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A novel all-composite blast-resistant door structure with hierarchical stiffeners

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ABSTRACT

To develop light-weight blast-resistant door structures, sheet molding compound (SMC) material reinforced by carbon fiber reinforced plastic (CFRP) has been applied to make all-composite protective panels by adopting the method of one-step forming in mold filling and hot-molding compression. With skins, frames, stiffeners and sub-stiffeners, the door panel has hierarchical stiffened structure, making the door strong enough but much lighter. The CFRP reinforced SMC panel is four times stronger in extension and twice stronger in flexure than the SMC panel. The all-composite blast-resistant door structure can resist blast wave with peak pressure over 0.45 MPa, companying with stiffener fractures, frame cracks and skin cracks. CFRC reinforced SMC material effectively restricts the stiffener fracture, reduces the crack width and decreases the flexure of the door structure. All these composite door structures have dominant-elastic-response under explosion and restore their initial configuration after explosion.

1. Introduction

In recent years, the prevailing of the terrorism is seriously threatening the public security. Accidental explosions within or near commercial or military constructions will cause severe damage on the building's external and internal structures, equipment and people. To guarantee security for persons, underground protective space is necessary for buildings. To completely seal off the entrances of the buildings or the underground protective space, a variety of blast-resistant doors were designed for various applications [1–6]. Usually such blast-resistant doors are constructed by steel plates or reinforced concrete structures, which are easily-made and non-expensive. But these traditional protective door structures are too heavy [7]. Composite structures can make the door structure ultra-light [8–11].

Hierarchical topology makes structure strong and stiff. Most importantly, hierarchy lets structure lighter [12,13]. Increasing the integral rigidity of the structure, hierarchy also cares the local response of the structure. Stiffened plates are stiff in global deformation [14–16], but local response within the grids encased by the stiffeners always turns to non-ideal. Sub-stiffeners are required to restrict the local failure [17].

In this paper, CFRC reinforced SMC composite was selected as the material to design and fabricate a novel all-composite blast-resistant door structure with hierarchical stiffened structure. Explosion experiments were performed to check the anti-blast ability of the novel structure.

2. Hierarchical stiffened door structure

2.1. Hierarchical stiffened structure

Stiffened structure is an efficient way to make light-weight anti-blast structures. The door structure has two-level hierarchical stiffeners, as shown in Fig. 1. The skin is firstly stiffened by the strong edge frames. One longitudinal stiffener and two transverse stiffeners supply strong supports to the skin. The global flexural rigidity of the panel is enhanced by the stiffeners and the global flexure and the flexural stress will be greatly decreased. The skin of the door is divided into six grids by the stiffeners. In each grid, there are two diagonal sub-stiffeners. These sub-stiffeners have much smaller cross-sectional dimensions and they only stiffen

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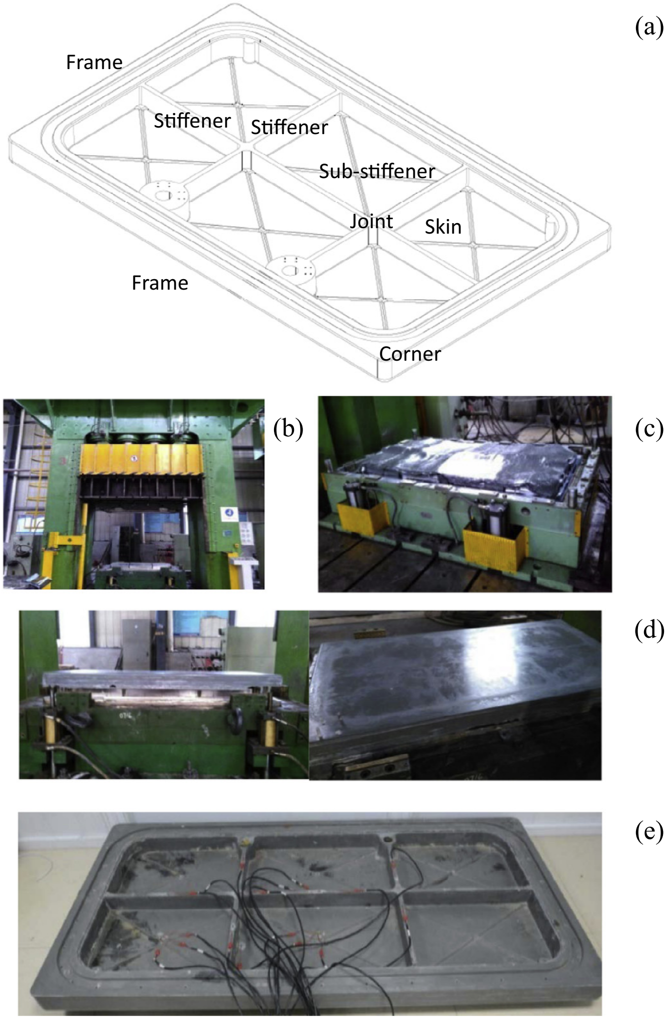

Fig. 1. Stiffened blast-resistant door structure: (a) hierarchical stiffened structure, (b) mold pressing method, (c) material placing, (d) demolding and (e) all-composite door structure.

the skin within the grid. Mono-grid flexural rigidity of the skin will be enhanced by the sub-stiffeners. Local failure strength can also be enhanced.

Hierarchical stiffened structure greatly improves the global and the local flexural rigidities of the door structure, as well as the global failure strength and the local failure strength.

2.2. Composite structure and materials

In this research, a level-6 civil defense door structure was designed and made by composites. The door structure is 1800 mm long and 900 mm wide. Its thickness is 85 mm, as listed in Table 1. The skin is 8 mm thick. The stiffener is 15 mm wide and the height is 70 mm while the sub-stiffener is only 5 mm thick and 5 mm wide.

Sheet molding compound (SMC) Carbon fiber reinforced plastic (CFRP)

Fig. 2. Structural materials applied to construct all-composite blast-resistant door.

SMC has been applied to construct the protective door, as shown in Fig. 2. SMC is usually reinforced by short glass fiber reinforced plastic (GFRP) fibers. The SMC sheet is 1000 mm wide and 2 mm thick. Its density is about 1850 kg/m^3. The stiffness and the strength of the SMC are rather small compared with continuous GFRP or CFRP panels, so that in this research CFRP EM114-175 sheets were inserted into the SMC layers to strength the SMC panel, as shown in Fig. 3. Each CFRC sheet is 260 g/m^2, with fiber fraction of 67% and thickness of 0.15 mm. Three composite door structures were designed to make a comparison. Door structure SMC is completely made of SMC. Door structures SC-1 and SC-2 have CFRP interlayers, as shown in Fig. 3. Each door has designed weight of 120 kg.

2.3. Material properties

Extensional and flexural behaviors of SMC-CFRP composite panels were revealed, as shown in Fig. 3. Layup constitutions are listed in Table 2. In extension, strength of SMC panels (S2 and S3) varies from 58.45 MPa to 68.23 MPa. Strength of CFRP panels (S1) varies from 629.13 MPa to 708.0 MPa. The CFRP panels are ten times stronger. The modulus of the SMC varies from 7.73 GPa (S3), 7.68 GPa to 8.38 GPa (S2), much smaller than 58.67 GPa or 58.39 GPa, the modulus of the CFRP.

By inserting CFRP layers, the modulus of SMC-CFRP panels varies from 17.03 GPa, 18.79 GPa (S6), 27.16 GPa and 28.89 GPa (S7). The strength of SMC-CFRP panel, S6, varies from 220.32 MPa to 231.09 MPa. The strength of SMC-CFRP panel, S7, varies from 327.28 MPa to 339.12 MPa. Strength and modulus of the SMC-CFRP panel, σ_{tsc} and E_{tsc}, can be predicted by the mixing rule as

$$E_{tsc} = \rho_s E_{ts} + \rho_c E_{tc}, \tag{1}$$

and

$$\sigma_{tsc} = \rho_s \sigma_{ts} + \rho_c \sigma_{tc} \tag{2}$$

where σ_{ts} and E_{ts} denote the strength and modulus of the SMC panel, respectively. σ_{tc} and E_{tc} denote the strength and modulus of the CFRP panel, respectively. ρ_s and ρ_c denote the volume fraction of the SMC and the CFRP, respectively, and $\rho_s + \rho_c = 1$. Predicted strength and modulus of S6 are 206.2 MPa and 19.2 GPa, respectively. Predicted strength and modulus of S7 are 290.1 MPa and 25.8 GPa, respectively. The maximum prediction error is 14.5% (S7) for the strength and 11.3% for the modulus (S6), respectively.

Table 1
Dimensions of the composite door panel.

Panel width (mm)	Panel length (mm)	Panel thickness (mm)	Frame width (mm)	Frame thickness (mm)	Skin thickness (mm)	Stiffener thickness (mm)	Stiffener height (mm)	Sub-stiffener thickness (mm)	Sub-stiffener height (mm)
900	1800	85	100	77	8	15	70	5	5