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Dynamic response of symmetrical and asymmetrical sandwich plates with shear thickening fluid core subjected to penetration loading

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ABSTRACT

Symmetrical and asymmetrical sandwich plates with a shear thickening fluid (STF) core were designed to be penetrated by a cylindrical projectile at various impact velocities. These STFs consist of SiO_2/PEG400, and the volume fractions of SiO_2 nano-particles are 54% and 56%, respectively. Failure mode of the rear face sheet of the symmetrical sandwich plate is petal perforation, but the rear face sheet of the asymmetrical sandwich plate failed in plug perforation mode at the velocity of less than 80 m/s and in the petal perforation mode at the velocity faster than 90 m/s. The results showed that both the face sheet and the STF core played different roles in impact resisting properties and energy absorption of the sandwich plate at different impact velocities. The thickness of the rear sheet has a significant influence on the energy absorption at low impact velocity, while this influence can be ignored at high impact velocity. The effects of the particle volume fraction, impact velocity and thickness of rear face sheet on the deformation mechanism and energy absorption of the sandwich plate were also discussed.

1. Introduction

A sandwich structure has been widely used as the energy absorption component in protection system against the penetration of the projectile. The core of the sandwich structure consists of metal foam, fiber, and other soft materials [1–4], and it has low specific mass, high specific stiffness and high energy absorption that can improve the impact resistance and energy absorption of sandwich structure. It is a challenge for researchers and engineers to find new materials with properties needed for the core of sandwich structures.

Shear thickening fluid (STF) consists of a stabilized dispersion of hard nano-particles in a carrier solvent, and its viscosity can increase immediately, even into solid-like state when subjected to impact loading, and then recover after the impact loading is removed. Due to their special properties, STF can be used as an energy absorber and vibration controller, etc. [5–6].

Over the past several decades a lot of research has been conducted on the mechanical properties and applications of STF [7–11]; for example, Jiang et al. [9] studied the propagation and attenuation of the stress wave in STF by using SHPB, and Lim et al. [10] evaluated the critical condition of STF transition from fluid to solid-like behavior at different strain rates, Petel et al. [11] investigated the influence that particle strength had on the ballistic performance of STF and found that suspensions with 61% SiO_2 and SiC exhibited the greatest projectile deceleration performance. Further work on STF was to improve the ballistic performance of fabric impregnated by STF at different load cases [12–19]. Feng et al. [18] illustrated the stab resistant properties of fabrics impregnated with STF with sub-micrometer silica and fumed silica particles on quasi-static loading. Park et al. [19] studied the energy absorption characteristics of Kevlar fabric impregnated by STF at the velocity between 1 to 2 km/s by experimental and numerical methods. However, very few researches are available to study dynamic performance of the sandwich structure incorporating STF its core [20]. This is the major motivation of this research.

In this work, STF was used as the core of sandwich plate subjected to penetration by a cylindrical projectile at the velocity ranging from around 30 m/s to 120 m/s. STF with 54% and 56% volume fraction was fabricated and used as the core of sandwich plates. To analyze the role played by STF in the impact resisting properties and energy absorption of sandwich plate, two kinds of rear face sheets with different thickness were designed and tested. The failure mechanism and energy absorption of the sandwich plates were also discussed.

2. Experimental procedures

2.1. Materials and specimens

In this paper the STF consists of SiO_2 nano-particles and polyethylene glycol of molecular weight 400 (PEG400). The SiO_2 sphere was fabricated

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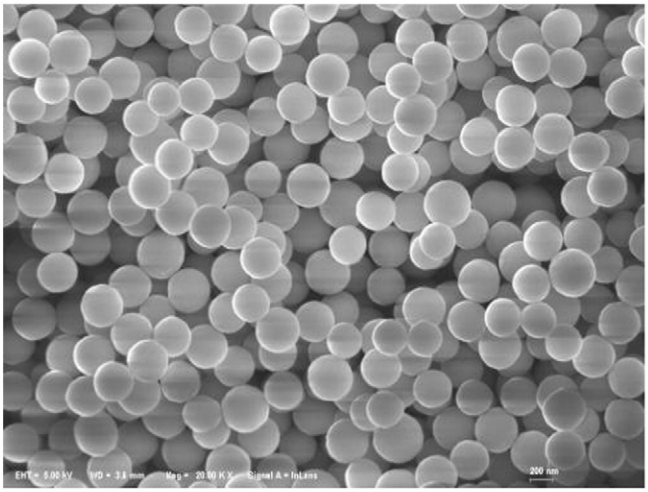

Fig. 1. The SEM graph of the SiO_2 particle.

by Stober methods [21,22], and the diameter is about 300 nm in diameter tested using S-4800 field emission scanning electron microscope (FE-SEM), as shown in Fig. 1. According to the SiO_2 volume fraction of 54% and 56%, the specific SiO_2 nano-particles and PEG400 mixture solvent were treated in a planetary ball mill for 2–3 h. And variation of the viscosity vs. shear strain rate of STF was tested by a rheometer (Anton-Paar MCR301) in the University of Science and Technology of China.

The sandwich plate consists of front and rear face sheets with the edges sealed by PMMA. Both front face sheet and rear face sheet are the pure aluminum. And the Young's modulus is approximately 71 GPa, the strength is 232 MPa [23]. Two types of sandwich plates were designed in this paper: (1) the front and rear sheets are both 0.2 mm thick (marked by 'S' which means symmetry), (2) the front face sheet is 0.2 mm thick and the rear face sheet is 0.5 mm thick (marked by 'A', means asymmetry), as shown in Table 1.

2.2. Experimental apparatus

The steel cylindrical projectile is Φ6 mm × 20 mm and weighs 4.2 g; it was fired by a light gas gun. Two laser velocimeters were used to measure the impact velocity and residual velocity of the projectile. The specimen was placed between these two laser velocimeters. The impact velocity varies from 30 m/s to 120 m/s. The schematic diagram of the light gas gun is shown in Fig. 2.

3. Results and discussion

3.1. Viscosity of the STF at different shear strain rate

The curves of viscosity vs. shear strain rate of STFs in this paper were tested and shown in Fig. 3. The viscosity of both STFs is about 50 Pa·s at low strain rate, and the maximum viscosity of 54% and 56% STFs is about 150 and 500 Pa·s at high shear strain rate, respectively. And it is obvious that the viscosity of 56% STFs is greater than the 54% STFs at high shear strain rates, while the critical shear strain rate of shear thickening of 56% STFs is less than the 54% STFs in Fig. 3. The particle volume fraction also has a significant influence on the viscosity of STFs [5]. For the case of high volume fraction, the particles are easier to form clusters or chains in STFs. Moreover, the distance between particles is closer, which also increases the lubrication hydrodynamics of neighbor particles in STFs.

3.2. Failure modes of the different types of structures

3.2.1. Case 1: symmetrical structure case

For the symmetrical structure, the front and rear face sheets are both 0.2 mm thick. The failure modes of the symmetrical sandwich plates with 54% and 56% STF cores were nearly the same as shown in Fig. 4. It can be seen from Table 1 and Fig. 4 that the failure mode of the

Table 1
The experimental results.

Specimen no.[a]	Thickness of face sheet/STF core/rear sheet (mm)	Impact velocity (m/s)	Residual velocity (m/s)	Energy absorption (J)	Failure mode
S-0-1	0.2/0/0.2	71.63	67.52	1.20	Perforation, plug failure mode
	0.2				
	/				
S-0-2	0.2/0/0.2	93.41	91.82	0.62	Perforation, plug failure mode
S-0-3	0.2/0/0.2	115.62	114.53	0.52	Perforation, plug failure mode in Fig. 4(a)
	/				
A-0-1	0.2/0/0.5	71.31	50.03	5.4	Perforation, plug failure mode
A-0-2	0.2/0/0.5	96.42	93.51	1.16	Perforation, plug failure mode
A-0-3	0.2/0/0.5	110.74	108.63	0.97	Perforation, plug failure mode
S-54-1	0.2/20/0.2	32.65	0	2.24	Perforation, petal failure mode
S-54-2	0.2/20/0.2	61.07	36.81	4.99	Perforation, petal failure mode in Fig. 4(b)
S-54-3	0.2/20/0.2	93.32	72.72	7.18	Perforation, petal failure mode
	0.2				
	20				
S-54-4	0.2/20/0.2	116.96	97.80	8.64	Perforation, petal failure mode
A-54-1	0.2/20/0.5	65.1	0	8.87	Plug, dish and bulge
A-54-2	0.2/20/0.5	70.67	35.53	7.84	Plug, dish and bulge in Fig. 5(a)
A-54-3	0.2/20/0.5	93.44	68.91	8.36	Perforation, petal failure mode in Fig. 5(b)
A-54-4	0.2/20/0.5	113.83	91.48	9.63	Perforation, petal failure mode in Fig. 5(c)
S-56-1	0.2/20/0.2	44.25	0	4.11	Perforation, petal failure mode
S-56-2	0.2/20/0.2	63.1	31.92	6.22	Perforation, petal failure mode
S-56-3	0.2/20/0.2	91.53	66.20	8.39	Perforation, petal failure mode
S-56-4	0.2/20/0.2	105.8	77.03	10.88	Perforation, petal failure mode in Fig. 4(c)
A-56-1	0.2/20/0.5	72.46	0	11.02	Plug, dish and bulge
A-56-2	0.2/20/0.5	80.1	20.20	12.61	Plug, dish and bulge in Fig. 5(d)
A-56-3	0.2/20/0.5	93.15	50.88	12.78	Perforation, petal failure mode in Fig. 5(e)
A-56-4	0.2/20/0.5	105.8	71.02	12.92	Perforation, petal failure mode in Fig. 5(f)

[a] The plates consist of three parts; the letters 'A' or 'S' in the first part mean symmetry or asymmetry, the second part is the thickness of the core, and the last part is the experiment number.