BUCKLING BEHAVIOR OF DELAMINATED AGS CONSIDERING HYGROSCOPIC EFFECT

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Abstract

The pre-buckling and post-buckling behavior of AGS considering hygroscopic effect and embedded circular delamination in the skin has been investigated using finite element method. Based on the first order shear deformation theory (FSDT), Von Karman non-linear deformation assumption, corresponding models and criterions of damages and finite element formulations considering hygroscopic effect, a numerical analysis have been carried out. By some numerical examples, the influences of delamination and hygroscopic concentration on the stability characteristics of AGS plate and shell structures have been discussed.

1 Introduction

Advanced grid stiffened structures (AGS) have many advantages compared with conventional structures, such as high impact and fatigue resistance, high strength and stiffness to weight ratios and damage tolerance. The AGS structures characterized by a shell or plate supported by a lattice pattern of ribs possess a widely application in today's aerospace and aircraft industries such as Aircraft fuselage, launch vehicle fuel tanks, business jets and manmade satellites due to the expensive manufacturing cost has been decreased greatly by the use of some new manufacture techniques and new innovative tooling concepts [1-2].

For AGS, the stability problem is a chief factor to structure design and optimise [1]. When considering the well known common flaws of composite structures, for example, the delamination, macro-cracks of resin matrix and the characteristic of sensitive to the variation of temperature and moisture ratio [4], the AGS will exhibit a much more complicated buckling behavior than that of the general simple stiffened panels. Delamination, can be defined as lack of adhesion and of continuity between two adjacent layers of a laminate, is one of the most severe types of damage. It may be caused by improper manufacture or impacts, which can reduce the failure stress of composite AGS. A delaminated AGS can buckle at a lower level of compressive loading, either maintaining a global critical shape or a local buckling mode. Some references about the effects of local delamination on critical and postcritical behavior of composite laminates are presented and some of them have proposed different methodology for studying the above problem [5-8]. In these works, a little perturbations technique is employed to achieve analytical results, such as Kutlu and Chang [8], included in the analysis the contact constraints.

The environmental effect is of great importance on AGS stability for long-term service. It has been extensively investigated [9-10], especially for aeronautical structures, to calculate the moisture concentration in composite materials exposed to environmental conditions. The importance of the non-mechanical residual stresses within the laminates has been shown in references [11-12]. Particular attention should be paid to the calculation of the transient stress components due to the non-uniform moisture concentration. But little work has been done however, on buckling behavior of AGS structures considering hygroscopic effect. In this paper, the hygroscopic behaviors of AGS laminates have been studied in order to find some general rules helping composite material structures designers.

2 Model and Formulations of AGS

2.1 Model of Finite Element Analysis

The AGS can be simulated by the combination of plate and beam elements. The stiffness matrix for both skin and rib can be calculated according to their own mid-planes, and then, the stiffness matrix and nodal force vector of the rib be converted to the mid-plane of the skin and add to the corresponding component of the skin by coordinate transformation based on the conditions of displacement compatibility along their connection line [13].

In current analysis, a four-node plate element and a two-node beam element are applied based on the first order shear strain effect laminated plate theory in conduction with Von-Karman non-linearity assumption. For AGS plate, the nodal displacement components for plate element and beam element can be expressed as $\{u_0\, v_0\, w_0\, \theta_x\, \theta_y\}$ and $\{u_0\, w_0\, \theta_x\, \theta_y\}$, while for AGS shell, both of them can be expanded as $\{u_0\, v_0\, w_0\, \theta_x\, \theta_y\, \theta_z\}$ by coordinate transformation.

2.2 Delamination Model

Considering a circular Delamination in skin within one lattice after low velocity impact of AGS, The delaminated skin can be divided into three parts: upper sub-laminates, lower sub-laminates and base laminates. The continuity of the displacements and rotations along the delamination front is satisfied by the imposed constraint equations according to the 'three-plate' delamination model [13].

2.3 Modeling of Hygroscopic Effect

For the laminated skin of AGS subjected to a hygroscopic concentration C, the in-plane moisture load and moment vectors can be obtained by the following formula

$$\{\Delta N_c \quad \Delta M_c\} = \sum_{k-1}^{n} \int_{z_k}^{z_{k-1}} \left[\overline{Q}\right]_k \{\overline{\beta}\}_k (1, z)\, C dz \quad (1)$$

In which, β is the moisture expansion coefficient. The corresponding constitutive relationships can be obtained by integrating the stress-strain equations

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon \\ k \end{Bmatrix} - \begin{Bmatrix} \Delta N_c \\ \Delta M_c \end{Bmatrix} \quad (2)$$

Where, N and M is the in-plane load and moment vector, respectively. For beam element, the constitutive equations considering any hygroscopic concentration C can be written as

$$\begin{Bmatrix} \sigma_x^b \\ \tau_{xy}^b \end{Bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{16} \\ \overline{Q}_{16} & \overline{Q}_{66} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_x^b \\ \gamma_{xy}^b \end{Bmatrix} - \begin{Bmatrix} \beta_x^b \\ \beta_{xy}^b \end{Bmatrix} C \right) \quad (3)$$

2.4 Governing Equations

The pre-buckling and non-linear governing equation for AGS considering hygroscopic effect can be written as

$$\left(\left([K]_f + [K_\sigma]_c \right) + \lambda [K_\sigma]_f \right) \{q\} = 0 \quad (4)$$

$$\left([K]_T + [K]_T^b \right) \{\Delta q\} = \{\Delta P\}_f + \{\Delta P\}_c - \{R\} - \{R\}^b \quad (5)$$

Where, the superscript f, c and b denote the mechanical load, moisture load and beam element, respectively.

3 Numerical Example and Discussion

3.1 Pre-buckling and Post Buckling of AGS Plate

Considering a square orthogonal isogrid AGS plate with a central circular delamination r =20mm in the 1/4 depth of the skin as shown in Fig.1. The length of the plate and spacing of the two adjacent ribs is 350mm and 70mm, respectively. The stacking sequence of the skin is $[45/-45/0/90]_s$ and that of the ribs is $[0]_{80}$. The thickness of each laminate for each skin and ribs is 0.125mm and the width of the rib is 2mm. The material parameters of skin and rib are as follows: E_1=126.0GPa, E_2=8.8GPa, G_{12}= G_{13}= G_{23}=4.47GPa, ν_{12}= 0.33. The moisture expansion coefficients are β_1=0 and β_2=0.6, respectively. Boundary conditions at the four edges are shown in Fig.1. The axial compressive load is applied in the form of a uniform increase in end displacement.

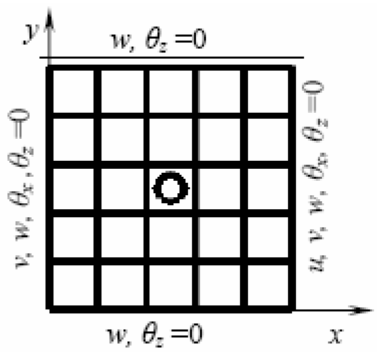

Fig. 1. Schematic of square orthogonal isogrid AGS plate with a central delamination

The results of pre-buckling analysis to the stiffen plan under different hygroscopic concentration are respectively shown in Fig.2, with a delamination and without delamination. The buckling displacement of the structure with a delamination is smaller than the one without delamination, and the buckling mode is local buckling in the delamination zone.

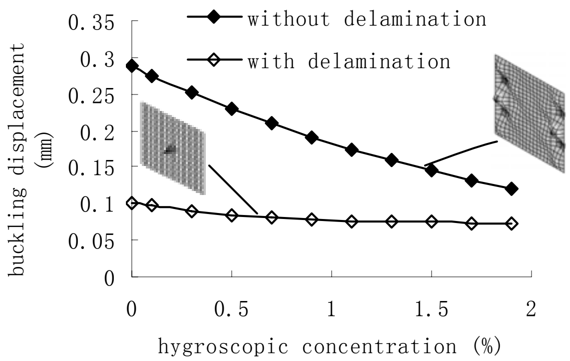

Fig. 2. Buckling loads vs hygroscopic concentration

Delamination is a common type of damage in composite engineering structure due to improper manufacture or by impacts. Nevertheless, the damage is usually inside of the skin and invisible. Stability of the structure has been prominent weaken. When local buckling occurred due to delamination, the extern loads will be redistributed, in some cases exhibits a change of global buckling model, so minor delamination of AGS sometimes can cause magnitude accident. Therefore, we must attach importance to the investigations about the AGS structure with delamination.

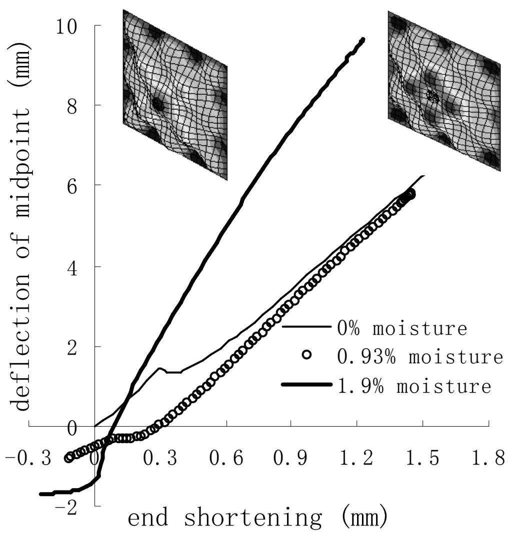

Fig. 3. Deflection of midpoint in the upper sub-laminates vs end shortening

The postbuckling paths are drawn as Fig.3. The curves in Fig.3 track out post-buckling process of the AGS planer under placement loading on the edges compared Fig.2 with Fig.3, it can be seen that that the hygroscopic effect and delamination are essential to the buckling behaviour of AGS plate, and generally, pre-buckling is an approximate compute method, the buckling behavior of AGS structure can't be reflected exactly, while the postbuckling analysis can provide the whole deformation the change of buckling modes in loading process, it is an important way in stability investigation.

3.2 Pre-buckling and Post Buckling of AGS Shell

Considering a AGS cylinder shell embedded a central circular delamination with r =11.05mm in the 2/5 depth of the skin as shown in Fig.4, the geometric parameters of the shell are R =115mm and L=500mm. The stacking sequence of the skin is $[50_4/\text{-}50_4/50_4/\text{-}50_4/50_4]$. The material parameters and the moisture expansion coefficients are the same as 3.1. The section of the rib is rectangle with a width b=10mm, and height h=6mm. Each ply in the rib is placed along its axial orientation. The span of circumferential ribs and inclined ribs are 16.428mm, respectively. The slope angle of the inclined ribs is $\pi/3$ rad. Boundary conditions at the four edges are shown in Fig.4. The axial compressive load is applied in the form of a uniform displacement increase in end displacement.

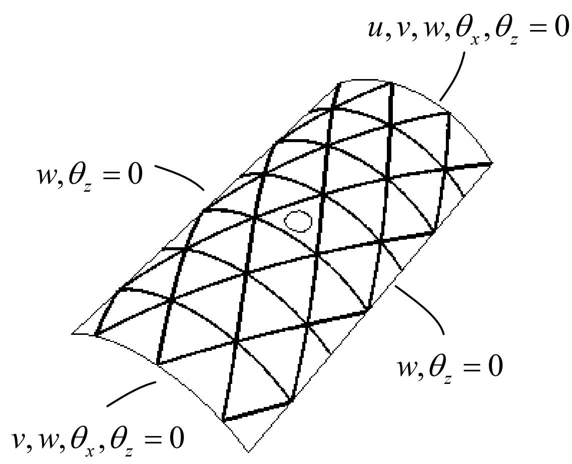

Fig. 4. Schematic of triangle AGS shell with a central circle delamination

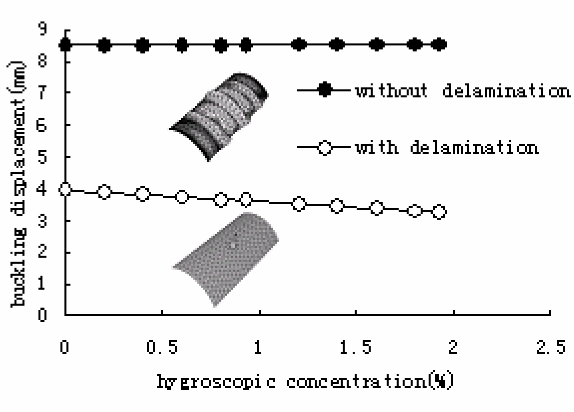

Fig. 5. Buckling loads vs hygroscopic concentration

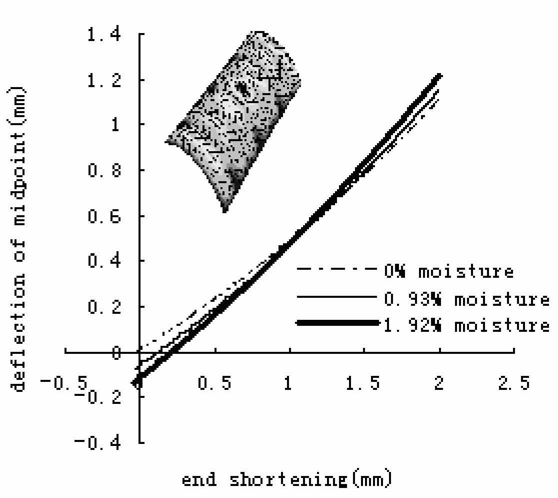

Fig. 6. Deflection of midpoint in the upper sub-plate vs end shortening

Compared Fig.2 with Fig.5, the structure with a delamination has a local buckling behavior in the delaminated zone, and the buckling displacement is smaller than the one of the structure without a delamination.

The post-buckle paths of AGS plate and shell considering three different moisture concentrations are shown in Fig.3 and Fig.6. It can be shown that when the end shorting equals to zero, midpoint of the structure has deflection for hygroscopic effect. From the slopes of the three curves, it indicates that high moisture concentration cause a early failure due to the change of moisture concentration which transform hygroscopic load applying onto the AGS structures. That is to say, the hygroscopic effect has decreased the stability of the AGS.

4 Conclusions

Hygroscopic effect decreased the stability of AGS for both prebuckling and postbucking behavior. The degree of hygroscopic effect relates to the buckling modes closely. The influence of Hygroscopic effect on the triangle stiffened cylindrical AGS shell is not as remarkable as orthogonal iso-grind AGS palte structure. For AGS structure with delamination, the eigenvalue analysis critical is conservative and the structure still possesses load capacity after initial local buckling occurred.

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