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PROGRESSIVE FRACTURE OF LAMINATED FIBER–REINFORCED COMPOSITE STIFFENED PLATE UNDER PRESSURE

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ABSTRACT

S-Glass/epoxy laminated fiber-reinforced composite stiffened plate structure with laminate configuration $(0/90)_5$ was simulated to investigate damage and fracture progression, under uniform pressure. For comparison reasons a simple plate was examined, in addition with the stiffened plate. An integrated computer code was used for the simulation. The damage initiation began with matrix failure in tension, continuous with damage and/or fracture progression as a result of additional matrix failure and fiber fracture and followed by additional interply delamination. Fracture through the thickness began when the damage accumulation was 90%. After that stage, the cracks propagate rapidly and the structures collapse. The collapse load for the simple plate is 21.57 MPa (3120 psi) and for the stiffened plate 25.24 MPa (3660 psi).

INTRODUCTION

The aircraft, marine and automotive industries use stiffened composite plates because of their low weight, high stiffness, and stability. Design considerations with regard to the durability stiffened plates require an a priori evaluation of the damage initiation and propagation mechanisms under expected service loads. Concerns of the safety and survivability of critical components require quantifications of the composite structural damage tolerance during overloads. Characteristic flexibilities in the tailoring of composite structures make them more versatile for fulfilling structural design requirements. However, these same design flexibilities render the assessment of composite structural response and durability more complex, prolonging the design and certification process and adding to the cost of the final product. It is difficult to evaluate composite structures because of the complexities in predicting their overall congruity and performance, especially when structural degradation and damage propagation occur. The prediction of damage initiation, damage growth, and propagation to fracture are important in evaluating the load-carrying capacity, damage tolerance, safety, and reliability of composite structures. Quantification of the structural fracture resistance is also required to evaluate the durability/life of composite structures. The most effective way to obtain this quantification is through integrated computer codes that couple composite mechanics with structural analysis and damage progression models. GENOA computer code was used in this study. The code is an updated and improved version of CODSTRAN computer code [1]. The simulation of progressive fracture has been verified to be in reasonable agreement with the experimental data, such as damage progression in carbon fiber reinforced plastic I-beams [2] and carbon/carbon composite plate specimen subjected to three-point bending [3]. A variety of composite structures used to simulate the damage progression such as: stiffened adhesively bonded composite structures [4], damage progression in bolted composite structures [5], damage tolerance of composite pressurized thin shell structures [6], and progressive fracture of laminated fiber-reinforced composite stiffened plate under mechanical and thermo-mechanical loads [7] to [9].

The purpose of this paper is to perform computational simulation to S-Glass/epoxy laminated reinforced-fibers composite structures (a stiffened plate and a simple plate) subjected to pressure load, in order to predict the damage progression, fracture thought the thickness and propagation to final fracture of the structures.

METHODOLOGY

The computational simulation is performed by coupling three modules: (1) composite mechanics, (2) finite element analysis, and (3) damage progression tracking. The damage progression module relies on the composite mechanics code ICAN [10] for composite micromechanics, macromechanics and laminate analysis, and calls a finite element analysis module that uses anisotropic thick shell elements to model laminated fiber-reinforced composite structures. The finite element module is based on the mixed finite element method [11]. By supplying the boundary conditions, the type of analysis desired, the applied loads, and the laminate properties, the module performs the structural analysis. In addition the finite element module provides the computed stress resultants to composite mechanics module, which continuously computes the developed ply stresses for each ply and checks for ply failure.

A computational simulation cycle begins with the definition of constituent properties from a material databank. Composite ply properties are computed by the composite mechanics module. The composite mechanics module also computes through-the-thickness structural properties of each laminate. The finite element analysis module accepts the composite properties that are computed by the composite mechanics module at each node and performs the analysis for a load increment. After an incremental finite element analysis, the computed generalized nodal force resultants and deformations are supplied to the composite mechanics module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate. Individual ply failure modes are determined using failure criteria associated with a) the negative and positive limits of the six ply stresses components (the in plane stresses (σ_{l11}, σ_{l12}, σ_{l22}) and the interlaminar stresses (σ_{l33}, σ_{l13}, σ_{l12})) b) a modified distortion energy (MDE) combined stress failure criterion, and c) interply delamination due to relative rotation of the plies.

The generalized stress-strain relationship for each node are revised according to the composite damage evaluated by the composite mechanics module after each finite element analysis. The model is automatically updated with a new finite element mesh and properties, and the structure is reanalyzed for further deformation and damage. If ply failure criteria indicate new or additional damage during a load increment, the damage tracking module degrades the composite properties affected by the damage and reanalyzes the structure under the same load. When there is no indication of further damage under a load, the structure is considered to be in equilibrium. Subsequently, another load increment is applied leading to possible damage growth, accumulation, or propagation. In the computational simulation cases presented in this paper, analysis is stopped when commencement of the damage propagation phase is indicated by laminate fracture. Laminate fracture is predicted when major principal failure criteria are met for all plies at a node. After laminate fracturing, the composite structure is anticipated to enter a final damage propagation stage that leads to ultimate structural fracture or collapse.

LAMINATED FIBER-REINFORCED COMPOSITE STRUCTURES

The structure used for this investigation is a continuous fiber-reinforced laminated composite stiffened plate (fig. 1).

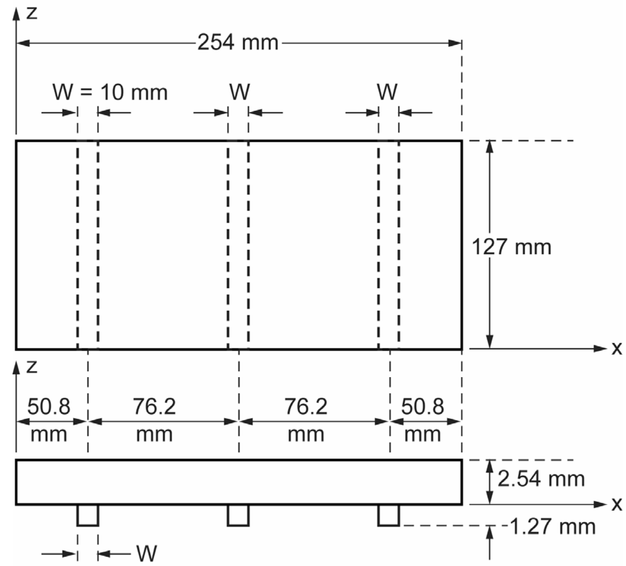

Figure 1. A laminated fiber–reinforced composite stiffened plate.

The length of the stiffened plate is 254 mm (10 in.) and the width is 127 mm (5 in.). The panel and the stiffened bands are made of the same polymer matrix composite materials S-Glass fiber and high strength (IMHS) epoxy matrix. The S-Glass fiber and epoxy matrix properties are given in tables 1 and 2. The fiber volume ratio is 0.60. The skin laminate of the panel consists of ten 0.254 mm (0.01 in.) plies, resulting in a composite thickness of 2.54 mm (0.10 in.). The laminate configuration is cross-ply [0/90]5.

Table 1. S-Glass Fiber Properties

Number of fibers per end	200
Fiber diameter, mm (in)	0.00762 (0.3×10^{-3})
Normal modulus, GPa (psi)	
Longitudinal	85.5 (12.4×10^{6})
Transverse	85.5 (12.4×10^{6})
Poisson's ratio	
ν_{12}	0.20
ν_{23}	0.20
Shear modulus, GPa (psi)	
G_{12}	35.67 (5.17×10^{6})
G_{23}	35.67 (5.17×10^{6})
Thermal expansion coefficient, /°C (/°F)	
Longitudinal	0.509×10^{-5} (0.280×10^{-5})
Transverse	0.509×10^{-5} (0.280×10^{-5})
Heat conductivity, J-m/hr/m^2/ °C (Btu-in./hr/in.^{2}/°F)	
Longitudinal	(5.208×10^{-2})
Transverse	(5.208×10^{-2})
Heat capacity, J/Kg/°C (Btu/lb/°F)	712 (0.17)
Strength, MPa (Ksi)	
Tensile	2482 (360)
Compressive	2068.33 (300)

Table 2. IMHS Epoxy Matrix Properties

Matrix density, Kg/m^3 (lb/in.^{3})	3×10^{-7} (0.0443)
Normal modulus, GPa (ksi)	3.394 (500)
Poisson's ration	0.35
Coefficient of thermal expansion, /°C (°F)	0.7704 (0.428×10^{-4})
Heat conductivity, J-m/hr/m^2/°C (Btu-in./hr/in.^{2}/°F)	(8.680E–03)
Heat capacity, J/Kg/ °C (Btu/lb/ °F)	738 (0.250)
Strength, MPa (Ksi)	
Tensile	103.41 (15.)
Compressive	241.3 (35.)
Shear	89.62 (13.)
Allowable strain	
Tensile	0.02
Compressive	0.05
Shear	0.045
Torsional	0.045
Void conductivity, J-m/hr/m^2/°C (Btu-in./hr/in.^{2}/°F)	16.8 (0.225)
Glass transition temperature, °C (°F)	216 (420)

The stiffened bands well bonded to the lower surface of the panel. The stiffened band has laminate configuration $[0/90]_5$, with ply thickness equal to 0.127 mm (0.005 in.) resulting in a total thickness equal to 1.27 mm (0.05 in.).

For comparison reasons a simple plate was used with the same polymer matrix composite materials, and geometry as the stiffened plate, (fig. 5). The thickness of the laminate plate is uniform equal to 2.54 mm (0.10 in.).

The 0^o plies are in the X-axis (fig. 1), the first ply (0°) lays at the bottom surface of the plate, while the last ply (90°) lies at the top surface of the plate.

The stiffened plate as well as the simple plate are loaded with a transverse and uniform pressure. The boundary conditions are fixed supported.

The finite element mesh consists of 396 elements and 442 nodes. Thick shell element was used for the computational simulation.

RESULTS AND DISCUSSION

Damage initiation and progression were monitored as the panel was gradually loaded with the pressure.

Damage Initiation

Damage initiation at the plies started at applied load 0.552 MPa (80 psi) with matrix failure due to transverse tensile failure mode, at the stiffened plate as well as at the simple plate.

At the stiffened plate, the damage initiation started mainly in the middle stiffener. Damages also developed at the panel areas close to the center of the plate, and at the locations close to the boundaries. The failure of the plies at the panel occurred at the bottom ply (0°) and the top ply (90°), and at the middle stiffener at the bottom ply (0°), the 3rd ply (0°) and the 19th ply (0°).

At the simple plate, the damage initiation started mainly in the middle of the plate in the longitudinal direction and at the locations close to the boundaries. The failure of the plies occurred at the bottom ply (0°) and at the top ply (90°).

Fracture Initiation and Collapse of the Structure

In general, overall structural damage may include individual ply damages and through-the-thickness fracture of the composite laminate. A scalar damage variable, derived from the total volume of the composite material affected by the

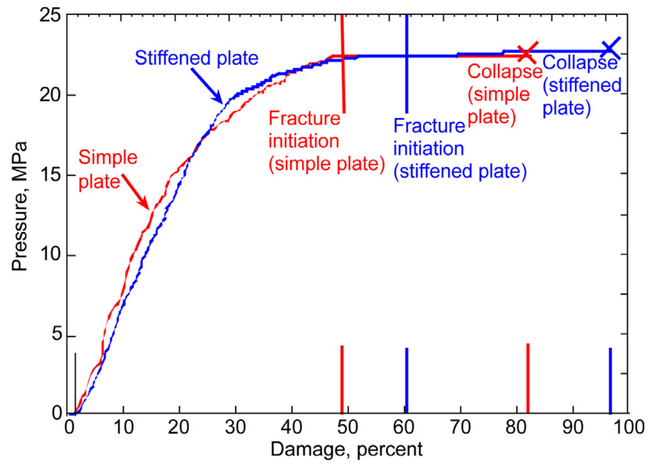

Figure 2. Damage progression under pressure S-Glass/Epoxy $[0/90]_5$. Stiffened plate and simple plate.

various damage mechanisms, is also evaluated as an indicator of the level of overall damage induced by loading. This scalar damage variable is useful for assessing the overall degradation of a given structure under a prescribe loading condition. The rate of increase in the overall damage during composite degradation may be used as a measure of the structural propensity for fracture. The damage progression of the stiffened plate (and simple plate) as a function of the applied load is shown in figure 2. In our studies, damage is defined as the volume of the damaged plies divided by the total volume of the structure.

As the damage accumulation is increased and the percentage of the damaged reached the amount of 90%, the plies extensively damaged due to matrix cracking, fiber fracture and interply delamination at the stiffened plate (and the simple plate). The fracture through the thickness initiated first at the simple plate at 12.89 MPa (1870 psi), (fig. 2), at the middle stiffener figure 3. At the stiffened plate the fracture initiation started at 15.72 MPa (2280 psi) (fig. 2), at the two panels figure 4.

After the fracture initiation, the cracks propagate rapidly and collapse of the structures occur at 21.57 MPa (3120 psi) at the simple plate and at 25.24 MPa (3660 psi) at the stiffened plate, figure 2.

Another measure to evaluate the structural resistance against damage propagation at different stages of loading is the global Damage Energy Release Rate (DERR). DERR is the ratio of the incremental work done by external forces to the incremental volume of damage created during a load increment that causes damage. The DERR gives useful information on the changes in the rate of energy used for the creation of unit damage. Figure 5 shows the DERR as a function of the pressure. The DERR usually reaches its peak value when global failure occurs. The composite stiffened plate reaches the first peak of DERR when fracture through the thickness initiates, by increasing the applied pressure another high peak of DERR occurs due to the high fracture growth. Increase the load further the fracture growth is stable and the DERR becomes minimum, but again when the fracture growth becomes unstable and increases rapidly new high peaks occurred in the DERR and finally the structure collapses.

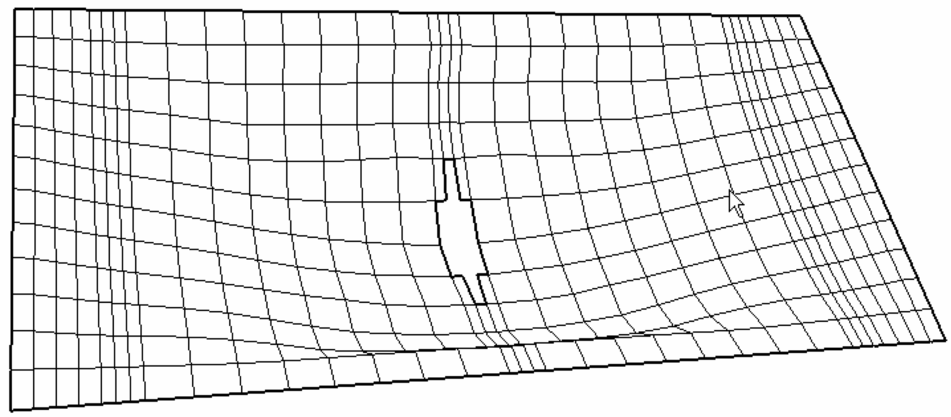

Figure 3. Fracture initiation at P = 12.89 MPa (1870 psi). Simple plate S-Glass/Epoxy $[0/90]_5$.

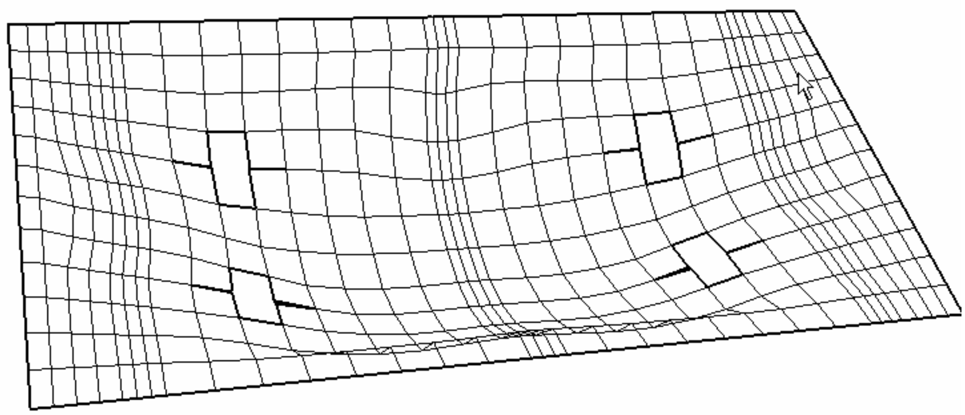

Figure 4. Fracture initiation. P=15.72 MPa (2280 psi). Stiffened plate S-Glass/Epoxy $[0/90]_5$.

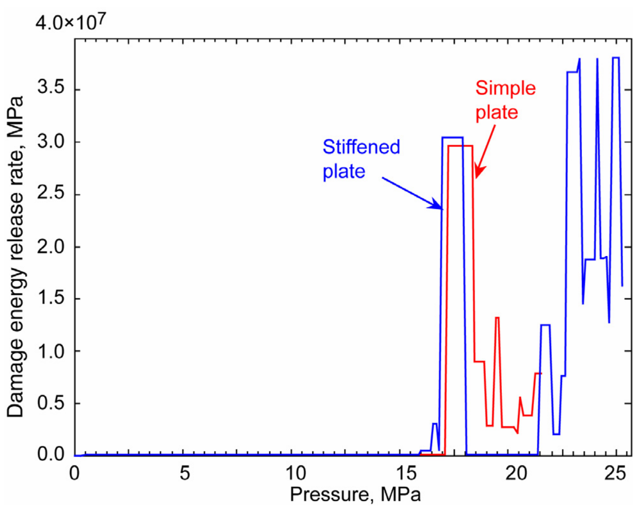

Figure 5. Damage energy release rates under uniform pressure S-Glass/Epoxy $[0/90]_5$. Stiffened plate and simple plate.

The composite simple plate reaches the maximum peak of the DERR at 17 MPa, because the fracture growth becomes unstable and increases rapidly. After that point the structure is loosing its resistance and strength, further fracture growth rapidly occurs and expressed by the two peaks of DERR and finally the structure collapses.

CONCLUSIONS

A computational simulation was used to evaluate the structural and damage progression response of a $[0/90]_5$ laminated fiber-reinforced composite stiffened plate (and a simple plate) under pressure. The following results were obtained:

1. Damage initiation began at low load level 0.552 MPa (80 psi) with matrix failure in tension at the plies, due to the transverse tensile failure mode, in both structures. At the stiffened plate, the matrix failure occurred at the panel at the bottom ply (0°) and at the top ply (90°) and at the middle stiffener at the bottom ply (0°), the 3rd ply 0° and the 19th ply (0°). At the simple plate, the matrix failure started at the bottom ply (0°) and at the top ply (90°).

2. Fracture through the thickness began, when 90% of the plies of the structures damaged, due to matrix cracking, fiber breaking and interply delamination. The fracture load for the simple plate was 12.89 MPa (1870 psi) and for the stiffened plate 15.72 MPa (2280 psi).

3. The fracture initiation followed by a rapidly crack growth resulting in the collapse of the structures. The collapse load at the simple plate was 21.57 MPa (3120 psi) and at the stiffened plate 25.24 MPa (3660 psi).

4. The stiffened plate had better damage tolerance than the simple plate.

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