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Dynamic Buckling of Composite Cylindrical Shells subjected to Axial Impulse

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Abstract— Advanced lightweight laminated composite shells are increasingly being used in modern aerospace structures, for enhancing their structural efficiency and performance. Due to the thin walled construction used, they are susceptible to buckling when subjected to significant static and dynamic or time dependent loadings. While numerous studies are available on the buckling and postbuckling behaviour of isotropic shells, relatively few investigations have been undertaken on the performance of laminated composite shells under dynamic loading conditions. The attempt to design shells to withstand time –dependent dynamic loads, sometimes quite severe, and thus may be susceptible to dynamic buckling is relatively new in aerospace structures. Landing impact of an aircraft is categorized as a dynamic loading condition where instability arises in very short time duration. This paper presents the results of a numerical study on the behaviour of laminated composite circular cylindrical shells under dynamic axial impact loads. Layup sequences, [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°] were used for the current study and their behaviour were compared under impact loading for different time durations.

Index Terms—Aerospace structures, Axial compression, Composites, Cylindrical shells, Dynamic buckling, Impact loads, Numerical study

1 INTRODUCTION

Composites refer to the class of materials formed by combining two or more distinct materials. They are preferred over other isotropic materials basically due to their weight sensitive properties. Laminated fibrous composites are widely used for defence and aerospace applications. Fairings, engine cowlings and radomes of aircrafts and base interface ring and payload fairing of launch vehicles are some areas where laminated composites are mainly employed.

Such structures may be subjected to a wide range of loads, both static and dynamic. Being very thin, they may be subjected to various types of instability conditions such as buckling. Buckling can be broadly classified into two, static and dynamic. Static buckling occurs under static loads and dynamic buckling occurs under dynamic loads. Dynamic buckling is of two types, vibration buckling and pulse buckling. The former is associated with the response of structures to oscillatory loads and the latter relates to the behavior of structures under pulse loads. Pulse buckling is one critical condition where the structure undergoes unacceptably large deformations under short duration.

The predominant force acting in shells erected in an aircraft or spacecraft structure is axial compression which causes buckling. Also, among all types of dynamic loading, the response under short duration forces called impact loads, is less investigated. Dynamic buckling has been studied extensively for many years but studies on structure under impact are very few. Fairly good numbers of studies are available for shells made of isotropic materials under axial impulsive compression. Coppa and Nash [1] conducted studies on the dynamic buckling of shell structures made of aluminium under axial impact loading. The work covered numerical and experimental investigations and a good agreement was recorded in results obtained in both cases. Hutchinson and Budiansky [2] have conducted dynamic buckling studies on long isotropic cylindrical shells imposing imperfections in shells. The results of the work gave an insight on the reduction of load carrying capacity under short duration loading in case of both perfect and imperfect shells. Xu et al. [3] studied local and global buckling phenomenon associated with axial impact dynamic loads on steel cylindrical shells.The work investigated the propagation of buckling waves under axial impact loads by reducing the problem into eigen type and solving using Hamiltonian dual equations.

Composite cylindrical shells are also studied for conditions of dynamic buckling but most works considered loads in lateral direction like hydrostatic pressure. Most of them concentrated on dynamic buckling under long duration pulse loading. Schokker et al. [4] carried out studies in relation with dynamic instability of unstiffened and interior ring stiffened shells under hydrostatic pressure. Shells made of isotropic, orthotropic and anisotropic materials and the response under pulse loads in long duration lateral pulse loads was investigated. The occurrence of unbounded response upon reaching the limiting conditions of dynamic buckling was remarked in the work. Tanov and Tabiei [5] conducted numerical studies on the behaviour of graphite epoxy laminated shells under suddenly applied lateral pressure having cross ply laminate configurations. The length and thickness of the shell was varied and critical loads were calculated. The results of the work revealed that load duration has greater influence on the load carrying capacity of the shell under suddenly applied conditions.

Studies on composite axisymmetric structures are very few under axial impulsive loads. Bisagni and Zimmermann [6] conducted buckling of fiber composite cylindrical shells under axial compression with finite duration of time analytically using commercially available finite element codes. Bisagni [7] has carried out dynamic buckling of fiber reinforced composite shells containing four plies under impulsive axial compression. In practical situations, the numbers of plies are increased in order to reduce the effects of coupling in laminated composites.

The objective of the present paper is to investigate the behaviour

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of thin walled composite circular cylindrical shells under impulsive axial compression. The problem is numerically solved using the finite element software, ABAQUS.

2 PROBLEM

2.1 Fibre Composite Cylindrical Shells

Laminated cylindrical shells made up of carbon fibre reinforced plastics (CFRP) and consisting of eight plies are used in the present study. Shells having a length (L) of 400 mm, mean diameter of 300 mm and a thickness (t) of 1 mm, with a nominal radius(R) to thickness ratio (R/t) of 150 are used in the present study. Two layup sequences, [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°] are considered, where the 0° corresponds to the meridional direction of the shell and the stacking sequence is taken from outside to inside. Each ply is 0.125 mm thick and has the material properties reported in Table 1[8].

TABLE 1
MECHANICAL PROPERTIES OF CFRP LAMINATE

Property	Value
Longitudinal Tensile Modulus E_{11} (MPa)	134780
Transverse Tensile Modulus E_{22} (MPa)	9250
Inplane Shear Modulus G_{12} (MPa)	4800
Poisson's Ratio ν_{12}	0.286
Density (gm/cm^3)	1.7
Thickness of Ply (mm)	0.125

The stacking sequence of plies in a laminated cylindrical shell influences the coupling properties and consequently the buckling strength of the laminate. Symmetric laminates are used in order to avoid coupling properties. Angle-ply laminates offer more shear stiffness than cross ply laminates due to which they find more applications over other laminate configurations [9]. This study aims at evaluating the performance of cross-ply and angle-ply laminated shells under axial impulsive loading. Hence, configurations representing crossply sequence, [0°/90°/0°/90°/90°/0°/90°/0°] and angle ply sequence [0°/0°/60°/-60°/-60°/60°/0°/0°] were selected for the current study.

2.2 Methodology

The buckling analysis of the CFRP shell is carried out using the finite element software, ABAQUS. ABAQUS is a general purpose finite element program with linear static, dynamic and non-linear analysis capabilities. At first, buckling analysis of the shell subjected to static axial compression is performed by linear static (eigen value) analysis and nonlinear static method using ABAQUS/Standard. A frequency analysis is also performed in order to determine the natural frequency of the shell and hence the natural period. The dynamic buckling analysis of shell under impulsive loading is then carried out by explicit integration scheme used in ABAQUS/Explicit. For impact loading, the load of constant magnitude is suddenly applied with finite duration. Different values of load duration, greater than and less than the natural period of the shell are considered for the present study. The dynamic buckling loads under axial impact are calculated using the Budiansky-Roth criterion. This approach is easily adapted to computational methods such as finite element analyses. The dynamic buckling loads thus obtained are compared with the static buckling loads.

2.3 Finite Element Model

Complete geometry of the cylinders are considered for the modelling since number and shape of waves in longitudinal and transverse direction is not known apriori to take advantage of the symmetry to model part of the composite cylinder. Cylindrical shells are done using 4-noded shell elements, S4R having six degrees of freedom per node, available in ABAQUS. They can be used for both static and dynamic analyses. Mesh sensitivity analyses were conducted and a model containing 13860 elements (180 elements in the circumferential direction and 76 elements in the axial direction) was chosen for further analysis taking into account the compromise with computational time and accuracy. All the six degrees of freedom, three translations and three rotations, are suppressed at the bottom end of the shell and only the axial translation is allowed at the other end of the shell where the axial compressive load is applied. Load is applied as uniformly distributed shell edge load.

3 STATIC BUCKLING

Two different analyses namely linear and nonlinear static analysis are carried out in the work. Linear buckling analysis gives the theoretical buckling strength by linear shell theories. The linear buckling strength will be greater than the actual buckling strength since it doesnot account for the nonlinear behaviour of shell. Hence, nonlinear analysis using modified Riks procedure is also performed to find the actual load carrying capacity of the shell. The values of buckling loads from linear and nonlinear static analyses for two layups are reported in Table 2. Static buckling modes of composite cylinders with layups [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°] are presented in Fig.1.

TABLE 2
STATIC BUCKLING ANALYSIS FOR THE TWO LAYUPS

Layup Sequences	Static Buckling Loads (kN)	
	Linear Analysis	Nonlinear analysis
[0°/90°/0°/90°/90°/0°/90°/0°]	97.19	93.23
[0°/0°/60°/-60°/-60°/60°/0°/0°]	120.39	115.73

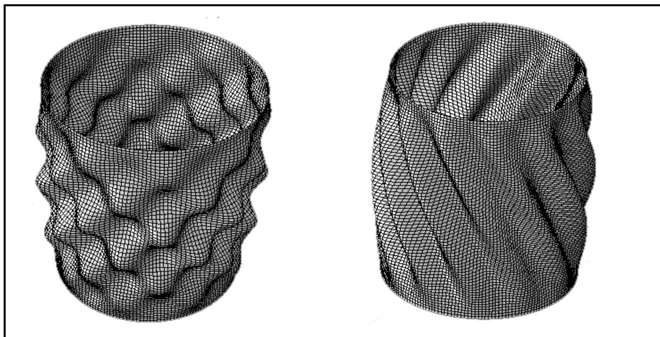
(a) [0°/90°/0°/90°/90°/0°/90°/0°] (b) [0°/0°/60°/-60°/-60°/60°/0°/0°]

Fig.1. Static buckling modes of composite cylinders

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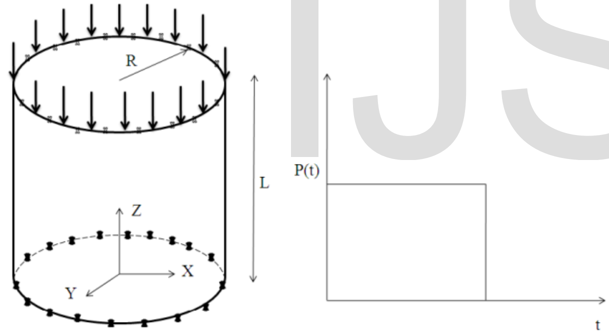
4 DYNAMIC BUCKLING UNDER IMPACT LOADS

Dynamic buckling due to impact load of constant magnitude applied for finite duration is investigated here. The Budiansky-Roth criterion is followed, where the equations of motion are solved for various values of the load parameter, and thus obtaining the system responses, are adopted in this study. The load value, at which there exists a sudden change in the responses, is called critical load for that particular load duration. The response of the system is monitored using displacements of selected points for small values of loading parameter. Small oscillations are observed about an equilibrium point at loads lower than the critical condition. When the loading reaches its critical value, the amplitude-time history curve experiences a sudden jump. The lowest load where there is a sudden change in the response is termed as critical buckling load for that particular load duration.

In the present study, the axial compression in the form of step pulse is applied as uniformly distributed shell edge load having constant magnitude applied suddenly with finite duration. The loading diagram is shown in Fig. 2. From the frequency extraction (free vibration) analysis, it was found that the lowest natural frequency of the shell is 427 Hz and hence the natural period of the system is around 2 ms. Based on this, five time durations of pulse loading namely T= 1ms, 2.5ms, 5ms, 10ms and 15ms are considered. Such a selection of load duration enables to understand the behaviour of shell under impulsive axial loading for different durations greater than and less than the natural period of shells.



a) Cylinder with axial loading b) Step pulse used for loading

Fig.2. Model Geometry and Loading Diagram

To be able to get good results from the dynamic analyses, the points for which displacements to be monitored, are carefully chosen, otherwise the plots produced may be rather obscure and confusing. Therefore, the axial displacement at a unique point on the loaded end of the shell is considered in this study. Fig.3 presents the axial displacement of a point on the loaded end of the laminated cylinder [0°/90°/0°/90°/90°/0°/90°/0°] subjected to suddenly applied axial compression for duration of 5ms with different load magnitudes. In this case, the curve corresponding to 82 kN show regular response and the cylinder vibrates about its equilibrium position. From 82 to 84 kN, there is a sudden change between the two responses. This indicates the dynamic buckling condition and the load average equal to 83 kN is regarded as the dynamic buckling load of the shell [0°/90°/0°/90°/90°/0°/90°/0°] for that time duration. Using this criterion to estimate the dynamic buckling loads, dynamic analyses are performed for different time durations for both layups and the results are reported in Table 3. The dynamic buckling loads for different time durations for both composite cylinders are presented in Fig. 4. The dynamic deformation of the shells at T= 5ms are presented in Fig. 5.

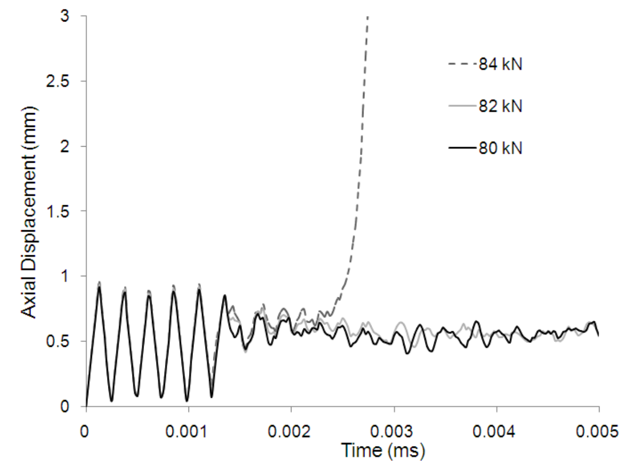


Fig.3. Axial displacement for different load magnitudes on cylinder-[0°/90°/0°/90°/90°/0°/90°/0°] at T= 5 ms

TABLE 3
DYNAMIC BUCKLING ANALYSIS FOR THE TWO LAYUPS

Time of Application of Load T (ms)	Dynamic Buckling Loads (kN)	
	[0°/90°/0°/90°/90°/0°/90°/0°]	[0°/0°/60°/-60°/-60°/60°/0°/0°]
1	205	219
2.5	111	137
5	83	112
10	80	80
15	80	79

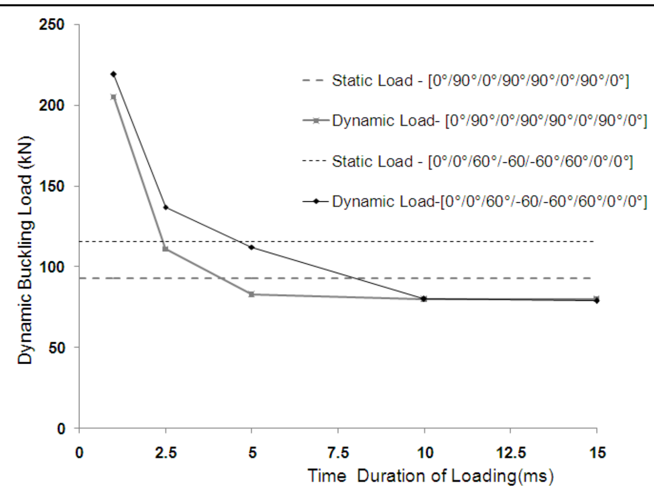


Fig.4. Dynamic Buckling Loads for different time durations for cylinders with layups - [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°]

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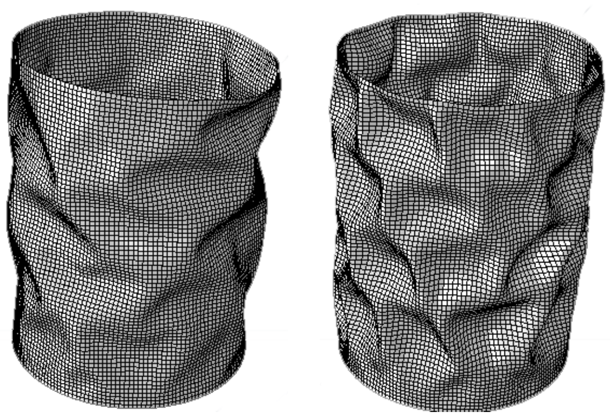

(a) [0°/90°/0°/90°/90°/0°/90°/0°] (b) [0°/0°/60°/-60°/-60°/60°/0°/0°]

Fig.5. Dynamic deformation of composite cylinders at duration T= 5ms

5 RESULTS AND DISCUSSIONS

Dynamic buckling of composite cylindrical shells under axial impulsive loading for different time durations are presented in the current study. Two layup sequences, [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°] were considered in the study. Static and dynamic buckling loads were calculated for the cylinders. The two buckling loads were then compared for both the layups and are plotted for different time durations as shown in Fig. 6.

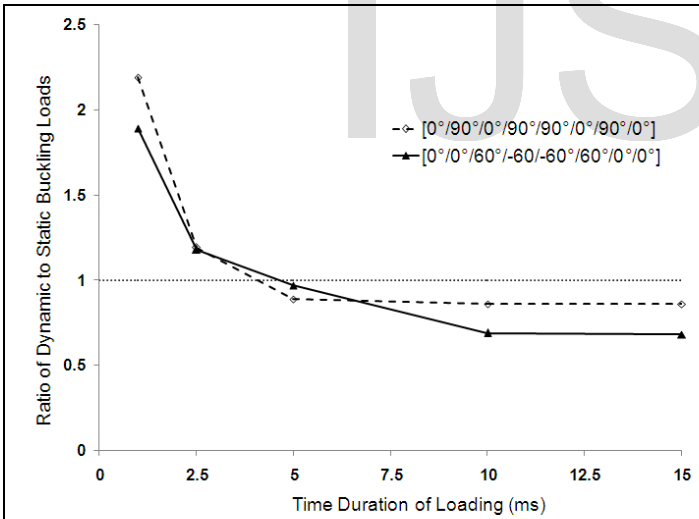

Fig.6. Ratio of dynamic to static buckling load for different time durations for cylinders with layups [0°/90°/0°/90°/90°/0°/90°/0°] and [0°/0°/60°/-60°/-60°/60°/0°/0°]

For both the layups, the dynamic load values under impulsive axial loading are higher than the static load for load durations less than the natural period of shell. As the load duration approaches the natural period of shell, a sudden decrease in dynamic buckling loads are observed in both cylinders. For durations higher than the natural period of the shell, the dynamic buckling loads are less than the static ones, thereafter the dynamic loads for different load duration remain more or less the same. This phenomenon is due to stress wave transmission between impacted ends and fixed ends of the shells [6].

For cylinder with layup [0°/0°/60°/-60°/-60°/60°/0°/0°], when the loading duration exceeds the natural period, the load values continues to decrease below the corresponding static values. Hence, cylinder with layup [0°/0°/60°/-60°/-60°/60°/0°/0°] show more sensitivity to load duration than [0°/90°/0°/90°/90°/0°/90°/0°] layup under impact loading conditions.

In general shells experience dynamic buckling loads larger than static buckling loads, if their duration is very short as compared to the natural period of the system and less than the static buckling load for longer durations. Hence, the ratio between the dynamic buckling load and the static buckling load is of practical importance as it gives a direct indication of the load carrying capacity of the shells exposed to suddenly applied load.

6 CONCLUSION

Composite circular cylindrical shells with two different layups having same length to radius (L/R) ratio were considered to study their behaviour under axial impact loading. The equation of motion approach, Budiansky-Roth criterion was adopted to calculate the buckling loads under dynamic impact conditions. Dynamic buckling loads were found to be larger than the static load values when time of application of load is less than natural period of the structure in both cylinders.When the load duration exceeds the natural period of shell, the load values were found to fall below the static load values in both the cylinders. This means that taking static buckling loads as the design load for dynamic problems might be unsafe under long duration impulse loading. Also, the duration of impact have appreciable influence on the buckling load of angle-ply laminates than cross-ply laminates. Therefore, the behaviour of composite shells under impact loads depends on the layup sequence of laminates.

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