Simulation of Fastener Pull-through Failure for Honeycomb Sandwich Structures with Inserts

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Abstract. Honeycomb sandwich structures are commonly assembled using a local reinforcement called "inserts" at the junction. In this paper, fastener pull-through tests are firstly conducted to investigate the strength properties and failure process of Nomex honeycomb sandwich structures with carbon fiber-reinforced composite skins and inserts. Loading capability and failure modes are analyzed and discussed. Based on these experiments, an analytical model simulating the failure process is then developed and implemented using the finite element code ANSYS, and a degradation model is proposed for the stress redistribution analysis. The database for determining the stiffness degradation factors Di of the honeycomb core is established by means of parametric fitting. The simulated results of the fastener pull-through failure process are will coincided with experimental results.

1. Introduction

Inserts act as important parts in sandwich panels, and variations in the material in the region of the insert will seriously affect the performance of the sandwich panel [1-4]. In this paper, the performance of Nomex honeycomb sandwich panels was investigated. The panel and the insert may be subjected to various types of loads, but here we only consider a load normal to the plane of the panel.

The honeycomb sandwich panels with inserts have been investigated by many researchers. With the multi-segment method of integration, Thomsen and Rits numerically solved the stress in the sandwich plates with through-the-thickness inserts subjected to axisymmetric and nonaxisymmetric external loadings [5]. Smith and Banerjee studied the reliability of inserts in sandwich composite panels and compared relevant analysis methods [6]. This study focuses on the strength properties especially nonlinear behavior and ultimate load bearing ability of the joints of Nomex paper honeycomb sandwich panels. First, the global behavior of the inserts during fastener pull-through tests is observed. Numerical analysis is carried out that led to the identification of the non-linear behavior of each component. The finite element simulation models are developed in ANSYS by the specific language APDL, which are able to represent the respective failure behaviors and ultimate strength effectively in large scale models. In this analysis, a honeycomb core stiffness attenuation model is proposed which agrees well with the experimental data.

2. Experimental study

2.1 Test preparation and procedures

A pull-through test is conducted on 10 honeycomb sandwich panel specimens. The potting material is potted into a circular area of the sandwich panel, The size of the potting area is shown in Fig. 1.

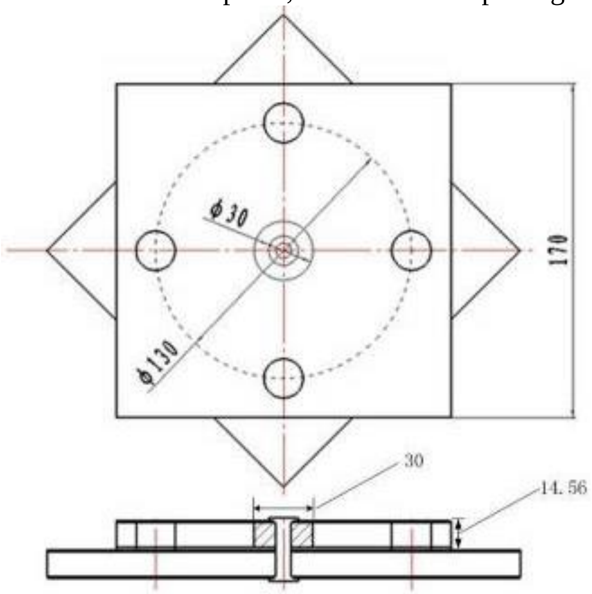

Figure. 1 The geometry of the sandwich specimen

Two identical face sheets are manufactured from carbon fiber ±45 fabric epoxy prepreg and have three layers, 0.31mm thick each, Total thickness of each composite laminate is 0.93 mm. The honeycomb core is made of Nomex paper, with a cell size of 3.175mm, density of 48 kg/m^3 and thickness of 12.7 mm. It is glued to the two face sheets with structure adhesive. The sandwich specimen is a 170×170×14.56 mm flat and square plate with constant rectangular cross-section (Fig. 1). A countersunk hole (8 mm in diameter) is drilled at the centre, where two such plates are joined together by a fastener, with one plate being rotated 45° with respect to the second plate. Each plate contains four additional holes in the periphery to accommodate a multi-piece fixture, which is designed according to ASTM D7332/ D7332M- 09 (Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite). Pull-through testing is conducted on a general-purpose testing machine set in the press mode. During static tests, the plates are pried apart by the application of compressive force transmitted through the fixture, producing a tensile load on the fastener and a bending load on the composite plates.

2.2 Experimental results and discussion.

The results of the pull-through testing of the ten specimens with the same type of inserts show high level reproducibility. The typical load-displacement response of the specimen tested firstly in each group is shown in Fig.2.

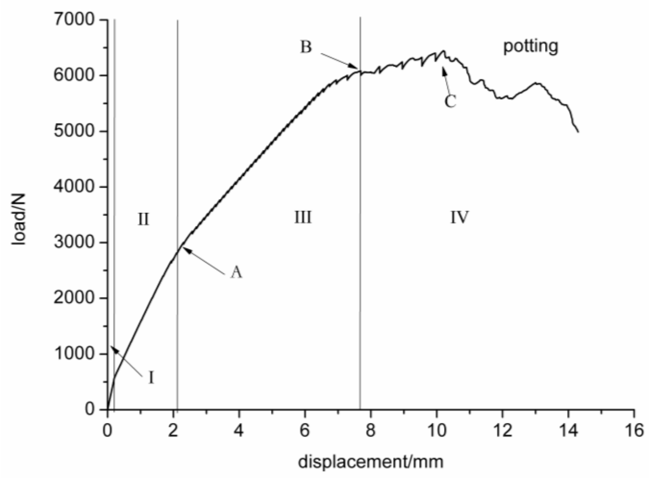

Figure. 2 Typical force-displacement responses of the inserts

In general, the load–displacement curve of the specimen with potted-in style inserts is globally nonlinear and can be divided into 4 parts. Area I could be the phase of establishing the contact between the fixture head and the specimen. Area II is nearly linear with no damages. Then the load-displacement curve starts to show nonlinear behavior at point A, possibly resulting from transverse shear failure of the honeycomb core adjacent to the potting mass. During this phase, especially near point A, noise was heard from the specimen. In Area III, a continuous crackling sound was present all the way. The load increases until point B is reached, which starts from Area IV. The whole potted area then exhibits a vertical displacement with the rest of the panel. The ultimate failure load was 6600N when the displacement was 10.4 mm.

3. Numerical simulation

3.1 Finite element model

A quarter of the specimen is included in the finite element model developed with ANSYS. The model consists of numerous 8-node hexahedral solid elements with six degrees of freedom at each node for the whole structure. The mesh and boundary conditions are shown in Fig.3.

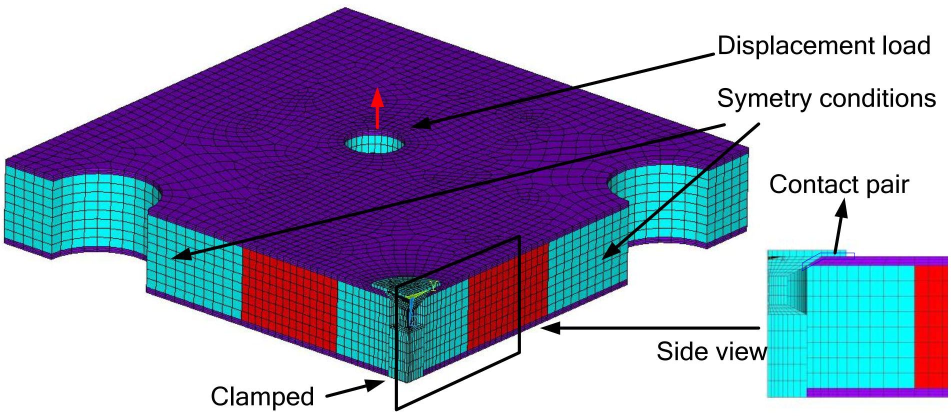

Figure. 3 Finite element model of the sample

Contact conditions are imposed between the fastener head and the face sheet. Fixed constraint is imposed on the bottom end of the screw. The displacement load is applied at the periphery hole accommodating the stud of the fixture.

3.2 Damage mechanics and material degradation.

1) Damage mechanics and material degradation of sandwich skins.

The sandwich skins are modeled as three layers of an equivalent orthotropic material, and it is assumed that the degradation of material properties is primarily responsible for the damage. Therefore, a progressive damage model for fiber-reinforced composites is adopted to predict the damage process and the extent of damage in the skins. First, a finite element model is developed to perform stress analysis. Then a set of failure criteria is applied to detect damaged elements, the material properties of which are degraded in the next computation. This procedure is repeated for progressively increasing load levels until the structure fails [7].

2) Damage mechanics and material degradation of honeycomb core

The most difficult part in the simulation of honeycomb sandwich structures with inserts is the complex nonlinear behavior and a variety of failure modes of the honeycomb core. For the analysis of the honeycomb materials, two standard modeling approaches have been employed: micromechanical and homogenized macro model. Homogenized macro model is more efficient and much more feasible to be implemented into a larger sandwich structure model. And this method makes it possible to introduce the stiffness degradation method in honeycomb core analysis.

Taken as an equivalent orthotropic body, the honeycomb core has three elastic symmetry planes, and the flexibility matrix can be represented as:

$$\left[S_{ys}^{*}\right]=\begin{bmatrix} \frac{1}{E_1} & -\frac{\upsilon_{12}}{E_2} & -\frac{\upsilon_{13}}{E_3} & 0 & 0 & 0 \\ -\frac{\upsilon_{21}}{E_1} & \frac{1}{E_2} & -\frac{\upsilon_{23}}{E_3} & 0 & 0 & 0 \\ -\frac{\upsilon_{31}}{E_1} & \frac{\upsilon_{32}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$

Cellular structures such as hexagonal honeycomb would not have transverse deformation when subjected to in-plane tensile, so we can define $\upsilon_{23}=\upsilon_{13}=0$. According to the Maxwell theorem, $E_1\upsilon_{21}=E_2\upsilon_{12}$, $E_2\upsilon_{32}=E_3\upsilon_{23}$, $E_3\upsilon_{13}=E_1\upsilon_{31}$, and E_1 and E_2 are relatively smaller and can be assumed identical value, Thus the stiffness matrix $\boldsymbol{C}_{ys}^{*}$ can be expressed as：

$$\left[C_{ys}^{*}\right]=\begin{bmatrix} C_1 & C_{12} & 0 & 0 & 0 & 0 \\ C_{12} & C_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & C_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_6 \end{bmatrix}$$

As the honeycomb core is mainly used to bear out-of-plane load and shear load in most conditions, only the failure modes under these loads are considered. C_3, C_4, and C_5 in the matrix above are related to out-of-plane modulus of compression and shear modulus, and when the out-of-plane load exceeds the ultimate strength, we can reduce C_3 with a degradation factor D_3. D_4 and D_5 are the degradation factors for C_4 and C_5 respectively.

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4. Numerical results and discussion

Finite element models are developed with ANSYS-APDL (ANSYS Parametric Design Language) and integrated into the main program representing the ultimate strength and corresponding failure behaviors. The potted-in style insert is taken as an example of introducing the simulation. The detailed flow chart of the solution algorithm is shown in Fig.4. Initially, the analytical model data such as the geometry, material properties and boundary conditions are given as inputs. Then a small displacement U0 is specified and the stress and strain is computed. The calculated stress in each element is then fed into the failure criterion corresponding to the component that the element belongs to. Once the damage has been assessed, the material properties are updated according to the failure mode and degradation factors Di (i =1~6) of each layer. If no element fails, an incremental load △U is added until new damage occurs. In what follows, the loading procedure is cycled until the final load is reached.

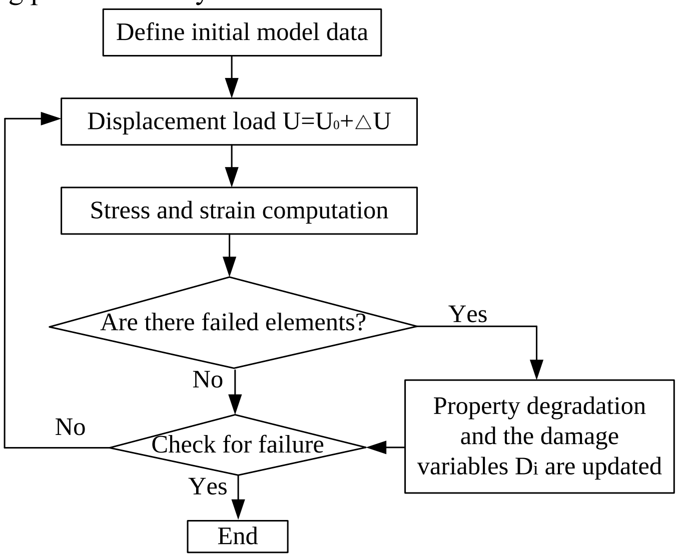

Figure. 4 Flow chart of the finite element analysis

As shown in Fig.2, the bearing force of the honeycomb structure under out-of-plane compressive loading drops rapidly when the load is beyond the maximum point, so D_3 is initially defined to be a small constant, for example, 0.01. Unlike the compressive loading, the shear failure is more sluggish, which is however the more critical failure mode in this case. As the stiffness of the honeycomb structure is almost the same in two in-plane directions, D_4 and D_5 are given the same value in the range of 0.01 to 0.9, in search of results better matching the experiment data.

After many adjustments, the appropriate parameters are selected, D_4 and D_5 have two sets of value, D_4^{1st}, D_4^{2nd} and D_5^{1st}, D_5^{2nd}, which are applied in two steps. First, let $D_4^{1st} = D_5^{1st}$ =0.6, and if the element is damaged according to the failure criterion, set, D_4^{2nd} and D_5^{2nd} =0.01.
Consider that when the failure occurs in one direction, the strength in other directions will be affected, so we define $D_3 = D_5$ =0.7 simultaneously after D_4^{1st} is changed to 0.01, in the same way, define $D_3 = D_4$ =0.7 after D_5^{1st} is changed to 0.01. If D_4^{1st} and D_5^{1st} are both change to 0.01, then let D_3 =0.7.

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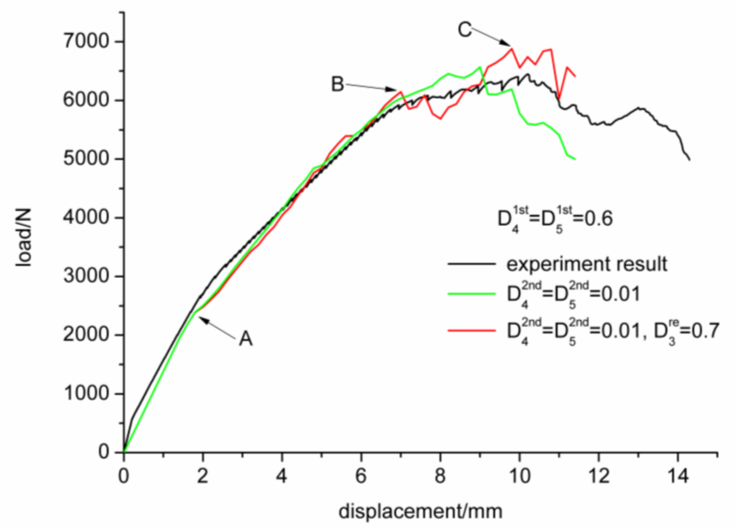

Figure. 5 Results after reduce the relevant degradation factor

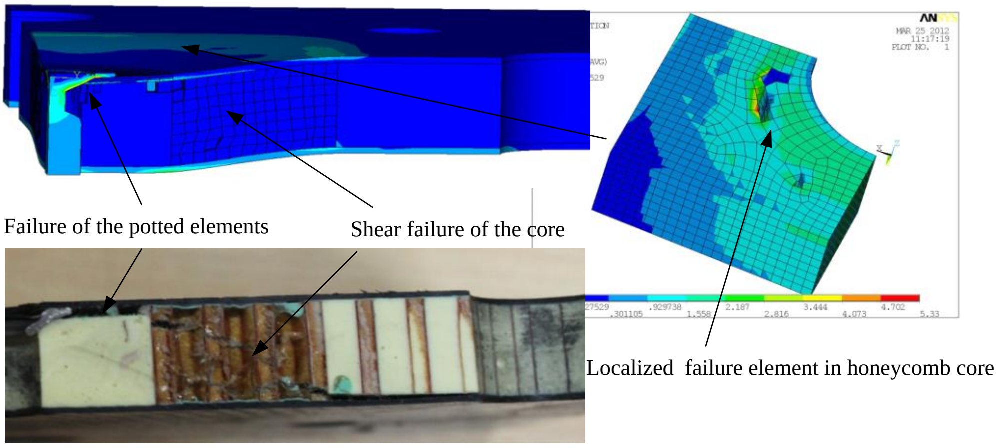

Figure. 6 Comparison between simulation and experimental results

Moreover, the slope of the calculated load-deflection curve changes at point A (Fig. 5) while the slope of the measured curve does not change there. This indicates that the initial localized shear buckling of honeycomb core cannot severely affect the entire structure at the beginning. As the numbers of failed elements increase, the curve becomes nonlinear until the load reaches the first maximum at point B, then the load drops because of the tensile rupture of the potted elements in the interface attached to the face sheet. Then the load starts to concussion caused by the failure of the elements of the potting material and the face sheet. When the load jitter to point C, the structure can hardly bear any more load, and the computation has to stop.

5. Conclusions

Experiments are conducted to evaluate the pull-through strength and damage behavior of Nomex honeycomb sandwich structures with inserts. Based on observation and analysis of the experimental results, a non-linear finite element model is proposed to analyze the non-linear behavior of the failure process using the stiffness degradation method. The database for determining the stiffness degradation factors Di of the honeycomb core is established by means of parametric fitting. The damage model is implemented using the commercial finite element code ANSYS-APDL, so this method can be universally applied as a computational tool for the design of honeycomb sandwich structure joints.

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Comparison of the experimental and numerical results demonstrates that the equivalent method for the honeycomb core can effectively simulate the structural behavior, and the stiffness degradation model is suitable for the joint analysis. The procedure developed in this study can be applied in the design and analysis of honeycomb sandwich structure with inserts.

6. References

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