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Research on the dynamic mechanical properties of polymethacrylimide foam sandwich structure

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ABSTRACT

Polymethacrylimide foam is fully closed-cell isotropic foam which possesses high stiffness and strength to weight ratios. The paper reports the findings of an experimental study developing to investigate the quasi-static and dynamic response of sandwich panels based on polymethacrylimide foam using compression tests and Split Hopkinson Pressure Bar, respectively. The effect of thickness of aluminum face sheet, thickness and density of the polymethacrylimide core on the mechanical properties of the sandwich structures are studied respectively. It is shown that core density has the greatest effect on compressive strength of sandwich structure. The elasticity modulus and compressive strength of sandwich decreased by 40% under quasi-static compressive when the density of the core reduced by 28%. Secondly, dynamic compressive experiment results show that when the density of the core reduced by 28%, at the strain rate of $150\,s^{-1}$, compressive strength decreased by 45%; strain rate $310\,s^{-1}$, compressive strength reduced by 42%. When the strain rate increased from $7.6 \times 10^{-4}\,s^{-1}$ to $150\,s^{-1}$, compressive strength increased by 26%; strain rate increases from $7.6 \times 10^{-4}\,s^{-1}$ to $310\,s^{-1}$, compressive strength increased by 43%. The dynamic mechanical properties of polymethacrylimide foam sandwich panels accompanied with the increase of strain rate. Finally, dynamic constitutive relation of Cowper-Symonds function is fitted.

1. Introduction

Fairbairn first proposed the concept of sandwich structure in 1849 [1]. Polymethacrylimide (PMI) as the sandwich core was first successful application for helicopter fuselage panels in 1971 [2]. PMI foam matrix is consist of Methyl methacrylate (MAA) and Methacrylonitrile (MAN) copolymers, its chemical stability, high heat distortion temperature and excellent mechanical properties are the preferred core materials for high performance composite sandwich structures.

Gibson and Ashby et al. [3] described the theoretical calculation formula of closed-cell foam compressive strength, considering factors such as pore-edge buckling and closed gas compressive.

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} \approx 0.3\left(\phi\frac{\rho^*}{\rho_s}\right)^{\frac{3}{2}} + 0.4(1-\phi)\frac{\rho^*}{\rho_s} + \frac{p_0-p_{at}}{\sigma_{ys}} \tag{1}$$

where ρ^* is foam density, ρ_s is matrix density, Φ is the cell wall edge contains the volume fraction of matrix, the value Φ of PMI is from 0.72 to 0.8; p_0 is closed gas initial pressure, p_{at} is atmospheric pressure.σ_{ys} is yield strength of matrix materials, then the compressive strength of different types of PMI foam σ_{pl}^* can be obtained.

Composite sandwich structure offer a number of advantages over traditional ship building materials including low radar signature, lightweight design and the combination of these factors to reduce fuel and maintenance costs. Quasi-static and dynamic models for response of sandwich panels subjected to impact have been developed [4].

A range of composite sandwich panels (glass fiber reinforced polymer face-sheets) with different polymeric foam cores and face-sheets were subjected to full-scale air and underwater blast testing. The research revealed that there is a trade-off between reduced panel deflection and damage [5]. Sandwich panels and foam filled tubular structures contributes to simultaneously reduce the weight of the automotive bodies and to improve the crashworthiness [6,7].

The low velocity impact behavior of composite sandwich panels with PMI foam cores was investigated by Shipsa et al. [8] along with the residual strength of the composite panels after impact. Arezoo et al. [9] studied the effect of strain rate ($10^{-3}\,s^{-1}$–$5 \times 10^3\,s^{-1}$) and temperature (203 K–473 K) on PMI foam, showing that the compressive collapse stress is generally found to increase with increasing strain rate and decreasing temperature; however this tendency is inverted at very

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low temperatures or very high strain rates.

PMI are common foam polymer types that are finding application in composite sandwich panels. After sandwich structure was damaged, the compressive and bending strength would drop significantly, which directly affects the overall mechanical properties. Therefore, researching on the sandwich structure impact resistance and destruction of the form has great significance. Rizov et al. [10] performed a quasi-static compressive test on a sandwich structure, experimental tests were carried out by a spherical indentor using an Instron 5505 Testing Machine under displacement control at cross-head speed of 2 mm/min. The specimens were manufactured by using rigid foam Rohacell WF51 as core and glass-fiber reinforced composite face sheets.

Fatt et al. [11] investigated the influence of the boundary conditions on the performance of sandwich panels impacted by a blunt cylinder. Equivalent single and multi-degree of freedom systems were used to predict the low-velocity impact response of rigidly supported, two-sided clamped, simply supported and four-sided clamped composite sandwich panels.

Duarte et al. [12] evaluate the quasi-static and dynamic compressive crush performance of integral-skin closed-cell aluminium alloy foam with and without radial constraints. The results show a significant increase in the collapse stress of the integral-skin closed-cell aluminium foam under quasi-static loading when radial constraints are applied. The strain hardening is also sensitive to the foam density, increasing with the density.

In a summary, the parameters that affect the mechanical properties of the sandwich structure are: strain rate, impact velocity, core thickness and face sheet thickness, core material density and core structure form. At present, most researchers are concerned with static compressive strength, failure form etc., and few studies on the dynamic mechanical properties of PMI foam sandwich structures. Due to the good performance of PMI foam, the research on the mechanical properties of PMI sandwich has become a hot topic.

The Split Hopkinson Pressure Bar (SHPB) experimental device was firstly designed by Hopkinson [13] in 1914, to measure the actual waveform of impact (explosion) load along with time. After that, SHPB experiment technology is further developed to study the high strain rate behavior of the material, known as the Split Hopkinson Pressure Bar, referred to as SHPB. In 1949, Kolsky et al. [14] placed the specimen between the incident bar and transmitted bar and obtained the stress versus time curves from the experiments. Taylor [15], Volterra [16], Davies [17], and Kolsky established improved SHPB technology that can measure material dynamic mechanics under shock loading conditions. Until today, researchers are gradually beginning to apply the improved Hopkinson bar device to measure the material dynamic mechanical properties.

The effect of the thickness of the aluminum face sheet, the thickness and density of the PMI core on the mechanical properties of the sandwich structures are studied respectively. Secondly, the dynamic impact compressive experiment was carried out by using the SHPB testing device with large diameter (φ100mm), the dynamic mechanical properties of PMI foam sandwich panels relationships with strain rate were obtained. Finally, the dynamic constitutive relation of Cowper-Symonds function was fitted.

2. Materials and experiment

2.1. Specimen

The experimental program was going to calculate the compressive strength and elastic modulus of the sandwich structure and compare the mechanical properties of the PMI foam sandwich structure influenced by face sheet thickness, different core layer thickness and different core layer density of the sandwich structure. The following four types of specimens were made, the sandwich panels were aluminum (5052AL), the core of the sandwich was ACCPMI foam, films (high temperature curing epoxy structural adhesive films) affixed between PMI foam and aluminum panel. Then, autoclave molding is used to made sandwich panels. The sandwich structure size was as shown in Table 1.

Table 1
The size and types of sandwich structures (length × width × thickness).

Specimen	Face plate size (mm)	Core size (mm)	Core type
A	60 × 60 × 1	60 × 60 × 20	ACCPMI 71
B	60 × 60 × 0.8	60 × 60 × 20	ACCPMI 71
C	60 × 60 × 1	60 × 60 × 15	ACCPMI 71
D	60 × 60 × 1	60 × 60 × 20	ACCPMI 51

2.2. Quasi-static

Experimental tests were performed by Instron 5505 Universal Test Machine (Fig. 1) under displacement control at cross-head speed of 1 mm/min. The experimental temperature was 20 °C. The measured size and types of sandwich structures shown in the Table 2.

Experimental errors will affect the accuracy of compressive strength values of the sandwich structure. Therefore, quasi-static compressive test was carried out by the five specimens. The compressive strength values would be got when the standard variance value under 0.1. The same experiments were carried out on other specimens (B, C, D), which changed the parameters of the sandwich structure.

2.3. Dynamic test

Strain rate ($\dot{\varepsilon}$) is the strain derivative time of the material and generally is used in mechanics to characterize material deformation rates. It is that strain rate dependent materials which mechanical properties changes with the strain rate. According to the value of strain rate is usually divided into the following categories: creep (strain rate range $10^{-8}\,s^{-1}$–$10^{-6}\,s^{-1}$), quasi-static ($10^{-6}\,s^{-1}$–$10^{0}\,s^{-1}$), high strain rate ($10^{0}\,s^{-1}$–$10^{4}\,s^{-1}$) and super high strain rate ($10^{4}\,s^{-1}$–$10^{8}\,s^{-1}$) [18]. As for the diffferent strain rate, choosing the appropriate experimental program. When the strain rate is lower than $0.1\,s^{-1}$, the experiment is carried out by the traditional quasi-static experiment machine; when the strain rate is between $0.1\,s^{-1}$ and $100\,s^{-1}$, the specially designed servo hydraulic control test machine is used; the strain rate $0.1\,s^{-1}$–$500\,s^{-1}$, the use of cam plastic machine and drop hammer experiments; $10^{2}\,s^{-1}$–$10^{4}\,s^{-1}$, the Hopkinson Pressure Bar is selected; $10^{3}\,s^{-1}$–$10^{5}\,s^{-1}$, using Taylor Impact Experimental to test the mechanical properties of materials. The common dynamic impact in engineering was the strain rate range of $10^{2}\,s^{-1}$–$10^{4}\,s^{-1}$ and used SHPB to study the dynamic mechanical properties of materials. The Hopkinson pressure bar device was shown in Fig. 2.

The typical SHPB device mainly include: bullet launcher, impact bar (bullet), speedometer, incident bar, transmission bar and energy absorbing devices, ultra-dynamic strain gauges, oscilloscopes, semiconductor strain gauges or resistance strain gauges. Different SHPB experimental device was adopted according to the size of the materials and different properties. For the dynamic mechanical properties of soft materials and foams, in order to increase the signal amplitude of transmitted wave, we used low elastic modulus materials as experimental bar or chose semiconductor strain gauges [19–22].

Large diameter SHPB experimental device was selected in the present study shown as Fig. 3. The diameter of impact bar (bullet), the incidence bar and the transmission bar are 100 mm. The bullet length is 600 mm. The length of incidence bar and the transmission bar are 3300 mm. The PMI foam sandwich structure was hold by the incident bar and the transmission bar. Preventing from the specimens fall under slightly disturbed, a proper amount of high-pressure grease on both sides of the sandwich structure. We tested the PMI foam at a low strain rate, found that the transmission signal was small and difficult to