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Mechanical Fastening of FGRP Composites

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Introduction

In this study, high-sensitivity moire interferometry was used to obtain the stress/strain distribution in the vicinity of hole arrays in composite materials. Three configurations were considered, one having the two holes in a row parallel to the load direction. Ideally, in this case, if all of the pins are identical and the pin/hole interactions are the same, symmetry can be assumed; then each pin will carry one-half of the applied load. This situation was simulated first using cables and pulleys to divide the load. However, in less ideal conditions, some load misalignment can exist, thus producing a nonuniform distribution of load between the hole pins. In order to simulate the worst condition, the holes were loaded individually, one at a time.

The purposes of these experiments were 1) to determine the stress/strain distribution around the loaded holes for the arrays; 2) to study the interactions between the holes; and 3) to determine the effects on the stress/strain distribution when only one hole is loaded.[1,2]

Background

Because of lower manufacturing costs, improved strength/weight performance, and greater design flexibility, composites are replacing metals in many fields. The increasingly large range of ingredients available, the improving quality of resin and fiber materials, and the increasing knowledge of the mechanics of fiber-reinforced materials further expands the potential range of application.

The automotive and aerospace industries, which use composite materials widely, seek improved design criteria and design guidelines. This creates the necessity for analyzing the most efficient joining methods from both the mechanics and production viewpoints. Mechanically fastened joints are necessary since, for reasons of maintenance repair and assembly, adhesive joining becomes inappropriate. This idea of mechanical connectors creates concern because the internal structure of the composite is disturbed, maybe even destroyed, by cutouts or holes.

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Composite materials are frequently joined by single or multiple bolts or rivets. The strengths of such joints depend on the number and spacing of the bolts, end distance, bolt clearance, load distribution, material properties, hole treatment, presence of washers, preloads, and so on. This introduces design problems since a design approach based on scientific knowledge, as opposed to phenomenological testing, is not yet available.

What is lacking is a thorough knowledge of the interaction of mechanical fasteners and the composite material. Modeling of fastener/material interactions and experimental inquiry with emphasis on stress/strain failure are necessary steps which will lead to the desired design protocol. This experimental analysis was endeavored to gain the needed mechanics data to aide in devising a further advanced model design.

Applications of Composites

There are many reasons for the use of fiber-reinforced composite materials; some are stated here: 1) To strengthen and stiffen the matrix, 2) to achieve controlled mechanical and physical properties, 3) to enhance the ratios between mechanical properties and the specific weight of structural materials, and 4) to attain manufacturing cost reductions while maintaining mechanical and other properties.

The aircraft industry has recognized the countless advantages of high-strength, low-weight composites, i.e., carbon and graphite fiber laminates, and is presently using these materials in wing assemblies and in various other areas. A drawback in using these high-duty composites is their extraordinary cost. This has kept their use in the automotive industry low, but the future should create the availability of other high-duty fibers instigating a competitive market and lower costs.

This great interest in composite materials leads us back to the investigation of mechanical fasteners, since they play a major role in maintenance and assembly.

Principle Mechanical Observations

A unique moire interferometer system and computer-based data acquisition and reduction capability, for measuring surface strains along three directions over a region, was developed and proven to have the correct sensitivities for research on composites.

Surface strain maps were obtained by the moire methods for single hole plus pin, two-hole, and three-hole staggered joint configurations. These maps include strains along the longitudinal, transverse, and 45-deg directions for the entire region of the joint.

A table of stress concentration factors (SCF) fastener arrays in various load configurations was developed from moire investigations of strain fields in the joint regions. For the single-hole array, the maximum SCF was 14, while the two-hole tandem, two-hole parallel, and three-hole staggered, exhibited SCF's of 5.6, 1.16, and 2.95, respectively. Since multiple-fastener arrays result in a statically indeterminate situation, the effect on SCF of manufacturing imperfections, which cause most of the load to be concentrated at one pin of the array, must be considered.

Fasteners that are not at right angles to the specimen surface, as would be caused by misaligned holes or crooked holes, can cause deviations in the stress values in excess of 200% of the value measured or calculated for the ideal case. Similar effects can be shown for holes that are tapered or bell shaped.

The well-fitted pin peak strains obtained by the moire techniques are higher than those observed for ill-fitting pins, and these can probably be taken as accurate worst-case strain distributions. These results can be used to simulate upper and lower bounds on the magnitudes of stresses that will be realized in comparable design situations.

Measurements of surface strain can be catastrophically misleading for laminated composites unless test conditions are carefully established and care is taken in the interpretation of test results.

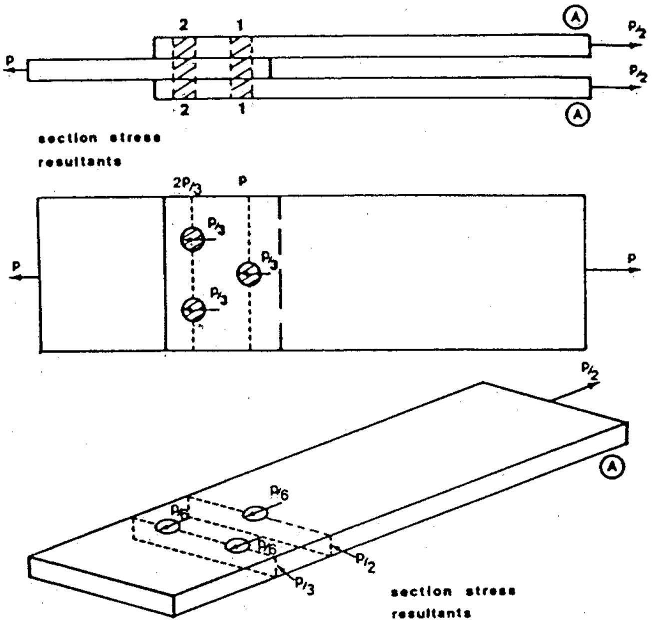

Fig. 1 Stress resultants for three staggered holes equally loaded.

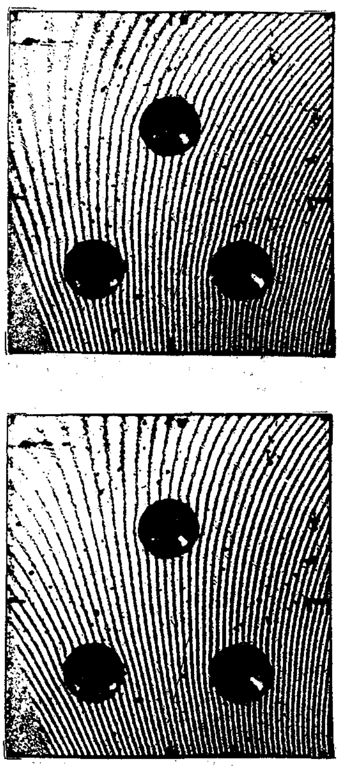

Fig. 2 Moire fringes of displacement perpendicular to direction of load for specimen with three-hole staggered array.

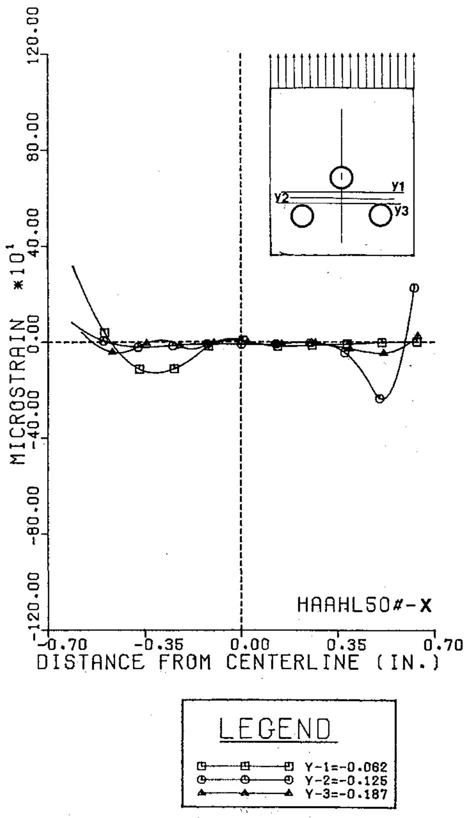

Fig. 3 Strain ϵ_x along lines perpendicular to direction of load.

Table 1 Comparison of stress concentration factors

	Two-hole tandem			Single-hole
	both loaded	up loaded	low loaded	
upper	5.57	12.1	4.97	14.0
lower	1.91	1.0	9.16	14.0
	Two-hole parallel		Single-rule	
	left hole	right hole		
	0.65	1.16	14.0	
	Three-hole array			Single-hole
upper hole edge left	upper hole edge right	lower-left hole	lower-right hole	
2.17	2.32	2.95	1.54	14.0

Experimental Procedures and Apparatus

The choice of an efficient experimental technique was limited by the following: 1) Nonlinear deformation fields, 2) necessity of full-field analysis, 3) opaque composites, 4) boundary and free-edge distortions, and 5) finding a suitable combination of birefringent materials to model an actual composite specimen. These limitations lead us to using the moire method of full-field information to study the inplane surface displacements.[3] It has a great potential for the macroscopic strain analysis of composites, and it does not suffer any limitations from anisotropy, inhomogeneity, or inelasticity of the composite material.

The basis of any moire method is the grating that is attached to the specimen surface, allowed to deform with the specimen, and compared with its undeformed state.

Inplane moire interferometry fringes depict inplane displacements of every point on the surface as maps of equal displacement.[4] In using this technique, the specimen carries a phase-type grating possessing a symmetrical corrugated surface which alters the phase of the incident beam in a regular, repetitive way. When the specimen is deformed, the grating on its surface deforms with it. The specimen grating will change in frequency and direction systematically from point to point. Consequently, plane wave fronts illuminating the specimen grating will be diffracted; but, because of the localized changes in frequency and direction of the grating lines, the emerging wave fronts will be slightly warped. The resulting interference fringe pattern of these warped wave fronts is a contour map of the angular separation of the two diffracted orders, since bright fringes of constructive interference separate dark zones of destructive interference.

Typical Moire Results and Analysis

The main objective of this portion of the paper is to illustrate the varying stress/strain fields in the vicinity of the hole arrays. Three configurations are considered. The first has two holes in a row parallel to the direction of load with both holes loaded equally. However, in less ideal conditions, some load misalignment exists, thus producing a nonuniform distribution of the load between the two pins. In order to simulate a worst condition, the holes were tested with individual loading. In the second case, two holes are in a row perpendicular to the direction of load and both holes are loaded equally. The third configuration considered has three holes in a staggered or triangular pattern. All of the holes were loaded equally and simultaneously. See Figs. 1-3 for typical results.

Summary and Conclusions

Table 1 compares the stress concentration factors for two of the hole arrays and load configurations studied.

Using a high-sensitivity interferometric moire technique, the stress/strain distribution was obtained for three different directions. The SCF was calculated at only one point located at the edge of the hole in the horizontal diameter for the two- and three-hole arrays. For the two-hole arrays in tandem, when both holes were loaded, the SCF for the upper hole was 2.9 times higher than that at the lower hole, indicating that the load sharing between both holes is not exactly given by a ratio of 2. In the case of two holes in tandem (lower hole loaded), the SCF for the lower hole was 1.84 times higher than the SCF for the upper hole. Some interaction between the two holes, one of them being loaded and the other acting as a stress raiser, defines the stress/strain field in the region between them, but the influence of the hole acting as a stress raiser on the loaded one is not very large. When the upper hole is loaded, the SCF for the upper hole produces a large influence in the stress/strain field of the lower hole. The ratio of SCF between both holes is 12. For the case of the two-hole array in parallel, there is a further reduction of the net section area, and an increase in the SCF was expected at the edge of the holes. In this case, the results showed a fairly uniform distribution of stress/strain around the hole.

In the case of the three-hole array in a staggered configuration, some asymmetry was observed for the SCF. For the upper hole, $k = 2.32$ and 2.17 for the right and left holes, respectively, and for the inner edges of the two lower holes, $k = 2.95$ and 1.54 for the right and left holes, respectively. This was an indication that the right half of the specimen had a higher SCF. Also, some high strain values were observed above the two lower holes in a symmetric position with respect to the specimen. The bearing area of the upper hole did have some effect on the strain field of the three holes.

If these results are compared with the results obtained by Herrera-Franco[6] and Cloud et al.[1] for a single pin-loaded hole, where the SCF at the edge of the hole was equal to $k = 14$, then the advantage of utilizing a multihole array in a connection is evident by the reduction of SCF at each hole.

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Use of Curvilinear Fiber Format in Composite Structure Design

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Introduction

COMPOSITE structures are currently being designed to make use of multiple layers of fiber-reinforced material. The fibers in each layer are aligned straight and parallel with each other. Within a particular layer, the fiber orientation is fixed. This is opposed to having a fiber orientation that varies from point to point within a layer or group of layers. The idea of using fibers in anything other than a straightline format has been hampered by the inability to implement such a design. However, contemporary fiber handling techniques, such as multiaxis tow placement devices[1] may eliminate this barrier. As such, it is worthwhile to consider the gains, or losses, that accompany the use of curvilinear fiber formats. It would seem from the outset that by allowing the reinforcing medium the additional freedom to have its alignment vary from point to point depending on geometry and load path, more efficient structures can be designed. Though this may appear to be the case, each particular application of such an idea has to be studied. For example, a plate with a centrally located circular hole would be a prime candidate for utilizing the curvilinear format. For such a problem, the basic issues are the following: Can the tensile capacity and/or the buckling capacities of a plate with a central hole be improved by using the curvilinear format? How should the fiber orientation vary from point to point? What mechanisms are responsible for this improvement? How sensitive are the gains to geometry, e.g., plate-width-to-hole-diameter ratio? There are other questions that must be asked. This Note begins to discuss the notion of a curvilinear fiber format for the specific problem of a plate with a hole. It should be noted that some work has been done in the area of curvilinear reinforcement.[2,3]

Problem Description, Design Philosophy, and Method of Analysis

Consider a plate of length L, width W, with a central hole of diameter D, and loaded on opposite ends by uniformly distributed forces. Given that graphite-reinforced material with a fiber-volume fraction of 65% is available, how can the material be used most effectively to construct a plate with a given geometry and loading? Here, the discussion will focus on a tensile loading. Buckling of the improved tensile designs will be evaluated, but design with the curvilinear format for improved buckling is not discussed. For purposes of limiting the problem, the plates discussed will be restricted to 16 layers.

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