The Study of Impact Properties of UDF/epoxy Composites with Shape Memory Alloy Wires (SMAs) under Low Velocity Impact

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ABSTRACT

The objective of this investigation is to study the impact properties of unidirectional glass fiber (UDF) reinforced epoxy laminates with shape memory alloy wires (SMAs) inserted. The SMAs/GF/epoxy laminates are manufactured with vacuum assisted resin injection (VARI) process. Then, the low velocity impact tests of such laminates were conducted at room temperature. The experimental result shows that the impact properties of laminates can be improved by embedding SMAs which may be due to the super-elasticity capacity of shape memory alloy wires (SMAs). The position of SMAs insertion has an effect on impact properties of composites, and the laminate with the ply code $[90^o/0^o/SMAs/(90^o/0^o)_7]$ *and* $[(90^o/0^o)_4/SMAs/(90^o/0^o)_3/90^o/SMAs/0^o]$ *have the best impact properties.*

KEYWORDS: *Low velocity impact, Critical energy, SMAs, UDF/epoxy composites, VARI process*

1. INTRODUCTION

Composite structures have been used extensively in various fields, such as aerospace and marine applications, due to their high strength, high stiffness and light weight. They are easily subjected to the low velocity impact and appear invisible damage[1]. Their impact properties are affected by many factors, such as the types of impactor and the composition of fabricated composites, etc.

Some researchers studied the responses of different specimens subjected to low velocity impact with various impactors. Mitrevski et al.[2-4] investigated the effect of impactor shape on the impact response and conducted a post-impact analysis for carbon/epoxy laminates under low velocity impact. They found only the hemispherical impactor at an initial impact energy of 4J produced barely visible impact damage (BVID) whereas the other impactor

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shapes produced permanent indentation and penetration. Zhou [5] studied thick glass-fiber-reinforced laminates of various dimensions subjected to low-velocity impact with a flat-ended impactor. They found delamination and fiber shear-out. Fiber fractures are found to be the predominant damage mechanisms in absorbing incident kinetic energy and controlling the load-bearing capabilities of the laminates.

Besides, some researchers have also studied the impact properties of composites having inserted SMAs. Pappadà et al.[6] investigated the influence of SMA wires with the diameter of 0.1mm and the volume fraction of 1% on the damage tolerance of glass fiber reinforced composites with stacking sequence of [0°, W_0, 90°, W_{90}, 0°, 90°, 0°]$_s$. Their experimental results show SMA wires are capable to improve the damage tolerance of glass fiber reinforced laminates, and SMA hybridized samples show a decreased extension of the damage area under low energy impact, especially the energies below 10J. Raghavan et al.[7] manufactured unidirectional super elastic SMA fiber reinforced composites. The results demonstrated the potential of embedding SMA fibers in composites for passive damping of low amplitude vibrations as well as enhancing toughness. Kang et al.[8] identified the effect of shape memory alloy on damage behavior and residual properties of composite laminates subjected to low-velocity impact at low temperatures. They found that the impact damage behavior of the base laminates was slightly affected by the temperature and the SMA laminate was more affected by the temperatures. Lau et al.[9] studied experimentally and theoretically the damage resistance properties of SMA stitched glass/epoxy composites with different wire interval spacings of 20 mm and 12 mm after low velocity impact. The results revealed that the delamination energy of composite plates after stitching super elastic SMA wires is smaller, and the damage also decrease. Tsoi et al.[10] studied the influence of the pre-strain, volume fraction and the position of SMAs on the impact behavior of composite laminates. It was found that the damage area decreases with the pre-strain increasing. For higher impact energy of around 18 J, 1.8% volume fraction of wires produces the best results. The impact damage resistance improved when the SMAs were stitched along the bottom layer of specimen. Paine et al.[11] studied the impact response of SMA hybrid composite material. The impact test results show that the impact resistance of the hybrid composite materials with the SMA fibers was increased, and composite-ply delamination was reduced as much as 25%. According to above analysis, we concluded that embedding SMAs into composites can effectively improve the impact properties of hybrid composites, and this is consistent with the result of Aurrekoetxea J. et al.[12]. The reason of improving the impact properties is due to the high dissipative energy and high recovery stress characteristics in SMA recovery process. However, studies on glass fiber reinforced composites from the viewpoint of the critical energy is relatively seldom, especially about the composites with SMAs inserted.

The aim of this paper is to study the impact properties of unidirectional glass fiber (UDF) epoxy laminates with shape memory alloy wires (SMAs) inserted from the viewpoint of the critical energy. Firstly, we manufactured the specimens by vacuum assisted resin injection (VARI) process. Then, we carried out the low velocity impact experiments.

2. EXPERIMENTAL PREPARATIONS

2.1. Materials and manufactures

The shape memory alloy is adopted 55.9wt.% Ni-Ti SMAs with 0.2mm of diameters and bright of surface state (Fig.1a), produced by Jiangyin Fasten-PLT Materials Science Co., Ltd (Pelertech), Jiangsu, P. R. China. The specific properties of the SMAs are shown in Table 1. Other reinforced material is unidirectional glass fiber (EDW800) cloth, which is shown in Fig.1b. The thickness of each layer of UDF cloth is 0.2mm, and the surface density of UDF cloth is 200g/m^2. The matrix in this experiment is epoxy vinyl ester resin (VER) 411. The resin can be cured at room temperature after adding 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 hardening agent and accelerating agent at mass ratio of 100:1.5:0.15. Fig.1c is the resin comparison schematic diagram before adding and after adding hardening agent and accelerating agent.

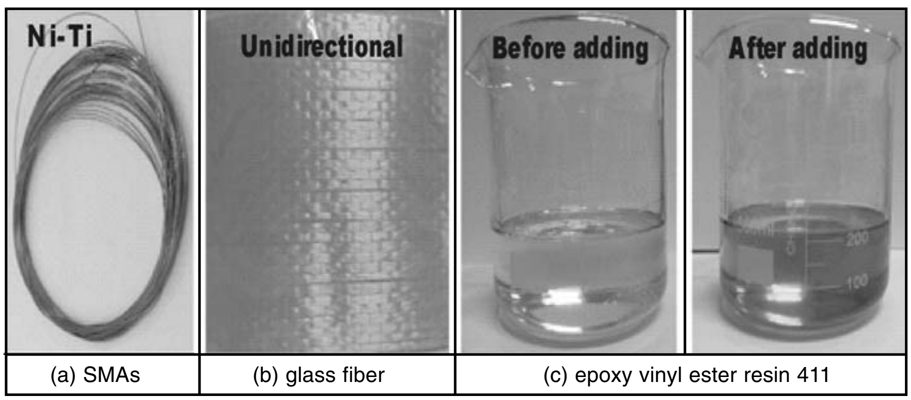


Fig. 1. The materials of composite laminates.

TABLE 1. The properties of shape memory alloy wires (Ni-Ti).

Diameters (mm)	A_f for Delivery (°C)	Upper Plateau Stress (MPa)	Tensile Strength (MPa)	Elongation (%)	Residual Elongation (%)
0.20±0.005	10	598.86	1559.90	12.56	—

The UDF/epoxy laminates with SMAs are fabricated by vacuum assisted resin injection (VARI) process. During the VARI process, a glass square plate is placed at the bottom as holder, and the specimen is manufactured over it. Firstly, release cloth is evenly coated on mold surface. Then the glass fiber clothes are placed on the release cloth, and the SMAs are inserted in the surface of the glass fiber clothes. Secondly, they are covered with the release cloth and infusion net, and then the laminate is closed by vacuum bag and sealant tape. Thirdly, after the vacuum is drawn, the airtightness of the device should be checked. Fourthly, after ensuring that the device does not leakage, the mixture resin is infused in the vacuum device by infusion port. The system is cured at room temperature and vacuum level of 600 mbar for 12 h, and then the laminates are made. The UDF/epoxy laminates with SMAs inserted are comprised of SMAs, unidirectional glass fiber and epoxy resin. The ply modes of UDF/epoxy laminates with SMAs (stacking sequence from top to bottom) inserted are $[90°/0°]_8$, $[90°/0°/SMAs/(90°/0°)_7]$, $[(90°/0°)_7/90°/SMAs/0°]$, $[90°/0°/SMAs/(90°/0°)_6/SMAs/90°/0°]$, $[(90°/0°)_4/SMAs/(90°/0°)_3/90°/SMAs/0°]$, as demonstrated in Fig.2. The 0°, 90° are the ply angles

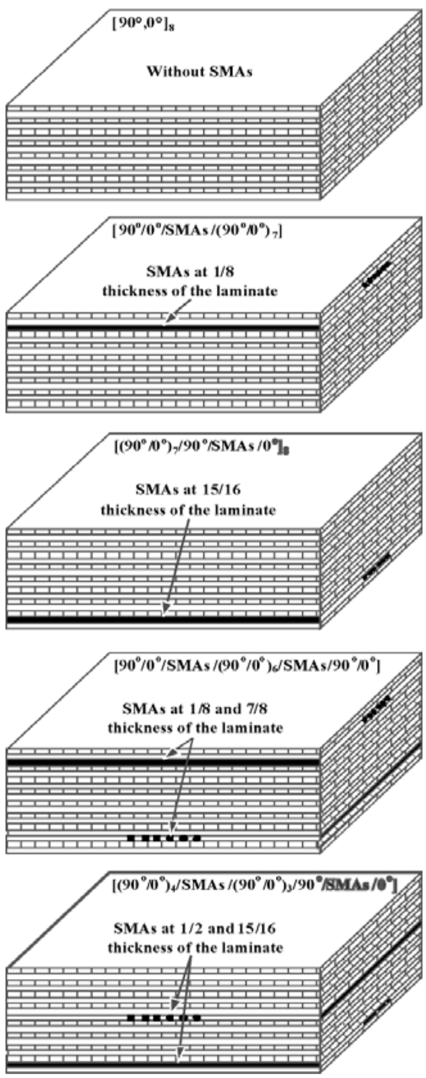


Fig. 2. The schematic diagram of unidirectional glass fiber laminates.

of glass fiber, and the direction of SMAs is parallel to the 0° direction of the glass fiber, and there are a total of 16 layers in the composite laminates. The ply modes indicate respectively the laminate without SMAs inserted, the laminates with one layer of SMA inserted in 1/8 thickness of specimen, the laminates with one layer of SMA inserted in 15/16 thickness of specimen, the laminates with two layers of SMAs inserted in 1/8 and 7/8 thickness of specimen, the laminates with two layers of SMAs inserted in 1/2 and 15/16 thickness of specimen. The theoretical average thickness value of UDF/epoxy laminates with SMAs inserted is 3.2mm.

The weight percentage of SMAs and Glass fibers in various specimens are listed in Table 2. For the laminate without SMAs inserted, the weight percentage of SMAs and glass fiber clothes in UDF laminates are 0 and 72.51%, respectively. For the laminates with one layer of SMAs inserted, the weight percentage of SMAs and glass fiber clothes in UDF laminates are 2.08% and 71.01%, respectively. For the laminates with two layers of SMAs inserted, the weight percentage of SMAs and glass fiber clothes in UDF laminates are 4.07% and 69.55%, respectively.

2.2. Test device and details

In this paper, we adopt the Instron Dynatup 9250HV Drop Weight Impact Testing Machine to conduct the low velocity impact test according to ASTM D7136-2007. Fig.3 shows the plane view of impact specimens. Fig.4 shows the Dynatup 9250HV machine, which is composed of a pneumatic clamping fixture and a data acquisition system. We adopt two types of impactors. To make it more convenient to express, we named them as impactor 1 and impactor 2, respectively, as seen in Fig.5. The impactor 1 is consist of steel nose with diameter 14mm and steel bar with diameter 14mm. The impactor 2 is consist of steel nose with diameter 14mm and steel bar with diameter 8mm. The total impact weight in all tests is 8kg. The diameters of two circular rings with clamp are 76mm. The initial velocity (V_i) of the impactor is set as 4 m/s, and the impact kinetic energy (E_i) is 64J as calculated by Newton's law: $E_i = 0.5mV_i^2$, respectively.

TABLE 2. The weight percentage of SMAs and Glass fibers in various specimens.

Laminates	SMAs (wt.%)	Glass fiber (wt.%)	Total mass (g)
Without SMAs inserted	0	72.51	47.15
One layer of SMAs inserted	2.08	71.01	48.51
Two layers of SMAs inserted‘	4.07	69.55	49.16

3. RESULTS AND DISCUSSIONS

3.1. The effect of the impactor on the critical energy under low velocity impact

Firstly, we conduct the low velocity impact test adopted impactor 1 for laminates without SMAs inserted, and their code are A1, A2 and A3, respectively. Then, the low velocity impact test adopted impactor 2 for laminates without SMAs inserted are performed, and their code are A4, A5 and A6, respectively. In these experiments of adopting impactor 1, we often find that the critical energy has larger deviation for the same specimen under perforated condition. Therefore, we adopt two types of impactors in this paper. The purpose of these tests is to compare the effect of impactor on

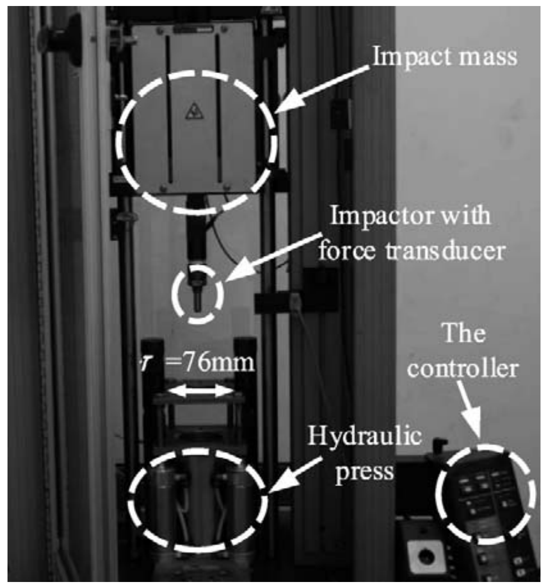


Fig. 4. Instron Dynatup 9250HV Drop Weight Impact Testing Machine.

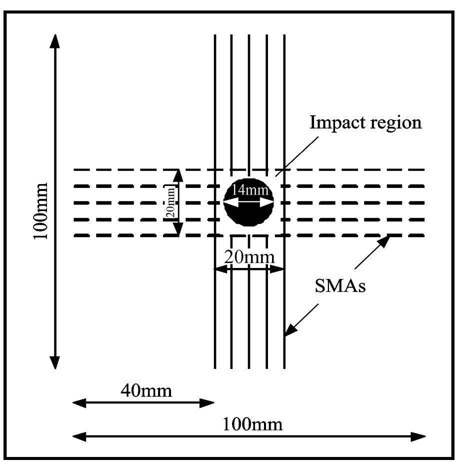


Fig. 3. The plane view of impact specimens.

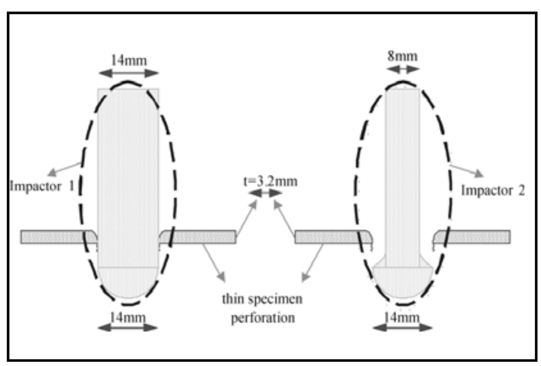
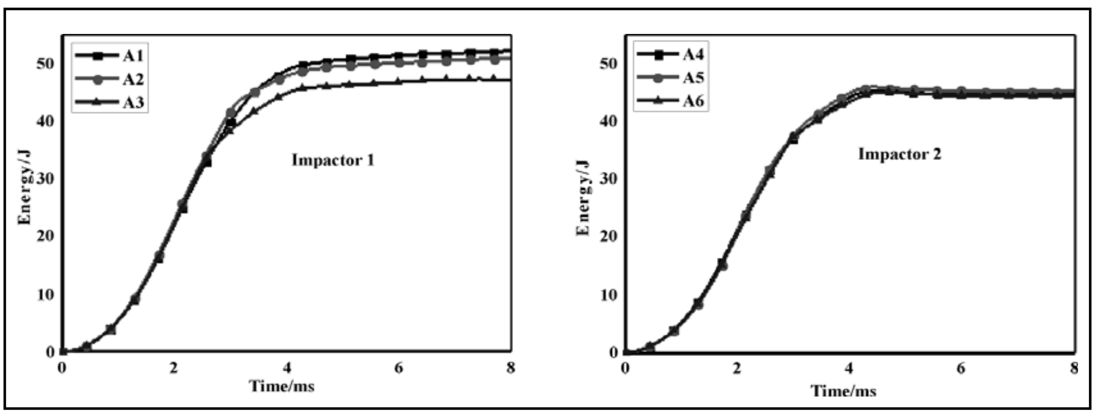


Fig. 5. The schematic diagram of impactors.

critical energy under low velocity impact. The energy-time curves of specimens subjected to low velocity impact are shown in Fig.6. It is found that the critical energy reaches a maximum and remains nearly constant. In Fig.6a, the values of critical energy of the three laminates without SMAs inserted are different. However, in Fig.6b, the values of critical energy of the three laminates without SMAs are almost same. To clearly state the difference, the specific values of the critical energy of specimens are listed in Table 3, and the deviation of critical energy of specimens are listed in Table 4. From the Table 4, we find that for the condition adopted impactor 1, the deviation of critical energy among three specimens are 2.90%, 10.84% and 7.72%, respectively. For the condition of adopted impactor 2, the deviation of critical energy among three specimens are 1.29%, 0.66% and 1.96%, respectively.

The reason for this phenomenon may be for the condition adopted impactor 1, the critical energy not only includes the energy absorbed by specimen, also includes the energy obtained by the friction between impactor bar and specimen. However, for the condition adopted impactor 2, there may be only includes the energy obtained by the friction between impactor bar and specimen. That is, there is two sources to obtain the critical energy under impact adopted impactor 1, and there is only one source to obtain the critical energy under impact adopted impactor 2. This result is consistent with that of Belingardi et al.[13], which indicate the growing energy further is due to the friction of the perforation hole edges



(a) Impact adopted the impactor 1 (b) Impact adopted the impactor 2

Fig. 6. The energy-time curves of a number of specimens subjected to low velocity impact with energy value 64J.

TABLE 3. The critical energy of UDF reinforced laminates without SMAs inserted under impact.

Critical energy (J)	A1	A2	A3	A4	A5	A6
Impactor 1	52.3828	50.9089	47.2587	—	—	—
Impactor 2	—	—	—	45.3394	45.9242	45.0414

TABLE 4. The deviation of critical energy of specimens.

	A1-A2	A1-A3	A2-A3	A5-A4	A4-A6	A5-A6
Deviation (%)	2.90	10.84	7.72	1.29	0.66	1.96

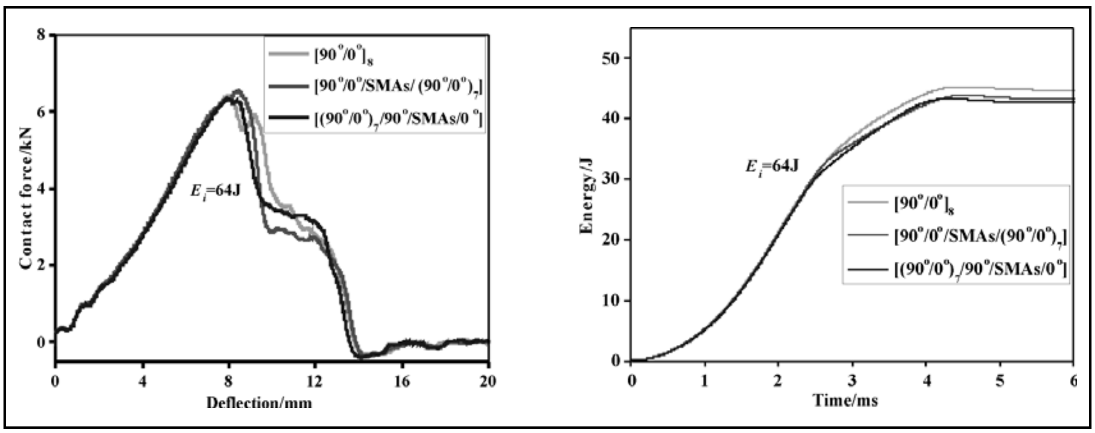
against the lateral surface of bar. The friction is different under different external condition, therefore, the values of energy under impact adopted impactor 1 often produce error. Comparing to the condition adopted impactor 1, the condition adopted impactor 2 does not consider this problem. Next, we conduct the low velocity impact tests adopted impactor 2 for the composite laminates with SMAs inserted.

3.2. The impact properties of UDF/epoxy laminates with one layer of SMAs

As is known, contact force [14] and energy are two important parameters to analyze impact process and access damage of composite laminates under low velocity impact. The contact force can be obtained by a data acquisition system, and absorbed energy can be calculated by the integration for contact force versus deflection curves. The absorbed energy is the energy absorbed by the composite specimen through the impact event by formation of damage inside specimen[15]. Fig.7 shows the contact force versus deflection (*F-D*) curves and energy versus time (*E-T*) curves of UDF/epoxy laminates with one layer of SMAs inserted under low velocity impact of energy value 64J. From the curves, we can know the *F-D* curves are open, and the three specimens were completely perforated. After unloading, the force remains nearly zero, which imply there is no contact between the impactor and specimen. It is also found that the *F-D* curves of three specimens are all mountain-like shapes, and there are increase firstly and then decrease. The peak force of three specimens have no significant different, however, the *F-D* curve of laminate without SMAs inserted drops suddenly then rises slightly after reaching peak force. This indicates that there has a momentary contact loss between impactor and specimen, which may be due to the fiber fracture of specimen under impact, and the external force exceeds the maximum load bearing capacity of the laminate. Compared to the condition of without SMAs, drop suddenly did not occur in the *F-D* curve of laminate with SMAs inserted. That is, from the viewpoint of contact force, embedding one layer of SMAs into laminates can effectively improve the load bearing capacity of the laminate.

Next, we analyze the impact properties from the viewpoint of critical energy. From the *E-T* curves in Fig.7b, we can find that the laminate without SMAs inserted has higher critical energy than the laminate with SMAs inserted. The critical energy of the laminates with ply modes of [$90°/0°$/SMAs/$(90°/0°)_7$] and [$(90°/0°)_7$/$90°$/SMAs/$0°$] have no significant different. In impact event, the impact energy is transformed by elastic deformation energy and plastic deformation energy, and the permanent damages and deformations of specimens are related to the plastic deformation energy. Ma et al.[16] illustrated that the higher the absorbed energy, the greater the damage occurred. From this point, we can conclude that the laminate with ply mode of $[90°/0°]_8$ has larger damage, and the laminates with ply modes of $[90°/0°/SMAs/(90°/0°)_7]$ and $[(90°/0°)_7/90°/SMAs/0°]$ have smaller damage. That is, under perforation, the higher the critical energy values of specimen, the greater the damage.

The values of peak force and the critical energy of SMAs/UDF/epoxy laminates obtained in Fig.7 are listed in Table 5. As seen in the table, the laminate of ply mode $[90°/0°/SMAs/(90°/0°)_7]$ has the largest peak force with value of 6.5688kN and smaller critical energy with value of 43.8837J. The laminate of ply mode $[(90°/0°)_7/90°/SMAs/0°]$ has the smallest peak force with value of 6.3603kN and smallest critical energy with value of 43.3652J. The laminate of ply mode $[90°/0°]_8$ has the smaller peak force with value of 6.4438kN and largest critical energy with value of 45.3394J. That is, the laminate of ply mode $[90°/0°/SMAs/(90°/0°)_7]$ has greater load bearing capacity than the other two. The laminate of ply mode $[(90°/0°)_7/90°/SMAs/0°]$ has smallest damage, the laminate of ply mode $[90°/0°]_8$ has largest damage.



(a) Contact force-deflection (b) Energy-time

Fig. 7. The impact parameters curve of UDF/epoxy laminates with one layer of SMAs under impact with energy value 64J.

3.3. The impact properties of UDF/epoxy laminates with two layers of SMAs

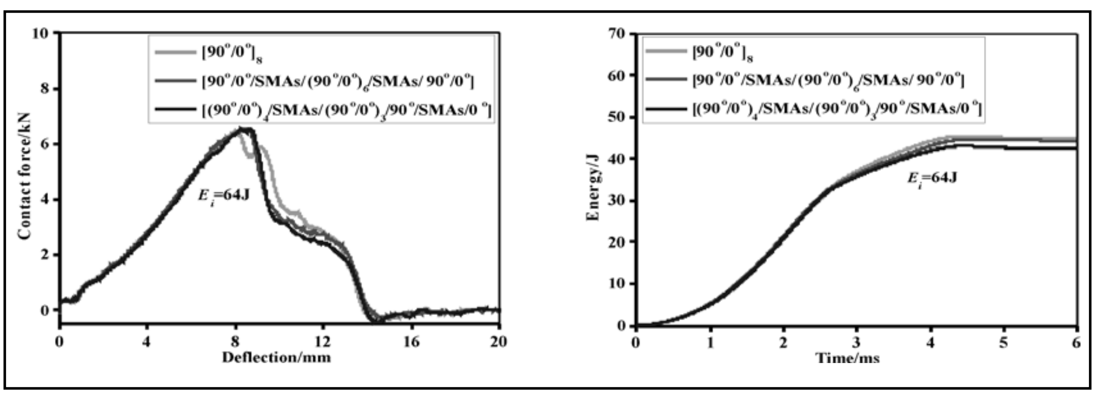
Based on the analysis for the UDF/epoxy laminates with one layer of SMAs inserted, we further study the impact properties of the UDF/epoxy laminates with two layers of SMAs inserted. Fig.8 shows the contact force versus deflection (*F-D*) curves and energy versus time (*E-T*) curves of UDF/epoxy laminates with two layers of SMAs inserted under low velocity impact of energy value 64J. From the curves, we can know the *F-D* curves are open, and the three specimens were also completely perforated. That is, from the viewpoint of contact force, embedding two layers of SMAs into laminates can also effectively improve the load bearing capacity of the laminate. However, from the *E-T* curves

TABLE 5. The values of impact parameters of UDF/epoxy laminates with one layer of SMAs inserted.

Stacking sequence	The peak force (kN)	The critical energy (J)
$[90°/0°]_8$	6.4438	45.3394
$[90°/0°/SMAs/(90°/0°)_7]$	6.5688	43.8837
$[(90°/0°)_7/90°/SMAs/0°]$	6.3603	43.3652

in Fig.8b, we find that the laminates with ply modes of $[90°/0°]_8$ and $[90°/0°/SMAs/(90°/0°)_6/SMAs/90°/0°]$ have nearly equal critical energy. The critical energy of the laminate with ply mode $[(90°/0°)_4/SMAs/(90°/0°)_3/90°/SMAs/0°]$ is lower than the other two. That is, the positions of SMAs inserted into laminate have a certain extent on the impact properties of laminates.

The values of peak force and the critical energy of SMAs/UDF/epoxy laminates obtained in Fig.8 are listed in Table 6. As seen in the table, the laminate of ply mode $[(90°/0°)_4/SMAs/(90°/0°)_3/90°/SMAs/0°]$ has the largest peak force with value of 6.5549kN and smallest critical energy with value of 43.0796J. The laminate of ply mode $[90°/0°]_8$ has the smallest peak force with value of 6.4438kN and largest critical energy with value of 45.3394J. The laminate of ply mode $[90°/0°/SMAs/(90°/0°)_6/SMAs/90°/0°]$ has the smaller peak force with value of 6.5377kN and larger critical energy with value of 44.6725J. That is, the laminate of ply mode $[90°/0°/SMAs/(90°/0°)_7]$ has greatest load bearing capacity and smallest damage. The laminate of ply mode $[90°/0°]_8$ has smallest load bearing capacity and largest damage.



(a) Contact force-deflection (b) Energy-time

Fig. 8. The impact parameters curve of UDF/epoxy laminates with two layers of SMAs under impact with energy value 64J.

TABLE 6. The values of impact parameters of UDF/epoxy laminates with two layers of SMAs inserted.

Stacking sequence	The peak force (kN)	The critical energy (J)
$[90^o/0^o]_8$	6.4438	45.3394
$[90^o/0^o/SMAs/(90^o/0^o)_6/SMAs/90^o/0^o]$	6.5377	44.6725
$[(90^o/0^o)_4/SMAs/(90^o/0^o)_3/90^o/SMAs/0^o]$	6.5549	43.0796

4. CONCLUSIONS

Based on the above analysis, several conclusions can be summarized as follows:

The different impactors have certain extent of effects on the value of critical energy. The value of critical energy obtained by using impactor 2 is more close the actual perforated energy. Embedding SMAs into composites can improve the impact properties of hybrid composites. Except the laminate of $[(90^o/0^o)_7/90^o/SMAs/0^o]$, the peak force of all other laminates are higher and the critical energy of all other laminates are lower than the laminate without SMAs.

The impact properties of composites are affected by the position of SMAs inserted. For the laminate with one layer of SMAs, the ply code $[90^o/0^o/SMAs/(90^o/0^o)_7]$ has the highest load bearing capacity and the smallest damage among the three specimens. For the laminate with two layers of SMAs, the ply code $[(90^o/0^o)_4/SMAs/(90^o/0^o)_3/90^o/SMAs/0^o]$ has the highest load bearing capacity and the smallest damage among the three specimens.

Acknowledgements

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