Analysis of bending stiffness of honeycomb sandwich structure filled with foam

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Abstract. Based on the knowledge of material mechanics and elastic mechanics, the theoretical calculation formula of bending stiffness of honeycomb core filled with foamed rubber is derived in this paper. The rationality and feasibility of the theoretical formula are verified by finite element analysis of three-point bending model of honeycomb sandwich structure with or without foamed rubber. At the same time, the relative error between the bending stiffness value of finite element analysis and the theoretical value is controlled within 10%, which makes the calculation formula of theoretical value of filled foamed rubber honeycomb core have certain reference significance and application value.

1. Introduction
Honeycomb sandwich structure with lightweight design, excellent thermal insulation and vibration isolation performance, good mechanical properties and other advantages, has been widely used in aerospace, ship, automobile and other fields [1-2]. Honeycomb sandwich structure is often subjected to bending load in use, so the research on its bending stiffness becomes particularly important.

For honeycomb sandwich panels, the main bending stiffness comes from the high moment of inertia due to the height of the core, but the premise is that the core keeps stable mechanical properties in the loading process. The earliest honeycomb sandwich structure theory is the "anti-plane" hypothesis proposed by Allen [3], which ignores the in-plane stiffness and bending stiffness of the honeycomb core, and considers that the honeycomb core is mainly subjected to transverse shear. This model is very simple and practical, and it was widely used in the early stage. However, the accuracy of the model is not high, because the honeycomb core is very soft, but it has a greater thickness than the panel. Simply ignoring the core will lead to great error to the stiffness evaluation of sandwich panels.

Many scholars have also improved their mechanical properties by filling other materials in honeycomb sandwich structures. The mechanical properties of three honeycomb sandwich core bodies under shear conditions were compared by Fathi [4], including pet foam, PVC foam and balsa wood. Liu [5] et al. Studied the mechanical properties of aluminum honeycomb core under plane compression and axial compression, including the influence on ultimate load, mean compressive strength, energy absorption rate and failure mode. Antali [6] et al. Studied the effect of the embedding of carbon fiber reinforced composite tube on the energy absorption characteristics of honeycomb sandwich structure. Zhang [7] studied the dynamic response of honeycomb structure filled with foam, and considered the influence of the density and loading rate of the foam on the failure mode of the structure.

In this paper, the improvement of bending stiffness of honeycomb core filled with EPP foam was studied by numerical analysis. The equivalent elastic modulus and bending stiffness of honeycomb
core filled with EPP foam were deduced according to material mechanics, the theoretical value of the
bending stiffness of the honeycomb core filled with EPP foam is compared with the displacement load
curve calculated by the three-point bending test of the honeycomb sandwich structure simulated by
finite element method.

2. Theoretical analysis

2.1. Calculation of equivalent modulus and bending stiffness of filled foamed rubber honeycomb core
Based on the theory of elastic mechanics, the following assumptions should be made for calculating
the bending stiffness of the honeycomb core filled with foamed rubber: (1) the foamed rubber is
uniformly filled and does not separate during the denaturation process, so it has a good bonding with
the honeycomb core;(2) The honeycomb core lattice is hexagonal in shape, which is anisotropic in
macroscopic view, that is, the mechanical properties are not consistent in the direction of length and
width;(3) As far as the bending stiffness of the honeycomb core filled with foamed rubber is
concerned, it is a linear elastic material as a whole.

According to the above assumptions, the deformation of the honeycomb core filled with EPP foam
is equal to that of the foam rubber during uniaxial compression. So it can be expressed as that:
\[ \varepsilon_c = \varepsilon_f = \varepsilon_t = \frac{\Delta l}{l} \]  

The stress of honeycomb core and foamed rubber can be obtained from the knowledge of material
mechanics:
\[ \sigma_c = E_c \varepsilon_c \]  
\[ \sigma_f = E_f \varepsilon_f \]

According to the stress balance, we can get the following equation:
\[ E_c \varepsilon_c A = E_f \varepsilon_f A_f + E_c \varepsilon_c A_c \]

The equivalent elastic modulus of the honeycomb core filled with EPP foam is obtained as follows:
\[ E_1 = \frac{E_f A_f}{A} + \frac{E_c A_c}{A} \]

Because the Poisson's ratio of foamed rubber and honeycomb core is different, the bending
stiffness should be corrected. According to Poisson ratio, the equivalent elastic modulus of the
honeycomb core filled with EPP foam can be obtained by assuming the same transverse deformation:
\[ E_2 = \frac{\mu_f}{\mu_c} E_1 = \frac{\mu_f}{\mu_c} \left( \frac{E_f A_f}{A} + \frac{E_c A_c}{A} \right) \]

In formula (1) - (6), the subscript l, f and c denote the total length of honeycomb core, EPP foam
and honeycomb core, respectively.

For the calculation of bending stiffness of honeycomb core filled with EPP foam, the definition of
bending stiffness according to the theory of material mechanics is also adopted:
\[ D_{ci} = E_i I_{yi} = \frac{E_i \cdot b \cdot h^3}{12}, i = 1, 2 \]

Where b is the cross-sectional width of the filled foamed rubber honeycomb core and h is the
height of the filled foamed rubber honeycomb core.

2.2. Calculation of bending stiffness of honeycomb sandwich plate
In this paper, the displacement load curves of hollow and filled honeycomb sandwich plates are
obtained by finite element numerical analysis. According to the obtained curves and the 9.4 bending
stiffness calculation formula of sandwich structure in GB/T 1456-2005 [8], the bending stiffness of
two kinds of honeycomb sandwich plates is calculated:
\[ D = \frac{l^2 \cdot a \cdot \Delta P}{16 f_i} \]  

Where the subscript \( l \) is the span of two fixed bases of three-point bending, and \( a \) is the extended length of honeycomb sandwich plate, \( \Delta P \) and \( f_i \) are load increment and displacement increment (or deflection increment).

3. Finite element analysis of three-point bending

3.1. Model material parameters and geometric dimensions

The material parameters and geometric dimensions of the three-point bending honeycomb sandwich structure model used for numerical simulation analysis are shown in Table 1 and Figure 1 below. The overall dimension of hollow and filled honeycomb sandwich plates is 112mm \( \times \) 28mm \( \times \) 8.6mm.

| Material         | Elastic modulus (MPa) | Density (g/cm\(^3\)) | Poisson’s ratio |
|------------------|-----------------------|-----------------------|----------------|
| Skin             | 68000                 | 2.73                  | 0.33           |
| Honeycomb core   | 70000                 | 2.73                  | 0.33           |
| EPP foam         | 250                   | 0.29719               | 0.3            |

Figure 1. Geometric parameters of three-point bending model of honeycomb sandwich panel

3.2. Finite element numerical analysis of honeycomb sandwich plate

The three-point bending numerical analysis model of hollow and filled honeycomb sandwich plates is shown in Figure 2, and the finite element model of two kinds of honeycomb sandwich structure is shown in Figure 3.

The three-point bending numerical analysis model of honeycomb sandwich panel adopts C3D8R element. The honeycomb core is modeled by solid body, with a side length of 4 mm and a wall thickness of 0.05 mm. The foam was filled together and filled with “Interaction-Embedded region” order into the honeycomb core. In order to study the bending stiffness of honeycomb sandwich structure better, “tie” is used to connect the honeycomb core and skin without considering the separation of skin and honeycomb core during loading. Both the base and the indenter are set as rigid bodies, and the contact between the base and the honeycomb sandwich plate is set as rigid contact. The displacement loading method is adopted to make the simulation closer to the actual test loading situation.
4. Results and discussion

The simulation results of hollow and filled honeycomb sandwich plates are shown in figure 4, and the displacement load curve of three-point bending finite element model loading point in the process of numerical analysis is shown in figure 5.

Figure 2. Three-point bending numerical analysis model of honeycomb sandwich structure

Figure 3. Finite element model of hollow and filled honeycomb sandwich plates

Figure 4. Out of plane displacement of two kinds of honeycomb sandwich plates: (a) Hollow honeycomb sandwich panel, (b) Honeycomb sandwich panel with EPP foam
Figure 4 is the out of plane displacement of two kinds of honeycomb sandwich structure when local buckling is about to occur. At this time, the displacement load curve is in the form of a straight line. Continuous loading will reduce the bending stiffness of honeycomb sandwich structure, and the structure will buckle and gradually lose stability. The calculation of the bending stiffness of the two honeycomb sandwich plates is mainly the bending stiffness before buckling, which is also the maximum bending stiffness, that is, the approximate straight line part of the displacement load curve, as shown in figure 5.

For the convenience of calculation, the displacement load curve is represented by scatter plot, and the front approximate straight line part is fitted by data. The slope obtained by data linear fitting is the ratio of load increment and displacement increment (deflection increment), which is brought into formula (8) for calculation. The results show that the bending stiffness of hollow honeycomb sandwich plate is 7.145 N•m^2, that of filled honeycomb sandwich plate is 8.522 N•m^2, and that of filled foam reinforced sandwich plate is 1.377 N•m^2.

In addition, according to the formulas (1) - (7), the equivalent elastic modulus $E_1$, the modified equivalent elastic modulus $E_2$ and the theoretical bending stiffness $D_{c1}$ and $D_{c2}$ of the honeycomb core filled with foamed rubber can be calculated and compared with the above numerical analysis. The specific calculation data are shown in table 2.

| Table 2. Theoretical parameters of foam filled honeycomb core |
|-------------------------------------------------------------|
| $E_1$/MPa | $E_2$/MPa | $D_{c1}$/N•m^2 | $D_{c2}$/N•m^2 | $D_f$/N•m^2 |
| Honeycomb core with EPP foam | 1246.43 | 1133.12 | 1.489 | 1.354 | 1.377 |

It can be seen from the data in Table 2 that the theoretical value of the bending stiffness of the filled foam honeycomb core is larger than that of the numerical analysis, and the theoretical value of the bending strength modified by Poisson's ratio is closer to that of the numerical analysis. The relative error between the numerical analysis and the theoretical value is 8.13%, and the relative error between the numerical analysis and the modified theoretical value is 1.67%, both within 10%, and the modified theoretical value is closer to the bending stiffness calculated by finite element method.
5. Conclusion
In this paper, the theoretical formula of bending stiffness of honeycomb core reinforced with EPP foam rubber and the modified theoretical formula are derived, the rationality and feasibility of the theoretical formula and the modified theoretical formula of the bending stiffness of the honeycomb core reinforced with EPP are verified by numerical analysis of the three-point bending model of the hollow and filled honeycomb sandwich plates. The relative error between the theoretical value of the bending stiffness and the finite element calculation value is 8.13%, and the relative error between the modified bending stiffness and the finite element calculation value is 1.67%. The work in this paper can be used as a reference for the calculation and prediction of bending stiffness of honeycomb sandwich structure filled with reinforcement.

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