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LOW-VELOCITY IMPACT CHARACTERISTICS OF COMPOSITE PLATES WITH SHAPE MEMORY ALLOY WIRES

Mi-Sun Rim, Eun-Ho Kim, In Lee
KAIST, Department of Aerospace Engineering, Daejeon, Korea
e-mail: inlee@kaist.ac.kr

Ik-Hyeon Choi, Seok-Min Ahn
Korea Aerospace Research Institute, Aeronautics Technology Division, Daejeon, Korea

Kyo-Nam Koo
University of Ulsan, Department of Aerospace Engineering, Ulsan, Korea

Jae-Sung Bae, Jin-Ho Roh
Korea Aerospace University, School of Aerospace and Mechanical Engineering, Geonggi-do, Korea

To investigate impact characteristics of shape memory alloy hybrid composites (SMAHC), several experiments were performed. Tensile tests of shape memory alloy (SMA) wires were carried out to investigate thermomechanical properties, and low-velocity impact tests of SMAHC plates and conventional composite plates without SMAs at the critical energy level. low-velocity impact tests of several types of composite plates, including composite plates with embedded SMAs/Fe/Al wires and conventional composite plates, were also done. Results of these experiments show that embedding SMAs in a composite plate can improve the impact resistance. Lastly, low-velocity impact tests of SMAHC plates with SMA wires embedded at different positions through the thickness were performed in an effort to improve the impact resistance. Embedding SMA wires at a lower position in the composite plates was the most effective for improving the impact resistance.

Key words: shape memory alloy, SMAHC, composite, low-velocity impact, impact resistance

1. Introduction

Composite materials which are reinforced with fibers have many advantages due to their high specific strength and specific stiffness. They can be fabricated to optimize the strength and stiffness by changing fabrication parameters such as the stacking sequence and the number of plies of hybrid materials. Due to these advantages, they are widely used in such as the aviation and aerospace fields, especially for weight savings. However, composite materials are weak against damage caused by impact loading owing to their low toughness. Therefore, impact resistance and impact damage are important issues for the safety of composite structures. Recently, several studies were performed for low and high velocity impact of composite structures (Ahn *et al.*, 2010; Nguyen *et al.*, 2010; Iannucci, 2006). Damage of composite materials can take complicate forms, including matrix cracking, delamination, fiber breakage and other types. Especially, the damage due to low velocity impact is often difficult to be observed because it typically appears at the side opposite to where the impact took place or inside the composite structure, both of which can lead to unexpected problems. Therefore, research on the topic of improving and predicting impact damage is necessary. Such efforts can be considered as a method of improving impact resistance to prevent sudden problems, and one recent direction of this research involves embedding some materials of high toughness into composite materials to absorb the impact energy.

Recently, smart structures which are combined with smart materials, such as piezoelectric materials (Qiu and Ji, 2010), shape memory alloys (SMAs), electrostructive/magnetostructive materials ER/MR fluids and etc., have being researched because of their attractive characteristics. SMAs have been a topic of research as an embedded material (Pain and Rogers, 1994). Because the phase of SMAs changes according to changes in the temperature or applied load, SMAs have several remarkable properties, such as large failure strain, large failure stress shape memory effect, and superelasticity. The shape memory effect (SME) is that when the load is applied and then removed, the residual strain can be fully recovered by raising the temperature. Consequently, the deformed SMAs recover their original shape. Another characteristic is superelasticity (SE) that SMAs achieve a large amount of strain upon loading, and they fully recover via a hysteresis loop during at above the austenite finish temperature, which is also the phase transformation temperature (Brinson, 1993). Due to superelasticity and the large failure strain, SMAs can absorb and dissipate a large amount of strain energy (Boller *et al.*, 2001).

When an impact load is applied to composite structures and causes damage, a large amount of deformation is induced locally around the damaged region. SMAs embedded in this region can resist the impact load by absorbing and dissipating the large strain energy with large deformation after the failure of stiff composite materials. Therefore, embedding SMAs into composite structures can improve the perforation resistance of fiber-reinforced laminated composite structures. Research in this area has been done since 1990's. However, experimental studies are still insufficient, so additional experimental studies are necessary.

In this paper, several experiments were performed to confirm the effects of embedding SMAs on impact characteristics of shape memory alloy hybrid composite (SMAHC) plates. First, tensile tests of SMA wires were performed to investigate characteristics and material properties of SMAs. A specific type of SMA wires was chosen according to results of tensile tests, and these wires were embedded into composite plates to fabricate SMAHC plates. Next, impact tests of SMAHC plates along with conventional composite plates without SMA wires were performed at the critical energy level, where the energy initiates catastrophic damage. To compare the effects of embedding SMA wires with other embedded metal wires, composite plates with embedded iron (Fe) and aluminum (Al) wires were also tested. Lastly, impact tests of composite plates with different embedded positions of SMA wires through the thickness direction were done.

2. Tensile tests of SMA wires

To choose the proper SMA wires to improve impact resistance of composite plates, characteristics of SMA wires should be investigated. Therefore, tensile tests of two types of SMA wires (Nitinol Devices & Components), SM495 (Ni54.5wt%) and SE508 (Ni55.8wt%), were done at various temperatures (Kang *et al.*, 2010). Thermo-mechanical properties investigated by these tests are presented in Table 1. SMA wires showed large failure strain that

Table 1. Mechanical Properties of SMA Wires

	SM495 (Ni54.5wt%)		SE508 (Ni55.8wt%)	
	Martensite	Austenite	Martensite	Austenite
Transfer coefficient	7.1 MPa/°C	6.7 MPa/°C	4.6 MPa/°C	6.4 MPa/°C
Elastic modulus	13.8 GPa	52.8 GPa	17.0 GPa	40.1 GPa
Failure stress	1179 MPa		1434 MPa	
Failure strain	14.9%		14.4%	

exceeded 14%. This level is very high compared to other materials. The elastic modulus of austenite was found to be greater than that of martensite. At room temperature (20°C), SE508 is stiffer than SM495 because SE508 has austenite and SM495 has martensite. Moreover, SE508 shows superelastic behavior at room temperature (Fig. 1). Superelasticity is effective for absorbing and dissipating large amounts of strain energy. Impact tests were performed at room temperature, therefore SE508 was chosen as an embedding material for reinforcing composite materials under low-velocity impact.

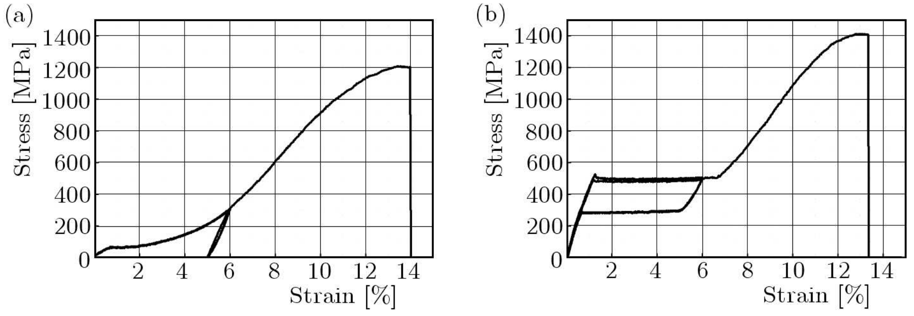

Fig. 1. Stress-strain behavior at room temperature (20°C); (a) SM495 (Ni54.5wt%), (b) SE508 (Ni55.8wt%)

3. low-velocity impact tests

Several low-velocity impact tests were performed to confirm the effects of embedding SMA wires into composite plates and to investigate the impact characteristics of these plates.

3.1. low-velocity impact tests at the critical energy level

low-velocity impact tests of SMAHC plates and conventional composite plates without SMA wires were performed at the critical energy level to determine the effect of embedding SMA wires into composite plates.

3.1.1. Conditions and procedure

Conventional composite plates without embedded SMA wires were fabricated with graphite/epoxy prepreg CU-125NS (Hankuk Carbon Co.) and SMAHC plates were fabricated by embedding SMA wires (SE508) into conventional composite plates. Table 2 presents the mechanical properties of CU-125NS (Kim *et al.*, 2004).

Table 2. Mechanical Properties of CU-125NS (Kim *et al.*, 2004)

Longitudinal modulus	135.4 GPa	Shear modulus	4.8 GPa
Transverse modulus	9.6 GPa	Poisson's ratio	0.31

Two impact tests were performed. Specimens were 100 mm by 100 mm square plates and 20 mm width along the edges was used to clamp the specimen. In the first case, the stacking sequence of conventional composite plates was $[90°/0°]_{3S}$. To fabricate SMAHC plates, SMA wires were aligned along the center of the plate, covering a width of 20 mm, with a volume fraction of 2.24%. When SMA wires are embedded in composite materials, the lumping resin creates weak regions that cause delamination (Tsoi *et al.*, 2003). To prevent this, SMA wires were aligned along the fiber direction and embedded in the center layer of the conventional composite plate between 0° plies. The thickness of specimens was 1.37 mm. In the second case, the stacking sequence of the conventional composite plates was $[45°/-45°/90°/0°]_S$ and the volume fraction of SMAHC plates was 7.57%. The thickness of specimens was 0.85 mm. The configurations of specimens are presented in Fig. 2.

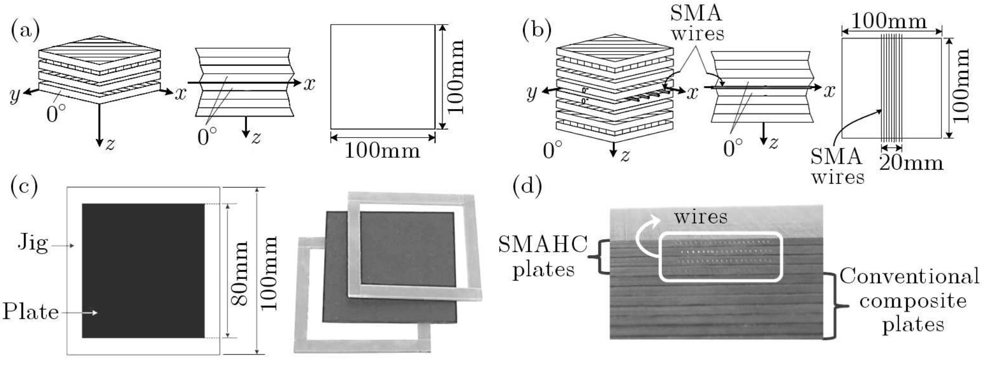

Fig. 2. Configurations of specimens; (a) conventional composite plate, (b) SMAHC plate, (c) specimen and jig, (d) actual configurations of specimens

These low-velocity impact tests were done at room temperature (20°C). A weight-drop-type universal impact testing machine was used, and a hemispherical steel impactor with a diameter of 15.35 mm and a mass of 2.38 kg was dropped to make an impact into the center of the plate-type specimen.

the impact load was applied at the critical impact energy level. The critical impact energy is the energy level at which point catastrophic damage is initiated. It was found by increasing the incident energy from a low energy level. The incident impact energy is defined by the following equation

$$E = mgh \tag{3.1}$$

Here, E is the incident impact energy, m is the mass of the impactor, and g is the acceleration of gravity, h is the height of the impactor. Thus, adjustment of the incident impact energy level is possible by changing the height (h). The critical impact energies were investigated by repeated tests with increasing h from 0.1 m until the height where the catastrophic damage is initiated. They were determined to be 20 J in the first case and 7 J in the second case. Therefore, these values were used as the incident impact energy levels.

3.1.2. Results and discussions

In the first case at incident impact energy of 20 J, specimens fractured at 3-4 ms, after the contact force suddenly decreased. There was no significant difference of the maximum contact force before the sudden decrease between conventional composite plates and SMAHC plates. Therefore, the embedded wires had no effect on that. Instead, the shape and material of the impactor or the condition of the specific impact surface affected this value. However, after a fracture occurred, it was found that the contact force of SMAHC plates was greater than that of conventional composite plates. It means that SMAHC plates resisted a greater amount of the impact load than conventional composite plates because SMA wires embedded in the composite plates resist much impact load after fracture of thr graphite/epoxy material and they prevent the damage propagation of composite plates (Fig. 3a). As shown in Fig. 4, the SMAHC plate was not penetrated while the conventional composite plate was at the critical energy level. The impact damage of SMAHC plate at the higher impact energy than critical energy level is shown in Fig. 5. The composite material was totally fractured, however, the SMA wires in the composite plate were not fractured and sustained the impact load after the fracture of the composite materials.

When the impact load is applied to the composite plate it absorbs the impact energy by elastic deformation or plastic deformation or damage. The absorbed energy by the elastic deformation of the composite plate was reduced by bouncing the impactor. The other energy was dissipated by plastic deformation and damage. The plastic deformation of composite materials is hardly caused because of their low toughness. Therefore in these experiments, the

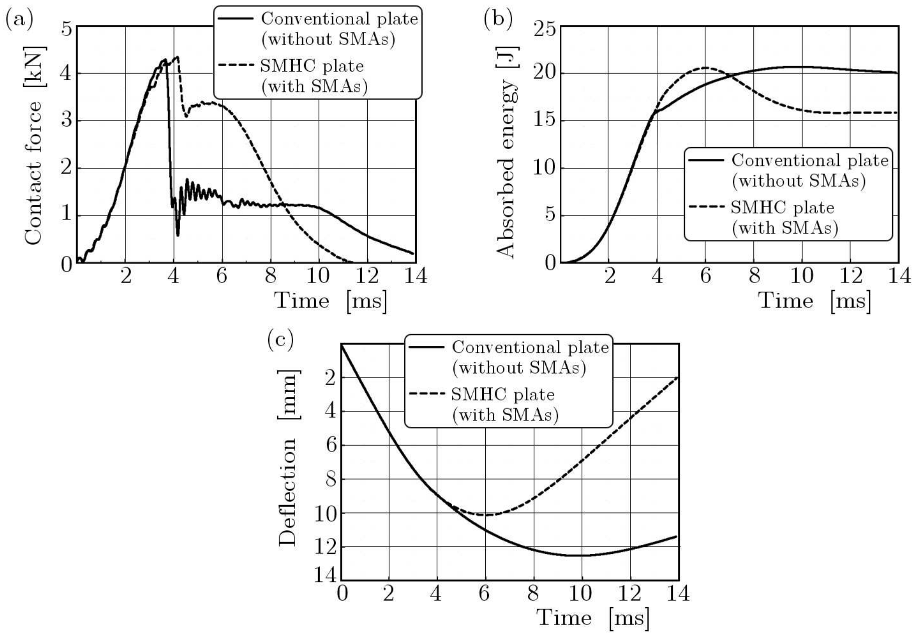

Fig. 3. Results of low-velocity impact tests at critical impact energy (20 J); (a) contact force, (b) absorbed energy, (c) deflection

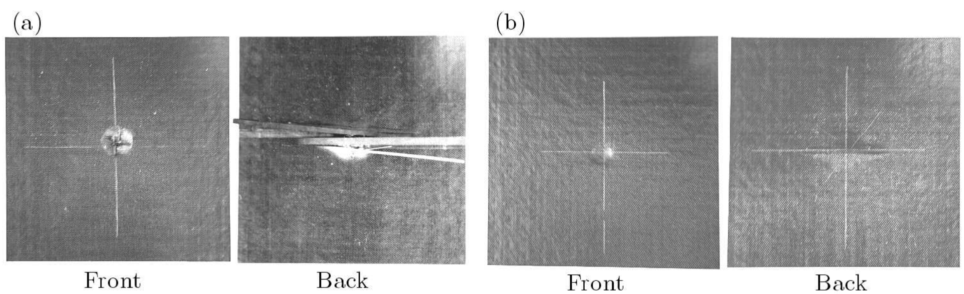

Fig. 4. Specimens after low-velocity impact tests (20 J); (a) conventional composite plate, (b) SMAHC plate

amount of energy causing the damage is much greater than that of the energy causing plastic deformation and almost of the remained absorbed energy contribute to the damage when the response of impact is completed. As presented in Fig. 3b, the absorbed energy of conventional composite plates was hardly reduced, and it means almost of the incident impact energy caused damage. In contrast to conventional composite plates, SMA wires absorbed a large amount of impact energy showing super-elastic behavior. This recovery allowed

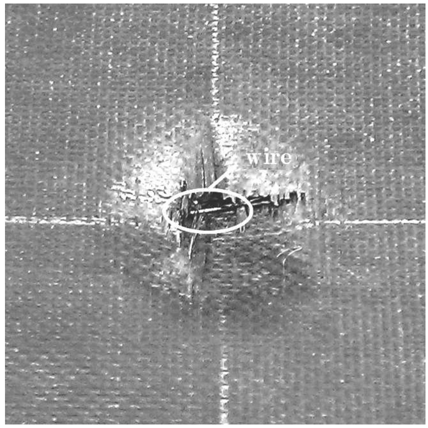

Fig. 5. Impact damage of SMAHC plate

SMAHC plates to bounce the impactor. As a result, the energy causing the damage was reduced, as was the damage to SMAHC plates.

Based on deflection diagrams (Fig. 3c), SMAHC plates deflected less than conventional composite plates, but this amount was not significant. However, the deflection of SMAHC plates recovered much more than it did with conventional plates, nearly recovering to its original shape. This large recovered deflection of SMAHC plates was due to small damage regions compared with conventional composite plates and the recovery stress generated by SMA wires. SMA wires have the large failure strain up to 14% and around 10% of the strain can be recovered generating a large recovery stress. Therefore, if the local strain at the damaged region is not reached to the failure strain, SMA wire will resist the impact load and generate the large recovery stress. The results of these tests are presented in Table 3.

Table 3. Results of low-velocity impact tests (20 J)

		Conventional composite plate	SMAHC plate
Max. contact force		4.36 kN	4.40 kN
Max. contact force after incipient damage occurs		1.47 kN	3.80 kN
Reduced energy		0.59 J (2.86%)	2.75 J (13.40%)
Deflection	Maximum	12.51 mm	10.04 mm
	Recovery	0.84 mm (6.74%)	9.02 mm (89.84%)

In the second case, specimens fractured at the critical impact energy of 7 J. Embedding a small amount of SMA wires into the composite plate did not much affect the maximum contact force. However, the contact force of SMAHC plates after fracture was greater, reduced energy was greater, deflection was smaller and recovered deflection was greater than those of conventional composite plates (Fig. 6). As Fig. 7 shows, conventional composite plates were damaged more than SMAHC plates but it is difficult to compare the damage extent. Therefore C-scan was additionally performed to investigate the damage area. Comparing the figures of C-scan, it is easier to confirm the smaller damage area of SMAHC plate (Fig. 8). The damage area of the conventional composite plate was 1.68 times bigger than that of SMAHC plates. The results are presented in Table 4.

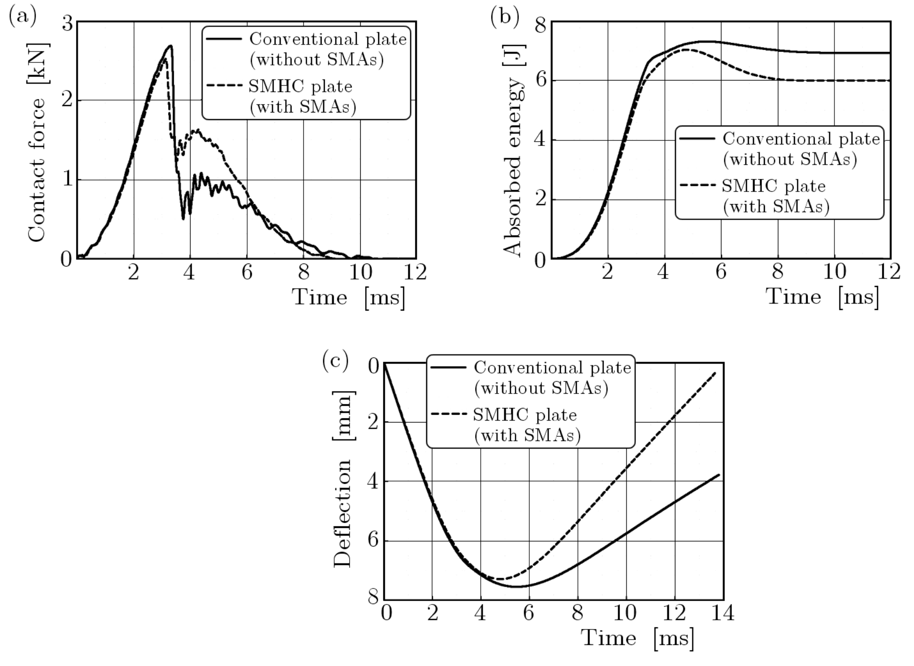

Fig. 6. Results of low-velocity impact tests at critical impact rnergy (7 J); (a) contact force, (b) absorbed energy, (c) deflection

Compared to conventional composite plates, for these reasons, embedding SMA wires can improve the impact resistance of composite materials.

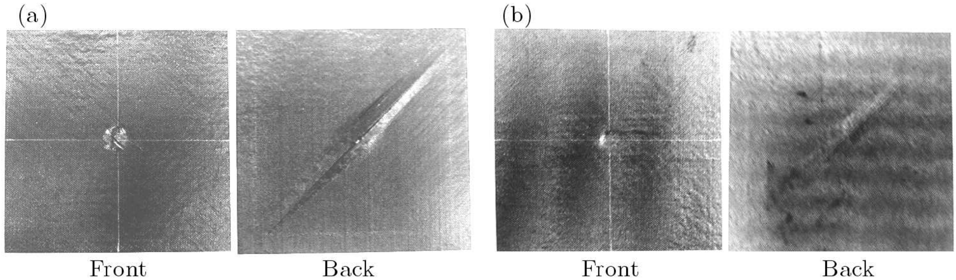

Fig. 7. Specimens after low-velocity impact tests (7 J); (a) conventional composite plate, (b) SMAHC plate

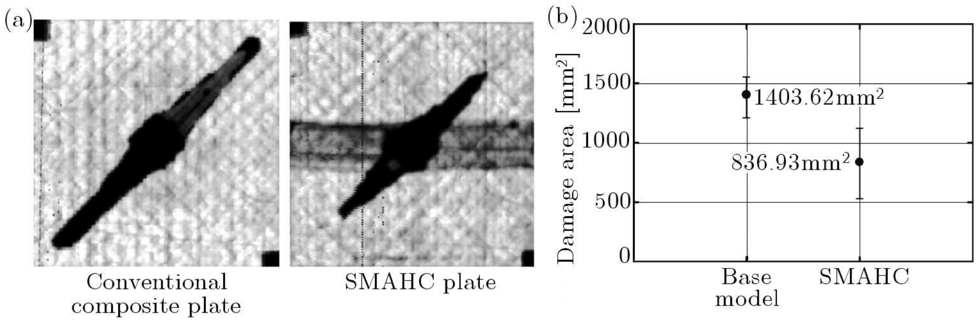

Fig. 8. C-scan results of specimens (7 J); (a) figure of damage area, (b) damage area

Table 4. Results of low-velocity impact tests (7 J)

		Conventional composite plate	SMAHC plate
Max. contact force		2.70 kN	2.48 kN
Max. contact force after incipient damage occurs		1.00 kN	1.60 kN
Reduced energy		0.32 J (4.38%)	1.17 J (16.04%)
Deflection	Maximum	7.46 mm	7.29 mm
	Recovery	3.39 mm (45.48%)	6.64 mm (91.04%)
Damage area		1403.62 mm^2	836.93 mm^2

3.2. low-velocity impact tests with different embedded materials

low-velocity impact tests of SMAHC plates, conventional composite plates, and composite plates with embedded iron (Fe) or aluminum (Al) wires were performed to compare the effects of embedding SMA wires and other materials.

3.2.1. Conditions and procedure

These tests were performed at room temperature, and the incident impact energy was 10 J, which is over the critical energy. The same equipment used in the previous impact tests was used here as well.

The stacking sequence of the conventional composite plates was $[45°/-45°/90°/0°]_S$. SMA wires (SE508) and pure iron (Fe) or aluminum(Al) wires 0.2 mm in diameter were embedded into conventional composite plates. The wires were embedded using the same stacking sequence as used in the second case in the previous impact tests. Therefore, the volume fraction and thickness were also identical to those of the previous specimens.

3.2.2. Results and discussions

All specimens fractured at 2-3 ms, after the contact force was suddenly decreased, similar to the results of the previous impact tests. The sustainable force after a fracture occurred was slightly different depending on the type of specimen. Conventional composite plates and composite plates with embedded Fe/Al wires showed a similar tendency in terms of the contact force after the fracture occurred. This shows that embedding Fe/Al wires into a composite plate does not improve the impact resistance, whereas SMAHC plates could withstand more contact force than the other types of specimens after the damage occurred. Based on the absorbed energy diagrams, conventional composite plates and composite plates with embedded Fe/Al wires show a similar tendency and almost amount of the incident impact energy was used to cause damage. On the other hand, SMAHC plates absorbed a large amount of the impact energy and then recovered. Hence, the energy causing damage was decreased. Deflections of conventional composite plates and composite plates with embedded Fe/Al wires increased continuously as they were penetrated. In contrast, SMAHC plates deflected less and recovered more than the other specimens. It was possible to confirm the damage of specimens because conventional composite plates and composite plates with embedded Fe/Al wires were penetrated, whereas SMAHC plates did not. To compare the damage area of them more quantitatively, C-scan was done. However, the average value of the damage area of SMAHC plates were smaller than in other specimens (Fig. 9, Table 5).

Based on contact force, absorbed energy, deflection and damage area, embedding SMA wires is more effective than using other materials such as iron (Fe) and aluminum (Al) to improve the impact resistance of composite materials.

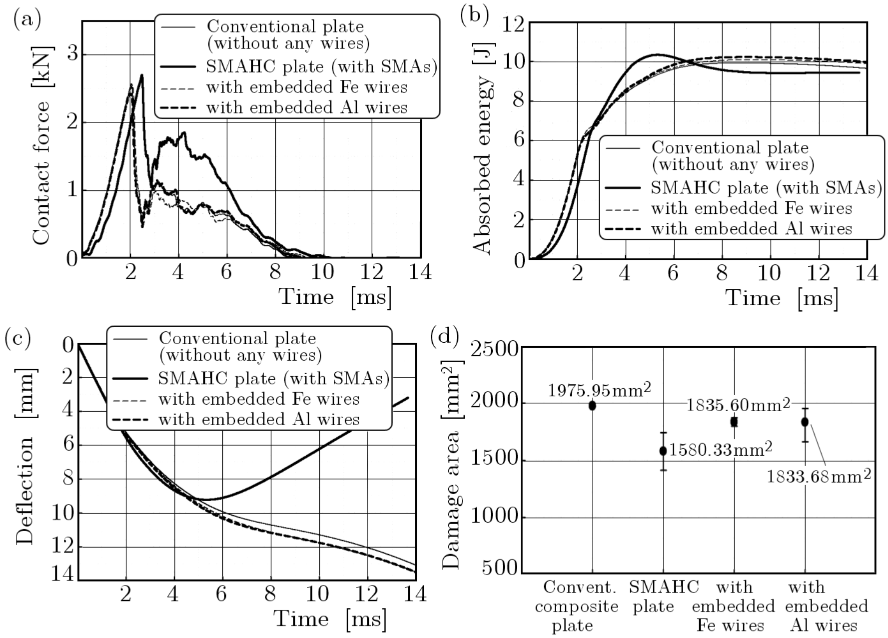

Fig. 9. Results of low-velocity impact tests for different embedded materials; (a) contact force, (b) absorbed energy, (c) deflection, (d) damage area

Table 5. Results of low-velocity impact tests for different embedded materials

		Convent. composite plate (penetrated)	SMAHC plate	Fe (penetrated)	Al (penetrated)
Max. contact force		2.89 kN	2.65 kN	2.76 kN	2.61 kN
Max. contact force after incipient damage occurs		0.85 kN	1.82 kN	1.04 kN	1.09 kN
Reduced energy		0.37 J (3.68%)	0.85 J (8.27%)	0.27 J (2.79%)	0.35 J (3.48%)
Deflection	Maxim.	13.78 mm	9.26 mm	13.02 mm	13.26 mm
	Recovery		5.78 mm (62.38%)		
Damage area		1975.95 mm^2	1580.33 mm^2	1835.60 mm^2	1833.68 mm^2

3.3. Low-velocity impact tests for different position of embedded SMA wires

To confirm the effect of embedding position and to improve impact resistance more effectively by changing the position, several types of specimens with different embedded wires positions were fabricated and low-velocity impact tests were performed.

3.3.1. Conditions and procedure

These impact tests were done at room temperature, and the incident impact energy was the critical one, 18 J. The same equipment used in the previous impact tests was also used here.

The stacking sequence was $[90°/0°_2/90°_2/0°]_S$, and wires were embedded at different positions in the thickness direction. They were placed in the center layer and off from the center layer at either 1/6 or 5/6 of the distance through the thickness of the plate (Fig. 10). SMA wires were embedded parallel to the fiber direction between the 0° plies at the center region with a width of 20 mm. The thickness was 1.436 mm and the volume fraction was 4.50%.

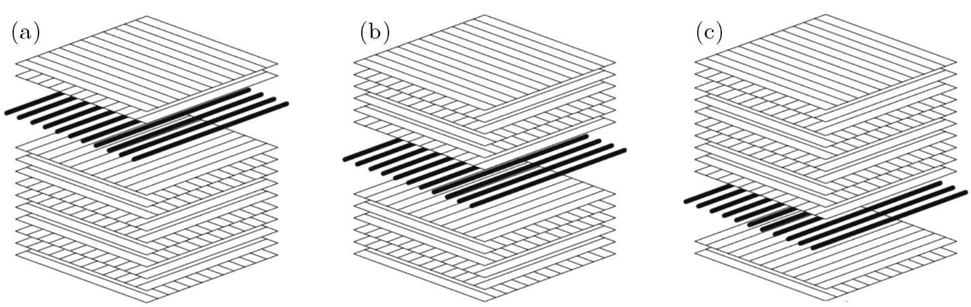

Fig. 10. Different positions in the thickness direction; (a) 1/6 from the top surface, (b) 3/6 from the top surface, (c) 5/6 from the top surface

3.3.2. Results and discussions

After fracturing, the contact force of SMAHC plates with embedded SMA wires in the upper layer (1/6) and the center layer (3/6) showed similar results. However, SMAHC plates with embedded SMA wires in the lower layer (5/6) sustained more contact force than the other specimens. The absorbed energy of plates with embedded SMA wires in the lower layer (5/6) showed a greater decrease compared to the others. This indicates that the absorbed energy causing damage was reduced by embedding SMA wires in the lower layer and it made the damage smaller. The deflection diagram also shows the effect of the embedding position. After the impact load was applied, the plates with SMA wires embedded in the lower layer (5/6) deflected less and recovered more than the other specimens. These results, based on the contact force, absorbed energy and deflection, demonstrate that embedding SMA wires at a lower position near the back face can improve the impact resistance more efficiently compared to other positions. When an impact load is applied to specimen, the specimen is bent and the most tensile deformation is occurred at the bottom of that. SMA wires can absorb the impact energy most effectively when large deformation is occurred, therefore the embedded wires near from the bottom absorb the impact energy most effectively. Results of tests are presented in Fig. 11 and Table 6.

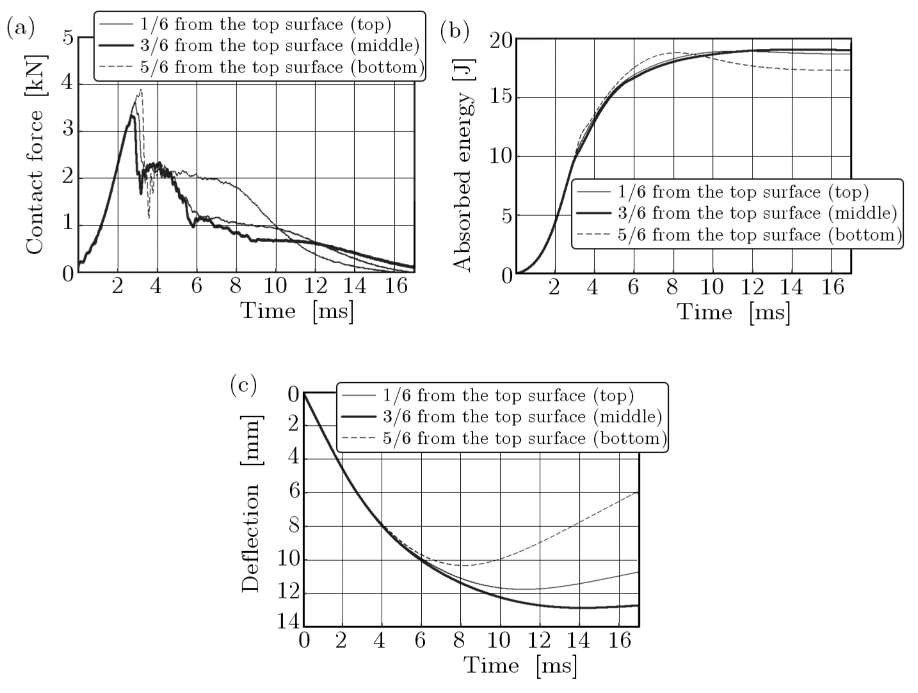

Fig. 11. Results of low-velocity impact tests for different position of embedded SMA wires; (a) contact force, (b) absorbed energy, (c) deflection

Table 6. Results of low-velocity impact tests for different position of embedded SMA wires

		1/6 from the top surface	3/6 from the top surface	5/6 from the top surface
Max. contact force		3.64 kN	3.34 kN	3.89 kN
Reduced energy		0.24 J (1.27%)	0.03 J (0.16%)	1.49 J (7.93%)
Deflection	Maximum	11.77 mm	12.85 mm	10.34 mm
	Recovery	1.04 mm (8.84%)	0.14 mm (1.09%)	4.44 mm (42.94%)

4. Conclusions

Tensile tests of SMA wires were performed to investigate the characteristics of SMAs as a preliminary test to improve the impact resistance. SMA wires have large failure strain and stress with superelasticity.

Several low-velocity impact tests were then performed to assess the effects of embedding SMA wires and to improve impact resistance using the energy absorbing ability of SMAs due to superelasticity of this material. In the first test, the effects of embedding SMA wires were confirmed by comparing a SMAHC plate with a conventional plate using two types of specimens at the critical impact energy level. The effect of the type of embedded materials, in this case none, SMAs, iron (Fe), aluminum (Al), was confirmed in the second test. SMAHC plates sustained contact force better and absorbed less energy causing damage than the other specimens after the damage occurred. It was also found that the deflection was less and the recovery was greater compared to the other specimens. These results demonstrate that embedding SMAs can improve the impact resistance of composite materials. In the third test, specimens with embedded SMA wires at different positions, 1/6, 3/6 and 5/6, were tested to investigate effects of the embedding position. The results showed that embedding SMA wires at a lower position near the back face of plates can improve the impact resistance more effectively compared to other positions.

Through several tests, the superiority of SMAs was demonstrated to improve the weak impact resistance of a composite material.

Acknowledgements

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Niskoprędkościowe charakterystyki uderzeniowe płyt kompozytowych zawierających włókna ze stopów z pamięcią kształtu

Streszczenie

Do analizy charakterystyk uderzeniowych hybrydowych kompozytów SMAHC zwierających włókna SMA ze stopów wykazujących efekt pamięci kształtu przeprowadzono szereg badań eksperymentalnych. Przeprowadzono próby na rozciąganie włókien SMA w celu zbadania ich właściwości termomechanicznych oraz niskoprędkościowe testy uderzeniowe płyt SMAHC oraz konwencjonalnych płyt laminowanych przy energii krytycznej. Wykonano także testy dla płyt kompozytowych zawierających włókna SMA/Fe/Al. Rezultaty doświadczeń pokazały, że wbudowanie w strukturę laminatu włókien SMA może zwiększyć odporność kompozytu na obciążenie uderzeniowe. Opisano również badania eksperymentalne płyt SMAHC z włóknami SMA wbudowanymi na różnej głębokości. Wykazano, że najlepsze parametry posiadają kompozyty z włóknami umieszczonymi możliwie daleko od uderzanej powierzchni.

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