Shape Memory Alloys (SMAs) based Composites for Automotive Crashworthiness Applications

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Abstract

Smart materials have brought a radical scientific shift in engineering design, mostly for highly functional and lightweight intelligent systems. Shape memory alloys (SMAs) are a class of smart materials with several wide range applications as components of adaptive structures. Due to their capability of crystallographic transformation between austenite and martensite phases, SMAs can undergo large reversible deformations under loading or thermal cycles and generate high thermomechanical driving forces. Integration of SMAs into composite materials has become one of key routes to take advantage of the extraordinary properties of such materials with a reduced cost. In this direction, SMAs in the form of long fibres (wires), ribbons, short fibres, and particles are often used as reinforcements in composites. Automotive applications is considered one of the first massive exploitations using SMA materials. Furthermore, SMAs reinforced polymer composites may offer a multitude of benefits and enormous potentials for automobile and energy-absorbing applications under the dominant role of lightweight materials. However, successful adoption of SMA composites for automotive structural components has yet to be achieved. Within this perspective, this paper represents a review that describes the potentials and possible designs for an automotive crash box and bumper system using SMAs and SMAs-based composites to improve the impact response and energy absorption. A full-structure bumper system is further simulated to illustrate the energy absorption of composite-based SMAs and effect of SMA addition on automotive's crashworthiness.

Keywords: Shape memory alloys (SMAs), Smart composites, Smart structures, Crashworthiness, Automotive

Introduction

Smart materials that can react to external stimuli and undergo changes in their shape, colour, or size have already received significant attention, and can further provide more extraordinary capabilities opening new perspectives for engineering applications [1, 2, 3]. Shape memory alloys (SMAs) belong to such a smart material family. SMAs are metallic materials with their capability to retrieve their original shape, which is induced by their special thermomechanical behaviour and microstructural mechanisms of crystallographic transformation between martensites and austenites [4, 5]. Automotive applications is regarded as one of the major applications using SMA materials. Furthermore, SMAs reinforced polymer composites may offer a multitude of benefits and enormous potentials for automobile and energy-absorbing applications under the dominant role of lightweight materials [6]. However, successful adoption of SMA composites for automotive structural components has not yet been realised. Therefore, this paper reviews and discusses the possibility and potential incorporation of such materials and whether they could effectively enhance vehicle safety and occupant protection. A full-structure bumper system is further simulated using finite element analysis (FEA) to demonstrate the added values of SMA on energy absorption of composite-based SMAs and their effects on automotive crashworthiness.

Shape memory alloys (SMAs) and Crashworthiness

Shape memory alloys (SMAs) are a class of smart materials that possess unique and intriguing properties, making them highly suitable for a wide range of applications. One of their most remarkable characteristics is their ability to sustain large inelastic strains that can be recovered by heating to a certain critical temperature (shape memory effects) or showing pseudoelastic effect during loading/unloading. These distinctive behaviours of SMAs stem from their capability to undergo a reversible crystallographic phase change called martensitic transformation [7], as shown in Figure 1. Owing to this unique thermo-elastic martensite transformation, SMAs exhibit superelasticity (or pseudoelasticity) and shape memory effect (Figure 1), and they have been extensively used in various engineering, aerospace, and biomedical applications [8]. One of the most important representatives class of SMAs is the NiTi alloy which has been widely used in the aerospace, automotive, and biomedical fields due to its excellent functional properties of superelasticity and shape memory effect [9, 10]. Crashworthiness is the ability of materials to absorb impact energy to protect passengers in a vehicle [11, 12]. Integrating shape memory alloy (SMA) into automotive structural components made of composite materials, e.g., crash boxes, bumpers, doors, and frames, could enhance their energy absorption and deformation resistance and ultimately improve crashworthiness. The unique properties of SMA materials, such as their shape memory effect, superelasticity, and good damping properties, can be leveraged to develop advanced energy-absorbing compo that can effectively dissipate the energy generated during a collision, thereby reducing the severity of the impact and minimising the risk of injury to occupants.

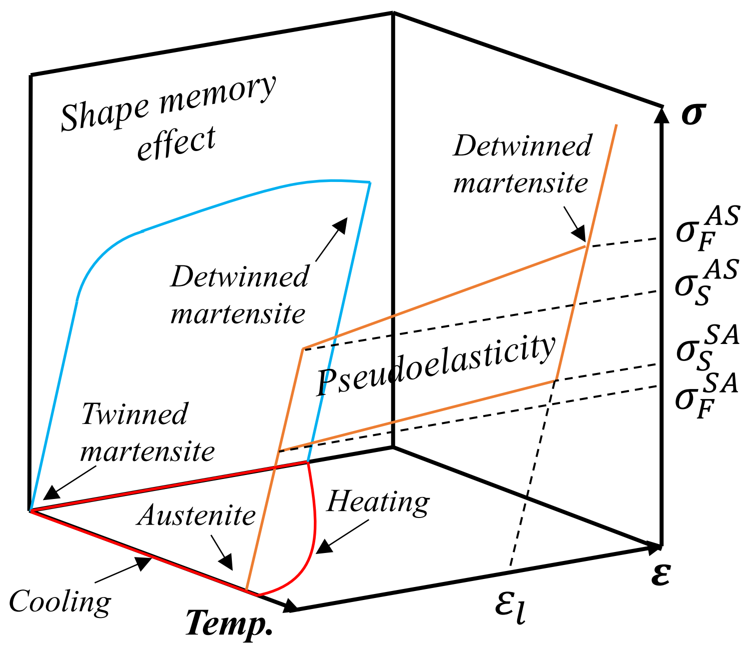


Figure 1: Phase transformation in shape memory alloys

SMA-based Composites for impact and energy absorption applications

A number of experimental and theoretical investigations have been performed on SMA hybrid composite for impact and energy absorption applications, with some of them being focused on experimental investigations and others on numerical simulations. Some others were focused on analytical analysis or a combination of different investigations on the impact properties of SMA hybrid composites.

Examples of experimental studies include Tsoi et al. [13] investigation of the impact damage behaviours of SMA hybrid laminates composites. They focused on the effects of SMA wires' pre-strains and their position and volume fraction. Their investigation revealed that the position and density of SMAs influenced the impact behaviours. Li et al. [14] studied the impact resistance changes of SMA hybrid polymer composites and showed that the inclusion of SMA wires in the hybrid laminates resulted in an enhanced impact response. Kang et al. [15] assessed the behaviour of glass fibre-reinforced polymer (GFRP) laminates which contained embedded SMA wires, and showed that impact damage of composite laminates was predominantly the delamination. Sun et al. [16] examined how the addition of SMA affected the impact response of a polymeric matrix, and analysed the effect of the SMA volume fraction on the impact properties of polymer-based composites. Pappadà et al. [17] investigated impact responses of composite plates containing embedded SMA wires, focusing on low-velocity impacts, and their results indicated that the incorporation of SMA wires could enhance their damage tolerance, particularly at impact energies below 10 J. Furthermore, the impact behaviour and mechanical properties of hybrid composites were examined by Pappadà et al. [18] with a particular focus on the impact of comspites incorporated with thin superelastic SMA wires, and they found that the inclusion of these wires led to an increase in impact strength. They also explored the impact of integrating thin superelastic wires on preventing damage propagation in composite materials [18]. Aurrekoetxea et al. [19] investigated low-velocity impact properties of SMA wires and carbon fibre-reinforced polymer (CFRP), and reported that SMA has a beneficial impact on the maximum absorbed energy as it can withstand higher maximum allowable loads. Rim et al. [20] explored impact characteristics of SMA hybrid composites, and their experimental outcomes demonstrated that incorporating SMAs in composite plates can enhance impact resistance. Additionally, low-velocity impact tests were performed on the hybrid composite plates containing SMA wires embedded at various positions throughout the thickness to further enhance the impact resistance. Eslami-Farsani et al. [21] evaluated the effect of SMA wires on the impact properties of fibre metal laminates and observed specimens with four embedded wires and a 2% pre-strain level showing the most absorbed energy.

An example of analytical investigations, is Khalili et al. [22] study on low-velocity impact response of doubly curved composite panels with embedded SMA wires, and their results obtained from the model analysis indicated that incorporating SMA wires in composite panels had a positive impact on their response to transverse low-velocity impact.
Another numerical study of the low-velocity impact on SMA composite plates was conducted by Meo et al. [23], who investigated the impact damage behaviour of CFRP composite plates embedded with superelastic SAM wires.

Examples of experimental tests with numerical analysis are Meo et al. [24] investigation on the low-velocity impact damage behaviour of SMA-CFRP smart hybrid composite. Their results showed increased damage resistance toughness and absorbed energy levels of composites by embedding SMA wires [24]. Michele et al. [25] analysed and compared the behaviour of SMA composites for aeronautical applications, and showed that SMA composites can improve composite materials' impact response and energy absorption due to the superelastic effect. Xu et al. [26] explored the impact characteristics of GFRP-NiTi SMA laminates and determined the energy thresholds required to cause impact damage in the hybrid composites through numerical simulation. Gupta et al. [27] evaluated the improvement in the damage performance of fibre-reinforced polymer due to the SMA embedment.

Clearly, all the above experimental and analytical studies showed that SMA wires could make composite materials more robust and improve their damage and impact resistance. A summary of SMA-reinforced composites for various impact and energy absorption applications is listed in Table 1.

Applications of SMA-based composites in automotive crashworthiness

SMAs can be used to improve the toughness and damage tolerance of the composite, making it more resistant to impact and deformation during a car crash. SMA-based composites can also be designed to have a higher energy-absorbing capacity than the composites without adding SMAs. This can help reduce the force of impact on the vehicle's occupants. Figure 2 illustrates several potential approaches to incorporate SMAs reinforcement within an automotive cash box. The first approach is to use SMA wires similar to reinforcing fibres in composite materials, as shown in Figure 2 (a). The second one is to use a grid made from a mesh of SMA (Figure 2 (b)), e.g. titanium alloy SMA wires woven into the mesh similar to a carbon fibre-reinforced polymer [28]. Other approach is the utilisation of SMA in a form of strip, as shown in Figure 2 (c). The final idea is to deploy an impact absorber made of SMA for the vehicle crash box, as shown in Figure 2(d).

When onboard sensors detect an imminent collision or hazard, the vehicle's computer uses this data for risk assessment. If risk is high enough, an electrical charge is sent to SMA composite structures embedded throughout the vehicle, which causes the metals to strengthen weak spots. Then, when a crash occurs, the SMA composite structure (e.g. crash box) absorbs the force of the impact. In addition to safety, using SMA reinforcement could help repair deformation from impact, and its stroking force and energy absorption can be adjusted, thus potentially reducing bodywork repair costs. Overall, the use of SMAs composites in automotive crashworthiness has the potential to improve the safety of vehicles and reduce the severity of injuries sustained by occupants during a collision. However, further research and development are needed to optimise the performance and cost-effectiveness of these materials for wide-range applications in the automotive industry.

Table 1: SMA-based Composites for impact and energy absorption applications

Matrix	Reinforcement	Results	Ref
		Experimental studies	
BMI resin	CF/TiNi SMA trigger	SMA trigger provided stable progressive crushing process and a 37.2% increase in the specific energy absorption.	Huang and Wang, 2010 [29]
Epoxy resin	GF/NiTi SMA wires	The embedment of SMA composites resulted in a 72.72% higher ballistic limit and better damage tolerance.	Verma et al. 2021 [30]
		Numerical studies	
Epoxy	CF/Nitinol SMA wires	Embedding SMA wires into composites leads to an increase in the damage resistance of hybrid composite structures.	Meo et al. 2005 [23]
Epoxy	GF/NiTi SMA wires	Modelling of viscoelastic laminates showing good conformance with the experimental results.	Shokrgozar et al. 2021 [31]
Epoxy	CF/Nitinol SMA strips	Embedding SMA strips were effective in improving the impact resistance of composite plates.	Kim et al. 2011 [32]
		Experimental and numerical studies	
PPS	CF/SMA wires	Embedding SMA wires increased the toughness of the composites and energy levels of absorbed energy before failure.	Meo et al. 2013 [24]
Epoxy resin	GF/Nitinol SMA wires	Embedding SMA wires enhance the energy absorption capacity of composite.	Xu et al. 2021 [26]

Epoxy resin	GF/NiTi SMA wires	The SMA wires can improve damage tolerance and impact resistance of GFRP laminates.	Wang et al. 2021 [33]

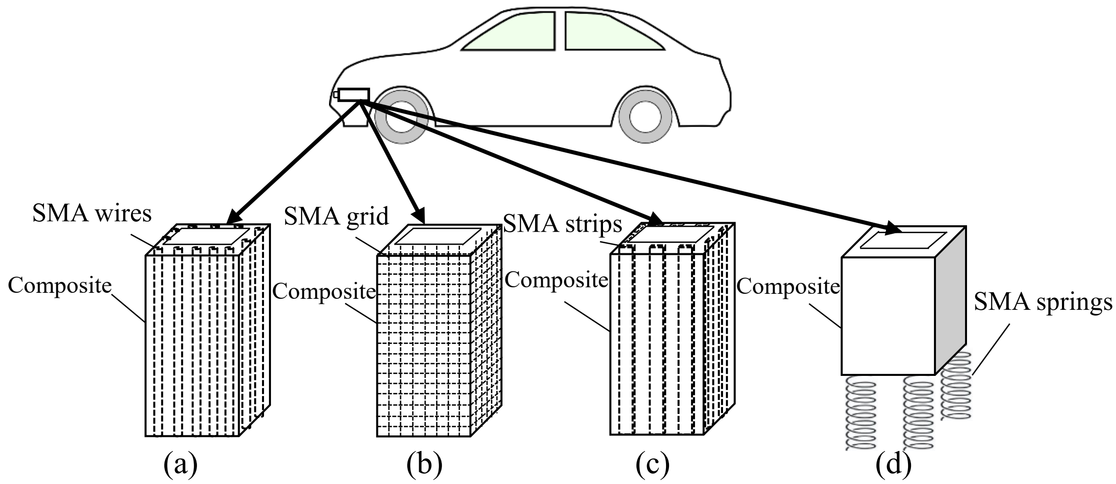


Figure 2: Potential SMA reinforcement integration in the automotive crash box :(a) *SMA wire,* (b) *SMA grid,* (c) *SMA strip reinforced composite and* (d) *SMA coil absorbers*

Demonstration of an SMA based Bumper System

Materials & Methods

Nonlinear finite element simulation with a simplified bumper system model (Figure 3) was performed using the commercial software LS-DYNA® (SMP R12.0.0, LSTC-ANSYS 2020). The model comprises four parts, two crash boxes, a transverse beam and a rigid wall. Three materials were considered here, i.e., the conventional material (mild steel), carbon-fibre reinforced polymer (CFRP) and CFRP-SMA hybrid composite material. The basic mechanical properties are elastic modulus E_{steel} =206 GPa, E^1_{CFRP} =127 GPa, E^2_{CFRP} =8 GPa, E_{SMA} =29.3 GPa, density ρ_{steel} = 7830 kg/m^3, ρ_{CFRP} = 1520 kg/m^3, ρ_{SMA} = 6450 kg/m^3,Poisson ratio ν_{steel} =0.39, ν^{21}_{CFRP} =0.0205, ν_{SMA} =0.33. An 800 kg mass was rigidly attached to the wall in order to simulate the vehicle mass and allowed to move with an initial velocity of 20 mph toward the bumper.

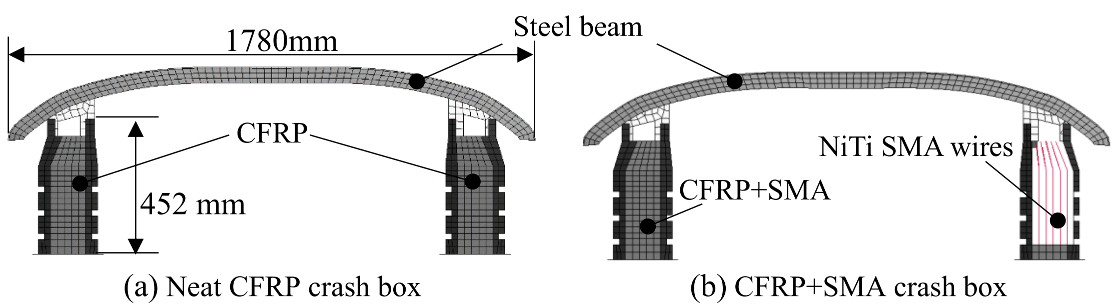
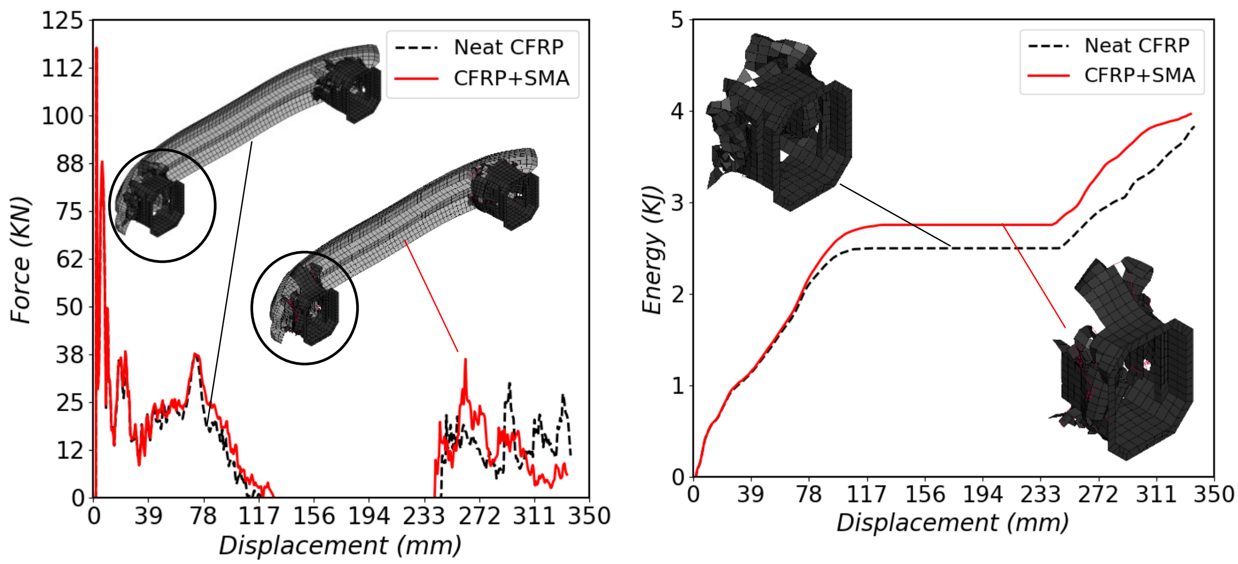


Figure 3: Finite element (FE) models of bumper system steel beam and (a) *CFRP crash boxes and* (b) *CFRP-SMA crash boxes*

Results & Discussion

Results of the simulation, as shown in Figure 4, highlight the contribution of the SMA by improving the impact resistance of CFRP composite, which represents an effective perspective in terms of safety for vehicle occupants. From a mechanical point of view, a small volume fraction (1%) NiTi SMA alloy increased the damage tolerance of CFRP and prevented/reduced instantaneous fragmentation and scattering of CFRP debris upon impact. In addition, it enabled the structure to maintain its integrity and continue resisting the impact load as a cohesive and unified entity.



(a) (b)

Figure 4: Comparison between simulation models: (a) *force vs displacement* (b) *absorbed energy vs displacement*

Discussions on challenges to SMA applications

Until now, the proposed applications of SMA for energy absorption applications are still in early research stage. The most significant limitation to the application of SMAs is their extremely low thermal efficiency [34]. The efficiency with which thermal energy is converted into mechanical energy is very low, resulting in a low mechanical power and poor thermo-mechanic performance [35]. Additionally, a portion of heat energy could be lost to the surrounding atmosphere due to convention, reducing the response efficiency of the targeted structural component. Overheating the SMA component due to excess current flow and power consumption is an additional risk as it could lose its trained shape [36, 37]. Therefore, a thorough assessment and understanding of the heat transfer mechanism are vital to developing a method that effectively increases the cooling rate and reduces overheating [38]. Unintentional or accidental triggering is another factor that limits the application of SMAs, e.g., parking the vehicle in a local high-temperature environment above phase transformation starting temperature may cause an unintended response or hinder a deliberate response. Finally, the lack of proper collaboration between academics and the industry causes difficulty of developing SMA applications for commercial implementation in automotive structures.

Conclusion

SMAs have the potentials to revolutionise the automotive industry by creating smart composite components that are more responsive, adaptable, and efficient compared to conventional composites in terms of weight-saving and energy absorption capability. Finite element simulation of full-structure bumper system illustrated that the energy absorption due to the integration of SMA to CFRP composite is increased by 3.6%. SMAs can also help to improve the strength and stiffness of the composites on transformation from the martensite to the austenite phase activated upon heating the SMAs. By utilising these smart materials, it is possible to design and fabricate lightweight, high-strength, and energy-absorbing components that can significantly improve the crashworthiness of the vehicle. However, much more research is needed to understand the properties and capabilities of SMA and composites, and how they can be commercially implemented in vehicle body parts and structural components for energy absorption and crashworthiness applications.

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