Composite Structures 111 (2014) 285–290

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

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

Zhibin Li [a,b], Zhijun Zheng [a,*], Jilin Yu [a], Chunqiang Qian [a], Fangyun Lu [b]

[a] CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[b] College of Science, National University of Defense Technology, Changsha, Hunan 410073, PR China

ARTICLE INFO

*Article history:*
Available online 9 January 2014

*Keywords:*
Sandwich beam
Aluminum foam
Three-point bending
Failure map
Elevated temperature

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.



## 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

* Corresponding author. Tel.: +86 551 6360 3044; fax: +86 551 6360 6459.
*E-mail address:* zjzheng@ustc.edu.cn (Z. Zheng).

0263-8223/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2014.01.005

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 $L_0$ 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]

$$\delta = \frac{PL^3}{48(EI)_{eq}} + \frac{PL}{4(AG)_{eq}}, \tag{1}$$

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

$$(EI)_{eq} = \frac{E_f bt^3}{6} + \frac{E_c bc^3}{12} + \frac{E_f bt(t+c)^2}{2} \approx \frac{E_f btc^2}{2}, \tag{2}$$

$$(AG)_{eq} = \frac{b(c+t)^2 G_c}{c} \approx bcG_c, \tag{3}$$

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 applicative here, which is given by [10,11]

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

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]

$$P_{cri\,cs} = \frac{3bt^2}{L}\sigma_{yf}(T) + 2bc\left(1+\frac{H}{L}\right)\tau_{yc}(T), \tag{5}$$

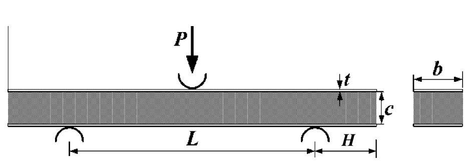


**Fig. 1.** A sketch of sandwich beam loaded in three-point bending.

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]

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

### 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

$$\frac{c}{L} = \frac{1}{2}\sqrt{\frac{\sigma_{yc}(T)}{\sigma_{yf}(T)}} - \frac{t}{L}, \tag{7}$$

$$\frac{c}{L} = \frac{1}{2}\left[\left(1+\frac{H}{L}\right)\frac{\tau_{yc}(T)}{\sigma_{yf}(T)} - \frac{2t}{L}\right]^{-1}\left(\frac{t}{L}\right)^2 \tag{8}$$

and

$$\frac{c}{L} = \frac{L}{L+H}\frac{\sigma_{yf}(T)}{\tau_{yc}(T)}\left[\left(\frac{\sigma_{yc}(T)}{\sigma_{yf}(T)}\right)^{1/2}\frac{t}{L} - \frac{3}{2}\left(\frac{t}{L}\right)^2\right], \tag{9}$$

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 $TiH_2$ 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