Experiment on Mode I/II Mixed Interfacial Fracture Characterization of Foam Core Sandwich Materials at Elevated Temperatures

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Abstract: Foam-cored sandwich materials have been widely used in the civil engineering due to their advantages such as lightweight, high strength, and excellent anti-corrosion ability. However, the interfacial bonding strength of foam-cored sandwich materials is weakened at elevated temperatures. In practice, the effect of high temperature cannot be ignored, because the composites and foams are sensitive to the change of temperature in the environment. In this study, a series of single-leg bending beams were tested at different temperatures to evaluate the influences of high temperatures on Mode I/II mixed interfacial fracture of foam core sandwich materials. The temperature was from 29 ℃ to 90 ℃, covered the glass transition temperature of composites and foam core, respectively. The Mode I/II mixed interfacial crack prorogation and its corresponding interfacial strain energy release rate were summarized.

Key words: foam core sandwich materials; Mode I/II mixed interfacial fracture; elevated temperature; single-leg bending; strain energy release rate

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0 Introduction

During the past 20 years, composite sandwich structures have been widely used in structure engineering as the load-bearing components due to their advantages of high specific strength, light weight, corrosion resistance, fatigue resistance and so on[1-5]. Although the mechanical performance of sandwich structures are excellent, the interfacial delamination become the mainly failure mode[6]. Moreover, the effect of high temperatures cannot be ignored because composites and foam are sensitive to the change of temperatures[7]. Hence, the interfacial delamination behavior of a sandwich material at elevated temperatures becomes a research hot topic[8-9].

However, it is hardly to find any references to investigate the Mode I/II mixed interfacial delamination of sandwich materials at elevated temperatures. It is the reason why to conduct this study. In this study, a series of single-leg bending (SLB) tests were conducted to evaluate the Mode I/II mixed interfacial fracture of composite sandwich materials under different environmental temperatures. The temperature ranged from room temperature 29 ℃ to 90 ℃, including the glass transition temperature (T_g) of glass fiber reinforced polymer (GFRP) face sheets and foam core, which are 85.38 and 69.36 ℃, respectively. The load-displacement curves, failure modes and crack length were recorded.

1 Experimental Program

1.1 Specimens

A total of 20 specimens were tested to evaluate the effect of high temperature on the mixed Mode I-II interfacial fracture of sandwich materials, which were fabricated by vacuum assisted resin infusion process[10-12]. The dimensions of specimens are shown in

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Fig.1. The face sheets were made of the E-type glass fiber fabric and the 980-type vinyl ester resin. The core material was polyurethane foam. All specimens were divided into four groups based on the testing temperatures, i.e. 29 ℃ (Room temperature), 50, 70, 90 ℃, with five replicates for each group.

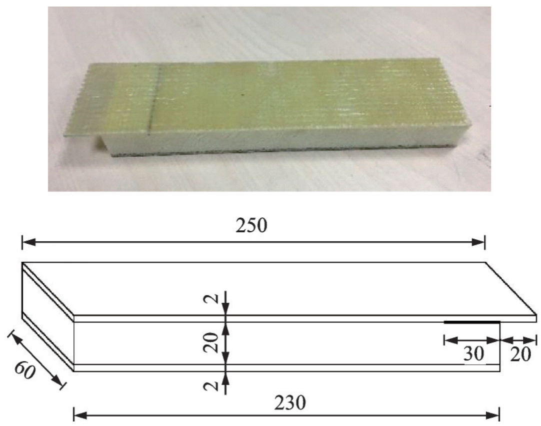


Fig.1 Single-leg bending specimen (unit: mm)

1.2 Material properties

The T_g of face sheets and foam core were measured by use of the differential scanning calorimetry (DSC), which were 85.38 and 69.36 ℃, respectively. The tensile and compressive tests of GFRP face sheets based on ASTM D3039/D 3039M-07[13] and ASTM D695-15 [14], respectively; the compressive tests of foam samples based on the standard of ASTM D1621-16[15]. The measured temperatures were 29, 50, 70, 90 ℃, respectively. Table 1 shows the material properties under different temperatures.

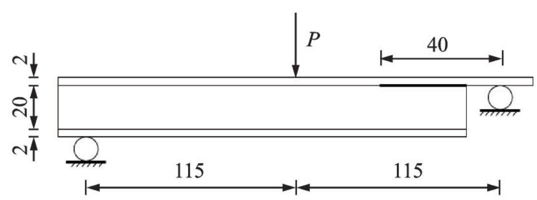
Table 1 Material properties of GFRP

Material	Temperature / ℃	29	50	70	90
Face sheet	Compressive strengh / MPa	167.21	157.15	93.08	79.12
	Compressive modulus / MPa	6 874	6 332	4 901	4 712
	Tensile strength / MPa	306.4	298.8	280.8	240.0
	Tensile modulus / MPa	13 250	12 481	10 392	7 843
Foam core	Compressive strength / MPa	0.44	0.35	0.34	0.30
	Compressive modulus / MPa	12.05	8.29	7.14	6.21
	Tensile strength / MPa	0.30	0.29	0.27	0.18
	Tensile modulus / MPa	12.59	11.85	9.29	8.49

1.3 SLB test at different temperatures

In this study, the Mode I/II mixed interfacial fracture was studied via the SLB tests on the basis of ASTM D6671/D6671M-13e1[16]. For each specimen, a pre-crack with 40 mm length was made between the top GFRP face sheet and the foam core. All tests were conducted in the ceramic heating cabinet, as shown in Fig.2. The clear span between the two roller supports was 230 mm. In the meantime, a K-type thermocouple was embedded in the center of a beam to control the temperature. The specimens were heated to the designed temperature before conducting the SLB testing. The load was applied under displacement control with a loading rate at 2.0 mm/min.


(a) Test set-up



(b) Loading sketch map

Fig.2 Test set-up of SLB tests (unit: mm)

2 Results and Discussion

2.1 Load-displacement response and load-crack length response

The values shown in Fig.3 are the average of the five sets of experiments. The load-displacement curves of SLB tests at four different temperatures are shown in Fig.3(a). The test results showed that the peeling load was decreased with the increase in temperature under the same displacement. When the displacement was 1 mm, compared with the load at 29 ℃, the loads at 50, 70, 90 ℃ decreased by 44.2%, 44.1% and 64.1%, respectively. When the displacement was 2 mm, compared with the load at 29 ℃, the loads at 50, 70, 90 ℃ decreased by 38.5%, 54.7% and 67.3%, respectively. Moreover, the displacement of specimens corresponding to the peak loads increased with the increase in temperatures. The reason is that the bending stiffness of GFRP skins decreased sharply when the temperature reached the T_g.

Fig. 3(b) shows load-crack curves of the SLB tests under different temperatures. The crack length is the sum of the pre-crack length of 40 mm and the measured length. Under the same length of crack growth, with the increase in the temperature, the peeling load showed a downward trend. In other words, the interfacial bonding strength between face sheet and foam core was weakened due to the high temperature. Compared with the maximum load at 29 ℃, the maximum loads at 50, 70 and 90 ℃ decreased by 8.3%, 24.8% and 38.5%, respectively.

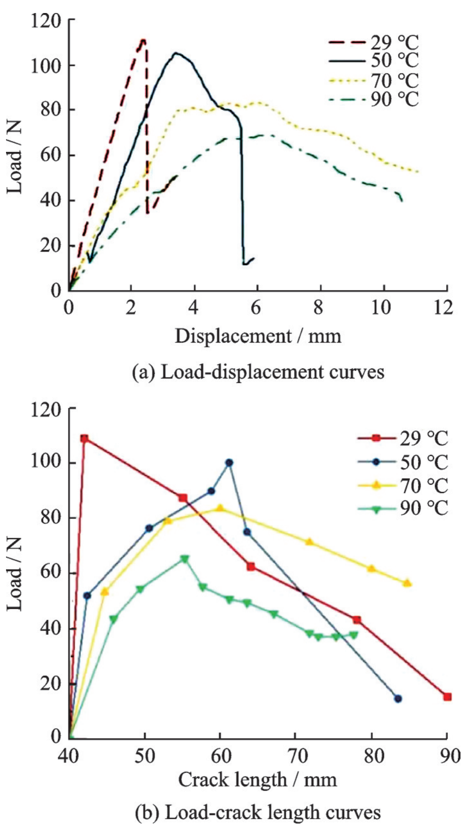


Fig.3 Behavior of specimens under different temperatures

2.2 The strain energy release rate

The strain energy release rate ($G_{I/II}$) is the energy consumption of the unit area when the crack is propagating. The classical plate theory was adopted to calculate the strain energy release rate. The mid-span deflection value δ, the load value P and the corresponding crack length a were considered in this method. The model of SLB specimens is shown in Fig.4.

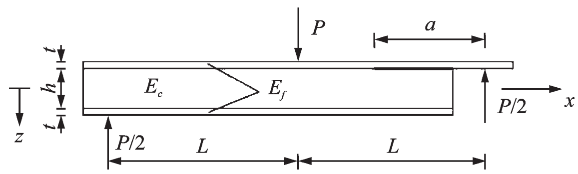


Fig.4 Coordinate system and nomenclature definition for the SLB specimens

The bending stiffness, per unit width, of the upper face sheet D_T is

$$D_T = \frac{E_f t^3}{12} \tag{1}$$

where E_f and t are the elastic modulus and thickness of the GFRP face sheet, respectively. For the sandwich structure with same upper and lower face sheets, the bending stiffness, per unit width, of the un-cracked region is

$$D = \frac{E_f t^3}{6} + \frac{E_f t(t+h)^2}{2} + \frac{E_c h^3}{12} \tag{2}$$

where E_c and h are the elastic modulus and thickness of the core, respectively. The variation of E-modulus with temperature is described by an empirical model[17]

$$E(T) = E_0\left(1 - \frac{T - T_r}{T_{\text{ref}} - T_r}\right)^g \tag{3}$$

where E_0 is the modulus at ambient temperature, T_r the ambient temperature, T_{ref} the high temperature at which the modulus vanishes, and g a power law index ranging from 0 to 1. Then the E_f can be expressed by $E_f(T)$. The fitting result is shown in Fig.5.

Using the classical plate theory, the equation for compliance of SLB specimens can be derived as

$$C = \frac{2L^3 + a^3(R-1)}{12bD} \tag{4}$$

where b is the width of the specimen, L the half-

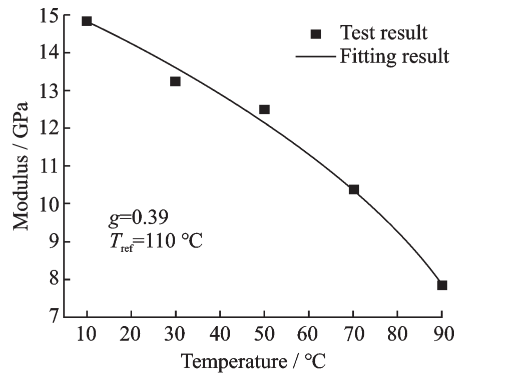


Fig.5 Variation of E-modulus of GFRP with temperature

span length, and R the ratio of bending stiffness of the un-cracked region to that of the top plate, i.e., $R=D/D_T$.

The strain energy release rate can be expressed by differentiating the compliance with respect to crack length

$$G_{\mathrm{I/II}}=\frac{P^2}{2b}\frac{\mathrm{d}C}{\mathrm{d}a} \tag{5}$$

Substituting Eq.(4) into Eq.(5), it becomes

$$G_{\mathrm{I/II}}=\frac{P^2a^2(R-1)}{8b^2D} \tag{6}$$

where the compliance is defined as the center-point deflection divided by the load, i.e., $C=\delta/P$. Then the strain energy release rate becomes

$$G_{\mathrm{I/II}}=\frac{3P\delta a^2}{2b}\left[\frac{R-1}{2L^3+a^3(R-1)}\right] \tag{7}$$

Fig. 6 shows the variation of the strain energy

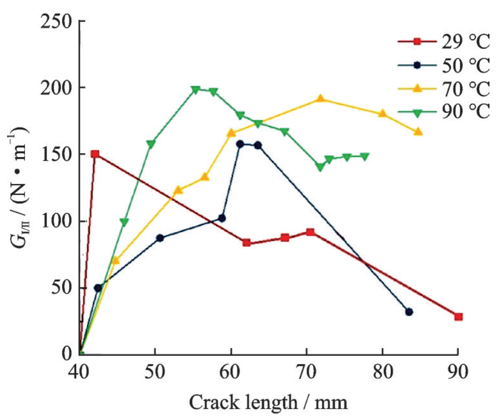


Fig.6 Strain energy release rate of specimens under different temperatures

release rate with the crack propagation length at four different temperatures. The results showed that for the specimens tested at 29 and 50 ℃, due to the instability of crack propagation, the strain energy release rate were very unstable. But the strain energy release rate become more stable at the temperature of 70 ℃ because the phenomenon of the instability of crack propagation was improved. When the temperature reached 90 ℃, although the crack propagation was stable and continuous, the strain energy release rate become unstable. The main reason was that the interface between the GFRP face sheets and the foam core was discontinuous when the GFRP and foam changed from elastomeric state to glassy state.

3 Conclusions

This paper presented an experimental study of Mode I/II mixed interfacial fracture of the composite sandwich panels at elevated temperatures. The test results showed that the peeling load decreased as the temperature increased. In the meantime, the stiffness of SLB specimens reduced with the increase in temperature. When the environmental temperature was larger than T_g, the strain energy release rate become unstable. The main reason was that the interface between the GFRP face sheet and the foam core was discontinuous when the material of the sandwich structure changed from elastomeric state to glassy state.

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Author contributions Prof. **WANG Lu** designed this study and wrote most of the manuscript. Mr. **YIN Chunxiang** conduct the tests. Mr. **SI Qinan** wrote Section 0 "Introduction".

Competing interests The authors declare no competing interests.

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高温下泡沫夹芯材料I/II混合型界面断裂特性试验

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摘要：泡沫芯夹层材料以其轻质、高强、耐腐蚀等优点在土木工程中得到了广泛的应用。然而，泡沫芯夹层材料的界面结合强度在高温下有所减弱。在实际应用中，由于复合材料和泡沫材料对环境温度的变化非常敏感，高温的影响是不可忽视的。在本研究中，通过一系列单臂弯曲梁在不同温度下的试验来评估高温对泡沫芯夹层材料I/II型混合界面断裂的影响。温度范围为29～90 ℃，覆盖了复合材料和泡沫芯的玻璃化转变温度。总结了I/II型混合界面裂纹扩展及其相应的界面应变能释放速率。

关键词：泡沫夹芯材料；I/II型混合界面断裂；高温；单臂弯曲；应变能释放率