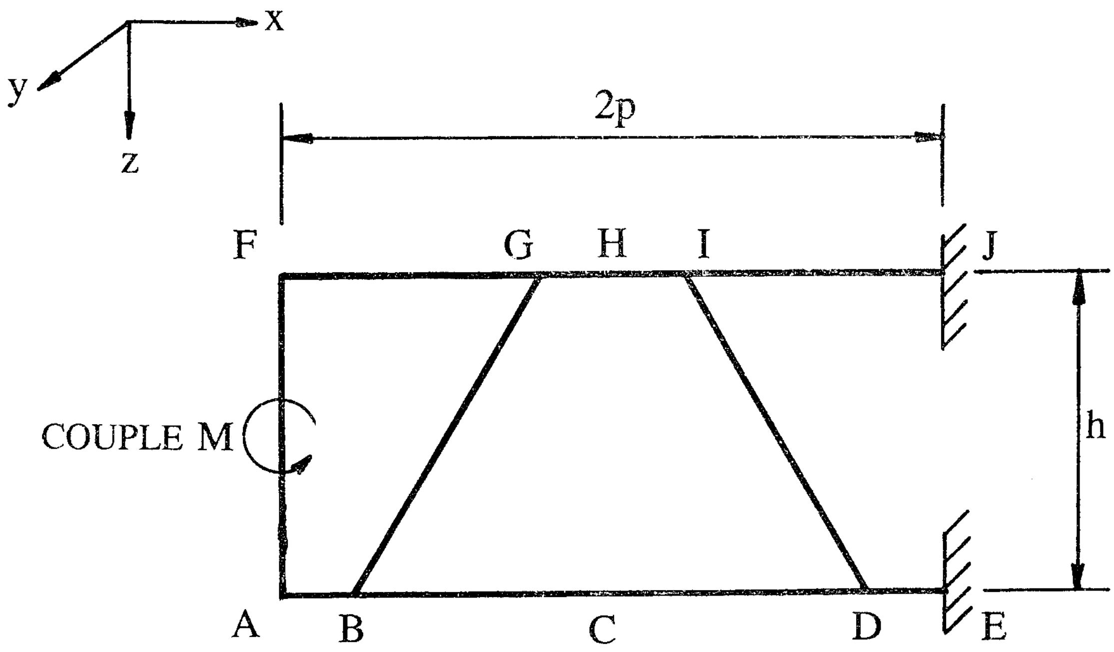


Figure B3. The element of a corrugated-core sandwich subject to a couple M.

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