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Quasi-static bending behavior of sandwich beams with thin-walled tubes as core

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ABSTRACT

Quasi-static three-point bending tests on sandwich beams with a series of identical thin-walled tubes as core are conducted. Three types of cores are studied, namely, closely arranged identical circular tubes, spaced circular tubes, and spaced square tubes. Relationships between the force and displacement at the mid-span of the sandwich beam are obtained from the experiments. Deformation mechanisms for beams with spaced circular tubes and square tubes are analyzed. FE simulations are also carried out using ABAQUS/EXPLICT and the results are compared well with the experimental and analytical results. Energy absorption and partition are calculated and they match well with the simulation. When the mass of the beams is equal, the smaller the diameter of the tube is, the larger the energy absorption the beam has. Optimized sandwich beam with the square tubes is identified as a more effective structure which has the largest energy absorption of all the structures investigated in this paper.

1. Introduction

Sandwich beams are widely used in industrial fields as protective structures due to their high shock resistance, stiffness, strength and energy absorption characteristics compared with monolithic structures of equal mass. Thin-walled structures are used extensively in the engineering fields because they can sustain large local and global permanent deformations to absorb plenty of energy under blast loading.

Quasi-static deformation behavior of sandwich beams is usually studied by conducting 3 point or 4 point bending tests [1]. Failure modes (face sheet compressive failure, debonding, wrinkling, indentation failure, and core compressive or shear failure) depend on many factors, such as loading types, material properties and geometries of the structures [2,3]. For sandwich beams under compression, or in pure bending, if the core was much stiffer than the skin in the thickness direction, compressive failure of the skins occurred; otherwise, facing wrinkling took place [4]. Tagarielli and Fleck [5] simulated three-point bending response of simply supported and clamped sandwich beams using ABAQUS. A modified energy-balance model coupled with the law of conservation of momentum, was developed by Foo et al. [6] to analyze the static indentation problem, and they identified that the core damage happened at initial failure. Sandwich structures with Y, Kagome and tetragonal cores under compressive and shear loading were simulated and the compressive responses were explored in detail [7,8]. Two types of collapse modes for sandwich beam were found: mode A–core shear accompanied with the formation of plastic hinges at the loading point; mode B-core shear accompanied with the formation of plastic hinges at both the mid-span and the support points [9]. According to quasi-static bending test results, Li et al. [10] proposed an elastic-plastic model to analyze the dynamic response of composite sandwich beams and the model characterized the bending responses in three regimes: namely, the elastic regime, the core-crushing regime and the final failure regime [10]. Experimental, analytical and numerical simulation investigations of steel square hollow sections subjected to transverse blast loads were studied [11–13]. Local collapse and global bending for thin-walled circular section beams under impulsive loading were analyzed by many researchers [14–16]. Both thin-walled square and circular sections are used extensively in the construction, offshore, mining and security industries due to large local and global permanent deformations to absorb energy [17].

Sandwich beams with thin-walled tubes as core which could be used as novel protective structures have seldom been reported. In this paper, quasi-static compressive loading is applied by using an indenter, to simply supported sandwich beams with three different kinds of cores with thin-walled tubes. The relationship between force and displacement was obtained from the experiments. Deformation mechanisms and energy absorption for sandwich beams with different cores are analyzed, by studying the

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energy dissipated in plastic deformation. Furthermore, finite element simulations are carried out and the obtained force and displacement curves are compared with the experimental results. Energy partition is also conducted.

2. Experiments

2.1. Materials and specimens

The new sandwich beams comprised the top and bottom skins, with cores being a series of thin-walled circular or square tubes (Fig. 1). Both the skin and core were made of mild steel. Stress–strain curves of the mild steel for the skin and core are shown in Fig. 2. The length of the skin was 750 mm, width was 50 mm, and its thickness was 2.9 mm. The cores of the sandwich beams include closely arranged identical circular tubes, spaced circular tubes (D=35.8 mm), and spaced square tubes (a=22.5 mm). For the beams with closely packed tubes, three specimens were used with circular tube's diameter D=22.5 mm, 35.8 mm or 42.4 mm. The thickness of all the tubes was 1.2 mm. Summary of the specimens is given in Table 1. All the tubes were welded to the skin. A wood block was inserted at each of the two ends to prevent the two skins from bending towards each other there. In all the tests, the sandwich beams were simply supported. Quasi-static compressive loading was applied by means of an indenter at a constant cross-head speed of 3 mm/min with an INSTRON machine.

2.2. Experimental set-up and results

Quasi-static tests at a constant speed of 3 mm/min were conducted on sandwich beams by using INSTRON machine. Fig. 3 shows the deformation progress of a sandwich beam with D42 circular tubes. Force–displacement curves for five different sandwich beams are shown in Fig. 4.

3. Finite element simulation and analytical modeling

Tagarielli and Fleck [5] gave equations of response of clamped and simply supported sandwich beams with a metal foam core. A three-stage analytical model was developed: elastic regime, initial collapse regime including face yielding, core shear and indentation respectively, and membrane phase [5]. In our analysis, we first conduct finite element analysis in order to reveal the detail mechanism of deformation and energy absorption, followed by an analytical model with idealized mechanism and rigid-perfectly plastic material model. Finite element analysis was conducted by using ABAQUS/EXPLICT, for simply supported sandwich beams under quasi-static compressive loading. The elements of the structures are linear hexahedron element, type C3D8R. True stress versus true plastic strains curves were used in the FEA, which were converted from the engineering stress–strain curves obtained in the tensile tests (Fig. 2). The test was conducted in the

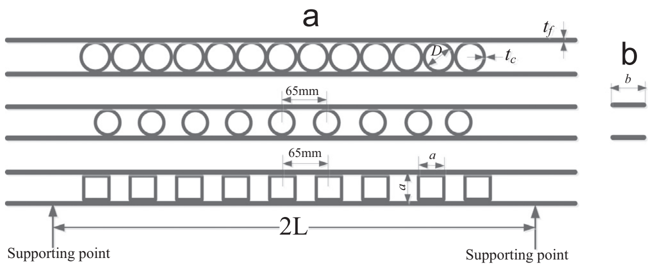

Fig. 1. Sketches of the specimens: (a) front view and (b) side view.

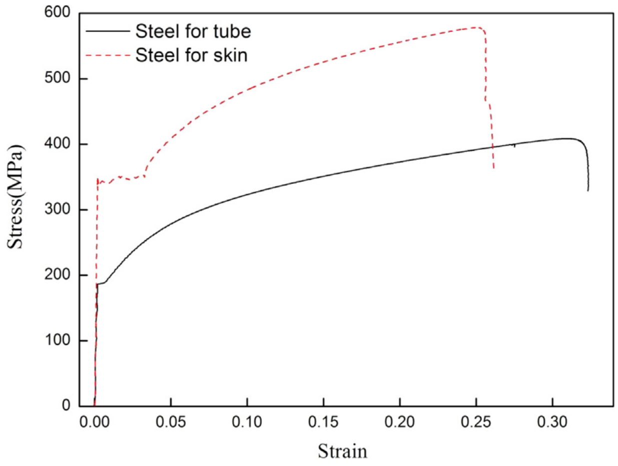

Fig. 2. Stress–strain curves for circular tube (D=22.5 mm/35.8 mm/42.4 mm) and skin steels.

Table 1
Summary of the specimens (mass of the faces is 1.58 kg; t_f=2.9 mm; t_c=1.2 mm; b=50 mm).

Specimen no.	Core	D or a (mm)	Number of tubes n	Mass of core (kg)	Mass percentage for cores
1	Circular	22.5	23	0.75	32
2	Circular	35.8	15	0.76	32
3	Circular	42.4	13	0.78	33
4	Circular (spaced)	35.8	9	0.46	23
5	Square	22.5	9	0.37	19

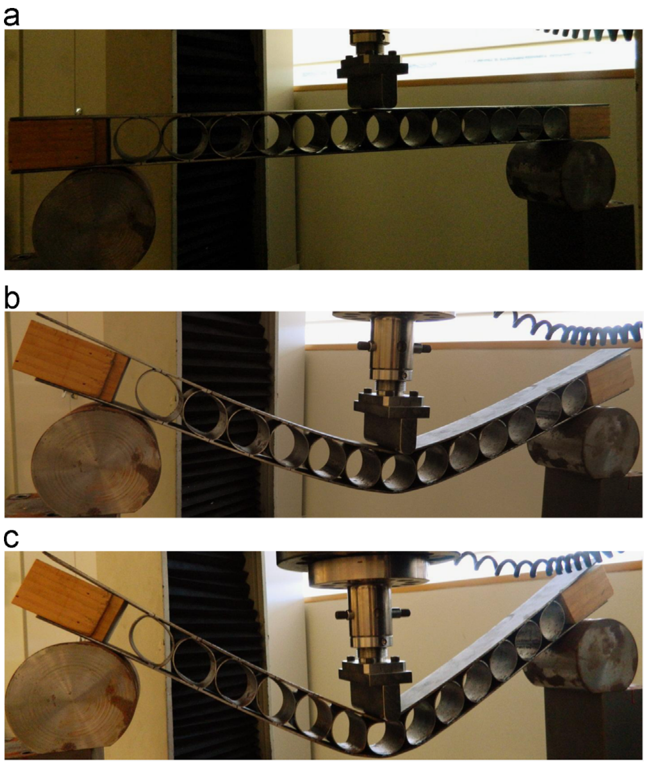

Fig. 3. Photographs of specimen D42 during test: (a) original shape of sandwich beam (D=42.4 mm); (b) deformed shape (displacement of the indenter u = 80 mm); and (c) deformed shape (displacement of the indenter u = 160 mm).