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POSTBUCKLING BEHAVIOR OF COMPOSITESANDWICH PLATE CONTAINING INTERFACIAL DEBONDING

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SUMMARY: Based on the zig–zag deformation model, the first order shear strain effect laminated plate theory and the Von-Karman non-linearity assumption, a finite element formula is established, which can be performed to study postbuckling behavior of the sandwich plates containing interfacial debonding. A Global-Local nonlinear analysis technique is developed in the present paper for saving compute cost, and a Modified Newton-Raphson scheme is also employed during the numerical iterative procedure. A nonlinear finite-element analysis code is developed. Some numerical examples are given for investigation of the effect of debonding sizes, ply angles of the faces, and boundary condition upon postbuckling behavior of the damaged composite sandwich plates.

KEYWORDS: Composite sandwich, Interfacial debonding, Finite Element Analysis (FEA), Postbuckling behavior

INTRODUCTION

Sandwich structures have many advantages including high flexural rigidity and strength, ease of manufacture, improved stability and ease of repair, but the interface between the face and core are much weaker than those in layered composite laminates or core materials. Therefore, the interfacial debonding is one of the most common flaws in the composite sandwich structures, which may occur as a result of manufacturing imperfections, impact of foreign objects, or high stress concentrations in the area of geometric or material discontinuities. Clearly, the presence of large areas of face/core debonding is likely to lead to a significant loss in the subsequent load-bearing properties of the structures. Such damaged structures, however, may undergo a large amount of deformation process before their final failure. From experiment observation, it full reveals that the imperfect composite sandwich plates are still capable of resisting increased compressive or shear edge loads well beyond the instant at which buckling occurs. Consequently, one of the topics playing a major role in the design of the composite sandwich plates is postbuckling behavior under edge loads (compressive and shear loads).

The problem on buckling and/or postbuckling analysis of the damaged composite sandwich structures has become a focus of several research works. Somers[1-4] developed an analytical beam model to study the buckling and postbuckling behavior of sandwich beams containing a through-the-width delamination, and the effects of delamination location, size, lay-up sequence and boundary conditions on buckling and/or postbuckling behavior of the composite sandwich beams are investigated. Lin *et al*[5] predicted the local buckling load of damaged composite sandwich plate. However, postbuckling behavior of the damaged composite sandwich plates is so complicated, that theoretical analysis of this problem is rather difficult and lack of reporting.

This study focuses on the postbuckling behavior of the composite sandwich plate containing an embedded interfacial debonding under axial compressive load. A finite element analysis (FEA) of the postbuckling behavior of the plates is conducted on the basis of the zig–zag deformation model, the first order shear deformation laminated plate theory and the Von-Karman's non-linearity assumption. Because the mainly failure mode of the plates possess of the local post-buckling, which often occurs in the upper debonding face as experiment observation, hence, a Global-Local nonlinear analysis technique is developed in the present paper for saving compute cost. The numerical analysis models and methods are briefly introduced in this paper and some numerical examples are presented to illustrate it, which would of great value for engineers to deal with composite sandwich structures.

MODELIZATION OF FINITE ELEMENT ANALYSIS

Zig–zag model and Mindlin first-order shear deformation theory

A typical sandwich plate consisting of two stiff strong faces bonded to a lightweight core is shown in fig.1.

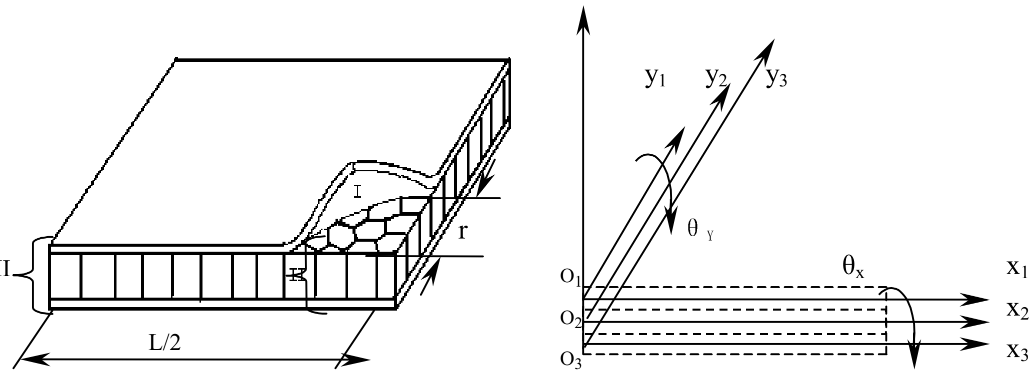

Fig.1 Schematic of composite sandwich plate and corresponding coordinate system

A zig-zag deformation model considering the transverse shear effect is used to describe deformation characteristics of the composite sandwich plates. Let the plate be divided into three components, namely upper face, core and lower face; the upper face, core and lower face, and assume the rotation angles of three components to be independent. Establishing the corresponding local coordinate systems (x_1, y_1 z_1), (x_2, y_2 z_2), and (x_3, y_3 z_3), the expressions of displacement field for three component can be written as follows:

for the upper face:

$$\left.\begin{aligned} u_1 &= u_0 + (t_1\theta_{y1} + h\,\theta_{y2})/2 + z_1\theta_{y1} \\ v_1 &= v_0 - (t_1\theta_{x1} + h\,\theta_{x2})/2 - z_1\theta_{x1} \\ w_1 &= w_0 \end{aligned}\right\}$$

for core:

$$u_2 = u_0 + z_2\theta_{y2} \quad v_2 = v_0 - z_2\theta_{x2} \quad w_2 = w_0$$

For the lower face:

$$\left.\begin{aligned} u_3 &= u_0 - (h\theta_{y2} + t_2\theta_{y3})/2 + z_3\theta_{y3} \\ v_3 &= v_0 + (h\theta_{x2} + t_2\theta_{x3})/2 - z_3\theta_{x3} \\ w_3 &= w_0 \end{aligned}\right\}$$

Where u_0, v_0 and w_0 denote translational displacement components in the x_1, y_1 and z_1 directions on the middle plane of the core; θ_{x1}, θ_{y1}, θ_{x2}, θ_{y2}, θ_{x3}, and θ_{y3} are rotational components about the x_1-, y_1-, x_2-, y_2-, x_3- and y_3-axis's, respectively, and t_1, h and t_2 are the thickness of the upper face, core and lower face, as shown in Fig. 1.

Delamination analysis model

Consider a composite sandwich plate embedded an interfacial debonding between the upper face and core, as shown in Fig.1. The plate consists of three portions: 'I' and 'II' are the 'imperfect' portions, which are above and below the debonding, respectively; and 'III' is the 'perfect' portion. The continuity of the displacement and rotations along the interfacial debonding fronts between the three sub-regions must be strictly satisfied, hence, the constraint deformation equations imposed can be written as

$$w = w_I = w_{II} = w_{III} \quad \theta_{x1}^{I} = \theta_{x1}^{III} \quad \theta_{y1}^{I} = \theta_{y1}^{III} \quad \theta_{x2}^{II} = \theta_{x2}^{III} \; \theta_{y2}^{II} = \theta_{y2}^{III}$$

$$\theta_{x3}^{II} = \theta_{x3}^{III} \; \theta_{y3}^{II} = \theta_{y3}^{III} \quad u_0^{II} = u_0^{III} \quad v_0^{II} = v_0^{III} \quad w_0^{I} = w_0^{II} = w_0^{III}$$

$$u_0^{I} = u_0^{II} + (t_1/2)\,\theta_{y1}^{I} + (h/2)\,\theta_{y2}^{II} \quad v_0^{I} = v_0^{II} - (t_1/2)\,\theta_{y1}^{I} - (h/2)\,\theta_{y2}^{I}$$

Global–local technique and Von-Karman large deflection theory

As experiment observation, the mainly failure mode of the damaged plates possess of the local post-buckling, which often occurs in the upper debonding face, hence, a Global-Local nonlinear analysis technique is developed in the present paper for saving compute cost. Using the Von-Karman non-linearity assumption, the nonlinear strain-displacement relationship for the debonded upper face can be expressed as:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \partial u_0/\partial x + z\,\partial\theta_y/\partial\theta_x + (\partial\omega_0/\partial x)^2/2 \\ \partial v_0/\partial y - z\,\partial\theta_x/\partial\theta_y + (\partial\omega_0/\partial y)^2/2 \\ \partial u_0/\partial y + \partial v_0/\partial x - z\,\partial\theta_x/\partial x + z\,\partial\theta_y/\partial y + \partial\omega_0/\partial x\cdot\partial\omega_0/\partial y \\ \partial\omega_0/\partial y - \partial\theta/\partial x \\ \partial\omega_0/\partial x + \partial\theta/\partial y \end{Bmatrix}$$

Where u_0, v_0 and w_0 denote displacements on the middle plane of the debonded upper face.

Finite element analysis formulation

The finite element stiffness matrix in the small deflection domain can be written as:

$$[K_0] = \sum_{i=1}^{3} \int_v [B_{L0}]_i^T [D]_i \ [B_{L0}]_i \ |J| d\xi d\eta$$

Here the indexes and subscripts i = 1,2,3 are the upper face, core and lower face, respectively. While for the large deflection theory domain, the element tangent stiffness matrix is

$$[K_T] = [K_0] + [K_L] + [K_\sigma]$$

Where

$$[K_L] = \int_v \left([B_{L1}]^T [D][B_{L0}] + [B_{L0}]^T [D][B_{L1}] + [B_{L1}]^T [D][B_{L1}]\right)|J| d\xi d\eta$$

$$[K_\sigma] = \int_v [G]^T [M][G]|J| d\xi d\eta$$

in which $[B_{L0}]$ and $[B_{L1}]$ are the linear and nonlinear strain-displacement matrices and the $[G]$ and $[M]$ are the geometrical stiffness and internal membrane force matrices, respectively;

Using the Newton-Rephson iteration scheme, the governing equations for finite element analysis in the i +1 incremental step is represented by

$$[K]_i \{\Delta q\}_{i+1} = \Delta P_i - R_i$$

where $[K]_i$ is the total tangent stiffness matrix of the plates, ΔP_i and R_i are the incremental load and the internal reaction force vectors in the i iteration step, and $\{\Delta q\}$ is the node incremental displacement vector, the i+1th iteration step.

NUMERICAL RESULTS AND DISCUSSION

Consider a composite sandwich plate embedded a central circular debonding. The external uniform compression loads are subjected to the edged x= L/2, -2/L. The dimensions for the plate are L=200mm, h=10mm and t_1= t_2=2mm. The mechanical properties of the faces and the core of the plate are:

For the upper and lower face: E_1=3792MPa，E_2=101MPa，G_{12} =G_{13}=484MPa，G_{23}=343MPa，μ_{12}=0.302; For the Core: E_1=E_2=200MPa，G_{12} =G_{13}=146MPa，G_{23}=90.4MPa，μ_{12}=0.3

Effects of debonding sizes and boundary conditions on postbuckling behavior of $[0/45/-45/90]_s$ / core / $[0/45/-45/90]_s$ composite sandwich plate

Fig.2 and Fig.3 respectively illustrate the postbuckling paths of normal displacements W at the center point of the damaged composite sandwich plates with simply and clamped supports along the four edges, respectively. In the figures, the dash-dotted and solid curves represent the results of the upper and lower portons of the debonding interface, the ordinate N/ N_{cr} is the normalized loads, where N_{cr} is the values of critical load for the corresponding perfect plates, and r is the debouding radius. From Fig.2 and Fig.3, it can be seen that the interfacial debonding has a significant effect on the post-buckling behavior. The magnitude values and the variations of W for the upper face with increasing load are much larger than that of the lower portion of the debonding interface and the above two portions deform toward to the opposite directions. Furthermore, the path-curve of the plates with large debonding is always below that with small debonding. Therefore, the existence of an interfacial debonding reduces the load-carrying capacity of a sandwich plate significantly, and the larger debonding area, the more significant, while for the plate with a small debonding area, as curve 1, it still has more potential load-carrying capacity. Moreover, It also can be found that the stiffeness of the end supports for the damaged sandwich plate possess of the small effect on the increase of the postbuckling load, which behavior is consistent with that of the face/core debonded sandwich beams provided in the Ref.[1].

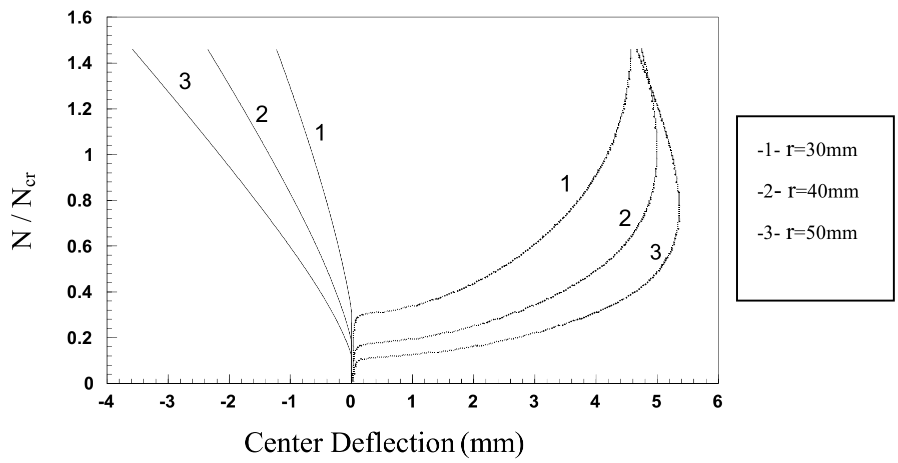

Fig. 2 Effect of debonding size on postbuckling paths (simply-supported)

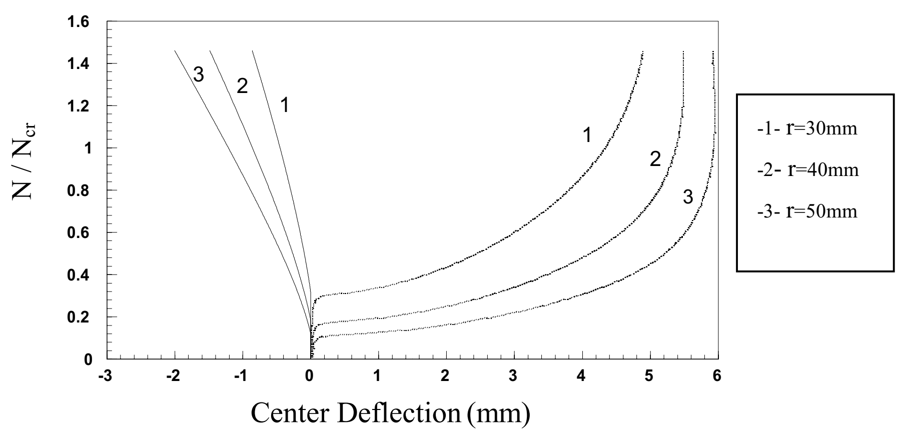

Fig. 3 Effect of debonding size on postbuckling paths (clamped)

Effect of face lay-up sequnce on postbuckling behavior of composite sandwich plate

The postbuckling paths of the plate with different face lay-up sequences are shown in Fig.4. From Fig.4, it can be seen that the influence of the face lay-up sequence and ply angles on the postbuckling behavior is significant, and a suitable face layup sequence and ply angle can improve the structure postbuckling load-carrying capacity.

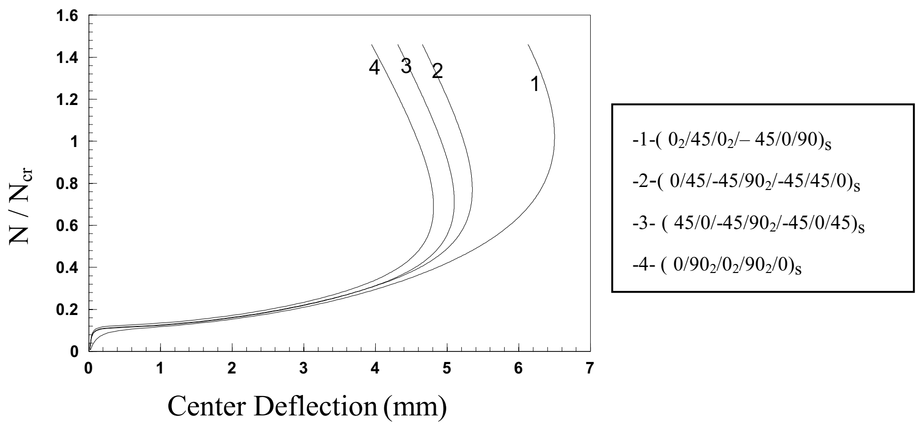

Fig. 4 Effect of face layup sequence on postbuckling paths

CONCLUSIONS

(1) The existence of interfacial debonding reduces the load-carrying capacity of the sandwich plates significantly, and the plates with a small size interfacial debonding still have more potential load-carrying capacity.
(2) The Stiffeness of the edge supports has a small effect on the postbuckling load of the damaged sandwich plate.
(3) An appropriate face lay-up sequence can improve the postbuckling load-carrying capacity of the plate.
(4) The global-local technique can save large amounts of computer resources.
(5) The methodology, model and numerical analysis method in this paper can be used for study the post behavior of the composite sandwich plates containing interfacial debonding.

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REFERENCES

1. Somers, M., Weller, T. and Abramovich, H., "Buckling and postbuckling behavior of delaminated sandwich beams", *Composite Structures*, 1992. Vol. 21, No. 4

2. Somers, M., Weller, T. and Abramovich, H., "Effect of delamination. Location on postbuckling behavior of sandwich structures", *TAE No.647*, Technion, Israel Institute of Technology, Haiifa, 1989.

3. Somers, M., "The buckling and postbuckling behavior of sandwich beams in the presence of damages", MSc thesis, Technion, Israel Institute of Technology, Haiifa, 1990.

4. Somers M., Weller, T. and Abramovich, H., "Influence of predetermined delaminations on buckling and postbuckling behavior of composite sandwich beams", *Composite Structures*. 1991. Vol. 17,No. 4

5. Lin Chien-Chang, Cheng Shou-Hsiung, Wang James Ting-Shun, "Local buckling of delaminated composite sandwich plates", *AIAA*, 1996, Vol. 34, No. 10