Deformation and failure mechanisms of sandwich beams under three-point bending at elevated temperatures

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ABSTRACT

Quasi-static three-point bending tests at different temperatures were carried out for sandwich beams with aluminum face sheets and closed-cell aluminum foam core. The deformation and initial failure behaviors were explored and of the three potential failure modes, i.e. core shear, indentation and face yielding, only the latter two were observed in the experiments at different temperatures. Failure mechanism maps which illustrate the dominant initial failure mode for practical beam designs were constructed for different test temperatures based on the modified Gibson model. It was found that upon increasing the temperature, the incidence of face yield mode increases and the incidence of core shear mode decreases. The theoretical predictions of the initial failure modes and limit loads according to the modified Gibson model are found to be in good agreement with the experimental results at different temperatures.

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1. Introduction

Sandwich structures are widely employed in aerospace and marine applications due to their advantages on in-plane and flexural stiffness, heat resistance, sound insulation and easy assembly [1,2]. Recently, sandwich structures with various different combinations of face sheet and core materials have been developed to improve their performance. There is a significant and growing interest in sandwich structures with aluminum foam core in applications where multi-functionality is important [3,4]. Aluminum foam can act as a structural component, a cooling apparatus or an acoustic damper [5]. Due to the great potential of sandwich structures to be used in some extreme environmental conditions where high temperature may be involved, it is necessary to understand their high-temperature structural responses.

The constitutive responses of aluminum foams at elevated temperatures have been investigated in several previous studies [6–8]. Research results reported by Li et al. [9] described the deep indentation response of closed-cell aluminum foams under different temperatures. It was found that the plastic collapse strength of closed-cell aluminum foams is temperature dependent and decreases almost linearly with the elevation of test temperature. However, researches on aluminum foam-cored sandwich structures have mainly been focused on their room-temperature structural behaviors, and the deformation behavior and failure modes of the sandwich beams with aluminum foam core subjected to three-point bending at elevated temperatures have been less documented.

Sandwich beams may fail by different competing mechanisms, such as face yield, core shear and indentation, depending on their geometries and material properties [3,4]. Gibson’s group [4,10] established a sandwich beam failure model (denoted as the Gibson model [11] hereinafter) and estimated the initial failure load as well as the peak load for each failure mode. The competing collapse modes of face yielding, face wrinkling, core yielding and indentation were distinguished. Two parallel research works carried out by Chen et al. [12] and Bart-Smith et al. [13] have verified this model. Yu et al. [11] considered a cylindrical loading head and cylindrical supports in the analysis and experiments instead of a flat punch and flat supports used in Ref. [10] and proposed a modified Gibson model. Three main failure modes of sandwich beams, i.e. face yield, core shear and indentation, were analyzed. Qin et al. [14–17] systematically investigated the dynamic large-deflection responses of sandwich beams with a metallic foam core struck by a heavy mass. The quasi-static four-point bending behavior [12,18,19] and low-velocity impact behavior [20,21] of sandwich beams with aluminum foam core have also been investigated experimentally at room temperature.

The present study aims to obtain some understandings concerning the deformation and failure behavior of sandwich beams at elevated temperatures via conducting three-point bending experiments on sandwich beams with closed-cell aluminum foam cores at temperatures ranging from 25 °C to 500 °C. The modified
Gibson model is applied and a failure mode map is constructed to predict the initial failure modes of the sandwich beams at different temperatures.

2. Analytical models

2.1. Elastic deformation of sandwich beams

Consider a sandwich beam of length $L_{c}$ and width $b$, comprising two identical face-sheets of thickness $t$ and an aluminum foam core of thickness $c$, loaded in three-point bending with a span length of $L$, as shown in Fig. 1. Smooth cylindrical punch and supports are used. Suffixes $f$ and $c$ in the subscript are used for the face sheets and core material in this study, respectively. Thus, $E_f(T)$ and $\sigma_{yf}(T)$ denote the Young’s modulus and yield strength of the face sheets, respectively. $E_c(T)$, $G_c(T)$, $\sigma_{yc}(T)$ and $\tau_{yc}(T)$ denote the Young’s modulus, shear modulus, compressive strength and shear strength of the aluminum foam core, respectively. These material parameters are considered to be dependent on the temperature $T$. The deflection of the sandwich beam under a load $P$ is the sum of flexural and shear deflections given by [4]

$$\delta = \frac{PL^3}{48EI_{eq}} + \frac{PL}{4(AG)_{eq}},$$

where the equivalent flexural rigidity ($EI_{eq}$) and the equivalent shear rigidity ($AG)_{eq}$ are defined as

$$EI_{eq} = \frac{E_f b t^3}{6} + \frac{E_c b c^4}{12} + \frac{E_f b (t + c)^2}{2} \approx \frac{E_f b t^2 c^2}{2},$$

$$AG_{eq} = \frac{b(c + t)^2 G_c}{c} \approx bcG_c,$$

based on the assumptions that the face sheets are much thinner than the core and the modulus of the face sheets is much greater than that of the core. Perfect bonding is also assumed.

2.2. Modified Gibson’s model

If the stress in the face sheets reaches the yield strength of the face sheet material, the initial failure will be in the face sheets. The analysis of face yield mode in the Gibson model does not involve the shape of the loading head and supports, thus the conclusion for the critical load of the face yield mode is still applicable here, which is given by [10,11]

$$P_{crf} = \frac{4bt(c + t)}{L} \sigma_{yf}(T),$$

in which the foam core strength has been ignored.

The shear force is carried mainly by the foam core when the sandwich beam is subjected to a transverse shear force. If the shear stress in the foam core reaches the shear strength of the foam core material, the initial failure will be in the foam core. The critical load of core shear mode is written as [11]

$$P_{cri} = \frac{3bt^2}{L} \sigma_{yf}(T) + 2bc \left(1 + \frac{H}{L}\right) \tau_{yc}(T),$$

where $H$ is the overhang distance beyond the support.

During indentation of the sandwich beam, plastic hinges form within the upper face sheet adjacent to the indenter with the underlying foam core crushed. The critical load of indentation mode is given as [11]

$$P_{cri} = 2bt \sqrt{\sigma_{yf}(T) \sigma_{yc}(T)}.$$  (6)

2.3. Failure mode map

The failure mode map can be constructed from Eqs. (4)–(6), with dimensionless parameters $t/L$ and $c/L$ as the coordinates. The diagram is divided into three regions. Within each region, one failure mechanism is dominant. The regions are separated by three transition lines, which represent the beam designs for which two mechanisms have the same failure load. The three transition lines are governed by

$$c = \frac{1}{L} \left[\left(1 + \frac{H}{L}\right) \tau_{yc}(T) - 2t \right]^{-1} \left(t \right)^2$$

and

$$c = \frac{L}{L + H \tau_{yc}(T)} \left[\left(\sigma_{yc}(T)\right)^{1/2} t - 3 \left(t \right)^2 \right],$$

respectively. It is clear that these transition lines depend mainly on the strength of face and core materials.

Here, the influence of temperature on the transition lines in the failure mode map is integrated in terms of the yield strength $\sigma_{yf}(T)$ of the face sheets, compressive strength $\sigma_{yc}(T)$ of the aluminum foam core, and the shear strength $\tau_{yc}(T)$ of the aluminum foam core.

3. Experimental investigation

3.1. Materials and specimens

A closed-cell aluminum foam is used as the core material in our experiments, which is produced by liquid state processing using TiH₂ as a foaming agent. Its relative density is about 0.11 and the average cell size is approximately 2 mm. Commercial pure aluminum (1060 of 99.2 pct purity) sheets with different thicknesses are used as face sheets. The sheets with the same thickness were obtained from one thin plate along the same direction. A series of tests, including the uniaxial tensile, compression and double-lap shear tests of foam cores as well as the uniaxial tensile test of face sheets, were conducted to obtain the material properties at different temperatures, and the results are collected in Table 1. As can be seen from Table 1, the yield strength of the face sheet material decreases moderately up to about 300 °C and then decreases fairly dramatically. This sufficiently large difference in slopes indicates different temperature sensitivity between these two temperature ranges, below 300 °C and above 300 °C, possibly due to the variation of microstructure of the material. The compressive strength of closed-cell aluminum foams decreases with the rise in temperature. Raising the temperature also decreases the tensile strength of the aluminum foam. The higher the temperature is, the lower the shear strength of the aluminum foam will be. According to our experimental results, the Young’s modulus of the face sheet material is found to be independent on the test temperature and no significant difference could be found on the Young’s modulus and shear modulus of the foam core at different
temperatures. However, precise quantitative analysis of the oscillations of the Young's modulus and shear modulus of the foam core with respect to test temperature needs further investigation.

In order to identify as many possible failure modes, different face sheet thicknesses and core thicknesses were used. Face sheets with thicknesses 1.0, 2.0 and 3.0 mm and foam cores with thicknesses 10, 20, 30, 40 and 50 mm were employed to fabricate sandwich beams with a total length \( L = 300 \text{ mm} \) and a uniform width \( b = 30 \text{ mm} \). Details of the sandwich beam geometries are listed in Table 2. The face sheets and foam core were bonded with high temperature inorganic adhesive AK04-4. Foam blocks and face sheets were degreased and cleaned by using white cotton cloth with acetone beforehand before bonding. All sandwich beam specimens were air-cured at room temperature for 24 h, after that heat-cured in an oven at 80 \(^\circ\text{C}\). Five different temperatures, namely 25 \(^\circ\text{C}\) (room temperature, RT), 200 \(^\circ\text{C}\), 300 \(^\circ\text{C}\), 400 \(^\circ\text{C}\) and 500 \(^\circ\text{C}\), were considered in our experiments. The deviation from each test temperature was within 5 \(^\circ\text{C}\).

### 3.2. Quasi-static three-point bending tests

Three-point bending tests of sandwich beams were performed at different temperatures to investigate the initial failure modes and bending responses. Quasi-static tests were conducted on an MTS810 testing system in the Engineering and Material Testing Center, USTC, using a three-point bending rig at a crosshead velocity of 0.05 mm/s. Cylindrical steel rollers with diameter 10 mm were used to load and support the sandwich specimens with a span length \( L = 250 \text{ mm} \). Five different temperatures, namely 25 \(^\circ\text{C}\) (room temperature, RT), 200 \(^\circ\text{C}\), 300 \(^\circ\text{C}\), 400 \(^\circ\text{C}\) and 500 \(^\circ\text{C}\), were considered in our experiments. The deviation from each test temperature was within 5 \(^\circ\text{C}\).

### 4. Results and discussion

#### 4.1. Initial failure mechanisms

The initial failure modes observed in the quasi-static experiments are shown in Table 2 and illustrated in Fig. 2. Sandwich beams may fail at a limit load set by face yield, indentation or core failure.

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### Table 1

Mechanical properties of the face sheet and foam core.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>( t (\text{mm}) )</th>
<th>( c (\text{mm}) )</th>
<th>( t/c )</th>
<th>( c/L )</th>
<th>( T (\text{C}) )</th>
<th>( P_{\text{max}} ) (kN)</th>
<th>( D_{\text{max}} ) (N/mm)</th>
<th>( D_{\text{exp}} ) (N/mm)</th>
<th>Failure mode</th>
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<td>2.0</td>
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<td>0.04</td>
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<td>1.26</td>
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<td>337.70</td>
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<td>0.08</td>
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<td>1130.68</td>
<td>1033.59</td>
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<td>0.08</td>
<td>25</td>
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<td>1033.59</td>
<td>FY</td>
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<td>0.008</td>
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<td>200</td>
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<td>874.53</td>
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<td>0.46</td>
<td>884.64</td>
<td>810.35</td>
<td>FY</td>
</tr>
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</table>

Note: "FY"—face yield mode, "IN"—indentation mode.
It is assumed that the operative collapse mechanism for a sandwich beam is the one associated with the lowest collapse load. By taking the face yield mode as an example, the simplest approach is to assume that plastic collapse occurs when the face sheets attain the yield strength $\sigma_{yf}$ while the core yields simultaneously at a stress level of $\sigma_{yc}$. Thus, we can estimate the initial failure load, corresponding to the first deviation from linearity in the load–deflection curve as well as the peak load for each mode. It deserves noting that in Fig. 2, the pictures were taken after the experiments and the sandwich beams had fully collapsed. The initial failure modes were recorded when a turning point was observed in the load–deflection curve. Failure of the sandwich beam may occur in one of several modes: plastic yielding of the face sheet, plastic yielding of the foam core, and indentation of the face sheet into the foam core. However, only two main initial failure modes, namely face yield and indentation, which are defined in Ref. [10], were distinguished. The core shear mode was not operative in the practical ranges of specimens in the present study. This may due to that the materials used in the experiments are not strong enough or thick enough, as referred by [11]. Debonding of interface was also observed in some of the experiments. However, after the occurrence of the initial failure, the sandwich beams finally may collapse in a different failure mechanism when the deflection goes large.

An initial failure mode map according to the geometry and material properties of sandwich beams at room temperature is predicted in Fig. 3, and the initial failure modes observed in the experiments are also plotted in Fig. 3. It deserves to be mentioned that there should have been more experimental data points at room temperature covering the whole diagram to support the conclusions for the analytical model. However, the present work is aimed at obtaining some information concerning the effect of temperature on the mechanical properties of sandwich beams and constructing the failure mode maps which illustrate the dominant failure mode for practical beam designs at elevated temperatures, while previous studies of our group [11,20] and others [4,5,10,12,13] have shown the validity of the Gibson model and the modified Gibson model. From Fig. 3, reasonable good agreement is obtained except for those with 3.0 mm face sheets and a 20 mm foam core, which failed in a face yield mode, rather than the core shear mode predicted theoretically. As referred to [11], the core shear mode will occur if the face sheets are too thick and too strong to be crushed. However, the tensile strength of the aluminum foam core used in the present study is a little weak and the specimens rarely fail in the core shear mode. In fact, the specimens with a 20 mm foam core failed in the indentation mode or face yield mode randomly due to the competition between the failure modes.

Fig. 4 displays the influence of test temperature on the transition lines between different failure modes based on the modified Gibson model with experimentally determined strength values at different temperatures. The arrows shown in Fig. 4 indicate the...
growing trend of the incidence of each failure mode as the temperature increases. The star in Fig. 4 shows the geometric parameters of the sandwich beams tested in the present study under three-point bending at elevated temperatures. Upon increasing the temperature, the incidence of face yield mode increases and the incidence of core shear mode decreases. Thus, the specimens with 2.0 mm face sheets and a 20 mm foam core are bent at elevated temperatures and fail in the face yield mode. Increasing the temperature, the strengths of the face sheets and the closed-cell aluminum foam will decrease. Thus, the face sheets tend to yielding when the sandwich beam is subjected to bending at elevated temperatures. If the aluminum foam core is thick, the upper face sheet of the beams can be easily indented into the foam core at the loading point at elevated temperatures and the indentation failure mode occurs. As a result, the incidence of the core shear mode, which only occurs when the face sheets are thick and strong, decreases as the test temperature increasing, as seen in Fig. 4.

Two symmetrical plastic hinges were assumed at the two supports in the analysis of core shear failure mode in the Gibson model [10]. However, an unsymmetrical deformation mode with plastic hinge formed at only one side of the beam, was observed in the present experiments, as shown in Fig. 5, which can be regarded as a verification of the modified Gibson model. In fact, when an initial failure occurs at one support of the sandwich beam, the stress in the beam will be released such that the other half of the beam does not deform plastically (Fig. 5). A similar phenomenon was also observed in the experiments by Yu et al. [11] and Crupi and Montanini [21].

4.2. Load carrying capacity

Details of the experimental results are summarized in Table 2, in which \( P_{\text{max}} \) is the maximum load, and \( D_{\text{exp}} \) and \( D_{\text{the}} \) are the experimental and theoretical elastic bending stiffness of the sandwich beams, respectively.

From the experiments, \( D_{\text{exp}} \) can be estimated by

\[
D_{\text{exp}} = \frac{\Delta P}{\Delta \delta}
\]

where \( \Delta P \) and \( \Delta \delta \) are the increments of the load and the displacement of the indenter, respectively. The theoretical elastic bending stiffness \( D_{\text{the}} \) can be obtained from Eqs. (1)–(3). The modified Gibson’s model has taken the contribution of face sheets and foam core on the structural bending resistance into consideration. However, it can be seen from Table 2 that the theoretical predictions of the elastic bending stiffness are generally lower than the corresponding experimental results. One possible reason is that the theoretical analysis does not consider the interaction between the face sheets and the foam core. Moreover, the adhesive which partially fills the foam core can also lead to a stiffening effect. Moreover, the elastic bending stiffness of the sandwich beams is not found to vary as the temperature increases.

Though the initial failure occurs with a face yield mode or an indentation mode, the structures finally collapsed in tensile crack of face sheets and foam core because of the substantial load-bearing capacity of the sandwich beams beyond the initial yield. Thus, it is necessary to evaluate the collapse strength in the design of sandwich beams in addition to their stiffness. The experimental and theoretical ultimate loads are compared in Fig. 6. The theoretical ultimate load is the maximum load under the corresponding failure mode predicted by the modified Gibson’s model and the experimental ultimate load is the peak load in the load–deflection curve, after which the load drops off dramatically. The experimental and theoretical ultimate loads are in reasonable agreement for different foam core thicknesses and face sheet thickness at room temperature, as can be seen from Fig. 6a and b. This is because that

![Fig. 5. A collapse mode observed in experiments.](image)

![Fig. 6. Comparison of ultimate loads of aluminum foam core sandwich beams for (a) different foam core thickness with face thickness of 2.0 mm at room temperature, (b) different face sheet thickness with core thickness of 20 mm at room temperature, and (c) different test temperature with face thickness of 2.0 mm and core thickness of 20 mm.](image)
the modified Gibson model is effective for the sandwich beams with thin/weak face sheets.

For the specimens subjected to three-point bending at different test temperatures, as shown in Fig. 6c, predictions of face yield mode and indentation mode by the modified Gibson model are given. As expected, the limit load decreases as the temperature increases. For cases at temperatures lower than 300 °C, the analytical predictions overestimate the ultimate loads and for those at temperatures higher than 300 °C, the predictions underestimate the limit loads. This is because that the critical load predictions of face yield mode and indentation mode by the modified Gibson model are strongly dependent on the face sheet material properties, and the yield strength of the face sheet decreases moderately up to about 300 °C and then decreases dramatically with increasing temperature, as mentioned earlier. However, the theoretical predictions from the core shear mode in the modified Gibson model and the experimental ultimate loads are in reasonable good agreement generally. Thus, the modified Gibson model can provide the guidance to the design and engineering applications of sandwich beams.

5. Conclusions

Sandwich beams with aluminum face sheets and closed-cell aluminum foam core are investigated under quasi-static three-point bending at ambient as well as elevated temperatures. The modified Gibson model is applied to describe the initial failure modes and critical loads at elevated temperatures. The initial failure mode maps under different temperatures are also constructed. Two main failure modes, i.e. face yield and indentation, were observed in the experiments. Upon increasing the temperature, the incidence of face yield mode increases and the incidence of core shear mode decreases. The theoretical predictions of the initial failure modes and the ultimate loads are in good agreement with the experimental results at different temperatures. Therefore, the modified Gibson model is still applicable to predict the behavior of the sandwich beams subjected to three-point bending at elevated temperatures.

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