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Hygrothermal ageing of polymeric sandwich structures used in structural engineering

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HIGHLIGHTS

- Hygrothermal conditions degraded mechanical properties of face sheets and cores.
- SEM and FT-IR confirmed degradation in fibre/matrix interfacial bonding.
- DCB tests were applied to investigate interfacial properties of sandwich structures.
- The analytical model can be used to predict the strain energy release rate at different ageing time.

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ABSTRACT

Foam core polymeric sandwich structures have been widely used in structural engineering due to their advantages such as lightweight, high strength, and so on. However, the mechanical properties of face sheets and foam cores, and the interfacial bond strength of sandwich structures are affected by the combined hygrothermal conditions, which is common in the most civil engineering applications. In this study, the mechanical properties of face sheets and foam cores in the combined hygrothermal conditions were investigated. Meanwhile, a series of sandwich double cantilever beams were tested at different ageing time to evaluate the effect of ageing time on interfacial fracture of polymeric sandwich structures. Furthermore, an analytical model, considering the effect of hygrothermal ageing, was proposed to predict the strain energy release rate of mode I interfacial fracture of the polymeric sandwich structures at different ageing time. The analytical results were found to be well matched with the experimental results.

1. Introduction

Polymeric sandwich structures consisting of fiber reinforced polymer (FRP) face sheets and polymeric foam cores have been widely used for bridge deck panels, facade panels, and roof structures [1–5] due to their better performances in comparison to some traditional materials in terms of lightness, relatively high strength- and stiffness-to-weigh ratios, and better energy absorbing capacity [6–8]. These properties are achieved through the use of FRP face sheets whose function is to carry bending loads, and lightweight polymer foam cores whose role is to carry transverse shear loads. A 21.6×18.5 m polymeric sandwich roof structure with 6–10.5 mm FRP face sheets and 600-mm-thich PU foam core for a main gate building was designed and built in Switzerland by Keller et al. [2]. The prefabrication of large and lightweight sandwich panels enabled easy transportation and rapid installation. However, this kind of polymeric sandwich structures are usually exposed to moisture at elevated temperatures in practice. From a design standpoint it is important to understand how the mechanical properties of their constitute materials are affected by the in-service hygrothermal environment.

It has been observed that a hygrothermal environment, defined as an environment with combined moisture and elevated temperature, causes swelling, plasticization, and degradation of the matrix, which degrades the mechanical properties of polymeric sandwich structures [9–12]. The effects of moisture and elevated temperature on the mechanical properties of FRP laminated composites and degradation of the fiber/matrix interface have been somewhat investigated [13–18]. But only a few investigations have addressed the behavior of foam cores and sandwich structures under high moisture and elevated temperature. Aviles and Aguilar-Montero [19] investigated the moisture absorption behavior of sandwich structures constructed from E-glass/polyester face

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sheets and a 100 kg/m^3 PVC foam core exposed to 95% relative humidity (RH) and immersed in sea-water for 11 months. They found that all moisture uptake curves exposed to 95% RH and immersed in sea-water exhibited an initial linear Fickian behavior followed by a nonlinear section and finally a plateau. The anomalous behavior of a cross-linked PVC foam core immersed in fresh water at 40 °C and exposed to 95% RH at 40 °C with long time (over 2.5 years) was observed by Earl and Shenoi [20]. They concluded that the classical Fickian one-dimensional diffusion model cannot describe the long-term absorption behavior due to the effect of the material inhomogeneity on the moisture transport mechanism. Furthermore, Aviles and Aguilar-Montero [19] compared the diffusion coefficient of sandwich structures immersed in sea-water with that of the same materials in the 95% RH condition. They found that the diffusion coefficient immersed in sea-water was greatly larger than that in the 95% RH condition. Siriruk et al. [21] indicated that the reductions of shear modulus and Young's modulus of sandwich structures constructed from carbon fiber/vinyl ester face sheets and a 100 kg/m^3 PVC foam core exposed to sea-water were 72% and 60% during three years, respectively.

Although the researches on the moisture absorption behavior and mechanical property of polymeric sandwich structures have been conducted, to some extent the effect of hygrothermal environment on the interfacial delamination fracture is limited. Siriruk et al. [22] also investigated the effect of sea-water on interfacial delamination behavior of PVC foam cored composite sandwich structures by using double cantilever beam (DCB) tests at room temperature. After 4 months immersion, the delamination fracture toughness decreased by 30%. Similar observations were made by Li and Weitsman [23] in which 36% decrease occurred in debonding fracture toughness at the face sheet/core interface of H100 PVC foam cored composite sandwich structures after 150 days exposure in sea-water. Furthermore, Veazie et al. [24] considered the effects of temperature and sea-water on the interfacial fracture toughness of sandwich composite composed of E-glass/vinylester face sheets and a divinycell H130/G PVC foam core. Results showed that the critical strain energy release rate (G_c) was reduced approximately 90% in specimens to 95% RH at 80 °C for 5000 h, whereas G_c was reduced about 50% in specimens immersed in sea-water.

As described above, many studies have been carried out on the mechanical performance of sandwich structures in marine and other applications. However, to the best of our knowledge, there has been little report on the degradation mechanism of polymeric sandwich structures in the combined hygrothermal conditions. This study analyzed the degradation mechanism of the face sheet and foam core in the combined hygrothermal conditions from a microstructural view using SEM and FTIR analyses of the changes in microstructures and chemical structures. Moreover, there is a need to evaluate the variation of strain energy release rate of polymeric composites in the combined hygrothermal conditions. In this study, DCB tests were conducted on polymeric sandwich structures with no environmental exposure at room temperature, as well as exposed to the combined hygrothermal conditions for 6480 h to obtain interfacial fracture toughness results. Additionally, an analytical model, considered the effect of hygrothermal ageing on the bending stiffness of the face sheets and the face sheet/core interface bonding property, was developed.

2. Materials and methods

2.1. Specimens

The sandwich composite panels were fabricated by manual lay-up process (Fig. 1). The panels were fabricated with bidirectional (0°/90°) E-glass woven fabrics at an areal density of 800 g/m^2 provided by Sinoma Nanjing Fiberglass Research & Design Institute (China). The matrix system was vinyl ester resins (HS-4430) provided by Changzhou Huake Resin Co., Ltd. (China). The polyurethane (PU) foam

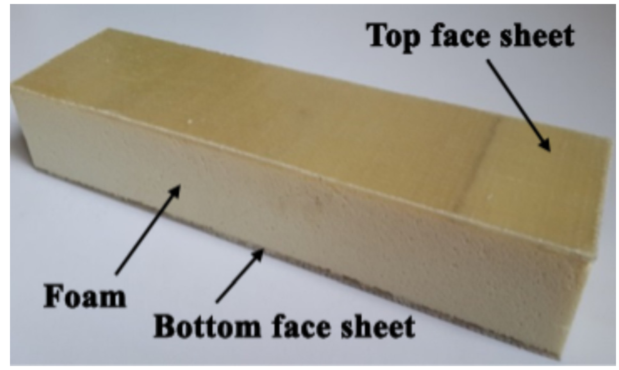

Fig. 1. Polymeric sandwich structures made of glass fiber/vinyl ester face sheets and polyurethane foams.

was used with the density of 100 kg/m^3 provided by Wuxi Kezhao New Materials Technology Co., Ltd (China). The length and width of a specimen were 300 mm and 80 mm, respectively wide rectangles (Fig. 2). The thickness of a PU foam core and a face sheet were 50 mm and 2 mm, respectively. A pre-crack with 50 mm length was made between the top face sheet and the foam core. According to the reference [25], for E-glass/Vinyl ester fiber-reinforced polymer composites, after 300 days of ambient storage the non-postcured samples approached the degree of conversion exhibited by those post-cured at 93 °C. Considering the limited conditions for the application in structural engineering, the specimens used in this study were not post-cured.

2.2. Techniques

2.2.1. Hygrothermal cyclic ageing

To study the effect of hygrothermal ageing on the properties of all compositions, all specimens as well as face sheets and foam cores, were aged in hygrothermal environmental chamber for different number of cycles, as shown in Fig. 3. The overall duration of each thermal cycle was 24 h, and it consisted of a combination of heating and cooling (20–60 °C) at a certain degree of humidity (95% RH), as shown in Fig. 4.

2.2.2. Water absorption test

The water absorption data of polymeric sandwich structures were recorded periodically after immersing the materials in water (termed as 'wet') and combined hygrothermal (20–60 °C, 95% RH, termed as 'hygrothermal') conditions, respectively (See details in Table 1). At regular time intervals, the samples were taken out, wiped of excessive water with filter paper, weighed until the weigh was constant, and returned to the swelling medium. The experiment was continued until the constant weight of the samples was achieved. The moisture absorption (M_t) can be calculated by Eq. (1).

$$M_t = \left[\frac{m_t - m_i}{m_i}\right] \times 100\% \quad (1)$$

where m_i is the initial mass of the specimen prior to immersion, and m_t is the mass of the specimen at exposure time t.

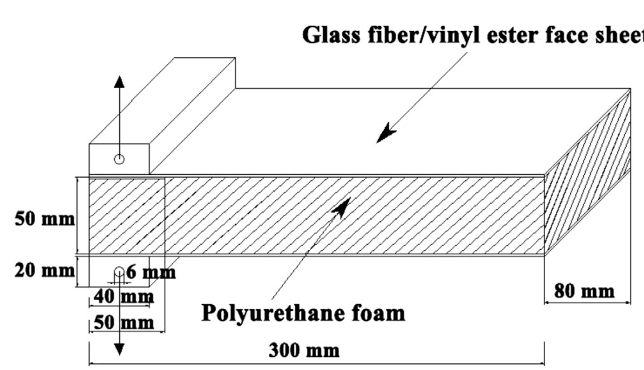

Fig. 2. Double cantilever beam specimen configuration.