STUDY ON THE OUT-OF-PLANE SHEAR PROPERTIES OF SUPERALLOY HONEYCOMB CORES

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1 Introduction

Honeycomb sandwich panels are used extensively due to their high specific stiffness and specific strength. These panels usually consist of two thin, stiff and strong face-sheets connected by a lightweight honeycomb core. Today these panels are used in aerospace industry (such as satellite structures, airfoil, tail unit, rotor blades, …) as well as in the marine industry (such as submarine hull, yacht, …).

The primary function of honeycomb sandwich panels is to carry bending loads, so the honeycomb core (Fig. 1) must be stiff and strong enough to ensure the face sheets do not slide over each other. These properties are mainly related to the out-of-plane shear moduli and strength of the honeycomb cores. Characterization of these out-of-plane parameters is quite critical for honeycomb cores.

Kelsey et al. [1] and Gibson et al. [2] derived the upper and lower bonds of mathematical expressions of the equivalent out-of-plane shear moduli of honeycomb cores using the theorems of minimum potential energy and minimum complementary energy. Grediac [3] used the finite element method to calculate the out-of-plane shear modulus as well as the state of stress in the cell walls of honeycomb core. Meraghni, Desrumaux and Benzeggagh presented a new analytical method to analyze the out-of-plane stiffness of honeycomb cores based on the modified laminate theory [4].

The out-of-plane shear strength is a significant stress of honeycomb cores. To present day, few studies have been conducted on the out-of-plane shear strength and shear failure models of honeycomb cores. Zhang and Ashby analyzed the buckling strength of a wide range of Nomex honeycomb cores [5]. Pan experimentally investigated the longitudinal shear deformation behavior and failure process of 5056Al alloy honeycomb cores using single block shear test and compared the results with the elastic buckling strength model, however the experimental shear strength results obtained were significantly higher than the theoretical ones [6]. Lee et al. investigated the compressive and shear deformation behavior and failure mechanism of honeycomb composites consisting of Nomex honeycomb cores and 2024Al alloy face sheets at room and elevated temperatures [7], However, experimental shear strength results obtained were significantly higher than the theoretical ones too. The mechanical behavior, especially the shear strength and failure process of honeycomb cores under shear loads still need to be further investigated.

2 Analysis

2.1 Prediction on the Equivalent Out-of-plane Shear Moduli of Metallic Honeycomb Cores

Typical regular honeycomb core is periodic, so a simple unit-element can be isolated which can be repeated exactly to build up the entire honeycomb core, and the analysis could be conducted on the unit-element instead of the entire honeycomb core. The unit-elements of "Kelsey" model [1] and "Gibson" model [2] are showed in fig. 2.

Honeycomb cores built up by repeating the unit-element of "Gibson" model are seldom used in engineering while honeycomb cores with double thickness horizontal walls are more familiar which can be built up by repeating the unit-element of "Kelsey" model. This paper proposed a more simpler unit-element as shown in fig. 3.

The stress distribution of cell walls of honeycomb core under out-of-plane shear loads is not simple; each cell wall suffers a non-uniform deformation. Exact calculations are possible only by using numerical methods. But upper and lower bounds of the out-of-plane shear moduli can be obtained by using the theorems of minimum potential energy and minimum complementary energy [1].

The first theorem gives an upper bound. It states that the strain energy calculated from any postulated set of displacements which are compatible with the external boundary conditions and with themselves will be a minimum for the exact displacement distribution.

A uniform strain, γ_{13}, is acting on the honeycomb in the 13 direction. The shear strains in walls a and b (as shown in fig. 3)are:

$$\gamma_a = 0 \tag{1}$$

$$\gamma_b = \gamma_{13}\cos\theta \tag{2}$$

The unit-element volume is:

$$V^* = \left(l_c + l_i \sin\theta\right) l_i \cos\theta b \tag{3}$$

Where b is the height of the honeycomb core. Almost all the elastic strain energy is stored in the shear displacements in the cell walls; the bending stiffness and energies associated with the bending are much smaller. Ignoring the energies associated with the bending, The theorems can then be expressed as an inequality which, for shear in the 13 direction, has the form:

$$\frac{1}{2} G_{13}^* \gamma_{13}^2 V^* \le \frac{1}{2}\sum_i \left(G_s \gamma_i^2 V_i\right) \tag{4}$$

Where G_s is the shear modulus of the cell wall material, γ_i are the shear strains in the two cell wall. Evaluating the sum gives:

$$G_{13}^* \le t\cos\theta G_s / \left(l_c + l_i \sin\theta\right) \tag{5}$$

Repeating the calculation for a shear γ_{23} in 23 direction, the strains in cell wall a and b are:

$$\gamma_a = \gamma_{23} \tag{6}$$

$$\gamma_b = \gamma_{23}\sin\theta \tag{7}$$

And

$$G_{23}^* \le \frac{tG_s\left(l_c + l_i \sin^2\theta\right)}{\left(l_c + l_i \sin\theta\right) l_i \cos\theta} \tag{8}$$

The minimum complementary theorem gives a lower bound for the moduli. It state, that, among the stress distributions that satisfy equilibrium at each point and are in equilibrium with the external loads, the strain energy is a minimum for the exact stress distribution. Expressed as an inequality, for shear in the 13 direction:

$$\frac{1}{2}\frac{\tau_{13}^2}{G_{13}^*} V^* \le \frac{1}{2}\sum_i \left(\frac{\tau_i^2}{G_s} V_i\right) \tag{9}$$

Considering, first, loading in the 13 direction. We postulate that an external stress τ_{13} induces a set of shear stresses τ_a and τ_b in the two cell walls. As the wall a is loaded in simple bending, it carries no significant load, so τ_a equal to zero.

Equilibrium requires that:

$$\tau_{13}\left(l_c + l_i \sin\theta\right) l_i \cos\theta = \tau_b t l_i \cos\theta \tag{10}$$

Then

$$\tau_b = \tau_{13}\left(l_c + l_i \sin\theta\right)/t \tag{11}$$

Then the inequality equation (7) give a lower bound:

$$G_{13}^* \ge t\cos\theta G_s / (l_c + l_i \sin\theta) \tag{12}$$

For loading in the 23 direction, we again postulate that the external shear stress τ_{23} induces a set of shear stresses τ_a, τ_b and τ_c in the three cell walls(as shown in fig. 4).

the equilibrium with the external stress gives:

$$\tau_{23}(l_c + l_i \sin\theta) 2 l_i \cos\theta = \tau_a l_c 2t + 2\tau_b l_i t \sin\theta \tag{13}$$

The equilibrium with the stress at the nodes require:

$$\tau_a(2t) = \tau_b t + \tau_c t \tag{14}$$

Symmetry require $\tau_b=\tau_c$, so $\tau_a=\tau_b=\tau_c$,and then

$$G_{23}^* \ge \frac{tG_s\left(l_c + l_i \sin\theta\right)}{\left(l_c + l_i\right) l_i \cos\theta} \tag{15}$$

Combining the equations (Eqn5, 8, 12, 15) gives:

$$G_{13}^* = t\cos\theta G_s / \left(l_c + l_i \sin\theta\right) \tag{16}$$

$$\frac{tG_s\left(l_c + l_i \sin\theta\right)}{\left(l_c + l_i\right) l_i \cos\theta} \le G_{23}^* \le \frac{tG_s\left(l_c + l_i \sin^2\theta\right)}{\left(l_c + l_i \sin\theta\right) l_i \cos\theta} \tag{17}$$

For the regular hexagon honeycomb cores, giving : $l_c=l_i=l$, $\theta=30^\circ$, these equations reduced to:

$$G_{13}^* = \frac{\sqrt{3}}{3}\frac{t}{l} G_s \tag{18}$$

$$\frac{\sqrt{3}}{2}\frac{t}{l} G_s \le G_{23}^* \le \frac{5\sqrt{3}}{9}\frac{t}{l} G_s \tag{19}$$

2.2 Prediction on the Out-of-plane Shear Elastic Buckling Strength of Metallic Honeycomb Cores

The cell walls of a metallic honeycomb core may buckle elastically under out-of-plane shear loads. The buckling load for a cell wall [9] is determined by the second moment of intertia of the cell wall and by the width l:

$$\tau_{crit} = \frac{CE_s}{(1-v_s^2)}\left(\frac{t}{l}\right)^2 \tag{20}$$

From Roark and Young [9], $C=8.44$ was choosen by Zhang and Ashby, which is the value intermediate to that for $b/l=2$ and that for $b/l=\infty$ for these particular boundary conditions.

In the calculation of the out-of-plane shear elastic buckling strength of honeycomb cores, the stress distribution of cell walls derived from the minimum complementary theorem was used.

For loading in the 13 direction, equilibrium of the stress requires τ_a equal to zero and:

$$\tau_{13}(l_c + l_i \sin\theta) l_i \cos\theta = \tau_b l_i t \cos\theta \tag{21}$$

Elastic buckling occurs in walls b; setting $\tau_b=\tau_{crit}$ then:

$$\tau_{13} = \frac{CE_s}{1-v_s^2}\frac{1}{l_c/l_i + \sin\theta}\left(\frac{t}{l_i}\right)^3 \tag{22}$$

Repeating the calculation for the 23 direction, equilibrium requires:

$$\tau_a = \tau_b,\ \tau_{23}(l_c + l_i\sin\theta) l_i \cos\theta = \tau_a l_c t + \tau_b l_i t \sin\theta \tag{23}$$

For the hexagon honeycomb core with $l_c=l_i=l$, elastic buckling occurs in wall b; setting $\tau_b=\tau_{crit}$ then:

$$\tau_{23} = \frac{1}{\cos\theta}\frac{CE_s}{1-v_s^2}\left(\frac{t}{l_i}\right)^3 \tag{24}$$

For the regular hexagon honeycomb cores, giving : $l_c=l_i=l,\ \theta=30°$, these equations reduced to:

$$\tau_{13} = \frac{2}{3}\frac{CE_s}{1-v_s^2}\left(\frac{t}{l}\right)^3 \tag{25}$$

$$\tau_{23} = \frac{2\sqrt{3}}{3}\frac{CE_s}{1-v_s^2}\left(\frac{t}{l}\right)^3 \tag{26}$$

3. Experimentation

3.1 Material Specimens

Superalloy honeycomb cores with designation 3.2-GH3536-0.05(which should be read as: cell size in mm-foil material-foil thickness in mm)were used for the static test. For the material of GH3536, the tension modulus is 205GPa, the possion's ratio is 0.32, and the yield strength at 0.2% offset is 379MPa. The foil is made into a corrugated sheet by means of a corrugated rolls first, and then the corrugated sheets are brazed together into honeycomb core. This process produces honeycomb cores with double thickness horizontal walls. The test specimens are sized in accordance to ASTM standard C273 [10], and were 120 mm in length, 50 mm in width and 10 mm in height. These specimens are rigidly bonded to two loading plates that are subject to opposing tensile displacements which result in a shear force on the sandwich cores. Two sets of specimens were made so that tests could conducted for two principal directions.

3.2 the Out-of-plane Shear Test Assembly

The static tests were conducted through a shear test fixture. In accordance to the ASTM standard C273 the test fixture and the loading plates should make sure that the line of action of the load passes thought the diagonally opposite corners of the honeycomb core. The test does not produce pure shear stress, but the specimens length is prescribed so that secondary stresses have a minimum effect. In order to improve the measure precision a fixture was designed to fix the gauge (as show in fig. 5).

3.3 Experimental Procedures and Results

The out-of-plane shear tests were conducted at room temperature, and the rate of cross-head movement was 0.5mm/min as the suggested rate in ASTM C273-00. The load-displacement curve of honeycomb cores during the shear test is shown in fig. 6 and fig. 7.

Based on the characteristic load-displacement behavior the process of shear deformation in 13 direction can be approximately categorized into five stages, named as Ⅰ, Ⅱ, Ⅲ, Ⅳ and Ⅴ. In stage Ⅰ, the elastic shear deformation of cell walls is observed; stage Ⅱ, just as the load-deformation curve of the tension on plastic material, is the "yield" stage until a maximum load appears; in stage Ⅲ and Ⅳ, the load decreases and then increases; in stage Ⅴ the load decreases again and the interface debonding between honeycomb core and the loading plate becomes prevalent. The modulus of out-of-plane shear in 13 direction can be obtained from stage Ⅰ, and the shear strength can be obtained from the first maximum load. In engineering, the first maximum load appearing is defined as "failure", so stages Ⅲ, Ⅳ and Ⅴ are not significative.

The process of shear deformation in 23 direction can be approximately categorized into three stages, named as Ⅰ, Ⅱ and Ⅲ. In stage Ⅰ, the elastic shear deformation of cell walls is observed; stage Ⅱ, just as the load-deformation curve of the tension on plastic material, is the “yield” stage until a maximum load appears; in stage Ⅲ, the load decreases rapidly and debonding occurs abruptly. The modulus of out-of-plane shear in 23 direction can be obtained from stage Ⅰ, and the shear strength can be obtained by the maximum load.

The test result and the analytical result are listed in table 1. The analytical result of out-of-plane shear modulus in 13 direction has a good agreement with the test result, while both the lower and upper bounds of analytical result of out-of-plane shear modulus in 23 direction is higher than the test result by 33.8% and 48.5% respectively. The analytical results of out-of-plane shear strength in 13 and 23 directions calculated with the elastic buckling model are both much higher than the test results respectively by 228% and 310%.

4 Yield Stress Model for Out-of-plane Shear Strength Prediction of Honeycomb Cores

The specimens which were tested in 23 direction debonded from loading plates just after the load reached the maximum, so attention were paid to these debonded specimens to explore the failure reason. The failure pattern of cell walls of the honeycomb core specimens is illustrated in fig. 8. Clearly the cause of failure is not elastic buckling but plastic buckling as the deformation of the cell walls don’t get back, and it is that the compression stress leads to the deformation of the cell walls. Then a model base on the yield stress of the cell wall was proposed to predict the out-of-plane shear strength of honeycomb cores.

In this model, the stress distribution of cell walls derived from the minimum complementary theorem was used. The cell wall is assumed to sustain pure external shear stress (as shown in fig. 9) with three principal stresses as:

$$\sigma_1 = \tau, \sigma_2 = 0, \sigma_3 = -\tau \tag{27}$$

, here τ is the assumed external shear stress. In this model the yield stress of the cell wall material σ_{ys} or the yield strength at 0.2% offset $\sigma_{0.2}$ is used. The model assume that when

$$|\sigma_3| = \sigma_{ys} \ \ or \ \ \sigma_{0.2} \tag{28}$$

, the shear load applied to the honeycomb core reaches its ultimate loading capability. It mean that, at the condition of pure shear stress, when the value of external shear stress reaches the value of yield stress or the yield strength at 0.2% offset of the cell wall material the cell wall yields and the honeycomb core fails. In this section, σ_{ys} was taken for example.

For specimens tested in 13 direction , the stress distribution of cell walls of honeycomb cores is showed in fig. 10.

The external shear stress applied to the cell walls are:

$$\tau_a = 0, \tau_b = \tau_c = \tau \tag{29}$$

For loading in the 13 direction, equilibrium of the stress requires:

$$\tau_{13}(l_c + l_i \sin\theta)2l_i \cos\theta = 2\tau l_i t \cos\theta \tag{30}$$

The model assume that when $\tau=\sigma_{ys}$ the honeycomb core reaches its ultimate loading capability and fails, then

$$\tau_{13} = \frac{1}{l_c / l_i + \sin\theta}\sigma_{ys}\frac{t}{l_i} \tag{31}$$

For specimens tested in 23 direction, the stress distribution of cell walls of honeycomb cores is shown in fig. 11.

$$\tau_a = \tau_b = \tau_c = \tau \tag{32}$$

And equilibrium with the external stress gives

$$\tau_{23}(l_c + l_i \sin\theta)2l_i \cos\theta = \tau l_c 2t + 2\tau l_i t \sin\theta \tag{33}$$

Then

$$\tau_{23} = \frac{1}{\cos\theta}\sigma_{ys}\frac{t}{l_i} \tag{34}$$

For the regular hexagon honeycomb cores, giving : $l_c=l_i=l, \theta=30°$, these equations reduced to:

$$\tau_{13} = \frac{2}{3}\sigma_{ys}\frac{t}{l} \tag{35}$$

$$\tau_{23} = \frac{2\sqrt{3}}{3}\sigma_{ys}\frac{t}{l} \tag{36}$$

This model can have a quite good prediction on the out-of-plane shear strength of superalloy honeycomb core (as shown in Table 2).

5. Conclusion

The equivalent out-of-plane shear moduli and elastic buckling strengths were analyzed. And the out-of-plane shear properties, including the out-of-plane shear moduli and strengths, of a superalloy honeycomb core were obtained by conducting a serious of shear properties tests that strictly followed ASTM-C 273-00. The analytical and the test data show that: the analytical result of out-of-plane shear modulus in 13 direction has a good agreement with the test result, while the lower and upper bounds of analytical result of out-of-plane shear modulus in 23 direction are higher than the test result by 33.8% and 48.5%; the analytical result of out-of-plane shear strength in 13 and 23 directions calculated with the elastic buckling model are much higher than the test result by 228% and 310% respectively. By carefully study the failure pattern of cell walls of the honeycomb core specimens, a model base on the yield stress of the cell wall was proposed to predict the out-of-plane shear strength. This model can have a quite good prediction on the out-of-plane shear strength of superalloy honeycomb core.

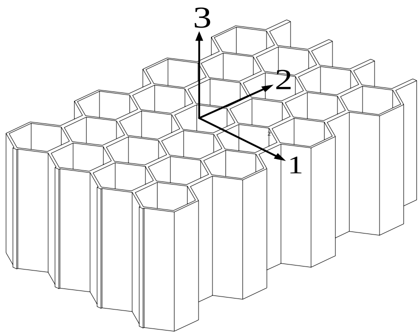
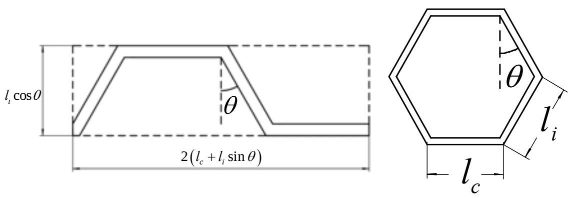


Fig. 1 Typical honeycomb core



(a) (b)

Fig. 2 The unit-elements of “Kelsey” model and “Gibson” model
(a) The unit-element of “Kelsey” model (b) The unit-element of “Gibson” model

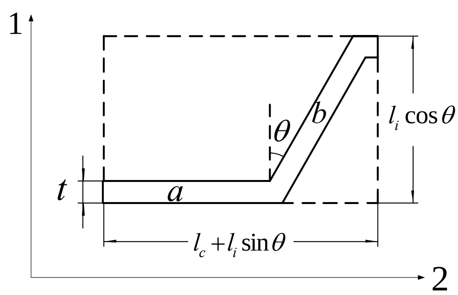


Fig. 3 The unit-element proposed

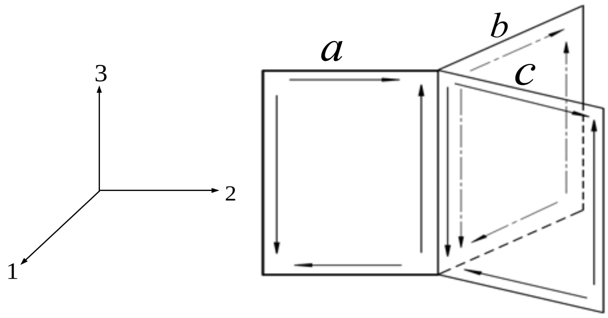


Fig. 4 The stress distribution of the cell walls

Fig. 5 The out-of-plane shear test assembly of a superalloy honeycomb core

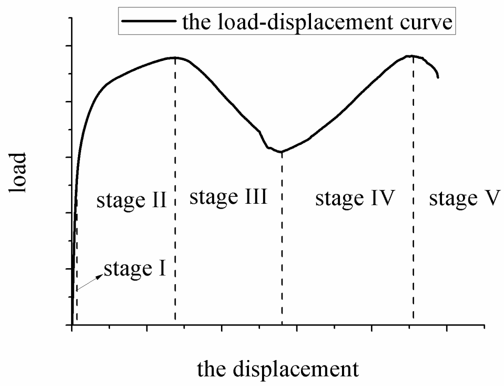


Fig 6 The load-displacement curve of honeycomb cores in 13 direction during the shear test

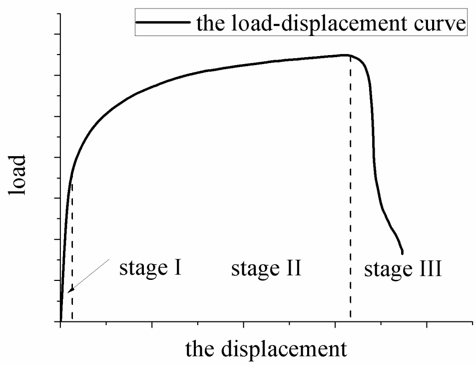


Fig 7 The load-displacement curve of honeycomb cores in 23 direction during the shear test

Fig 8 The failure pattern of cell walls of the honeycomb core specimens tested in 23 direction

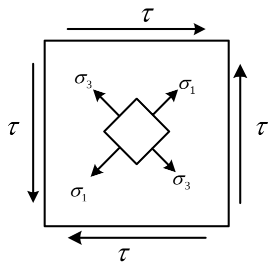


Fig. 9 The stress distribution of a cell wall sustaining pure external shear stress

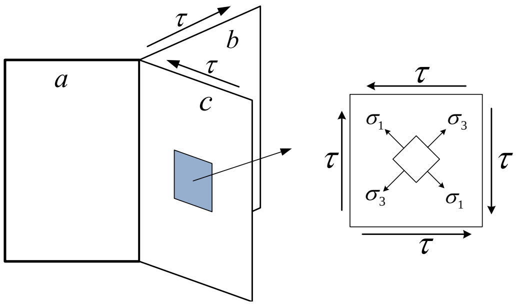


Fig. 10 The stress distribution of cell walls

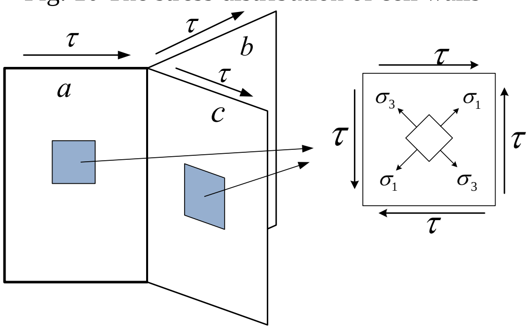


Fig. 11 The stress distribution of cell walls

Table. 1 The test result and the analytical result

	G_{13}(GPa)	G_{23}(GPa)	S_{13}(MPa)	S_{23}(MPa)
test result	1.20	1.36	7.75	10.72
analytical result	Eqn18 1.21	Eqn19 1.82 ~ 2.02	Eqn25 25.4	Eqn26 43.9

Table. 2 The test result and the analytical result

Strength(MPa)	13 direction	23 direction
Test value	7.75	10.72
Elastic buckling model	25.4	43.9
Yield stress model	6.83	11.83

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