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ANALYSIS/DESIGN OF STRIP REINFORCED RANDOM COMPOSITES (STRIP HYBRIDS)

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COMPOSITES (STRIP HYBRIDS)

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ABSTRACT

Results are described which were obtained by applying advanced analysis methods
and composite mechanics to a strip-reinforced random composite square panel with fixed
ends. This was done in order to illustrate the use of these methods for the apriori as-
sessment of the composite panel when subjected to complex loading conditions. The
panel was assumed to be of E-Glass/Random Composite. The strips were assumed to
be of three advanced unidirectional composites to cover a range of low, intermediate,
and high modulus stiffness. The panels were assumed to be subjected to complex loadings
to assess their adequacy as load-carrying members in auto body, aircraft engine nacelle,
and windmill blade applications. The results show that strip hybrid panels can be several
times more structurally efficient than the random composite base materials. Some of the
results are presented in graphical form and procedures are described for use of these
graphs as guides for preliminary design of strip hybrids.

INTRODUCTION

The need for making composite panels which are both structurally effective and cost-
effective has been highlighted in special sessions at four recent conferences. Desirable
material attributes identified in these sessions are low material cost, adaptability to mass
production and sufficient stiffness to minimize the problems associated with local insta-
bilities (buckling), vibratory stresses, and concentrated load deflections. Panels made
from such materials are suitable in relatively low stress, stiffness-controlled designs
such as aircraft nacelles, auto bodies and windmill blades.

In order to calculate complex structural responses such as buckling, periodic excit-
ations and stresses in composite panels due to impulsive loads, advanced analysis methods
are required in conjunction with composite mechanics. In order to size and/or design
such panels to satisfy diverse design requirements including low cost, advanced design

methods are required. The objective of this paper, therefore, is to illustrate, via the description of computational results, how available composite mechanics and advanced structural analysis methods can be used to assess, apriori, the performance of composite panels that are subjected to complex loadings and are required to meet diverse design requirements. The latter may include structural integrity, durability and cost effectiveness.

The investigation described is computational. A square panel with fixed edges (built-in) was selected. The panel was assumed to be made from random composite (either chopped fiber or random mat) reinforced with unidirectional composite strips. The panel was assumed to have been subjected to static, cyclic and impulsive loads to illustrate the application of advanced analysis methods. All required analyses were performed using the finite element capability of NASTRAN. The results obtained from the various analyses are presented graphically to illustrate the significance of material parameters and may be used as a guide in preliminary design.

STIFF, LIGHTWEIGHT COMPOSITES-STRIP HYBRIDS

Stiff, light-weight structural panels can be made by embedding strips of high stiffness unidirectional composite (UDC) in selected locations in inexpensive random composites. Henceforth, planar random composites reinforced with UDC composite strips will be called strip hybrids. For example, UDC composite strips from high modulus graphite/resin (HM/R) ($30/lb), intermediate modulus graphite/resin (T300/R) ($18/lb), or Kevlar-49/R ($8/lb) can be embedded in planar random E-glass/resin (E-G/R) composites ($0.50/lb). Note that these costs show that HM/R is about 60-times more expensive than E-G/R whereas T300/R is about 36 and Kev-49/E is only 16-times more expensive.

Schematics showing two possible locations of UDC strips in a random composite are shown in figure 1. It is important to note that for analysis purposes the embedded strips were assumed not to increase either the thickness or the weight of the composite. However, the materials and fabrication of strip hybrids increase the cost. For example, the composite shown in figure 1(b) contains about 20-percent by volume of strip reinforcement and would have an average cost of $6.40/lb if the strips were made from HM/R, $4.00 lb if they were made from T300/R, and $2.00/lb if they were made from Kev-49/R.

It is important to select the amount, type and location of the strip reinforcement judiciously. The selection is made, in part, on data generated by using composite mechanics and advanced analysis methods such as finite element analysis. However, in any intended application the structural performance advantages of strip hybrids must outweigh any material and fabrication cost disadvantages.

PROPERTIES OF PLANAR RANDOM COMPOSITES

Physical and mechanical properties of planar random composites (PRC) may be measured or they may be calculated by using the quasi-isotropic analogy (QIA) procedure described in reference 1. Briefly, in the QIA procedure, composite mechanics (composite micromechanics, composite macromechanics, combined-stress failure criteria and laminate theory) are used to predict the mechanical and physical properties of PRC. Hence, composite mechanics enter the analysis and design of strip hybrids through the use of the QIA procedure. Properties obtained using the QIA procedure are suitable for

preliminary design and analysis of strip hybrids. Properties described below were obtained using this procedure.

The physical properties of planar random composites (PRC) described herein include; heat capacity, in-plane and through-the-thickness heat conductivities, thermal expansion coefficient and density. These properties are plotted versus fiber volume ratio (FVR) in figure 2. The heat capacity and heat conductivity properties are required in heat transfer analyses for determining the temperature in nacelles and for determining the heat losses through auto bodies for heater and air conditioner sizing. The thermal expansion coefficients are needed to calculate the thermal stresses associated with temperature changes or gradients in strip hybrid panels.

The normal modulus, shear modulus and Poisson's ratio are plotted versus FVR in figure 3. Note that all three elastic properties vary nonlinearly with FVR, and therefore, cannot be extrapolated or interpolated using a linear relationship when only data for two FVR's is available.

In-plane fracture stresses (strengths), tension, compression and shear, are plotted versus FVR in figure 4. Note that tensile strength varies linearly with FVR while the compressive and shear strengths vary nonlinearly.

The following rules of thumb (given here without verification) may be used for approximating PRC strengths: (1) the tensile strength is approximately one-fourth the UDC longitudinal tensile strength from the same composite system at the same FVR; (2) the compressive strength is one-half the UDC longitudinal compressive strength; and (3) the in-plane shear strength (measured by the rail test) is approximately one-half the PRC compressive strength or one-fourth the UDC longitudinal compressive strength. The interlaminar shear strength of PRC, as measured by the short-beam-shear test, is about the same as that of the UDC. These approximations are believed to be conservative estimates of the strengths of PRC. If measured values are significantly below these estimates then the fabrication process should be examined for possible improvements. For limited experimental data see references 2 and 3.

Oftentimes the amount of fiber, or resin, in PRC is given by weight percent, ratio or fraction. Conversion from weight ratio to FVR, for either fiber or resin in E-glass composites is presented graphically in figure 5 (ref. 4). As can be seen in this figure, both volume ratios (fiber and resin) vary nonlinearly with weight ratio. When the weight fraction of a PRC is given, figure 5 can be used to obtain the corresponding FVR. This FVR can then be used to obtain the thermal and mechanical properties from figures 2, 3, and 4.

The preceding discussion illustrates that composite mechanics can be used to predict physical and mechanical properties of PRC for preliminary design and/or analysis of strip hybrids.

ADVANCED ANALYSIS AND DESIGN METHODOLOGY

Strip hybrids as structural members in aircraft nacelles, auto bodies, or composite windmill blades would be designed to meet several diverse and competing requirements usually controlled by stiffness. The design requirements may be specified as: (1) upper limit on lateral displacements under steady, periodic and impulsive loads, (2) minimum critical buckling load resistance and, (3) the avoidance resonance at certain excitation frequencies that are expected in the service environment. In addition, demands for minimum cost and minimum weight must be considered. Determination of these com-

plex structural responses requires advanced analysis methods such as those provided in NASTRAN (ref. 5).

The design procedure is iterative. The steps in the procedure, broadly speaking, are as follows: (1) select the component geometric configuration; (2) select the material; (3) determine the various structural responses of the component subjected to the specified load conditions and service environments; (4) compare these structural responses to their their corresponding limits specified in the design criteria; (5) perform parametric studies using different materials; and (6) select the most cost-effective design. A cost effective design is usually judged on the basis of: low material cost, ease of fabrication, ease of maintenance, operational cost, durability, and light weight. When the above steps are computerized, the design procedure is called computer aided design or automated design. When the above steps are cast into a mathematical programming problem, the design procedure is called optimum structural design or, more specifically, structural synthesis.

Herein, we present typical results of advanced analysis methods (NASTRAN finite element capabilities) applied to a square panel made from strip hybrids. And we indicate how these results may be used in assessing preliminary designs on a comparative basis.

The strip hybrid square panel dimensions were $50.8 \times 50.8 \times 0.13$ cm ($20 \times 20 \times 0.05$ in.). The random composite was E-Glass/resin (E-G/R). The panel was reinforced with two way strips (fig. 1(b)) which were from three UDC's: high-modulus graphite-fiber/resin composite (HM/R), intermediate-modulus graphite-fiber/resin composite (T300/R) and Kevlar-49 fiber/resin composite (Kev-49/R). The strips constitute about 20-percent of the volume of the panel. The panel was assumed to be fixed along all its edges.

The panel was assumed to have been subjected to the following load conditions: (1) static concentrated load at the center, (2) in-plane loads producing buckling, (3) a periodic excitation at the center, and (4) impulsive load at the center. The structural responses associated with these load conditions are: (1) maximum displacement and stress, (2) minimum buckling load, (3) free vibration frequencies, (4) periodic excitation response, and (5) impulsive load transient response with and without damping. These structural responses were determined using, respectively, the following NASTRAN Rigid Formats: 1, 5, 3, 8 and 9.

Five different panels were analyzed: (1) E-G/R only (base panel), (2) strip hybrid E-G/R with HM/R, (3) strip hybrid E-G/R with T300/R, (4) strip hybrid E-G/R with Kev-49/R, and (5) structural steel for comparison purposes. Each panel was evaluated using the above load conditions.

The finite element representation (FER) of the panel for NASTRAN analysis is shown in figure 6. The FER consisted of 65 nodes (grids) with 175° of freedom (DOF), 48 quadrilateral plate elements and 4 triangular plate elements. The elements used account for bending and membrane responses and for anisotropic material behavior. As can be seen in figure 5, the UDC strips run parallel to the x and y axes and are located near the center portion of the panel. The concentrated load and the impulsive load were applied at node 65. The membrane load for the buckling analysis was applied parallel to the x-axis. Note that the strip finite elements were assigned E-G/R material properties for the case where the whole panel was assumed to be E-G/R and were assigned steel material properties for the steel panel. The material properties of the five panels, required as inputs for NASTRAN, are given in table 1. Note that the properties used for the planar random E-G/R composite correspond to typical sheet molding compound

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with about 33 percent fiber by volume (0.33 FVR figs. 2 and 3). Those for the UDC are typical values and correspond to about 60 percent fiber by volume. Note also that the curves in figures 2 and 3 can be used to select E-G/R planar random composites with other FVR. The results obtained from the above analyses are summarized below.

ADVANCED ANALYSIS RESULTS AND DISCUSSION

The NASTRAN predicted results for the various structural analysis responses are summarized in table II. The panel made from E-G/R random composite will be referred to herein as the base panel. A panel made from steel is considered for comparison purposes. The majority of the comparisons are made on panels of equal thickness, which may be interpreted to imply a thickness constrained design. In the last two rows of table II results are also shown for an E-G/R panel with twice the thickness of the base panel and a steel panel with 0.7 the base panel thickness. These results are included to illustrate the panel thickness effect on the various responses.

Concentrated Load

The displacement and stresses at the center of the panels due to a 44.6 N (10 lb) load at the center are summarized in the first two columns of table II. As can be seen, the reinforcing strips reduce the displacement as follows: 40 percent for Kev-49/R, 60 percent for T300/R and 70 percent for HM/R. These reductions are substantial since only 20 percent of the volume is strip reinforcement (10 percent each way). The effectiveness of the strip reinforcement in carrying load in the strip hybrids is shown in figure 7. The maximum stresses in the reinforcing strips and in the random composite (base material) are plotted versus reinforcing strip modulus. The maximum stress in the HM/R reinforcing strips is about 10 times greater than that in the base panel. However, this stress is relatively low compared to the fracture stress of HM/R composites. In addition, the UDC strips considered have fatigue limit stresses which are about 80 percent of their static fracture stresses. Consequently, the stresses induced in the strips will not be critical from either a static or a fatigue standpoint. The shear stresses at the strip/base material interfaces are anticipated to be negligible. However, these stresses must be determined in actual design application. Compared to the base panel the stress in the equal thickness steel panel is about the same while the displacement is about 6 percent (table II). The thickness effects on the stress and displacement of the base and steel panels are shown in the last two rows of table II. These comparisons show, as one would expect, that the displacement and stress in the base panel can be reduced considerably when the thickness is a free design variable.

The important conclusion here is that advanced analysis methods results show that, on an equal thickness basis, strip hybrids can be sized (designed) to significantly reduce the displacement compared to the base panel. The 44.6 N (10 lb) load was used strictly for illustrative convenience. The results can easily be normalized with respect to applied load and compared on a relative basis.

Buckling

The buckling loads of the various panels are given in the third column of table II. Recall the panel for this case was considered as having been loaded parallel to the x-axis

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(fig. 6). The improvement in the buckling load in the strip hybrids compared to the base panel for equal thickness panels is about 1.5 times that for the Kev-49/R strips, 2 times that for T300/R, and 3 times that for the HM/R. Note that the buckling load of the steel is about 17 times greater than the base panel and about 6 times greater than the HM/R strip hybrid. The thickness effects on the buckling load of the base and steel panels are shown in the last two rows of column 3, table II. A conclusion from the previous discussion is that available analysis methods can be used to assess the relative buckling resistance of strip hybrids. However, if the design turns out to be buckling critical, then the calculated buckling load of strip hybrids should be experimentally verified. Another conclusion is that on an equal thickness basis strip hybrid panels can be sized to have 3 times the buckling load of the base panel.

Natural Vibration Frequencies

The lowest natural vibration frequency of the various panels is given in the 4th column of table II. The increase in the lowest natural frequency for the various strip hybrids compared to the base panel is approximately as follows: 30 percent for Kev-49/R, 60 percent for T300/R, and 90 percent for HM/R. The frequency for the steel panel is about the same as that for the HM/R strip hybrid (5 percent higher). The thickness effects of the base and steel panels are shown in the last two rows of column 4, table II. The important conclusion is that, on an equal thickness basis, strip hybrids can be sized to have lowest natural vibration frequencies which are about twice that of the base panel and in the same range as that of the steel panel.

Periodic Excitations

The periodic load for this case is: $F(f) = (23.0 + 0.3 \, (f)) \sin(2\pi ft)$ where f is in Hertz and was selected to yield responses in the strip hybrids about 5 times those of the concentrated load case. This selection was made in order to obtain better discrimination among the responses of the different strip hybrids. Although a periodic excitation producing 5 times the static response may be severe for auto body applications, it is considered reasonable for nacelles and windmill blades during gust excitations.

The response of the various panels due to the above periodic excitation load applied at the center of the panel with a forcing frequency of 22 Hz (about the same as the lowest natural frequency of the base panel) is given in terms of the maximum displacement and stress (base panel material) in the fifth and sixth columns of table II. The 22 Hz excitation frequency was expected to produce large displacements and stresses in the base panel. However, it was of interest to see how the displacements and stresses change at this excitation frequency with the addition of the UDC strips.

The displacement is at the panel center while the quoted stress occurs at the centroid of the triangular elements (fig. 6). Note the predicted maximum displacement of the base panel is 59.2 cm (23.3 in.). This is physically incompatible with the panel edge length of 50.8 cm (20 in.). The decreases in displacement of the strip hybrids compared to the base panel are approximately: 85 percent for Kev-49/R, 90 percent for T300/R, and 95 percent for HM/R. The corresponding decreases in the stresses of the base material are: 80 percent for Kev-49/R, 90 percent for T300/R, and 90 percent for HM/R. These results illustrate the effectiveness of the strip hybrid for reducing the displacement and stress due to periodic excitations occurring near resonance of the base

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panel. This is desirable since it increases the fatigue life of the base material.

Note that the displacement and stress reductions for the steel panel compared to corresponding values of the base panel are about 100 percent and 80 percent respectively. Note, also, that the stresses in the base material of the strip hybrids are smaller than those in the steel panel by: 6 percent for Kev-49/R, 46 percent for T300/R, and 63 percent for HM/R. In actual applications the strip hybrid selected must be checked for large displacement or stress and fatigue damage that may be induced by excitation frequencies near its own resonance. The maximum stresses in the strips range from about 4 to 10 times those in the base material. These stresses are only about 25 to 50 percent of the corresponding fatigue limits of the strips. However, the stress in the steel panel is comparable to its fatigue limit. The thickness effects on the periodic excitation responses of the base and steel panels are shown in the last two rows of columns 5 and 6, table II. Increasing the base panel thickness has a comparable effect on the periodic excitation responses as using strips to reinforce the base panel.

From the above discussion it can be seen that, on an equal thickness basis, strip hybrids can be sized to cause a significant change in panel resonant frequency. This will result in relatively small displacements and stresses in the base material compared to the base panel when excited near resonant frequency. As can be seen from the results of the last two sections, available analysis methods can be used to assess strip hybrids with respect to (1) natural vibration frequencies and (2) periodic excitation response.

<center>Impulsive Load</center>

The displacement and stress of the various panels caused by an impulsive (dynamic) load are given, respectively, in the seventh and eighth columns of table II. The impulsive load is shown in figure 8. This impulsive force represents, roughly, a low velocity particle point impact at the center of the panel, or an abruptly released displacement, at this point.

The decreases in the dynamic displacements in the strip hybrid panels compared to the base panel from column 7, table II are: 26 percent for the Kev-49/R, 44 percent for the T300/R, and 56 percent for the HM/R. The corresponding decreases in the dynamic stresses in the base material are about 35 percent for the Kev-49/R, 50 percent for the T300/R, and 55 percent for the HM/R. The decreases for both displacements and stresses in the base material are substantial.

The dynamic displacement of the steel panel is about 90 percent less than that of the base panel and the dynamic stress is about 40 percent higher. Also, the dynamic stresses in the base material in the strip hybrids compared to that in the steel panel are smaller by about 50 percent for the Kev-49/R, 65 percent for the T300/R, and 70 percent for the HM/R. As can be observed from these percentages, the strip hybrid panels sustain considerably less dynamic stress in the base material than steel panels for the same impulsive load. The comment made in the last section about the maximum stresses in the strips applies here as well. The thickness effects on the impulsive load responses of the base and steel panels are shown in the last two rows of columns 7 and 8, table II.

The important conclusion from the previous discussion is that available advanced analysis methods can be used to assess the transient response of strip hybrids subjected to impulsive loads. Another conclusion is that, on an equal thickness basis, strip hybrids can be sized which would sustain considerably smaller dynamic displacements and stresses in the base material than the base panel.

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A general observation from all the load cases considered is that the calculated stresses in the strip hybrids (both in the base material and in the strips) were considerably lower than the corresponding tensile static strengths. And in most cases, the stresses were well below their fatigue limits.

ADVANCED DESIGN GUIDELINES

The structural responses described previously can be used to provide design guidelines for sizing and designing strip hybrids for aircraft engine nacelle, windmill blades and auto body applications. Several examples are described below to illustrate the procedure.

The displacement and base material stress of the strip hybrids for the concentrated load, the buckling load, and the lowest natural frequency are plotted versus reinforcing strip modulus in figure 9. As can be seen in this figure the displacement and stress (fig. 9(a)) and the lowest natural frequency (fig. 9(c)) vary nonlinearly with reinforcing strip modulus while the buckling load (fig. 9(b)) varies linearly. These figures can be used to select reinforcing strip moduli for sizing strip hybrids to meet several specific design requirements. Of course, these figures are restricted to square fixed-end panels with 20 percent strip reinforcement by volume. For designing more general panels, suitable graphical data has to be generated.

The maximum vibratory stress in the base material of the strip hybrids due to periodic excitations with 3 different frequencies is plotted versus reinforcing strip modulus in figure 10. As can be seen in this figure, the maximum vibratory stress in the base material varies nonlinearly and decreases rapidly with reinforcing strip modulus to about 103 GPa (15×10^6 psi). It decreases mildly beyond this modulus. The significant point here is that the modulus of the reinforcing strips should be about 103 GPa (15×10^6 psi) to minimize vibratory stresses (since they may cause fatigue failures) for the strip hybrids considered. For more general strip hybrids, graphical data with different percentage reinforcement and different boundary conditions are required.

The maximum dynamic stress in the base material of the strip hybrids due to an impulsive load is plotted in figure 11(a) versus reinforcing strip modulus for two cases: (1) undamped and (2) with 0.009 percent of critical damping. The points to be noted from this figure are: (1) the dynamic displacement varies nonlinearly with reinforcing strip modulus and (2) the damping is much more effective in strip hybrids with reinforcing strip moduli less than 103 GPa (15×10^6 psi). Corresponding displacements are shown in figure 11(b). The behavior of the dynamic displacements is similar to that of the stress as would be expected. Curves comparable to those in figure 11 are needed to size and design strip hybrid panels so that impulsive loads will not induce displacements or stresses in the base material greater than those specified in the design requirements or are incompatible with the material operational capabilities.

The previous discussion and the conclusions derived therefrom were based on panels of equal thickness. Structural responses for panels with different thicknesses can be obtained from the corresponding responses in figure 9 as follows (let t = panel thickness): (1) The displacement due to a concentrated static load varies inversely with t^3 and the stress varies inversely with t^2; (2) The buckling load varies directly with t^3; (3) The natural vibration frequencies vary directly with t. No simple relationships exist for scaling the displacement and stress due to periodic excitation or impulsive loading. Also, all of the above responses vary inversely with the square of the panel edge dimension.

Responses for square panels with different edge dimensions but with all edges fixed can be scaled from the corresponding curve in figure 9. The significance of the scaling discussed above is that the curves in figure 9 can be used directly to size square strip hybrids for preliminary design purposes. The values shown in the last two rows in table II (except for the last two columns which were obtained using NASTRAN) were obtained by using the above scaling procedures.

Weight, cost and energy comparisons for the panels of equal thickness are summarized in table III. Some of the information in this table was obtained with the aid of reference 6. The weights of the various panels are given in the first column of this table. The weights of the base panel (random composite panel) and the three strip hybrids are about the same while that of the steel is about 4.3 times greater on an equal thickness basis. The estimated panel material cost is given in the second column of table III. Compared to the base panel the cost for the other panels is greater by: 3.3 times for the Kev-49/R strip hybrid, 6.9 for the T300/R strip hybrid, 11 for the HM/R strip hybrid and 2 times for the steel panel.

The energy needed for fabrication of the various panels is given in the third column of table III. The fourth column presents a normalized operational cost of the panel in a 5 year automotive application. Since both columns 3 and 4 are based only on weight, the strip hybrids need about the same amount of energy for fabrication and for a 5 year period of operation.

The above comparisons were made assuming equal thickness panels. It is possible to select base material panels with different thicknesses which will have structural responses comparable to the strip hybrids shown in table II. Also, steel panels with different thicknesses may be selected which can be more cost effective than the strip hybrids. Both of these aspects can be assessed on the basis of equal displacement, frequency, or buckling resistance using the scaling procedure described previously.

The important conclusion from the previous discussion is that results from available advanced analysis methods and appropriate scaling procedures can be used to generate data applicable for apriori assessment and/or design of a large class of strip-hybrid, fixed-end panels that are subjected to complex loading conditions.

CONCLUSIONS

The results of this investigation illustrate the use of advanced analysis methods and composite mechanics to predict the complex structural responses of composite material panels such as strip hybrids. Panels from these hybrids, which were assumed to consist of E-G/R random composite reinforced with strips from unidirectional composite, can be sized (i.e., designed) to have improved structural responses compared to the random composite panel. For example, on an equal thickness basis, the concentrated load deflection can be 70 percent smaller; the buckling load can be 3 times greater; the lowest natural vibration frequency can be about 85 percent higher; the periodic excitation (vibratory) stress in the base material of the strip hybrids can be about 95 percent smaller; and the impulsive load stress can be about 55 percent smaller. Results from available advanced analysis methods and appropriate scaling procedures can be used to assess apriori the performance of strip-hybrid, fixed-end panels subjected to complex loading conditions.

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TABLE I. - MATERIAL PROPERTIES

Property	Material				
	[a]E-Glass/ resin	[b]Kevlar/ resin	[b]Thornel 300/ resin	[b]HM Graphite resin	[c]Structural steel
Density, g/cm^3 (lb/in^3)	1.80 (0.065)	1.38 (0.050)	1.52 (0.055)	1.55 (0.056)	7.70 (0.278)
Modulus, 10^3 MPa (10^6 psi)					
Longitudinal	13.1 (1.9)	75.7 (11.0)	138 (20)	241 (35)	207 (30)
Transverse	13.1 (1.9)	5.5 (0.8)	10.3 (1.5)	5.5 (0.8)	207 (30)
Shear	5.0 (0.73)	2.1 (0.3)	6.9 (1.0)	4.1 (0.6)	79.3 (11.5)
Poisson's ratio	0.3	0.32	0.32	0.22	0.3
Thermal expansion coefficients 10^{-6} m/m/^{o}C (10^{-6} in/in/^{o}F)					
Longitudinal	16.7 (9.3)	-2.9 (-1.6)	0.02 (0.01)	~0	13.3 (7.4)
Transverse	16.7 (9.3)	56.3 (31.3)	22.5 (12.5)	33.3 (18.5)	13.3 (7.4)

[a]Planar random composite - isotropic in the plane (about 33 by volume).
[b]Unidirectional composite strips.
[c]Isotropic material.

TABLE II. - SUMMARY OF PREDICTED STRUCTURAL RESPONSES OF SQUARE PLATES MADE FROM STRIP HYBRIDS AND

COMPARISONS WITH OTHER MATERIALS

[Strips 20 percent by volume; panel size: 20 by 20.]

Material	Structural response						[d]Impulsive load	
	[a]Concentrated load		[b]Buckling	Natural lowest frequency, cps	[c]Periodic excitation			
	Displacement, in.	Stress in base material, ksi	Load, lb/in.		Displacement, in.	Stress in base material, ksi	Displacement, in.	Stress in base material, ksi
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
E-Glass/resin random (0.05 in. thick base panel)	0.97	3.5	4.3	23	23.3	64.8	4.3	18.0
[e]Strip hybrids (0.05 in. thick) E-Glass/resin with								
Kevlar-49/resin	.61	2.4	6.4	30	3.5	11.8	3.2	12.0
Thornel 300/resin	.42	1.7	8.9	36	1.9	6.8	2.4	8.9
HM-Graphite/resin	.30	1.3	12.0	43	1.2	4.6	1.9	7.9
[f]Steel	.06	3.5	71.8	45	.2	12.5	.4	25.0
E-Glass/resin random (0.10 in. thick base panel)	.12	.87	34.5	46	.49	2.4	.9	5.3
Steel (0.035 in. thick)	.18	7.1	24	32	1.0	33	1.1	48.9

[a]Concentrated load at center, 10 lb.
[b]Buckling load parallel to x direction, fig. 6.
[c]Periodic excitation force F(f) = (23 + 0.3 f) sin(2πft) (evaluated at f = 22 cps).
[d]Impulsive load at center: F(t) = 5000 t (0 ≤ t ≤ 0.002); F(t) = 150 - 25 t (0.002 ≤ t ≤ 0.006).
[e]Strips made from unidirectional advanced composite.
[f]Included for comparison.

Conversion factors: 1 in. = 2.54 cm; 1 lb = 4.46 N; 1 ksi = 6.9 MPa; lb/in. = 176 N/m.

TABLE III. - WEIGHT, COST, AND ENERGY-NEEDED COMPARISONS OF

STRIP HYBRIDS AND OTHER MATERIALS

[Strips 20 percent by volume; panel size: 50.8 by 50.8 by 0.127 cm
(20 by 20 by 0.05 in.).]

Material	Panel weight, lb	Estimated panel material cost, dollars	[a]Energy needed for auto body applications	
			[b]Fabrication	[b]5-year operation
	(1)	(2)	(3)	(4)
E-Glass/resin random (base panel)	1.30	0.65	60	30
Strip hybrids: E-Glass/resin with				
Kevlar 49/resin	1.24	2.12	60	30
Thornel 300/resin	1.26	4.48	60	30
HM-Graphite/resin	1.26	7.12	60	30
Steel (structural)	5.56	1.39	100	100

[a]Based on that needed for steel (100 percent) (estimated from data from ref. 6, p. 55).

[b]Normalized with respect to steel panel (100).

Conversions: 1 lb = 4.46 N; MPG = 0.423 kM/litre.

(a) ONE WAY STRIPS.

(b) TWO WAY STRIPS.
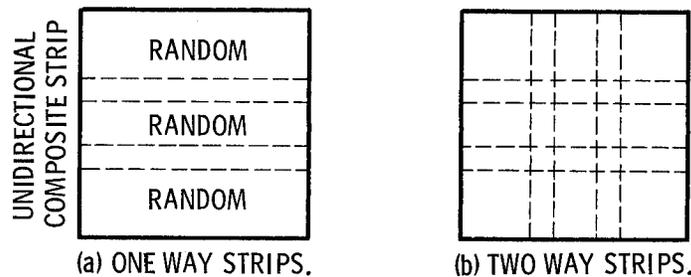
Figure 1. - Schematic of strip hybrids depicting possible location of advanced unidirectional composite strips in a random composite.
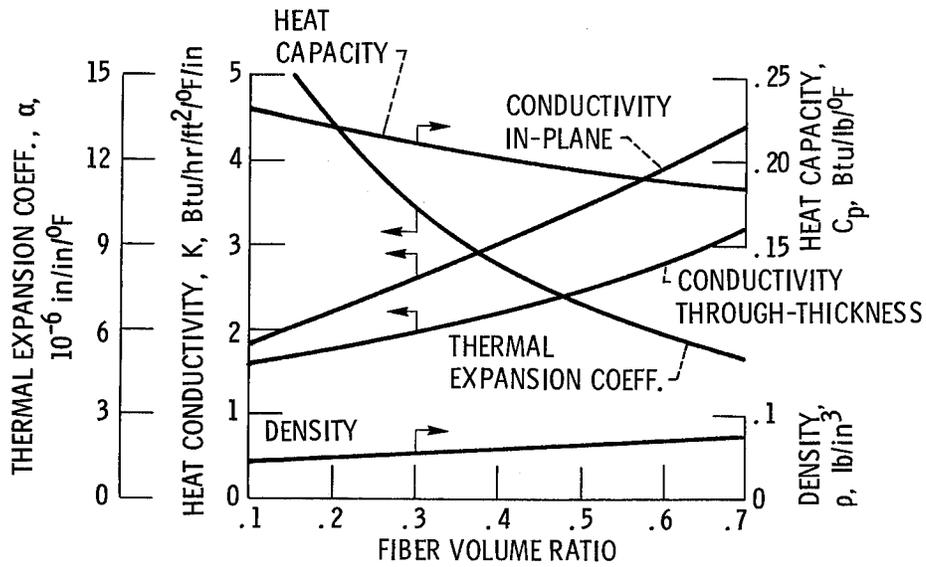
Figure 2. - Physical properties of planar random E-glass/
resin composites predicted using the quasi-isotropic
analogy (ref. 1). SI unit conversion factors: α,
in/in/°F = 0.56 cm/cm/K; K, Btu/hr/ft²/in = 6.94 W/m/K;
C_p, Btu/lb/°F = 4.19x10³ J/kg/K; ρ, lb/in³ = 27.7 g/cm³.
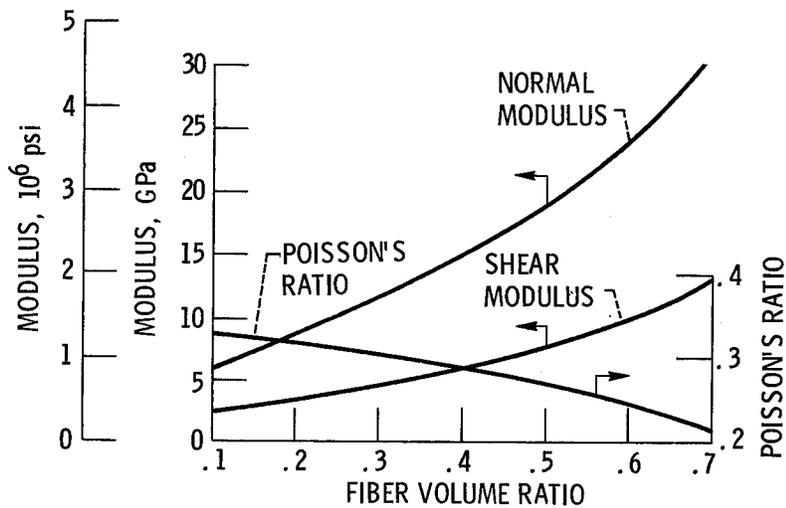
Figure 3. - Elastic properties of planar random E-glass/
resin composites predicted using the quasi-isotropic
analogy (ref. 1).
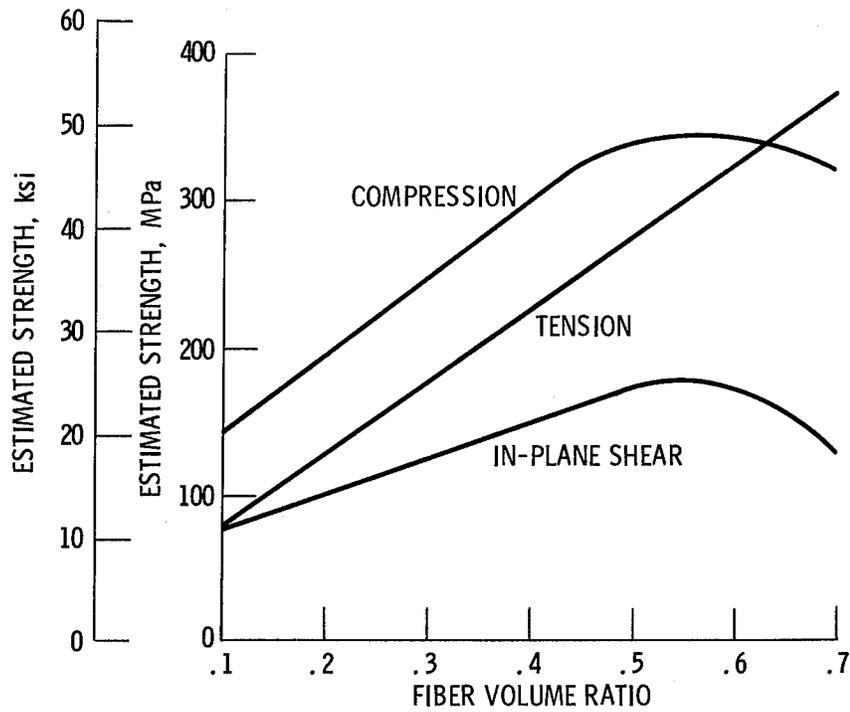
Figure 4. – Estimated fracture stresses (strengths) of planar random
E-glass/resin composites.
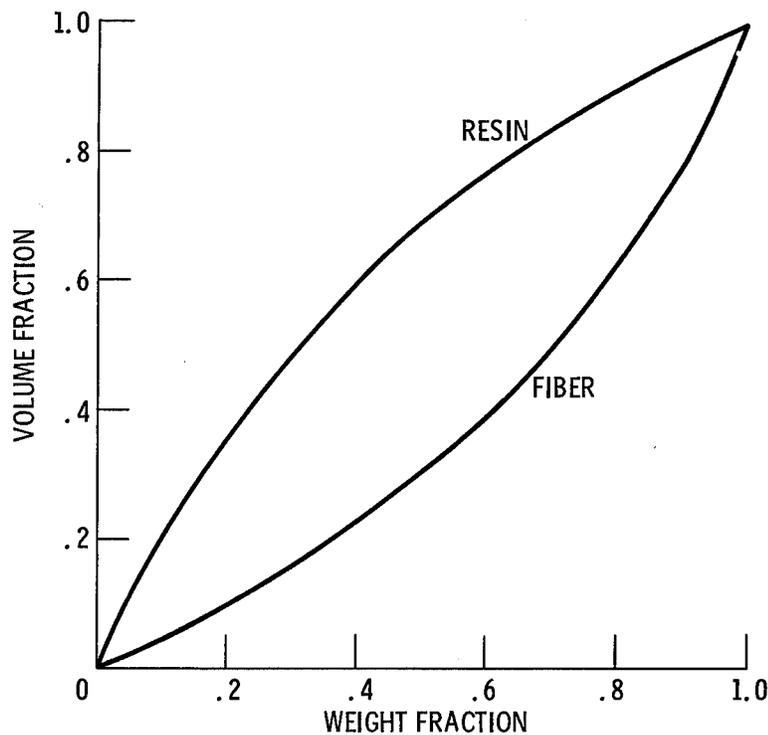
Figure 5. – Volume fraction versus weight fraction glass-
resin system (fiber density = 2.60 g/cm^3 (0.094 lb/in^3),
resin density = 1.19 g/cm^3 (0.042 lb/in^3)) (ref. 4).

Figure 6. – Finite element representation of a random composite flat panel reinforced with unidirectional composite strips (strip hybrid).

Figure 8. – Impulsive load for determining the relative dynamic response of strip hybrids.

Figure 7. – Maximum stresses in strip hybrid square plates with fixed edges and subjected to concentrated load 44.6 N (10 lb) at the center. E-glass/resin planar random composite reinforced with two-way unidirectional composite strips 20 percent by volume (50.8 by 50.8 by 0.128 cm (20 by 20 by 0.05 in.)).
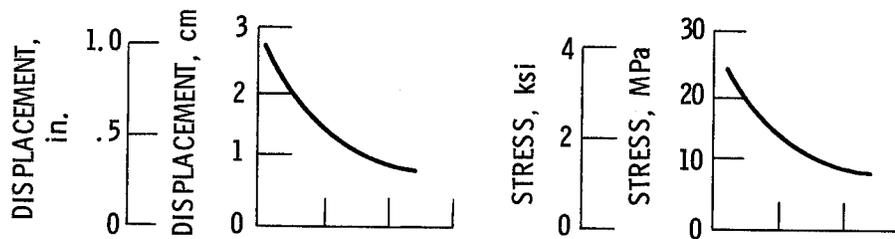
(a) CONCENTRATED LOAD AT CENTER, 44.5 N (10 lb).
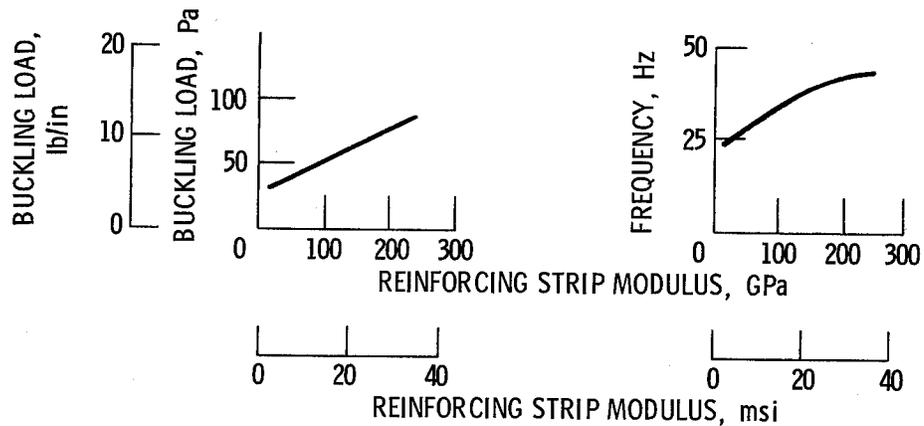
(b) BUCKLING LOAD.　　　　　　(c) LOWEST FREQUENCY.

Figure 9. - Structural responses of strip hybrid square plates with fixed edges. E-glass/resin planar random composite reinforced with two-way unidirectional composite strips 20 percent by volume (50.8 by 50.8 by 0.127 cm (20 by 20 by 0.05 in.)).
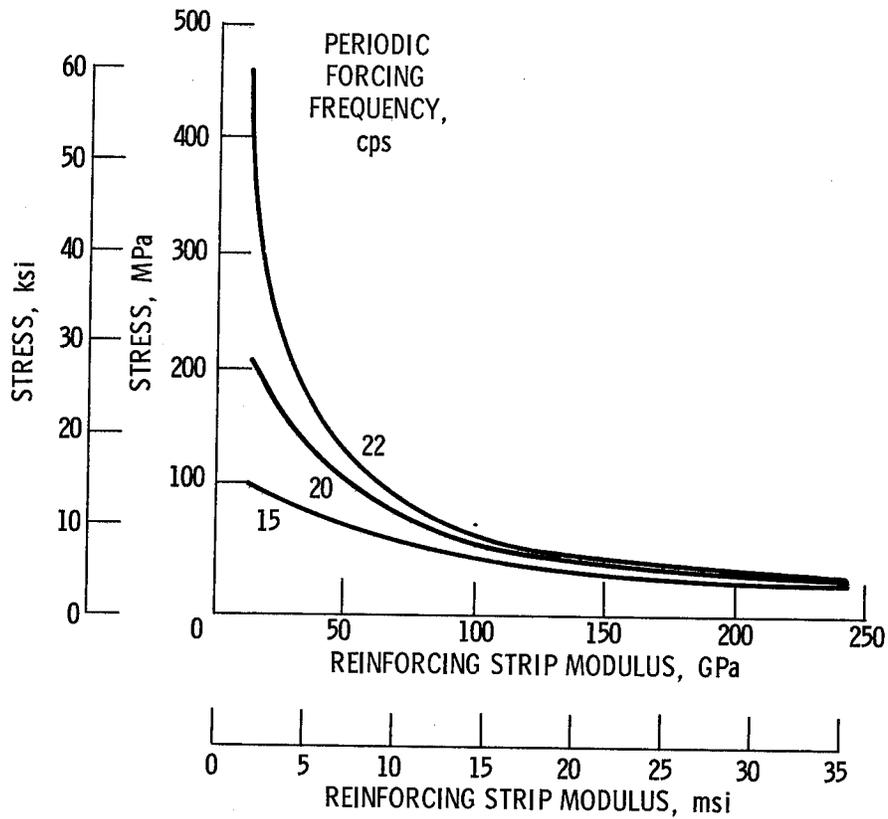
Figure 10. - Base material maximum stresses in strip hybrid square plates with fixed edges and subjected to periodic excitations at center with forcing frequencies below resonance. E-glass/resin planar random composite reinforced with two-way unidirectional composite strips 20 percent by volume (50. 8 by 50. 8 by 0. 127 cm (20 by 20 by 0. 05 in.)).
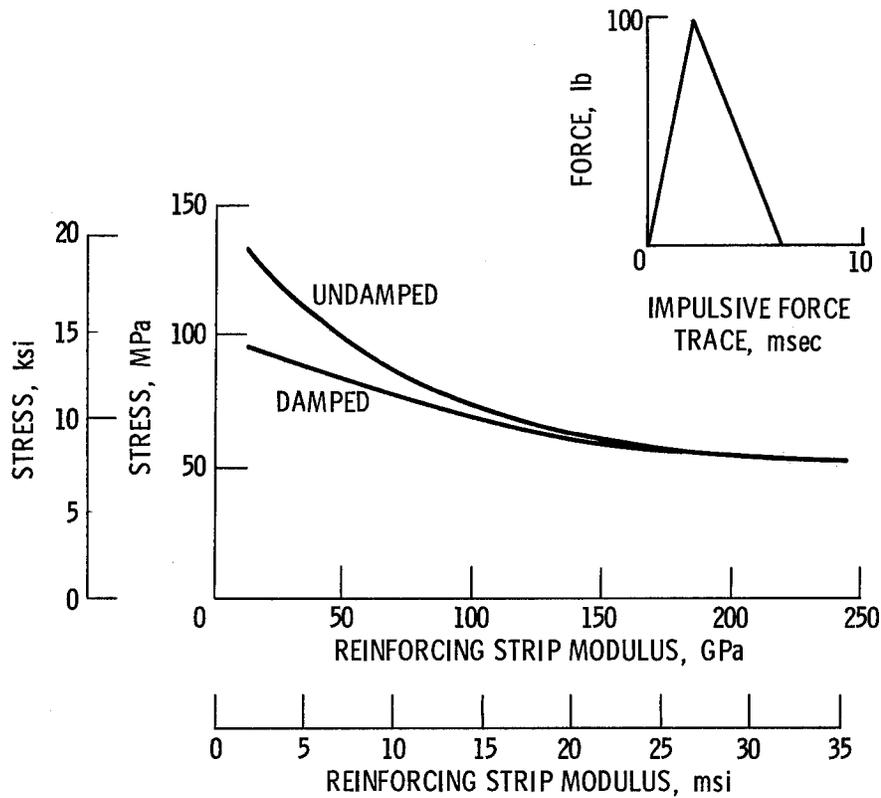
(a) MAXIMUM IMPULSIVE STRESS AT CENTER.

Figure 11. – Structural dynamic response of strip hybrid square plates with fixed edges subjected to an impulsive load at the center. E-glass/resin planar random composite reinforced with two-way unidirectional composite strips 20 percent by volume (50.8 by 50.8 by 0.127 cm (20 by 20 by 0.05 in.)).
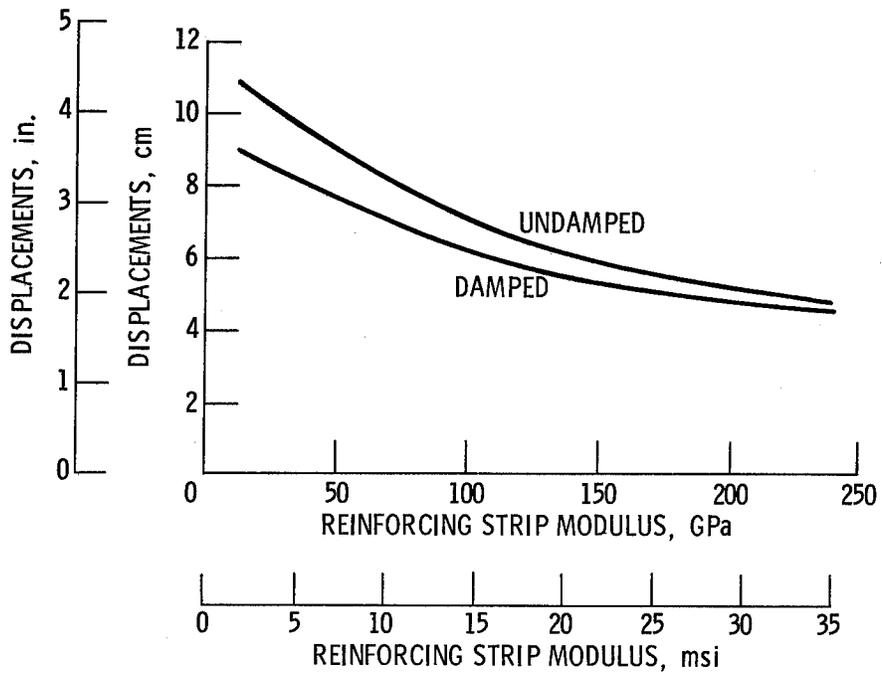
(b) MAXIMUM IMPULSIVE DISPLACEMENT.

Figure 11. – Concluded.

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15. Supplementary Notes

16. Abstract

Results are described which were obtained by applying advanced analysis methods and composite mechanics to a strip-reinforced random composite square panel with fixed ends. This was done in order to illustrate the use of these methods for the apriori assessment of the composite panel when subjected to complex loading conditions. The panel was assumed to be of E-Glass/Random Composite. The strips were assumed to be of three advanced unidirectional composites to cover a range of low, intermediate, and high modulus stiffness. The panels were assumed to be subjected to complex loadings to assess their adequacy as load-carrying members in auto body, aircraft engine nacelle and windmill blade applications. The results show that strip hybrid panels can be several times more structurally efficient than the random composite base materials. Some of the results are presented in graphical form and procedures are described for use of these graphs as guides for preliminary design of strip hybrids.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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