Research Article

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Experimental study on the low-velocity impact failure mechanism of foam core sandwich panels with shape memory alloy hybrid face-sheets

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Abstract: Superelastic shape memory alloy (SMA) as an advanced smart material has been used to improve the impact performance of fiber-reinforced composites in recent decades. Due to the low impact toughness of the thin composite face-sheet and the poor strength of the foam core, sandwich panels are sensitive to the transverse loading. SMA fibers were embedded into the composite laminated to improve the impact resistance of the traditional foam core sandwich panel in this work. Five new types of SMA hybrid panels were prepared, and the testing panels with penetration failure were observed at the impact energy of 50 J. The impact mechanical responses and the damage morphology were analyzed, and the impact failure mechanism was also revealed. Results show that all sandwich panels were failed, the fiber breakage occurred at the impact region in the traditional panels, while part plies of the rear face-sheets split-off in the SMA hybrid panels. The impact performance of the SMA hybrid panels is improved when compared with the traditional panel, the reduction of the delamination area by 48.15% and the increase of the load-bearing threshold by 32.75% are acquired for the hybrid sandwich panel with two layers of SMA fibers in the rear face-sheet.

Keywords: shape memory alloy, low-velocity impact, foam core sandwich panel, failure mechanism, delamination

1 Introduction

Composite sandwich panels have been widely used in the aerospace, automobile, and shipbuilding fields for superior performances such as high stiffness and strength to weight ratios, good energy absorption capacity, and ease of manufacturing in recent years [1–3]. However, due to the poor impact damage resistance of the thin composite face-sheets and the low stiffness and strength of the core materials, most composite sandwich structures are sensitive to the out-of-plane transverse loading. Damage modes (matrix cracking and delamination in the composite face-sheets, face-sheet/core debonding, and core cracking and crushing) are easily caused when composite sandwich panels suffer from the low-velocity impact loading as one common of the out-of-plane transverse loading in service [4–7]. The mechanical properties such as flexural properties and compression performance after impact are significantly decreased resulting from the occurrence of different damage modes in composite sandwich structures [8–10], which poses a serious threat to the safety and durability of sandwich panels. Hence, research on the impact damage mechanism and approaches to improve the impact resistance of composite sandwich panels has been a focus issue in the field of composite sandwich structures.

Many studies have been done on the impact damage mechanism of composite sandwich panels, and three kinds of methods, enhancing the mechanical performance of the face-sheets, increasing the skin/core bonding performance, and improving the structural properties of the core materials, can be applied to improve the impact damage resistance of the sandwich panels. To acquire excellent impact resistance, researches [11–14] mainly focused on the enhancement of the mechanical properties of the skins. The influence of skin thickness on the low-velocity impact response of foam core sandwich panels was studied by Atas and Potoğlu [11]. The thickness of the face-sheets was changed by the layer numbers. They found that the

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impact perforation threshold is increased with skin thickness increasing almost in a linear relationship. The influence of face/core bonding on impact damage of foam core sandwich panels was investigated by Imielińska et al. [15]. The face/core bonding was formed by the matrix resin and two different adhesives. The results indicated that, based on the frequency of core fracture, the adhesive bonding of the foam core to the face is weaker to the wet-lay-up process; hence, the impact resistance of the sandwich panel is weaker. Meram and Cetin [16] studied the effects of face/core interface property on the impact damage of honeycomb sandwich panels. Due to the formation of more voids, interface, and cohesive cracks, the weak face/core interface resistance resulted in a lower impact performance of the sandwich panel. Different foam core configurations were designed to enhance the impact tolerance of sandwich panels in researches [17–19]. The influence of new foam core designs with internal face-sheets on the impact response of sandwich panels was investigated by Al-Shamary et al. [17]. The results show that the foam core inserted with composite plies can improve the impact tolerance of sandwich panels, and the foam core configuration with two internal face-sheets exhibits the best energy dissipation capacity.

Due to the superior thermodynamic property, the shape memory alloy (SMA) embedded into the face-sheets, as an alternative method, has been applied to improve the impact damage resistance of sandwich panels in recent decades [20–22]. The influence of pre-strain SMA fiber on the damping capacity and impact performance of polymer composites was studied by Raghavan et al. [23]. Compared to the panels with SMA without any pre-strain, the passive damping capacity was increased by the increase in pre-strain beyond the value for stress-induced phase transformation of austenite. The toughness was also improved for the distributed damage attributed to the introduction of SMA fibers under impact loading. The effect of SMA position on the impact resistance of composite laminates was investigated by Sun et al. [24]. The research indicated that the impact performance of composite laminates is improved for the embedding of SMA fibers, and the optimal scheme is to insert two layers of SMAs with one layer at the middle and another at the bottom of the laminate. The influences of SMA fibers on the impact damage response and residual flexural properties of glass fiber-reinforced laminates under low temperature were studied by Kang and Kim [25]. The results show that the low temperatures have a little more influence on the impact damage behavior of composite laminates embedded with SMA fibers, and the SMA hybrid laminates have higher threshold energy than the base laminates.

The influences of position, content, and size of SMA fibers on the low-velocity impact responses of sandwich panels have been investigated by many researches, while more research is needed to understand the impact failure mechanism of the SAM hybrid sandwich panels with penetration damage. In this work, new SMA hybrid foam core sandwich structures with one and two layers of SMA fibers were prepared, and the low impact responses of the sandwich panels were evaluated in terms of contact force, deflection, and energy. The damage morphology of the impacted panels was analyzed using the methods of visual inspection and scanning electron microscopy (SEM); the effect of SMA fibers on the impact resistance of foam core sandwich panels and the failure mechanism of SMA hybrid panels with penetration damage were revealed.

2 Materials and methods

2.1 Materials

In this work, five new types of foam core sandwich panels embedded with SMA fibers are prepared with the base panel without SMA fibers. The unidirectional glass fiber-reinforced epoxy resin composite laminates enhanced with or without SMA fibers were applied as the face-sheets of the designed structures. The vinyl ester resin, methyl ethyl ketone peroxide, and dimethylaniline were used as the polymer matrix, hardening agent, and accelerating agent, respectively, and the mixture can be easily cured at room temperature with the weight ratio 100:1:0.2. All the constituent materials of the base composite face-sheet were provided by the Tongxiang Mentai Reinforced Composite Material Company. The surface density of the glass fiber cloth was 200 g/m^2 , and the single-layer thickness of the manufactured face-sheet was 0.2 mm. The foam core, purchased from DIAB Group (Laholm, Sweden), was a 6 mm thickness polyvinyl chloride (PVC) foam with a density of 60 kg/m^3 , the compressive modulus and strength of which are 75 and 0.84 MPa, respectively. To benefit the immersion of resin, there were $20 \text{ mm} \times 20 \text{ mm}$ diversion trenches on the surface of PVC foam. The 0.2 mm super-elastic 55.7 wt% Ni balance Ti fibers were provided by PeierTech, Jiangyin, China, as the reinforcement to the face-sheet of sandwich panels. The SMA fiber starts to transform to austenite at -5.6°C (A_s) when heated, and the transformation is finished at 10.9°C (A_f). Therefore, the SMA fiber is completely austenitic at ambient temperature. The mechanical properties of the SMA fiber acquired by

Table 1: The mechanical properties of the SMA fiber

Modulus (GPa)	Tensile strength (MPa)	Failure strain (%)	Upper plateau stress (MPa)	Lower plateau stress (MPa)	Recoverable strain (%)
62.2	1530.2	12.5	538.5	165.8	7.9

tensile tests at ambient temperature are summarized in Table 1. A hysteresis loop can be generated when the stress in the SMA exceeds the critical phase transformation stress (538.5 MPa in this paper), and lager energy can be dissipated due to the high critical stress and large recoverable strain.

2.2 Specimen preparation

The vacuum-assisted resin injection (VARI) preparation technology was applied to manufacture the five new SMA

hybrid sandwich panels and the base panel [26]. It has been known that the SMA/matrix interface adhesion property is critical to the mechanical performance of SMA hybrid composites [27–31]. In this paper, acetone was applied to remove impurities on the SMA fiber surface, and then 200 and 400 grit papers were used to enhance the roughness of SMA fibers. The schematic diagrams of manufactured foam core sandwich structures are presented in Figure 1. Mode I with a lay-up of $[0^{\circ}/0^{\circ}/90^{\circ}/90^{\circ}/\text{core}/90^{\circ}/90^{\circ}/0^{\circ}/0^{\circ}]$ stands for the reference sandwich panel without SMA fibers, Mode II and III represent the hybrid sandwich panels with one layer of SMA fibers, and two layers of SMA fibers are embedded

Figure 1: Ply modes of foam core sandwich panels.

Figure 2: Schematic plot of the VARI process.

into Mode IV to VI hybrid sandwich panels. To improve the compatibility of SMA fibers with surrounding glass fibers, SMA fibers with a 0.3-mm gap were inserted along the glass fiber orientation of adjacent layers [32]. To balance the mechanical properties of hybrid sandwich panels with two layers of SMA fibers, the two embedded SMA layers were orthogonal.

The schematic plot of the VARI process is presented in Figure 2. A glass plate can be used as a workbench. One layer release cloth, the prepared sandwich panel lay-up, another layer release cloth, one layer diversion net, and a vacuum bag were placed in sequence from the bottom to up. The whole structure can be sealed with the sealant tape sticking the vacuum bag and workbench together. Two delivery pipes located at the entrance and exit were applied to ensure the resin immersing uniformly. A 650 mbar vacuum level was set and the system was cured for 24 h at room temperature. After the resin mixture

was fully cured, SMA hybrid sandwich panels were produced with the release cloth removed. Based on the American Society for Testing and Materials (ASTM) D5420-2010 standard, the samples of $100\text{ mm}^3 \times 100\text{ mm}^3 \times 7.5\text{ mm}^3$ in dimensions were cut by a diamond saw blade cutting machine.

2.3 Low-velocity impact testing

The low-velocity impact testing was carried out by the Instron Dynatup CEAST 9350 (Instron, Norwood, MA, USA) machine at room temperature. The testing device is shown in Figure 3. The testing system consists of a drop hammer device, clamping fixture, and a data acquisition system. Specimens were firmly fixed by two steel circular rings with a 76-mm diameter hole in the center. Sandwich

Figure 3: The device of the impact testing.

specimens were tested based on the ASTM D5420-2010 standard. For the impact mechanical responses, the contact force was measured by a load cell on the projectile head, the displacement was recorded through a laser detector fixed on the machine frame, and the impact absorbed energy was integrated by the contact force and the corresponding displacement. For this work, the 50 J impact energy level was set to penetrate the testing specimens. The hemispherical projectile with 3.77 kg mass and 16 mm diameter was guided by two smooth columns which prevents the specimens from a second impact. For each type of specimen, three specimens at least were impacted and the average mechanical responses were determined.

2.4 Damage morphology observation

There are some damage modes induced in the failure sandwich panels, such as matrix cracking, fiber breakage, SMA fiber breakage, and delamination in the face-sheets, face-sheet/foam core interface debonding, and foam core compression crushing. It is need to observe the damage morphology of impacted specimens to reveal the damage evolution of sandwich panels subjected to low-velocity impact. For this work, the visual inspection and SEM (Hitachi S-4300, Tokyo, Japan) technology methods were applied to observe the damage modes and extent induced in the failure specimens. The visual inspection method was used to identify the damage on the specimen surfaces, and the SEM pictures were used to present the micro-damage morphology in the failure regions, which is useful for understanding the damage mechanism of hybrid panels enhanced by SMA fibers. For the foam core sandwich panels, the foam core cracking and crushing damage were easily identified by the visual inspection, and the macro-damage and micro-damage morphology of the specimen face-sheets were observed by visual inspection and SEM technology, respectively. The SEM pictures of different resolutions were acquired on the cross-sections cut from the center of the failure specimens.

3 Results and discussions

3.1 Damage morphology of the failure sandwich panels

There are different damage modes induced in the impacted foam core sandwich specimens subjected to low-velocity

impact. Typical damage morphology of the failure specimens in front, back, and transverse views are shown in Figure 4. It is clear that all specimens are destructively damaged.

For all specimens, the front face-sheets are penetrated, damage modes of fiber breakage and delamination are easily distinguished on the front surfaces. Compared to ply mode I, less fiber breakage and delamination are induced in the front face-sheets of SMA hybrid sandwich panels. The rear face-sheets of all specimens are failed. The damage mode of delamination exists on the rear face-sheets of all specimens. The fiber breakage is also appearing in the impact region beneath the projectile for ply mode I panel, whereas there is no apparent fiber breakage in the rear skin of specimens embedded with SMA. Generally, the delamination region with a peanut shape exists on the front face-sheet surface. An elliptical shape delamination region appears on the rear face-sheet surface, and the long axis orients the lower layer direction where adjacent layers directions are changed, which is consistent with the works on the fiber-reinforced composites subjected to low-velocity impact [33,34].

From the cross-section pictures, it is obvious that a cavity with a diameter of about 16 mm is residual in all specimens, which also indicates the penetration of the front face-sheets. Damage modes of fiber breakage, delamination, core cracking, and core compressive crushing are easily identified in the cross-section pictures. Compared to the SMA hybrid specimens, the failure region is relatively concentrated beneath the projectile. For ply mode I, the foam core beneath the projectile is entirely destroyed, while the damage of foam core is weaker for specimens reinforced with SMA, especially for ply mode VI with two layers of SMA fibers in the bottom face-sheet. For ply mode II and IV, foam core cracking is found near the residual cavity. The bottom face-sheets in a transverse view again indicate that the damage modes of fiber breakage and delamination occur in ply mode I, and delamination with few fiber breakages appears in the SMA hybrid sandwich panels. It is also observed that part plies of the bottom face-sheet split off and a few SMA fibers pull out in the hybrid panels.

The damage mode of delamination occurs in both face-sheets in the failure specimens. The delamination area is a useful parameter to reveal the damage extent of composite panels [12,13]. As indicated in studies [34,35], the impacted specimens can be generally divided into three regions, the failure region, the delamination region, and the intact region. Around the intensive circular failure region with a diameter slightly larger than that of the projectile can be regarded as the delamination area evidently consisting of stress whitening in this work. The boundary

Figure 4: Typical damage morphology in the failure specimens. The center $60 \text{ mm}^2 \times 60 \text{ mm}^2$ region is shown for the pictures in a front view, the whole rear surface is presented for the pictures in a back view, and the center width of 60 mm along the long axis of the delamination region is revealed for the pictures in a transverse view.

between the stress whitening (delamination region) and the remaining intact region is easily distinguished in the damage morphology, and the delamination generally develops in the interface between different adjacent ply orientations. With the help of computer-assisted image-processing technique, the delamination areas in the front and rear face-sheets are determined and summarized in Figure 5. Generally, compared to ply mode I, the damage areas in the front face-sheets of sandwich panels embedded with SMA are decreased, and the reduction is more remarkable for panels inserted with two

layers of SMA. And for the rear face-sheets, the delamination areas of the SMA hybrid sandwich panels make not much difference with that traditional panel without SMA reinforcement. The delamination area is about 810 mm^2 in the front face-sheet of the traditional panel in detail, and compared to ply mode I, the delamination area of ply mode II, III, IV, V, and VI makes a reduction of 12.96, 19.75, 14.94, 38.02, and 48.15%, respectively. For the rear face-sheet of the traditional panel, the delamination area of 1430 mm^2 is induced. The delamination areas of the SMA hybrid sandwich panels are a little larger

Figure 5: Delamination areas of the failure specimens.

than that of the traditional panel, and the difference is not larger than 80 mm^2 . While almost no fiber breakage is induced in the rear face-sheets of the SMA hybrid panels relative to the destructive failure of the traditional panel with serious fiber breakage observed.

The impact resistance of the SMA hybrid sandwich panels is improved when compared with the traditional

panel based on the analysis earlier. Specially, the enhancement is the most remarkable for ply mode VI, the foam core sandwich panel embedded with two layers of SMA fibers in the bottom face-sheets. As revealed by the works [23–25], the strength and stiffness of composite laminates are improved due to the enhancement effect of SMA. Due to the super-elasticity performance of SMA fibers, partial impact energy can be absorbed; thus, the impact energy resulting in the damage into the composite panels is reduced, the extent and scope of the composite face-sheet damage are decreased. In addition, the compressive crushing of the foam core can also be prevented owing to the protection of the SMA hybrid face-sheets with higher mechanical performance relative to the traditional composite panels.

The micro-damage morphology obtained by SEM technology is useful for understanding the damage mechanism of the sandwich panels. The damage modes of the foam core mainly include compressive crushing and cracking, which can be clearly identified through visual inspection and has been indicated earlier. Hence, the SEM technology is mainly applied to reveal the micro-damage morphology of the composite face-sheets. The failure region around the residual cavity is chosen, and the representative SEM images are shown in Figure 6. For the images of the

Figure 6: Representative SEM images in the face sheets.

reference face-sheet without SMA fiber, the damage modes of delamination and fiber breakage are easily observed, and the micro-matrix cracking, fiber breakage, and fiber/matrix debonding are clearly indicated in the enlarged image. For the face-sheet with SMA, the SMA/matrix debonding can also be identified beside the damage modes of delamination, fiber breakage, matrix cracking, and fiber/matrix debonding induced in the face-sheet without SMA. Attribute to the synergistic effect of different damage modes and the deformation incompatibility between SMA fibers and composite layers, a separation region around the SMA fibers is observed. Some impact energy can be dissipated by the SMA/matrix debonding and the synergistic effect with other damage modes; thus, the impact resistance of the SMA hybrid sandwich panels is enhanced.

3.2 Impact responses of the SMA hybrid sandwich panels

The impact mechanical responses of composite panels mainly include the contact force, deformation, and impact absorbed energy. The typical contact force versus time curves is plotted in Figure 7. It can be easily seen that two peak contact forces are recorded in all curves, and the contact force is nearly constant at the end of the impact testing, which revealed the failure of the two face-sheets in sequence and the loss of continuing sustaining loading. Corresponding to the damage morphology identified earlier, the sharp drop of the contact force following the first peak force indicates the penetration of the front face-sheet. With the progressive compression and densification of the foam core, the contact force is gradually increased until reaching the second peak force. The second sudden drop of the contact force presents the disastrous damage of the rear face-sheet. After the impact time of 0.006 s, the contact force is almost not changed, which reveals the whole failure of the foam core sandwich panel. Generally, the impact contact forces of the SMA hybrid sandwich panels are larger than the traditional panel. Compared to ply mode I panel, the first peak force of ply mode II and IV panels has a little increase, while the increase is prominent for ply mode III, V, and VI panels. The second peak force of the SMA hybrid sandwich panels are much larger than that of the panel without SMA. Therefore, larger loading bearing capability is acquired for the SMA hybrid sandwich panels with respect to the reference panel, that is to say, the impact performance of the sandwich panels incorporated with SMA fibers is enhanced.

The typical force-displacement, displacement, and absorbed energy versus time curves are displayed in Figure 8. The sandwich panels experience elastic behavior at the initial phase of the low-velocity impact events. Compared to the traditional sandwich panel, it is evident that the SMA hybrid sandwich panels produce less displacement under the same contact force in Figure 8(a), which indicates the larger flexural stiffness of the SMA hybrid sandwich panels relative to the traditional panels. It is obvious that the deformation of the SMA hybrid panels is smaller than the traditional panel, and there is not a large difference in the maximum displacement between the SMA hybrid sandwich panels except for ply mode II panel. As indicated in the researches [29,36], the mechanical properties of the SMA hybrid composites are improved attributing to the reinforcement effect of SMA fibers. As the stiffness and strength of the SMA hybrid panels are improved with SMA fiber-reinforced composite face-sheets, the impact damage tolerance of the foam core sandwich panels is increased, and the impact resistance of the SMA hybrid panels is improved. The difference in the absorbed energy is not large between the sandwich panels with and without SMA fibers. Almost no plastic deformation is caused on the composite face-sheets because of the brittle failure of the thermosetting resin and the low fracture strain of the glass fibers. Therefore, the impact energy is mainly dissipated through different damage modes, including matrix cracking, delamination, fiber breakage, and foam core crushing [17,18]. Though the dissipated energy is nearly the same, the impact resistance of the SMA hybrid sandwich panels is improved due to the less damage relative to the traditional panel revealed by the damage morphology earlier. Some impact energy is absorbed by the SMA fibers possessing superelastic performance and large failure strain. Moreover, a small amount of impact energy is dissipated by the SMA/matrix debonding.

The values of the two peak contact forces and the maximum displacement of the testing sandwich panels are summarized in Figure 9. Generally, the two peak contact forces of the SMA hybrid sandwich panels are larger than that of the traditional panel. The first peak force of the traditional panel is about 6.51 kN, the value of ply mode II is comparable to the traditional panel, and the value of ply mode IV has a little increase of 12.62%. The increase is more for ply mode III, V, and VI panels reaching 30.15, 24.39, and 32.75%, respectively. Compared to ply mode I, the second peak force of ply mode II, III, IV, V, and VI panels has an increase of 11.78, 7.86, 17.88, 10.49, and 9.94%, respectively. Generally, the deformation is relatively small for the whole failure

Figure 7: Typical contact force versus time curves. (The comparison of ply mode II and ply mode I (a), ply mode III and ply mode I (b), ply mode IV and ply mode I (c), ply mode V and ply mode I (d), ply mode VI and ply mode I (e)).

Figure 8: Typical force-displacement (a) displacement-time (b) and energy-time (c) curves.

of the sandwich panels. The maximum displacement of ply mode I panel is about 13.07 mm, and compared to ply mode I, the reduction is 7.99, 11.61, 12.31, 12.80, and

13.94% for ply mode II, III, IV, V, and VI panels, respectively. For ply mode II and IV panels, the SMA fibers are incorporated into the front face-sheet, the front

Figure 9: Values of the two peak contact forces (a) and maximum displacement (b).

face-sheet is penetrated during the testing, the superior mechanical properties of SMA have not fully exploited for the deformation of the structure is small; thus, the first peak force is comparable to the traditional panel. While the stress can be delivered through SMA fibers, and a broader range of foam core is compressed due to the protection of the SMA layer, so the second peak force can have a considerable increment. For ply mode III, V, and VI panels, part or all of the SMA fibers are embedded into the rear face-sheet, the SMA fibers can have a large plastic deformation, the stress-induced martensitic phase transformation process is motivated, more energy can be dissipated by the superelastic mechanical property of SMA fibers. Hence, the impact resistance of SMA hybrid panels is enhanced, and the loading support capability is improved with the two peak forces increasing. Combined with the damage morphology, it can also be seen that the impact resistance of sandwich panels with two layers of SMA fibers is better than that with one layer. With the volume fraction of SMA fibers increasing, the stiffness and strength of the panels are improved, especially for the panel with the two layers of SMA fibers in the rear face-sheet, the mechanical response of superelastic deformation is perfectly induced; thus, less damage is caused owing to more impact energy is absorbed by the SMA fibers. Hence, the impact performance of the SMA hybrid sandwich panels is improved, and the impact damage tolerance is higher for the panels with two layers of SMA fibers, especially for the panel with the two layers of SMA fibers in the rear face-sheet.

3.3 Damage evolution of SMA hybrid foam core sandwich panels

Different damage modes are induced in the sandwich panels in sequence with loading increasing during a testing process. The damage evolution of the foam core sandwich panels embedded with SMA fibers can be described as the following. First, the sandwich panels mainly experience elastic deformation for the loading imposed on the panel is low at the initial phase of the impact event. And almost no damage occurs in the panel. Second, the foam core is gradually compressed and crushed because of the initial poor compression resistance and low strength. As presented in the work [7,11], the initial damage of foam core reduces the structure stiffness, which is also indicated by the impact mechanical responses revealed in this work. Meanwhile, damage modes of matrix cracking, fiber/polymer debonding, and SMA/polymer debonding are induced in the face-sheets, but it is not apparent in visual inspection. The occurrence of damage at this phase cannot result in the disastrous failure of the panels. Third, with loading increasing, the front face-sheet is gradually penetrated, the first contact peak force is reached, and a sharp drop of the contact force occurs with the serious failure of the front face-sheet and the foam core. The damage modes of matrix cracking, delamination, and fiber breakage are present in the front face-sheet, and the progressive foam core crushing is induced resulting from the erosion of the projectile. The SMA fiber breakage occurs when the SMA fibers are embedded into the front face-sheets of the SMA hybrid sandwich panels. Also, matrix

cracking and delamination are caused in the rear face-sheet. Fourth, the front face-sheet is penetrated and a circular hole is formed. Apparent foam cracking presents near the hole in the hybrid panels with SMA fibers in the front face-sheets, and the damage is relatively concentrated in the hybrid panels with SMA fibers in the rear face-sheets. With the progressive crushing and densification of the foam core, the contact force is increased and reaches the second peak force. Lastly, the whole sandwich panel is failed with large damage occurring in the rear face-sheet, and the second steep drop of the contact force occurs. Fiber breakage is induced in the rear face-sheet of the traditional panel. Mass delamination is produced and part plies of the rear face-sheets split off in the SMA hybrid panels. The impact responses related to the SMA fibers, such as the superelastic mechanical response, SMA/matrix debonding and SMA fiber breakage, make a positive influence on the impact energy dissipation. Compared to the traditional sandwich panel, the impact performance of the SMA hybrid panels is enhanced due to the reinforcement effect of SMA fibers.

4 Conclusion

New foam core sandwich panels embedded with one or two layers of SMA fibers into the face sheets are designed for improving the impact performance in this paper. Five types of SMA hybrid panels subjected to low-velocity impact are estimated at the impact energy of 50 J. The impact mechanical properties of the SMA hybrid panels with the whole failure are evaluated. The following conclusions can be drawn:

- (1) Compared to the traditional sandwich panel, the impact damage resistance of the SMA hybrid panels is improved. Especially for the hybrid sandwich panel with two layers of SMA fibers in the rear face-sheet, the delamination area can have a 48.15% reduction, the improvement of the load-bearing capability can reach 32.75%, and the maximum displacement decreases by 13.94%.
- (2) The impact performance of the hybrid panels is better with the SMA volume fraction increasing. Compared to the SMA fibers embedded into the upper part of the hybrid panels, the impact damage resistance of the hybrid panels with SMA fibers in the lower part is better.
- (3) Damage modes including matrix cracking, delamination, foam core crushing, and fiber breakage occur in the traditional sandwich panel with penetration damage; SMA/matrix debonding, SMA fibers pulling

out, and SMA fibers breakage also induced in the SMA hybrid panels. Owing to the superelastic mechanical property of SMA and the synergistic effect of different damage modes, the impact performance of the SMA hybrid panels is enhanced with respect to the traditional panel.

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