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Project #: E-20-M17            Cost share #:                          Rev #: 0
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Project unit:                 CIVIL ENGR    Unit code: 02.010.116
Project director(s):
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Sponsor/division names: OPTIMAL CORPORATION              / SAN HOSEA, CA
Sponsor/division codes: 214                              / 019


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Does subcontracting plan apply ?: N

Title: CONCEPTS FOR IMPROVING STRESS REDISTRIBUTION IN COMPOSITE STRUCTURES


                                PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U              ONR resident rep. is ACO (Y/N): N
Defense priority rating   :   N/A          N/A supplemental sheet
Equipment title vests with:    Sponsor X        GIT
  PER FAR CLAUSE 52.245-5 I.
Administrative comments -
  INITIATION OF PROJECT.
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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 06/18/96

Project No. E-20-M17 Center No. 10/24-6-R8854-0A0

Project Director YIN W-L School/Lab CIVIL ENGR

Sponsor OPTIMAL CORPORATION/SAN HOSEA, CA

Contract/Grant No. SUBCONTRACT DATED 2/27/96 Contract Entity GTRC

Prime Contract No. DAAE07-96-C-X026

Title CONCEPTS FOR IMPROVING STRESS REDISTRIBUTION IN COMPOSITE STRUCTURES

Effective Completion Date 960614 (Performance) 960614 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
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Other	N	

Comments

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
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GTRI Accounting/Grants and Contracts	Y
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NOTE: Final Patent Questionnaire sent to PDPI.

E-20-M17
#1

CONCETPS OF IMPROVING STRESS REDISTRIBUTION IN COMPOSITE STRUCTURES

Final Report

Project No. E-20-M17

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ABSTRACT

Significant improvements in the design of composite structures for weight and cost reduction may be achieved by appropriate redistribution of stresses in critical regions including joints and interfaces. Local strengthening, structural tailoring, use of stiffener attachments and toughened interleaves are potentially effective methods to control stress concentration and to suppress interface damage and delamination failure. Implementation of these methods requires the development of efficient and accurate analysis procedures for evaluating the localized stresses in critical regions. An anlysis methodology is suggested based on the substruturing approach, local singularity analysis of multimaterial sectors, and interfacial failure criteria.

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0. INTRODUCTION

Laminated structural components made of advanced composite materials offer a number of significant advantages including reduced weight, high specific strength and stiffness, superior fatigue and corrosion resistance, and the flexibility of tailoring material anisotropy and inhomogeneity to meet special performance needs and design requirements. However, composite structures are susceptible to a variety of failure modes, including failure of fiber, resin or interface, microbuckling, delamination, etc. In addition, such structures are prone to high local stress at joints, edges, bolt holes, openings, and other geometrical and material discontinuities. These unique characteristics of advanced composite materials present special challenges in designing structural components that are required to efficiently transmit and diffuse primary loads from mounting locations, while maintaining structural integrity and cost effectiveness.

Military ground vehicles, including combat vehicles and tactical vehicles, must endure large vertical and lateral static "g" loads in rough terrain. These loads must be transmitted and diffused efficiently from the mounting points to the support structure. Current design concepts for the interfaces of metal and FRP components in military vehicles mainly rely on mechanical fastening using bolted connections. The pre-load in the bolt provides compression constraint on the FRP laminate and suppresses local bending and/or buckling. However, bolts are susceptible to fatigue failure due to its relatively high stiffness, and to pre-load loss resulting from viscoelastic behavior of the resin material. In structural components subjected to lesser loads, the need to control high stresses near mounting locations often results in global overdesign of structural members.

The challenges presented by the preceding problem may be confronted by a combination of two approaches: (i) exploitation of the strong anisotropy and inhomogeneity of the stiffness and strength properties of FRP composites and flexibility of the preforming process; (ii) expanded use of the adhesive bonding technology aided by design and optimization based on efficient analysis methods for localized stress near edges and material discontinuities.

Although the present study is mainly targeted towards problems related to composite armored vehicles (CAV), the concepts developed and the solutions proposed are believed to be generally applicable to composite automotive and marine structures. In particular, the proposed analysis procedure for evaluating intense localized stresses in critical regions based on the substructuring approach and singularity solutions of multi-material sectors are directly applicable to a wide range of interface and discontinuity problems in composite members and multi-material structures. The methodology of study combines global and local finite element analysis with singular elasticty solutions of critical regions and fracture-mechanics-based failure criteria.

1. PERFORMANCE REQUIREMENTS OF COMPOSITE ARMORED VEHICLES (CAV) AND THE IMPACT ON STRUCTURAL DESIGN

The major considerations in the concept development of Composite Armored Vehicles (CAV) that have significant impact on structural design are summarized in the following, along with their implications.

(1) Mobility and rapid deployment This is the main drive for employing a light weight composite vehicular structure. The potential for weight savings, performance enhancement, parts

consolidation and resistance to environmental attacks makes advanced composite materials particularly attractive for structural automotive applications and new generations of military ground vehicles [1-3]. However, composite structures are susceptible to a variety of failure modes and prone to high local stresses at joints, edges, bolt holes, openings, and other geometrical and material discontinuities. These unique characteristics present special challenges in designing structural components that are required to efficiently transmit and diffuse primary loads while maintaining structural integrity and cost effectiveness.

(2) Signature management Low radar cross-section (RCS) requirement dictates that the external surface of the vehicle be composed of a limited number of large flat plates generally devoid of concave or convex curvatures. This in turn leads to a structural configuration of upper and lower hulls composed of large flat laminates with or without stiffeners, while prohibiting the use of curved panels and shell structures that may be more efficient in transferring and diffusing torsion and out-of-plane shearing forces.

(3) Heavy operating loads and severe environment The major design loads are those associated with suspension attachments, gun-firing, ballistic shock and mine blast, airdrop and transportation life cycle fatigue, tree impact and other accidental shock loads. Large vertical and lateral dynamic loads in rough terrain operation cause severe stresses and fatigue, particularly in various adhesively bonded and mechanically fastened structural joints. Material degradation and fatigue in critical regions may be aggravated by harsh environment associated with extreme temperature and humidity.

(4) Manufacturability and repairability CAV depends on efficient, cost effective manufacturing processes to meet size, complexity, shape, strength and other structural requirements. Provisions for inspection and repairability are important considerations affecting material selection and structural design.

2. INNOVATIVE DESIGN CONCEPTS AND STRUCTURAL TAILORING

The challenges presented by the stringent performance requirements of CAV may be confronted by several approaches including improvement in the materials, the interphase and mechanical fastening fixtures. Other promising solutions include increased use of adhesive bonding and advanced joining technology, local strengthening and innovative design of the mounting mechanisms, laminates and stiffeners. While the viability and effectiveness of the various approaches depend on the structural configuration and function, the best approach must exploit new developments in materials, adhesives, and processing technology, and make ingenious use of the unique characteristic inherent in a laminated construction, including heterogeneity, strong anisotropy in stiffness and strength, and flexibility in forming optimal structural shapes.

The shape, thickness and ply configuration of composite laminate may be modified and varied spatially, subject to practical constraints, to facilitate transfer of load from mounting locations. Efficient load diffusion is characterized by reduced total weight, member cross-section area, or other cost measures, without exceeding allowable stress and other design limits. Starting from a tentative design, sensitivity analysis may be performed to assess the effects of changing design parameters and to guide the search for a better or optimal solution.

In an anisotropic laminate the preferred direction for load transmission follows the local direction of maximum stiffness. The efficiency of load diffusion may be controlled by varying stiffness and axes of anisotropy. Laminate thickness, ply orientation and fiber concentration may be suitably tailored using structural optimization schemes. New manufacturing technologies including fiber placement and the use of woven and braided composites allow selective enhancement of stiffness and strength in preferred directions and in critical regions to facilitate stress redistribution along optimal paths. Furthermore, various types of stiffeners may be used to enhance strength and stiffness of flat laminates under torsion and out-of-plane shear loads. Since the suggested solutions generally involve interfacing of dissimilar and heterogeneous material regions, or otherwise introduce local discontinuities in geometry and material, the issues of interface and bond strength again become crucial.

3. CRITICAL ISSUES IN STRUCTURAL DESIGN OF CAV -- INTERFACE STRENGTH AND DURABILITY OF COMPOSITE JOINTS

Except for the regions associated with the mounting points of primary loads, the various separate components of the CAV structure are in general adequately designed for operating loads when the requirements for defeating ballistic threat are met. The critical issue is the strength and damage tolerance of structural joints connecting, and transmitting loads among, the major vehicular components. The composite technology survey and integration study of CAV by United Defence Ground Systems Division [4] proposed structural subelement test plan in five critical regions including turret ring/top plate, trunnion mount/turret bulkheads, upper hull/lower hull side joint, suspension and final drive attachments. The evaluation criteria for all eleven subelement tests of the critical regions involve, without exception, joint and interface response (see Table 5-50 of Ref. [4], "Critical structure test summary", p. 5-104).

Recognizing the crucial importance of joint strength and interface response and the need to minimize metallic fasteners for the sake of improving weight efficiency, producibility and signature reduction, the previously mentioned report further suggests the use of finite element models of joint regions to evaluate local stress concentrations associated with in-plane or interlaminar stresses. Although the suggested approach is appropriate for evaluating in-plane stress concentration, *it is wholly inadequate for addressing the more threatening issue of interlaminar stresses and interfacial failure*. This is because the stresses near joint edges and bolt hole boundaries reach exceedingly high levels and show singular behavior in an elasticity analysis. Generalized stress intensity factors and other measures of interfacial action, which properly indicate the severity of stress singularity, *bear no relation to the nominal (average) stresses across the joint area, or to the apparent peak stress values resulting from finite-element analysis*. A local singularity analysis based on anisotropic elasticity or more refined material models is the only valid approach to correctly assess the criticality of interlaminar stress concentration at joint edges and bolt hole boundaries [5].

4. SUGGESTED FOCUS OF FUTURE STUDY

According to the preceding arguments, the strength and performance of the various joints that transmit primary loads may be identified as the dominant issue affecting the structural integrity of CAV. Consequently, it is suggested to focus future study to the analysis and evaluation of the various joints and interfaces in the loading path, and to novel concepts and improved design of joint configurations. Although structural tailoring concepts and optimization schemes are considered no less important and effective for achieving proper transfer and diffusion of loads, it was decided to defer detailed investigations of these matters to the Phase II study because the methodology and the resulting benefits are expected to be more predictable. In contrast, it is perceived that there is currently insufficient attention to, and understanding of, stress concentration at joint edges and its relation to interface failure behavior, and that more dramatic and cost-effective improvements in structural strength and performance may result from a focused study of this issue.

It is well known that the peeling and shearing stresses in the thin adhesive layer of an axially-loaded, adhesive-bonded joint are not uniformly distributed along the length of the joint but assume very high values at the two ends where an elasticity solution predicts singularity of stress. Hence joint failure is not governed by a criterion of maximum stress; it is determined by intense interlaminar stresses in an immediate vicinity of the joint edge. Contrary to common expectation, increasing joint length has very little effect on alleviating stress concentration near the end edges. On the other hand, significant changes of the stress in the adhesive layer may be caused by altering the local geometry including edge inclination, adhesive layer thickness, the elastic moduli of the adhesive, the anisotropic elastic properties and fiber orientation angle of the adherends. These effects provide opportunities to control interlaminar action and to suppress edge delamination by appropriate material selection and modification of joint geometry. However, such improvements can only be realized with the development of (i) efficient and accurate analysis methods for assessing joint stresses and (ii) realistic interfacial failure criteria for predicting damage initiation and crack growth.

5. ADHESIVE BONDING AND MECHANICAL FASTENERS

Adhesive bonding of composite structures show many advantages in aerospace applications and are gaining emphasis in the technology development of automotive composites [1]. New high strength adhesives are available with the effect that failure of composite adherends occurs before adhesive failure. Experimental tests of bonded double-strap joints with beveled covered plates using American Cyanamid FM 73 film adhesive demonstrated high load capacity and performance of an adhesive scarf joint for thick FRP laminates, making it an effective alternative or complementary solution to mechanically fastened joints under severe loads [6]. Furthermore, local stress concentration near the edges of bonded joints may be significantly alleviated by using adhesive interleaves between critical plies [7,8].

Bolted joints in composite laminates have a number of possible failure modes and the strength and durability of bolted laminates may be affected by many factors including laminate and hole geometry, bolt preload and the use of restraining plates and washers [9-11]. Current methods for enhancing the strength and durability of mechanical fasteners in aerospace metallic structures include washer reinforcement, teflon coating, interference-fit holes, high-fatigue-life bushing and bearing [12,13]. It should be emphasized that bolt failure is generally preceded by severe local deformation which induces debonding of adhesive and delamination. Hence a key consideration in bolt design for composite laminates is to provide restraints for suppression local deformation and edge stresses around the bolt hole boundary. A singularity analysis of a simplified model that dramatically suggests the effectiveness of bearing restraint for suppressing free-edge peeling action has been completed in a related study.

6. CRITERIA AND METHODOLOGY FOR REACHING OPTIMAL DESIGNS

Because the strength and damage tolerance of joints and interfaces are considered as dominant issues for CAV structures, numerical measures of the criticality of a singular stress field must be precisely defined and the criterion of interface failure must be formulated in terms of such measures and on the basis of fracture mechanics concepts. Furthermore, a methodology for computing the various fracture parameters at singularities and for comparing the merits of different designs should be developed. The methodology proposed in this report relies on an analysis procedure comprising the following four steps:

(1) A global structural analysis using conventional finite element codes to obtain the stress and displacement solutions in the structural components traversed by the load path.

(2) Define a local analysis model that includes the joint region, and obtain more accurate solutions of the stresses and displacements within the model using refined finite-element modeling. The boundary conditions of the local analysis model are obtained from the approximate solutions of the global analysis in Step 1.

(3) For each singularity associated with the intersection of an interface and a free edge, select a bimaterial or multi-material sector centered around the singularity (see Figs. 1-4 of Chapter 2). A rigorous anisotropic elasticity solution of the interfacial stresses within the sector will be obtained based on eigenfunction expansions and the traction boundary data on the circular boundary of the sector. These boundary data are obtained from the local analysis of Step 2. The coefficient of the leading eigenfunction yields the generalized stress intensity factors.

(4) Develop a fracture-mechanics-based interface failure criterion in terms of the singular solutions of the interfacial stresses near the free edge, and apply the criterion to the solution of step 3 to assess the criticality of interfacial action and to predict the load level associated with the initiation and growth of interface crack.

This analysis procedure makes effective use of the substructuring method (Steps 1 and 2) to significantly reduce the size of global structural analysis problem. It also exploits the highly localized nature of free edge singularity, which implies that the singular elasticity analysis of Step 3 may be essentially decoupled (without incurring appreciable error) from the local finite-element analysis of Step 2 and that an iteration process will not be needed. Finally, Step 4 introduces a fracture-mechanics-based failure criterion to predict accurately and realistically the load level associated with interfacial failure.

The rigorous analysis procedure described above is not only desirable from a mechanistic viewpoint, it is also exceedingly efficient because no iteration process is needed in going through the two levels of substructuring. The finite element analyses of the first two steps may be implemented on work stations using standard codes such as ANSYS, it may even be performed on personal computers using simplified versions of finite element codes (as done in Chapter 2 and verified by bench mark solutions). The singular elasticity solution of Step 3 requires extensive symbolic algebraic manipulations but only an insignificant amount of numerical computation, both can be achieved using the *Mathematica* software on a personal computer.

7. DESIGN PARAMETERS OF ADHESIVE-BONDED JOINTS AND THEIR EFFECTS

The strength, performance (as measured by joint efficiency) and durability of adhesive composite joints depend on the joint geometry, adhesive thickness and mechanical properties, strength and stiffness of the adherends, and other factors. A variety of design alternatives including lap, strap, stepped and scarf joints (single or double; simple, beveled or radiused) may be considered in selecting the joint configuration.

As mentioned previously, interlaminar failure in composite joints and interfaces is not governed by a criterion of maximum stress but is rather determined by the energy release rate and other fracture parameters associated with the singularity solution at the free edge or crack tip. Fracture toughness (i.e., the critical level of the energy release rate at crack growth) depends on the adhesive material and, in case of metallic adherends, is strongly influenced by surface treatment. Most polymeric materials have low fracture resistance in mode I (peeling) action. The mode I fracture toughness of toughened adhesives, such as the elastomer-modified epoxies, may be an order of magnitude greater than that of brittle adhesives, even though the fracture toughness associated with the shear modes are comparable for the two types of adhesives. Interleaving with toughened layer may significantly increase joint strength. The mechanical behavior of toughened adhesives is distinctly nonlinear.

Renton and Vinson [14] showed that significant changes in the stress of the adhesive layer may be caused by altering the overlap length, adhesive layer thickness, the elastic moduli of the adhesive, the anisotropic elastic properties and fiber orientation angle of the adherends. The effect of bond thickness on joint stress was further studied by Ojalvo and Eidinoff [15]. Yin [16] studied the effect of free edge inclination and found that changes in the inclination angle may drastically affect the interlaminar stresses. The question of optimal parameters (bond length, tapering angle of the adherends, etc.) and optimal joint profiles were further investigated by Lerchenthal [17], Cherry and Harrison [18], Thamm [19] and others. The analysis methodology developed in this study may be used to achieve optimal or improved design of joints based on the results of parametric studies and sensitivity coefficients.

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