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First ply failure analysis of laminated composite thin hypar shells using nonlinear finite element approach

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A R T I C L E I N F O

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A B S T R A C T

In this paper the nonlinear finite element approach is used to solve the problems of first ply failure of laminated composite skewed hypar thin shell roofs. The geometrically nonlinear strains terms are incorporated in the present finite element code which is validated through solution of the problems solved and published by earlier researchers. The first ply failure loads of the industrially popular, aesthetically appealing hypar shells are studied meticulously for varying aspect ratios and thicknesses for clamped boundary condition. The paper gives specific recommendations regarding choice of linear and nonlinear approaches for obtaining failure loads in different specific cases.

1. Introduction

In the last three decades, the laminated composites have gained immense popularity in different weight sensitive engineering branches including civil engineering applications. As a natural consequence, a good number of papers on composites have come up which discuss characterisation of these materials from different practical angles. High fatigue strength, capacity of being assembled fast, high strength to weight and high stiffness to weight ratios, less susceptibility to thermal expansion and low decay due to weathering actions and moisture make the laminated composites a lucrative material to the practicing structural engineers. One of the application areas of laminated composites is about fabricating civil engineering thin plate and shell surfaces to be used as roofing units. Doubly curved thin shells are architecturally appealing and frequently favoured for roofing large column free open areas. Among the shells, the doubly curved skewed hypar shell apart from being good looking is a doubly ruled anticlastic surface and easy to cast and fabricate. However, most of the researchers have focussed on composite plates and some of them have worked on cylindrical and spherical shells only. Researchers like Nayak and Bandyopadhyay [1], Neogi et al. [2], Sahoo and Chakravorty [3] and Kumar et al. [4] studied some important aspects on laminated composite hypar shells considering geometrically linear finite element formulation. The free vibration responses of the stiffened hypar shells and the impact studies of unstiffened hypar shells were reported by Nayak and Bandyopadhyay [1] and Neogi et al. [2] respectively. On the other hand the static responses including the deflections and stresses of stiffened and unstiffened hypar shells considering different geometry, boundary conditions and stacking sequences were reported by Sahoo and Chakravorty [3] and Kumar et al. [4] respectively.

Since the last two decades many researchers have concentrated on the failure of composite materials. Research reports on composites establish that the failure of composites is progressive in nature and the ultimate ply failure load of a composite laminate is significantly greater than the first ply failure load. These findings were come out from the research activities carried out by Reddy et al. [5], Singh and Kumar [6], Padhi et al. [7], Pal and Ray [8], Prusty [9], Kelly and Hallström [10], Akhras and Li [11] and Ganesan and Liu [12]. The progressive failure of marine glass fiber reinforced plastic (GFRP) laminates subjected to out-of-plane static and impulsive water pressure respectively were investigated by Chung and Lee [13,14]. The ultimate strength analysis of simply supported, rectangular, composite plates under in-plane compressive load was carried out by Yang and Hayman [15]. The authors established an efficient, semi analytical method based on large deflection theory and first order shear deformation theory with linear degradation of the material properties. A finite element model was proposed by Chen et al. [16,17] to study progressive failure of laminated composites. The proposed model considered elasto plastic damage including plasticity effects exhibited by composite materials. The authors first developed the model considering in-ply damage only [16] and later modified it to account for delamination damage also [17]. Falzon and Apruzzese [18] proposed a progressive intralaminar failure methodology to simulate damage growth of laminated composite materials and some structural applications of this progressive failure model on

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Nomenclature

X, Y, Z	Global coordinate axes.
1, 2, 3	Local coordinate axes.
a, b, c	Length and width in plan and rise of hypar shell.
R_{xy}, h	Radius of cross curvature and total thickness of shell.
A	Area of shell.
ε_x, ε_y	In-plane strains along X and Y axes of the shell.
γ_{xy}, γ_{xz}, γ_{yz}	In-plane and transverse shear strains, respectively.
κ_x, κ_y, κ_{xy}	Curvatures of the shell due to loading.
$\{d_e\}$	Element displacement field.
N_x, N_y, N_{xy}	In-plane normal and shear force resultants.
M_x, M_y, M_{xy}	Bending moment and torsional moment resultants.
Q_x, Q_y	Transverse shear resultants.
np	Total number of ply.
z_k, z_{k-1}	Top and bottom distances of the k^{th} ply from mid-plane of a laminate.
$[B]$, $[B']$	Linear and nonlinear parts of the strain displacement matrix.
$[\overline{B}]$	Strain displacement matrix.
$[K]_T$, $[K]_S$	Tangent and secant stiffness matrices respectively.
$[K]_L$	Linear stiffness matrix.
σ_1, σ_2, τ_{12}	Normal stresses along 1 and 2 axes and shear stress acting on 1–2 surface of a lamina, respectively.
ε_1, ε_2, γ_{12}	In-plane normal strains along 1 and 2 axes and shear strain acting on 1–2 surface of a lamina, respectively.
E_{11}, E_{22}, E_{33}	Modulus of elasticity along the directions 1, 2 and 3.
G_{12}, G_{13}, G_{23}	Shear modulus of a lamina in 1–2, 1–3, and 2–3 planes corresponding to the local axes of that lamina, respectively.
ν_{ij}	Poisson's ratio.
σ_{1T}^u, σ_{2T}^u	Ultimate normal tensile stresses along 1 and 2 direction, respectively.
σ_{1C}^u, σ_{2C}^u	Ultimate normal compressive stresses along 1 and 2 direction, respectively.
ε_{1T}^u, ε_{2T}^u	Ultimate normal tensile strains along 1 and 2 direction, respectively.
ε_{1C}^u, ε_{2C}^u	Ultimate normal compressive strains along 1 and 2 direction, respectively.
τ_{12}^u, τ_{13}^u, τ_{23}^u	Ultimate shear stress values in 1–2, 1–3, and 2–3 planes corresponding to the local axes of that lamina, respectively.
γ_{12}^u, γ_{13}^u, γ_{23}^u	Ultimate shear strain values in 1–2, 1–3, and 2–3 planes corresponding to the local axes of that lamina, respectively.

composite plates were implemented later [19]. The authors [19] also highlighted the importance of considering the nonlinear behaviour in shear by comparing the model proposed by them with the Hashin's model.

In order to confidently apply the laminated composite shell roofs in practical industrial conditions, a practicing engineer should know its load carrying capacity before failure initiates. The laminated composites are weak in transverse shear and failure may initiate due to normal static overloading at any inner lamina or interface and remain undetected and unattended. Such latent damages may lead to sudden catastrophic collapse under service conditions. Thus, the first ply failure of laminated composite shell roofs is important to study. The analytical and experimental first ply failure loads of laminated pressure vessels subjected to internal pressure loads were investigated by Chang [20] and later Chang and Chiang [21] reported the first ply failure loads of anti-symmetrically laminated composite plates subjected to central point loads. Different case studies of laminated composite plates were presented by Nali and Carrera [22] in order to compare the failure results corresponding to the different two dimensional popular failure criteria including Hashin's criterion subjected to mono-axial and biaxial loadings. Coelho et al. [23] worked on punctured laminated composites under in-plane tension load and predicted damage initiation using the Hashin's failure criterion. Lal et al. [24] evaluated nonlinear stochastic first ply failure response of composite plate under compressive loading, using classical failure criteria proposed by Tsai-Wu and Hoffman for random input material and strength properties. Gadade et al. [25,26] used this stochastic first ply failure study considering material nonlinearity under hygro thermal environment and different biaxial loadings. Clamped, simply supported and hinged end conditions of plates were taken up. They used Puck's failure criterion. Prusty et al. [27,28] reported first ply failure of composite cylindrical and spherical shells with and without stiffeners. First ply failure prediction of an internally pressurized shell was carried out by Gohari et al. [29]. They studied theoretical and analytical failure loads of unsymmetrically laminated ellipsoidal woven GFRP composite shell. Gohari et al. [30] studied failure of a circular cylindrical thin walled shell made of GFRP composite subjected to static internal and external pressures. Deformation, delamination, shear deformation and micro buckling failure were investigated. Reinoso and Blázquez [31] reported the post buckling responses of a composite cylindrical stiffened panel subjected to uniform pressure load employing geometric nonlinearity. Wagner and Balzani [32] studied the post buckling response of a stringer-stiffened laminated composite cylindrical airframe panel under axial compression using Hashin's criterion considering both geometric and material nonlinearities. The failure behaviour of sandwich walled cylindrical shells with metallic lattice truss cores and fiber reinforced composite face sheets under uniaxial compression were discussed by Xiong et al. [33]. Adali and Cagdas [34] reported the linear first ply failure loads of laminated composite singly and doubly curved shell panels subjected to static loading. Maimí et al. [35] proposed a new constitutive model for the prediction of the onset and growth of intralaminar failure mechanisms in composite laminates under plane stress condition using a simplification of the LaRC04 failure criteria. A three dimensional consistent anisotropic damage model for laminated fiber reinforced composites based on the Puck's failure criterion was established by Reinoso et al. [36]. The damage model was modified with a transverse shear and trapezoidal locking free solid shell formulation by the Assumed Natural Strain (ANS) method in order to account for geometrically nonlinear effects in thin walled applications. Bakshi and Chakravorty [37,38] calculated the first ply failure loads of composite conoidal shells considering geometrically linear strains and composite cylindrical shells considering geometrically nonlinear strains respectively. Arciniega and Reddy [39] reported a tensor based geometrically nonlinear finite element formulation considering transverse stretching, thus establishing a three dimensional constitutive relationship. The Sander's geometrically nonlinear strain theory and arc – length method was adopted by Zhao and Liew [40] to report displacements and axial stresses of isotropic and functionally graded cylindrical shells subjected to mechanical and thermal loading. Xue et al. [41] presented an extension of Karman – Donnell's theory for non-shallow, long cylindrical shells undergoing large deflection. The governing equation was derived by considering the influence of initial curvature of the shell. The von – Karman's nonlinear theory and total Lagrangian approach were combined with first order shear deformation theory by Van et al. [42] to study displacements of simply supported and clamped square and circular laminated composite plates and also clamped and hinged composite cylindrical shells.

The review of literature establishes that the study of displacements and stresses of laminated composite plates, cylindrical and spherical shells including the failure aspects of these structural elements have