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First ply failure study of thin composite conoidal shells subjected to uniformly distributed load

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ABSTRACT

The civil engineers often need to cover large column free open spaces with thin shell structures. The doubly curved shells are characteristically stiff and the ruled surfaces are easy to fabricate. The aesthetically pleasing conoidal shells satisfy both these criteria and are preferred by structural engineers. The engineers now look out for strong but lightweight materials and as a result the laminated composites have evolved. The first ply failure is very important issue for laminated composites. Such studies for plates are reported but similar work on thin shells is very scanty. This paper is aimed to fulfill this lacuna.

1. Introduction

Thin shells are capable of covering large unsupported column free areas without any stability problem due to their curved geometry, and are found in shopping malls, airport lobbies, auditoriums and car parking lots. Among different shell forms reported in the literature, the conoidal shells have a preference in the industry as these shell forms are singly ruled surfaces which can be generated by placing straight shuttering between two curved boundaries in the opposite edges. Moreover, the doubly curved conoidal shells are stiffer and aesthetically appealing than the commonly used singly curved cylindrical shells. Further the conoidal shell geometry allows entry of daylight and natural air which make them popular in medicine and food processing units.

Laminated shells are preferred to the civil engineers compared to the isotropic ones due to the high stiffness/strength to weight ratio of the composites. As a result, application of these light weight materials to fabricate shell surfaces reduces gravity forces and mass induced seismic forces. Moreover, laminated composites offer flexibility to optimize the stiffness and strength properties by varying fiber orientations and lamina stacking sequences which made laminated composite conoids even more attractive to the civil engineers.

No wonder a number of researchers are working to explore different behavioral aspects of laminated conoidal shells. Researchers like Nayak and Bandyopadhyay [2–4], Das and Chakravorty [5–8], Kumari and Chakravorty [9,10] and Pradyumna and Bandyopadhyay [11,12] reported static, dynamic and instability behaviors of laminated thin conoidal shells. Free and forced vibration responses of simply supported and clamped stiffened conoidal shells were reported by Nayak and Bandyopadhyay [2–4]. Das and Chakravorty [5–8] reported bending and free vibration studies on laminated conoidal shells with and without stiffeners while bending response of the delaminated graphite-epoxy conoidal shells was reported by Kumari and Chakravorty [9,10]. Static bending and free vibration studies of laminated conoidal shells using higher order shear deformation theory was reported by Pradyumna and Bandyopadhyay [11]. The authors [12] further reported dynamic instability behavior of laminated conoids.

It is important to note here that laminated composites fail in a progressive manner which initiates from the weakest lamina of the laminate and the corresponding load is termed as the first ply failure load. Singh and Kumar [13], Akhras and Li [14] and Ganesan and Liu [15] observed that the load at which the total laminate fails is significantly higher than the first ply failure load. However to ensure design reliability, an engineer should be informed well about the first ply failure load of a laminate as damage initiates at that load and if undetected it may lead to a sudden catastrophic collapse under service conditions. Many researchers felt this and reported first ply failure of laminated composites which are mostly on laminated plates. Pandey and Reddy [16] reported first ply failure of simply supported graphite-epoxy plates subjected to

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Nomenclature

A area of the shell.
a and b length and width of shell in plan respectively.
$\{d_e\}$ element displacement vector.
$\{d\}$ global displacement vector of the shell.
E_{11}, E_{22}, E_{33} elastic moduli.
1,2 and 3 local co-ordinates of a lamina.
G_{12},G_{23}, G_{13} shear moduli.
ne number of elements.
R_{yy} radius of curvature along y axis of the conoidal shell.
R_{xy} radius of cross curvature of the conoidal shell.
T shear strength of a lamina.
T_ε allowable shear strain of a lamina.
V volume of the shell.
X_T and X_C normal strengths of a lamina along the fiber direction in tension and compression respectively.
$X_{\varepsilon T}$ and $X_{\varepsilon C}$ allowable normal strains of a lamina along the fiber direction in tension and compression respectively.
Y_T and Y_C normal strengths of the matrix in tension and compression respectively.
$Y_{\varepsilon T}$ and $Y_{\varepsilon C}$ allowable normal strains of the matrix in tension and compression respectively.
x, y and z global Cartesian co-ordinates of the shell.
$\bar{x}$ x/L
$\bar{y}$ y/L
ε_x,ε_y inplane normal strains of the shell.
ε_1,ε_2 inplane normal strains of lamina.
ε_6 inplane shear strain of lamina.
γ_{xy} inplane shear strain of the shell.
ν_{ij} Poisson's ratio.
σ_1, σ_2 inplane normal stresses.
σ_6 inplane shear stress.
κ_x, κ_y, κ_{xy} curvature changes of the shell due to loading.

uniformly distributed loads. Reddy and Reddy [17] reported first ply failure loads of laminated plates using geometric linear and nonlinear formulations while first ply failure loads for carbon-epoxy unsymmetrical cross ply laminated strips subjected to uniform lateral pressure were reported by Turvey and Osman [18]. Experimental first ply failure loads of laminated plates were first reported by Kam and his colleagues. Kam and Jan [19] reported experimental first ply failure loads for graphite-epoxy moderately thick plates while Kam and Sher [20] and Kam et al. [21] worked on experimental failure loads for thin plates. The authors further compared efficiencies of different numerical methods in predicting failure loads of laminated plates by comparing the theoretical results with the experimental values. The authors used layerwise linear distribution method [19], Ritz method [20] and finite element method [21] to obtain the theoretical failure loads. The finite element method was proved to be the most efficient numerical tool to study the first ply failure of laminated composites as the results obtained using this method showed smallest deviations from the experimental values. Sciuva et al. [22] studied linear and nonlinear first ply failure loads and failure locations of simply supported and clamped graphite-epoxy thick and thin plates. Analytical and experimental first ply failure loads of laminated pressure vessels subjected to internal pressure loads were reported by Chang [23]. Further Chang and Chu [24] worked on experimental and analytical first ply failure loads of laminated composite shafts subjected to bending load, torque load and their combination. First ply failure studies for laminated stiffened plates were reported by Ray and Satsangi [25] and Kumar and Srivastava [26]. Both the authors used the finite element method and geometric linear formulations to get the failure loads. Ray and Satsangi [25] used eight noded plate elements and three noded beam elements to model the plate and the stiffener respectively while six noded triangular plate elements were used by Kumar and Srivastava [26]. They considered blade, I and hat section stiffeners. Recently Chang and Chiang [27] reported experimental and theoretical first ply failure loads of antisymmetrically built laminated composite plates subjected to central point loads and a detailed review on damage modeling and finite element analysis for composite laminates was reported by Zheng and Liu [28]. Thus it is evident that although researchers explored first ply failure characteristics of laminated plates in depth but similar studies regarding composite shells are really scanty. Prusty et al. [29] were the only authors who reported first ply failure of laminated cylindrical and spherical shells with and without stiffeners respectively. The authors combined linear strain displacement relationship with finite element method to obtain the failure loads. It is evident from the literature that there exists void regarding first ply failure loads of composite conoids.

Hence the present paper aims to study first ply failure characteristics of thin laminated composite conoidal shells by finite element approach. Practically encountered uniformly loaded simply supported thin shells are taken up for the present study. Well accepted failure theories like maximum stress, maximum strain, Tsai-Hill, Tsai-Wu and Hoffman failure criterion are used to evaluate the failure loads. Apart from the failure loads, failure locations and failure modes are also presented.

2. Mathematical formulation

2.1. Governing equations

A doubly curved thin laminated composite conoidal shell (Fig. 1) is considered in the present study. The shell has uniform thickness 'h' which may have any number of thin laminae. Fibers in each lamina of the composite shell may be arbitrarily oriented along the local axis of the lamina and at an angle 'θ' with reference to the global x-axis (Fig. 2). The governing equation of a composite shell is derived based on the principle of minimum total potential energy. The total potential energy 'π' is expressed as sum of strain energy 'U' and work done due to external load 'W' as,

$$\pi = U + W \tag{1}$$

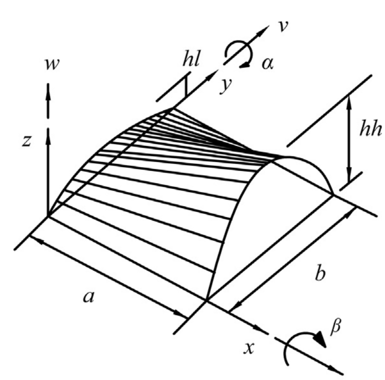

Fig. 1. Conoidal shell.