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Study on the low-velocity impact response and CAI behavior of foam-filled sandwich panels with hybrid facesheet

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ABSTRACT

Foam-filled sandwich panels with six types of facesheets were manufactured by vacuum-assisted resin injection (VARI) process. Low velocity impact test and compression after impact (CAI) test of the prepared panels were performed. Failure modes of different sandwich panels were analyzed by observing the contact surface and the cross section through damage region. Scanning electron microscope (SEM) was carried out to study the microstructure of the impacted specimens. It is found that matrix cracking, fiber breaking, foam cracking and debonding are the damage modes of sandwich panel with pure carbon facesheet, while other specimens merely show some of these modes after impact test. Panels with pure carbon facesheet have poor impact resistance properties, while panels with pure glass facesheet have preferable properties among all the specimens. Hybrid panel with ply mode of [C_2/G_2/Foam core/G_2/C_2] could provide higher maximum contact force and absorb more impact energy by carbon fiber breaking on the contact surface. In CAI test, wrinkling of facesheet and buckling of foam and skin are the two main damage modes. [C_4/Foam core/C_4] shows highest compress strength decline rate, while [G_4/Foam core/G_4] shows lowest rate. Decline rate of [C_2/G_2/Foam core/G_2/C_2] is very low but the compress strength of its undamaged specimen is not high.

1. Introduction

Sandwich structures in high performance applications could offer a very high stiffness due to their optimal use of components. For example in bending test, two thin but stiff and strong facesheets sustain in-plane loads, while the thick, light-weight and weaker core sustains the shear load. However, under impact load, the integrity and damage tolerance of sandwich panels are usually very low. Damages from low energy impact are of particular concern. This is because they can reduce the mechanical strength of composite sandwich panels. Meanwhile, damages in composite panels are usually undetected in routine visual inspections. The most affected residual mechanical property of sandwich panels is the compressive strength. The compressive strength can be reduced up to 50% after an impact event [1,2]. Thus, it is essential to investigate the damage mode of sandwich panels in impact events, and studies on compression after impact (CAI) behavior of sandwich panels are also valuable.

For a typical sandwich structure, three key factors should be taken into consideration when referring to its performance and function: the facesheet, the core, and the bond between the core and facesheet [3]. In this work, we will primarily focus on the facesheets. Generally, the facesheets applied in sandwich structures are comprised of unidirectional fiber (UDF) skins. The skins usually include carbon or glass fibers with different ply angles [4,5]. Such composites facesheets are characterized by high specific stiffness and high specific strength. However, UDF skins in sandwich structures are highly susceptible to impact damage due to their low transverse tensile strength. One of the approaches to improve the impact damage tolerance of UDF reinforced sandwich panels is to use woven fabric layers (WF) instead of UDF skins. Because the transverse tensile strength of WF composites is much higher than UDF composites, WF composites have been recognized to have superior impact resistance characteristics. Recently, due to the high specific stiffness and strength, woven carbon fabric clothes are being widely used in many applications such as aircraft structures, satellite launch vehicles, automotive and sporting goods industries. Unfortunately, the low toughness of carbon fibers has limited their applied scopes. This disadvantage is especially obvious when referring to the applied field where dynamic load may

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occur [6–8]. One of the possible ways to solve this problem is the application of hybrid composites. Hybrid composites are materials made by combining two or more different fibers in a common matrix. Commonly there are five kinds of structure styles of hybrid composites: intraply, interplay, sandwich, intraply/interplay, and super hybrid composites. Many references [9–13] have investigated the influence of design parameters such as stacking sequence, thickness, and geometry on the mechanical performance of hybrid composites. Generally in these references, it is found that hybrid composites could offer a range of properties that cannot be obtained by using a single reinforcement in the material. Meanwhile, it is also found that the hybridization effect allows designers to tailor the composite properties to meet the exact needs of the structure under consideration.

Recently, the mechanical response of sandwich structures under low-velocity impact load has been extensively studied. Many researchers have conducted impact tests on sandwich panels that comprised of different facesheets and core materials. Moreover, CAI tests of sandwich panels are also investigated by numerous researchers. In particular, Wang et al. [4] presented the results of an experimental and numerical study on the low-velocity impact behavior of foam-filled sandwich panels. Nemes et al. [14] tested sandwich panels made by woven glass epoxy prepreg skins with honeycomb core. Hosur et al. [15] fabricated foam-filled 3-D integrated core sandwich composite laminates with additional facesheets using vacuum-assisted resin infusion molding process. Alaattin et al. [16] studied the effect of stacking sequence on the impact behavior of sequentially stacked woven/knit fabric glass/epoxy hybrid composites, and the impact and post-impact (CAI) behavior of hybrid composites at various impact energies were investigated. In reference [17], they also investigated the effect of stitch pattern on the impact and post impact (CAI) behavior of eight ply woven–knit hybrid composite panels. Sarlin et al. [18] investigated the effect of impact energy and rubber thickness on the impact properties of layered steel/rubber/composite hybrid structures. Cho et al. [19] studied the complex vibration characteristics of an actual spacecraft structure using the FEA code in conjunction with experimental data. They demonstrated a modeling technique and discussed the applications of numerical analysis theories. Castanie et al. [20] proposed a core crush criterion to determine the residual strength of impacted sandwich structures. Sanchez et al. [21] studied CAI behavior of different carbon fiber reinforced composite laminates at low temperature. Mannov et al. [22] manufactured fiber reinforced composite laminates with a graphene oxide modified epoxy matrix, and CAI behavior of the obtained materials were also presented.

In this paper, foam-filled hybrid facesheet sandwich panels made by woven carbon/glass cloth and urethane foam are prepared by vacuum-assisted resin injection (VARI) process. After determining the fundamental mechanical properties of each constituent of the sandwich panel (including the matrix, foam core, glass fiber and carbon fiber), six sandwich panels with ply mode of [C_4/Foam core/C_4], [C_2/G_2/Foam core/G_2/C_2], [G_2/C_2/Foam core/C_2/G_2], [G/C]$_2$/Foam core/[C/G]$_2$, [G/C_2/G/Foam core/G/C_2/G] and [G_4/Foam core/G_4] are manufactured. Specimens with dimension of 100 mm × 100 mm × 16 mm are subjected to low-velocity impact test at the energy level of 30 J. The impact response of different specimens is analyzed and reported in terms of peak load, contact time, and absorbed energy. The damage modes of different specimens are studied by visual observation as well as SEM method. Moreover, compression after impact (CAI) test is carried out to understand the residual strength of different sandwich panels after impact, and failure modes formed in the compression test are also analyzed.

2. Experimental details

2.1. Materials and manufacturing

In this study, the polymer used as matrix is vinyl ester resin. This resin can be cured at room temperature in the presence of hardening agent and accelerating agent. The hardening agent is Methyl Ethyl Ketone Peroxide (MEKP), and the accelerating agent is Dimethylaniline. The resin is mixed with accelerating agent and hardening agent at mass ratio of 1%:1%:0.1%. The reinforced material is plain weave glass fabric cloth and carbon fabric cloth. Fig. 1 shows the two-dimensional orthogonal plain woven fabric cloth used in the experiment. Table 1 lists the parameters of the fabrics. In the table, g_w, g_f are the gap between adjacent strands, and a_w, a_f are the strand width. The superscript w and f indicates the warp and fill direction of the woven fabric, respectively. The thickness of the foam core is 12 mm. To ensure the resin could totally immerse the foam core during the manufacturing process, the adopted foam core has resin diversion trenches on the surface and diversion outlets inner it. As shown in Fig. 1, distance between diversion trenches is 20 mm × 20 mm, and the through-thickness diversion outlets have the diameter of 2 mm.

Foam-filled sandwich panels with six kinds of facesheets are prepared by vacuum-assisted resin injection (VARI) process [23]. Sandwich panels, comprised of two thin laminated facesheets and foam core, are manufactured with dimensions of 1000 mm in length, 150 mm in width, and 16 mm in thickness. Thickness of the core material is 12 mm, while each layer of fiber in the facesheet has the thickness of 0.5 mm. The ply modes of the panels are [C_4/Foam core/C_4], [C_2/G_2/Foam core/G_2/C_2], [G_2/C_2/Foam core/C_2/G_2], [G/C]$_2$/Foam core/[C/G]$_2$, [G/C_2/G/Foam core/G/C_2/G] and [G_4/Foam core/G_4], as demonstrated in Fig. 2. The photograph of VARI process adopted in this paper is also given in Fig. 1. During the VARI process, a glass square plate was placed at the bottom as holder, and then release agent was evenly coated on mold surface. The foam and the hybrid composite laminate were placed on the glass holder, and then covered with peel ply and silk ply. Note that stacking sequence of the fabric clothes and the foam should accord with the schematic diagram shown in Fig. 2. Then the laminate was closed by vacuum bag and sealant tape. To ensure the resin could flow uniformly, a delivery pipe was fixed at the entrance. After infusing the resin, the system was cured at room temperature and vacuum level of 600 mbar for 24 h. To test the mechanical behavior of foam core sandwich panels with different hybrid facesheets, cuboid specimens with dimension of 100 × 100 × 16 mm^3 were cut from the square laminates by a low speed diamond saw blade cutting machine. The mass distribution of different components in the sandwich panels is listed in Table 2. As seen, sandwich panels with pure glass facesheet have the mass of 90.52 g, while panels with pure carbon facesheet have the mass of 71.22 g. There are totally four layers of carbon fabrics and four layers of glass fabrics in the hybrid facesheet, and sandwich panels with hybrid facesheet have the mass of 82.62 g.

2.2. Determination of mechanical parameters of woven fabric composite panels and the foam core

To evaluate the fundamental mechanical properties of the single composition in the sandwich panels, specimens that including vinyl ester cast, woven carbon fabrics/vinyl ester (CF/VE) laminates and woven glass fabrics/vinyl ester (GF/VE) laminates are manufactured by the VARI process. To estimate the mechanical properties of the selected form core, compression test of the foam is carried out. The vinyl ester casts in tensile test have the dimension of 146 × 10 × 6 mm^3. All the fiber reinforced composites have the