

Shape Memory Hybrid Composites

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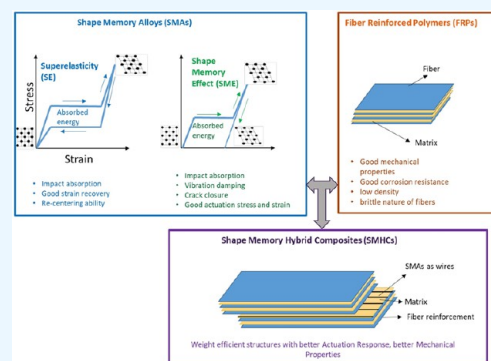
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ABSTRACT: Smart structures can help to resolve many issues related to conventional materials that are being used in different industries. Shape memory alloys (SMAs) are smart materials with better actuation response, vibration damping characteristics, and large strain recovery, making them good candidates due to their high strength and corrosion resistance for various engineering applications. The performance of fiber-reinforced polymer (FRP) composite materials that are replacing many conventional materials due to their good strength, stiffness, and lightweight potential especially in fuel-consuming industries such as aerospace and automotive, can further be improved by impregnation with SMAs. This review discusses the SMA-reinforced FRP composites, leading to shape memory hybrid composite materials, the issues and limitations in composite manufacturing, and their uses in different research arenas including impact and damping applications, seismic protection applications, crack closure applications, shape morphing applications, and self-deployable structures.



1. INTRODUCTION

Shape memory alloys (SMAs) are a class of smart materials that, after deformation, can recover their original shape on heating above reverse transformation temperature, termed as thermoelastic transformation.^{1,2} Thus, they have the property to remember their original shape. They exhibit another unique property called superelasticity that occurs above their austenitic finish transformation temperature, where they can be deformed with the application of stress and regain their original shape on removal of the load, without any need for temperature stimulus.³ Thus, these materials can impart important characteristics to the structure where they are used.

With development in different research industries, there is a need to develop structures utilizing smart materials that can impart actuating and sensing characteristics to the structure without using separate mechanical configurations, especially in the fields of automotive, aerospace, aircraft structures and engines, space, chemical processing, biomedical, robotics, and sports industries.^{3–9} Also, in the case of the transport industry, there is a need to develop weight-efficient materials with better strength to weight ratio. This will lead to fuel-efficient transportation with inherent good mechanical properties. These include strength, stiffness, vibration control, and impact resistance, among others.⁵

The aim of this review is to highlight the development of shape memory materials integrated in fiber-reinforced polymers (FRPs) to form hybrid composite materials. FRPs are known for their high specific strength and modulus, good corrosion resistance, controlled mechanical properties, and environmental friendly characteristics. Incorporation of shape memory alloys

into FRP will help with improved performance of the hybrid composite material for various engineering applications.

There is an increasing trend of research in the area of shape memory composites, especially since 2006. A plot of publications in this research field as acquired from PubMed is shown in Figure 1.⁶

1.1. Shape Memory Alloys. SMAs are characterized by austenite and martensite phases defined by phase transformation temperatures that define their operating temperatures and applications. These are four temperatures defined as austenitic start temperature, A_s , austenitic finish temperature, A_f , martensitic start temperature, M_s , and martensitic finish temperature, M_f . Above A_f , the material is in the austenite phase, and below M_f , a self-accommodated twinned martensitic phase is formed. There is no macroscopic shape change during this transformation as the martensitic structure is self-accommodating and the transformation is a shear-like mechanism termed as diffusionless martensitic transformation.⁷ The martensitic twins have glissile phase boundaries and can easily be deformed in the direction of applied load, such that the variants that are in the direction of force grow at the expense of variants in other directions, which shrink. Thus, this structure can be easily deformed by application of stress, leading to

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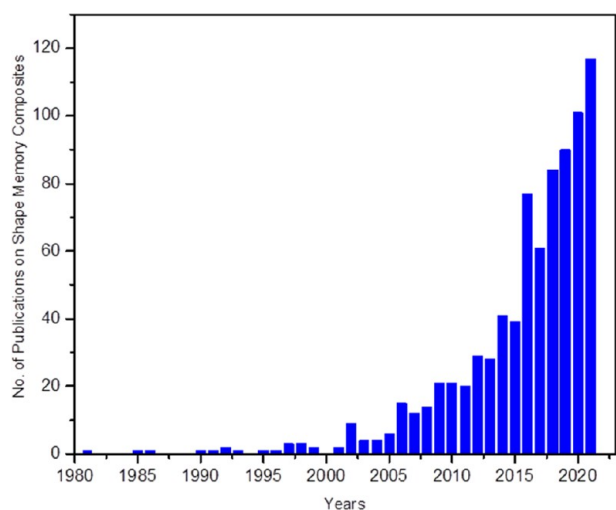


Figure 1. Published articles each year from a search in the PubMed database in December 2021 using “Shape Memory Composites” as a topic keyword.⁶

martensite reorientation and detwinning. On heating above A_f the material transforms back to the parent austenite phase and regains its original shape. This is termed as shape memory effect (SME).⁸ A schematic of SME shown in Figure 2a. Figure 2b shows shape changes of a coil spring during SME.

The stiffness of the SMAs in austenitic phase is higher than in the martensitic phase due to its structure (B2 for austenitic

phase and B19' for martensitic phase).¹⁰ The martensitic transformation can also be induced by application of stress (a shear stress that assists the transformation). Thus, both temperature reduction (quenching from austenitic phase) and stress can result in martensitic transformation, and the relation between the two is a straight line as governed by Clausius–Clapeyron relation in thermodynamics:²

$$\frac{d\sigma}{dT} = \text{constant} \quad (1)$$

The transformation temperature, however, as described previously is not a single temperature but has a range from M_s to M_f and A_s to A_f where each of these temperatures follows the Clausius–Clapeyron relation approximately on a stress–temperature (σ – T) curve.⁷

1.2. Superelasticity. In the case of superelasticity (SE) that occurs in the isothermal range, when stress is applied to the SMAs above A_f , stress-induced martensitic (SIM) transformation takes place, which is unstable at that temperature and upon unloading transforms back to the austenite phase. A schematic of the superelastic effect is shown in Figure 3.

The energy absorption on loading of austenite resulting in the transformation to stress-induced martensite occurs in an isothermal range and is characterized by energy hysteresis on a stress–strain diagram, as shown in Figure 4.

The properties of SMAs are mostly determined by their composition and heat treatments. The transformation temperatures of SMAs can be measured through many techniques such

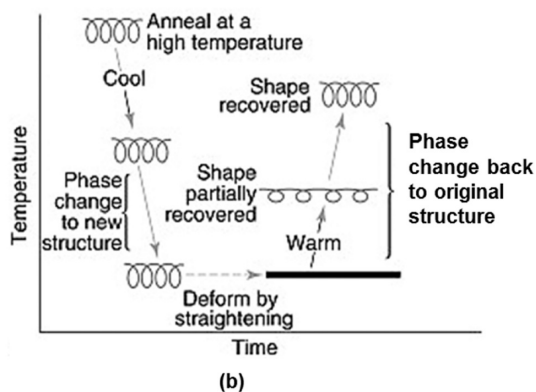
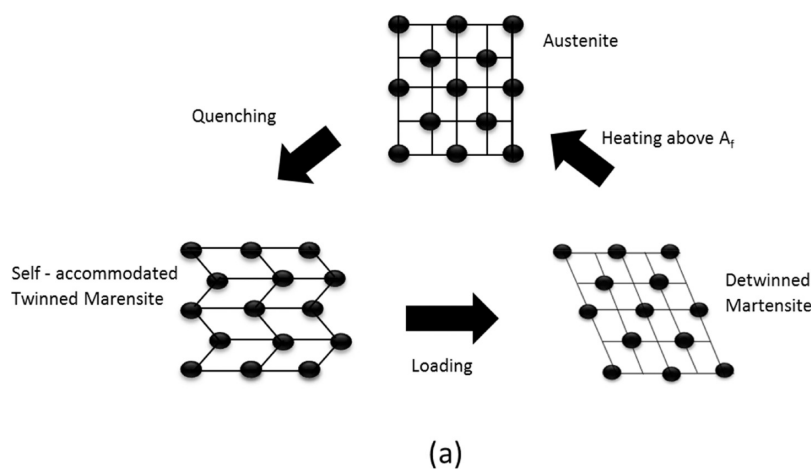


Figure 2. (a) Shape memory effect. (b) Shape changes of a coil spring SMA during SME. Reproduced with permission from ref 9. Copyright 2005 Elsevier.

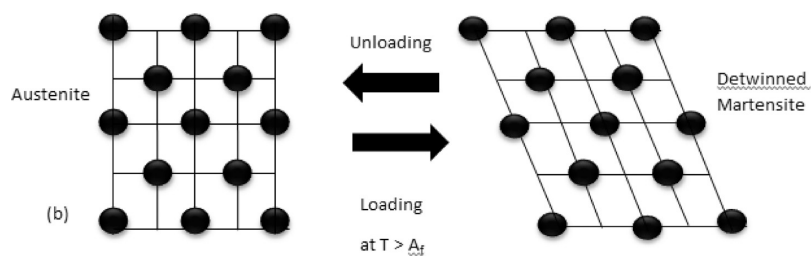


Figure 3. Superelasticity illustrating transformation from the austenitic to the detwinned martensitic phase during loading at $T > A_f$ and back to the austenitic phase during unloading.

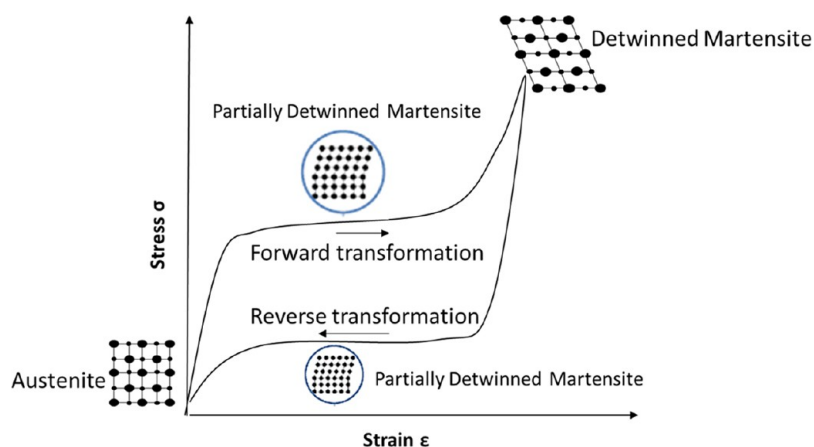


Figure 4. Forward and backward transformation from the austenite to the stress-induced martensite phase of superelastic SMAs at $T > A_f$ showing energy hysteresis.

as differential scanning calorimetry, change in electrical resistivity with temperature, and dilatometry.^{2,7,11,12} Among all SMAs, the most commercially adopted are NiTi (Nitinol, nickel titanium alloy named for its discovery at Naval Ordnance Laboratory), Cu-based, and Fe-based alloys.^{13–18} SMAs with Cu and Fe as the base material are mostly adopted as a cost-effective replacement of NiTi because of their good shape memory properties, damping capability, and other properties that make them good functional materials. However, functional long-term use of these alloys is susceptible to stabilization of phase, energy hysteresis, and aging that may lead to brittleness and affect their service efficiency. On the other hand, for Fe-based alloys, the small strain recovery of these alloys limits their use in commercial applications.^{10,18} Other groups of SMAs include Au–Cd alloys and Ni–Mn alloys.^{19,20}

For high-temperature applications, HTSMAs, the transformation temperature is usually increased by addition of ternary alloys to NiTi.²¹ Other systems such as NiAl and CuAlNi alloys have high-temperature shape memory characteristics.²² Many research groups are working on developing SMAs in the search for better strain recovery and transformation temperatures for targeting different applications including aircraft structures, engines, chemical processing, diesel engines, and heating and cooling industries.²³ Our goal is toward hybrid smart composites utilizing the two unique characteristics of the SMAs, i.e., SME and SE, that make them important functional materials for smart composite structures.

1.3. Fiber Reinforced Polymer Composites. Composite structures offer a better combination of properties that can be tailored according to the demand of the industry. The growing need for weight-saving solutions for various engineering applications has led to a rapid pace of research toward FRP

composites owing to their high strength to weight ratio, good corrosion resistance, and good fatigue resistance.²⁴ There are many natural and synthetic fibers used as reinforcements in composites. Among synthetic fibers, Kevlar, glass, and carbon fibers are most commonly used in engineering applications and will be discussed in this review as reinforcements.

Glass fibers were first developed for electrical applications at high temperatures in 1930. Recently, they have been used in electronics, aircrafts, and land vehicles to name a few. They have good mechanical and chemical properties. Glass fibers are available as Roving's, chopped fibers, mats, yarns, and fabrics, where each configuration has unique properties to be used for numerous applications as polymer composites for many areas.²⁵

Carbon fibers are among the most important industrial materials since the 1960s due to their excellent mechanical properties, chemical stability, and heat resistance.²⁶ The good overall performance of carbon fiber composites makes them efficient candidates for various applications such as space, aerospace, aeronautics, automobiles, sports, as well as renewable energy.²⁷

Kevlar fibers that belong to the polyaramid group are mainly popular due to their high impact strength and are extensively used in military applications, ballistic armor, bulletproof helmets and vests, helicopter blades, pneumatic reinforcements, sports, etc.²⁸ However, disposal of used Kevlar is not environmentally friendly and pollutes the environment. Significant efforts are being made to use Kevlar fibers for improving impact resistance due to their capabilities of energy absorption and dissipation to improve ballistic resistance of advanced composites, a contribution toward green technology.²⁹

Glass, carbon, and Kevlar fiber reinforcements will be discussed in this review toward development of hybrid

composites as these fibers are mostly used as structural materials and in targeting important engineering and military applications.

2. SHAPE MEMORY HYBRID COMPOSITES

Apart from their good mechanical behavior and corrosion resistance, FRPs often undergo brittle failure as they do not undergo plastic deformation, and some fibers such as carbon do not have good impact properties.^{30,31} Such issues can lead to barely visible impact damages (BVID) that reduce the fracture strength of FRPs. Integration of SMAs in FRPs can offer a better solution to this issue. The martensitic phase has glissile interfaces that can absorb the energy of impact, leading to better energy damping. The intrinsic damping can also be utilized in superelastic materials that can dampen the impact energy by stress-induced martensitic transformation. Shape memory effect can also be utilized toward tuning of vibrational frequencies, as when SMAs are heated above A_p , the change in the Young's modulus and reduction of damping capacity can contribute to changing the vibrational properties of the materials.³²

Moreover, SMA reinforcement helps to improve strength and stiffness of composites. In the case of the shape memory effect, the phase transformation of the SMA on heating from the martensite to the austenite phase that has comparatively high stiffness produces tension in SMAs within the composite to augment the overall reaction. The structural reinforcement of the hybrid composite is depicted in Figure 5.³³

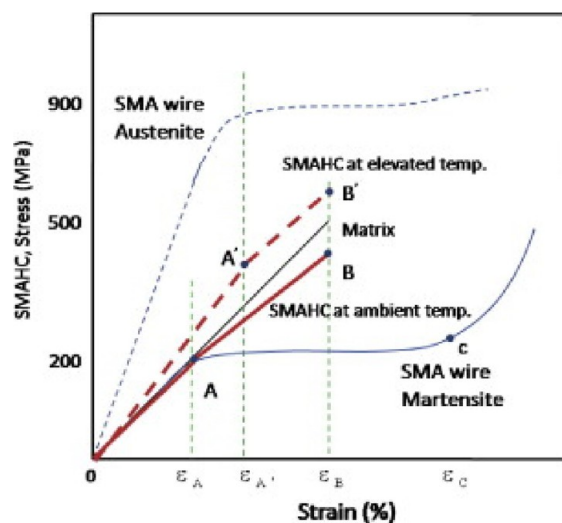


Figure 5. Tensile plot of the SMAHC plate and SMA wire (in martensitic and austenitic phase) at ambient and high temperatures. Reproduced with permission from ref 33. Copyright 2011 Elsevier.

Thus, shape memory alloys integrated into a polymer matrix, strengthened by fiber reinforcement, known as shape memory hybrid composites (SMHCs), offer a better combination of reduced weight, strength, stiffness, ductility, vibration damping, impact resistance, damage resistance, and fatigue life.^{34,35} The smart SMHCs may integrate actuators and sensors to react to their working environment during processing, manufacturing, assembly, or service. Such sensors can detect or repair damage of structures during service conditions.³² The SMAs are now available as wires that can be integrated in composites, feasibly without changing their composition. A schematic of SMA as wires integrated in FRP laminate and epoxy matrix is shown in

Figure 6.³⁶ Such composite materials can be used for various functions such as change in shape or natural frequency of

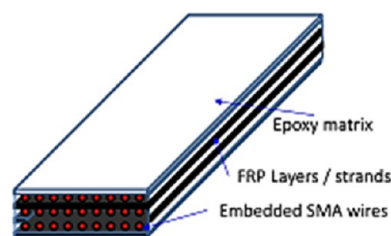


Figure 6. Schematic of SMHCs consisting of SMA as wires integrated in FRP laminate, with epoxy as the matrix. Reproduced with permission from ref 36. Copyright 2014 American Society of Civil Engineers.

vibration to control the thermal expansion or repair damage. The activation of SMAs (with stress or temperature) from heat transfer kinetics can affect their response time.³²

A study of the material property maps as given by Ashby (Figure 7) illustrates that SMAs (as shown by bulk in the diagrams) show better actuation stress and strain and better axial stiffness as compared to that of other materials but at the cost of high density. However, FRPs have better actuation stress, low strain, and better axial stiffness at low density. A combination of SMAs and FRPs can offer a better combination of mechanical properties and actuation behavior at low density and thus high stiffness to weight, actuation to weight, and strength to weight ratios, leading to weight-efficient structures.³⁷

Lei et al. investigated SMHCs with sandwiched SMA wires in a glass fiber/resin matrix and showed improvement in mechanical strength and stiffness of the SMHC with increasing number of wires, as depicted in Figure 8a,b.³⁸ In a recent study, Taheri-Behrooz et al. showed that, for elevated temperature applications, SMA wire reinforcement can be integrated in composites having lower strength/stiffness compared to that in the austenite phase of SMA. This can help to reduce the degradation of composites at high temperatures, but if the strength/stiffness of the host composite structure is comparable that of austenitic SMAs, the reinforcement with SMAs will not help in appreciable improvement of the mechanical properties.³³

Figure 9 shows the SEM micrograph of SMA wires embedded in GFRP laminate, with GFRP parallel to the SMA fiber adjacent to it and perpendicular to the SMA fiber in the subsequent layer.³⁹ This hybrid composite is found to offer a better combination of strength, impact performance, and flexural performance benefiting from both FRP and SMAs. The mechanical properties of such hybrid composites are highly dependent on the interfacial strength of SMA/FRP/resin laminate. The interfacial mechanics will be discussed in section 2.1.

The SMAs possess appreciable recovery stresses if constrained (~ 800 MPa) with recovery strains ($\sim 8\%$), which can lead to their applications in clamping devices, manufacturing of self-deployable structures for robotics, transport, and space-based applications.^{2,32,40}

Figure 10 shows recovery stresses generated by the TiNiCu wire and a TiNiCu-reinforced (11.8%) Kevlar fiber composite. In both cases, the wires are prestrained to 3%.⁴¹ It can be observed that the SMA shows a small hysteresis, and the hysteresis of the KFRP SMA composite is also small. SMAs present characteristics such as a power to weight ratio and noiseless actuation and can be actuated for bidirectional motion

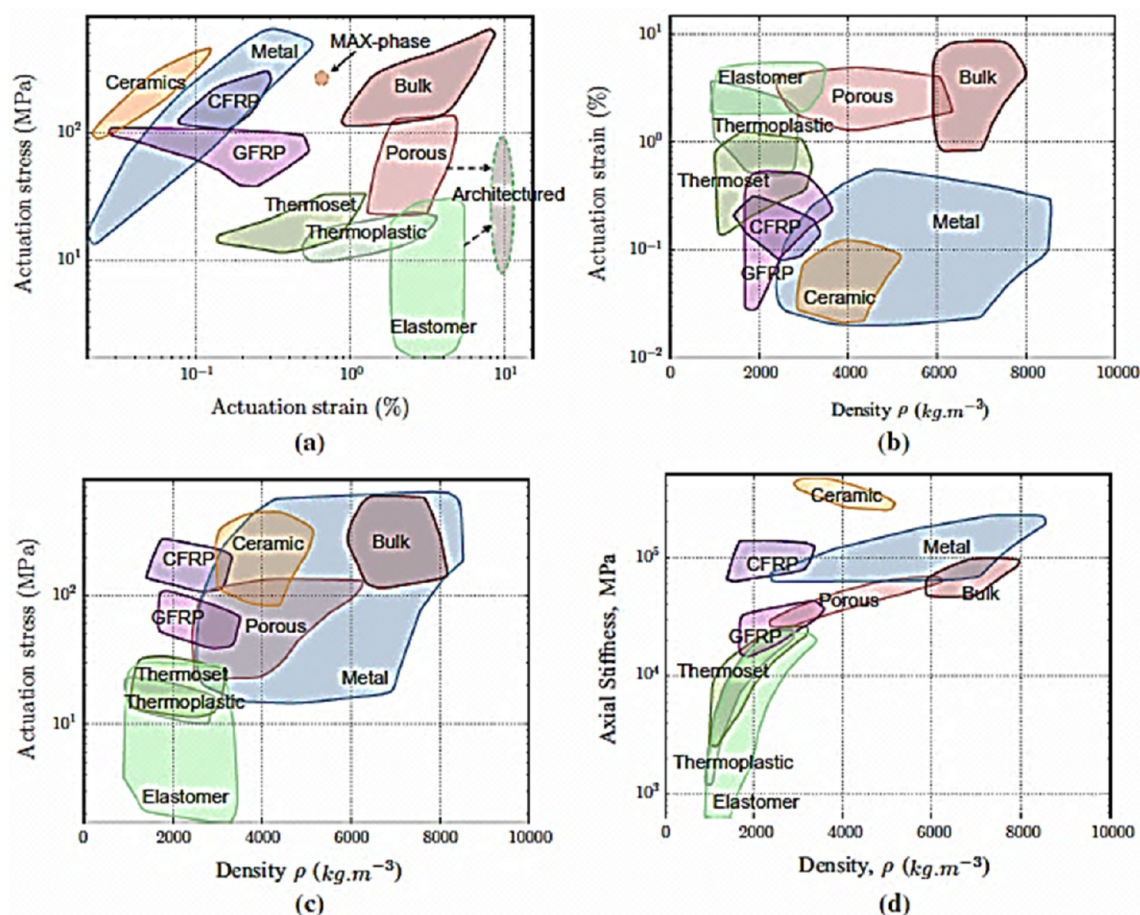


Figure 7. Material property maps: (a) actuation stress vs actuation strain, (b) actuation strain vs density of different materials groups, (c) actuation stress vs density of materials groups, and (d) axial stiffness vs density of different materials groups, where bulk shows bulk SMAs and porous refer to porous SMAs. Photograph courtesy of Lester et al.³⁷ Copyright 2015.

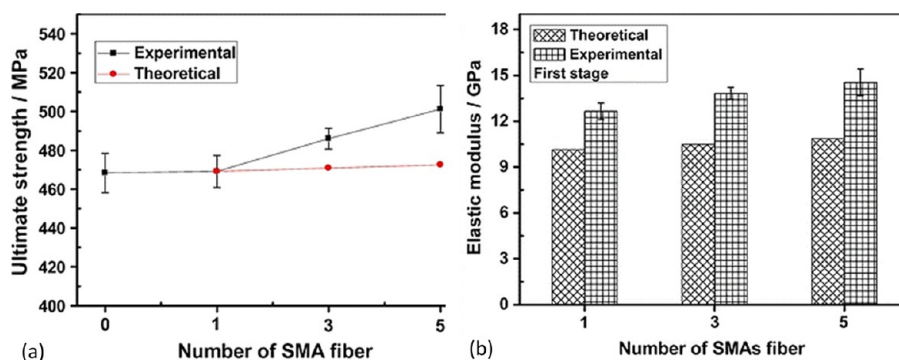


Figure 8. Experimental and theoretical data: (a) ultimate tensile strength of SMA/glass/resin composites and (b) elastic moduli of SMA/glass/resin composites, as a function of the number of SMA wires. Photograph courtesy of Lei et al.³⁸ Copyright 2013.

in limited operational space, which make them ideal for robotic applications.^{42–44}

SMHCs have various applications in many areas such as aerospace, automotive, marine industry, oil and gas industry, wind turbines, and structural applications to name a few.^{45–49} Some of the applications of SMHCs are discussed in section 3. A flowchart of the SMHCs that will be discussed in this review is presented in Figure 11.

The development of shape memory and superelastic hybrid composites is being investigated toward improvement of vibration damping behavior, impact resistance, crack closure properties, shape morphing behavior, and good fatigue

resistance.^{7,12–14,50–52} Integration of SMAs in various configurations in FRP composites depends on the type of application to be addressed. If vibration and damping resistance is to be improved, SMAs are sandwiched in an in-plane configuration on a neutral axis; if shape morphing is to be introduced, integration has to be on a non-neutral axis in an in-plane configuration; if impact resistance is to be considered, SMAs are integrated in an in-plane configuration as stitches or on a neutral axis, and if crack closure properties are considered, integration of SMAs has to be in the transverse direction to the crack direction, as stitches or with some healing agent for self-healing materials.^{32,53}

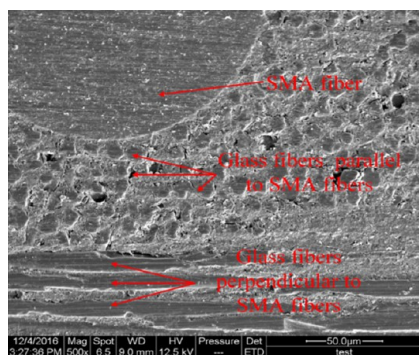


Figure 9. Cross-sectional SEM morphology of SMA/GFRP laminate. Photograph courtesy of Wang et al.³⁹ Copyright 2018.

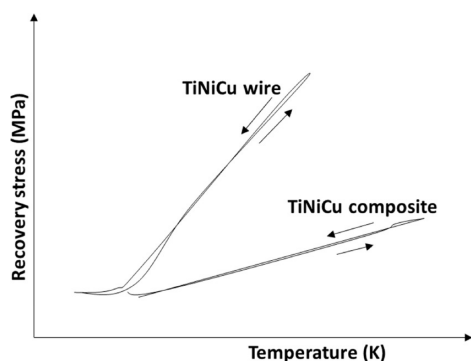


Figure 10. Recovery stresses in prestrained TiNiCu wire (3%) and TiNiCu wire-reinforced Kevlar fiber composite. Redrawn with permission from ref 41. Copyright 2005 Elsevier.

The manufacturing of the SMHCs can be carried out in different ways as the composite manufacturing using hand lay-up technique, resin transfer molding (RTM), vacuum-assisted resin transfer molding (VARTM), compression molding, or autoclave manufacturing depending on the part size, shape, and

application industry. A summary of SMA-reinforced composites for various engineering applications is given in Table 1.

2.1. Interfacial Strength and Mechanics. Interfacial strength and mechanics play an important role in SMHCs. A limiting feature in SMA–FRP hybrid composites is the interfacial debonding between SMA and the matrix. The interface should be strong enough to resist any debonding or delamination at the site of the interfacial region. The interfacial debonding occurs mainly due to an outside force, actuation of SMAs by temperature, or may be due to both effects.⁶¹ Taheri-Behrooz et al. developed an axisymmetric model (three cylinder) utilizing a pull-out method to predict stress transfer and interfacial behavior for the superelastic SMA wire, matrix, and interphase.⁶² Nissle et al. investigated the load transfer characteristics of active hybrid SMA–FRP composite structures.⁶³ The shear, normal, and radial stresses that are generated on activation of SMA elements is shown in Figure 12a. The stresses, due to shear or normal forces, σ_τ and σ_n , are intense in some areas at the interphase between SMA and FRP and the radial stress, σ_r , in the SMA wire, as shown in Figure 12. The outer regions (Figure 12b) have high shear stresses at the interphase as the transfer of load occurs between SMA and FRP in this area, whereas the central region (Figure 12c) has a high radial stress or normal stress due to the force of the wire to change from a bent to a linear configuration. If the shear stress in the outer regions exceeds a critical value, then interfacial failure occurs in the region of maximum stress. To improve interfacial load transfer characteristics, research has been conducted by chemical treatment and mechanical modification of the wire by many researchers.^{64,65}

Wang et al. examined the stress transfer of the SMA fiber pulled out from an elastic matrix using an analytical model and studied the influence of temperature and transformation characteristics of the SMA fiber.⁶⁶ It was observed that a temperature increase results in prolonging the martensitic transformation while reducing the stress intensity factor.

Shi et al. investigated the interfacial adhesion and mechanical properties of SMA composites.⁶⁷ They proposed that an

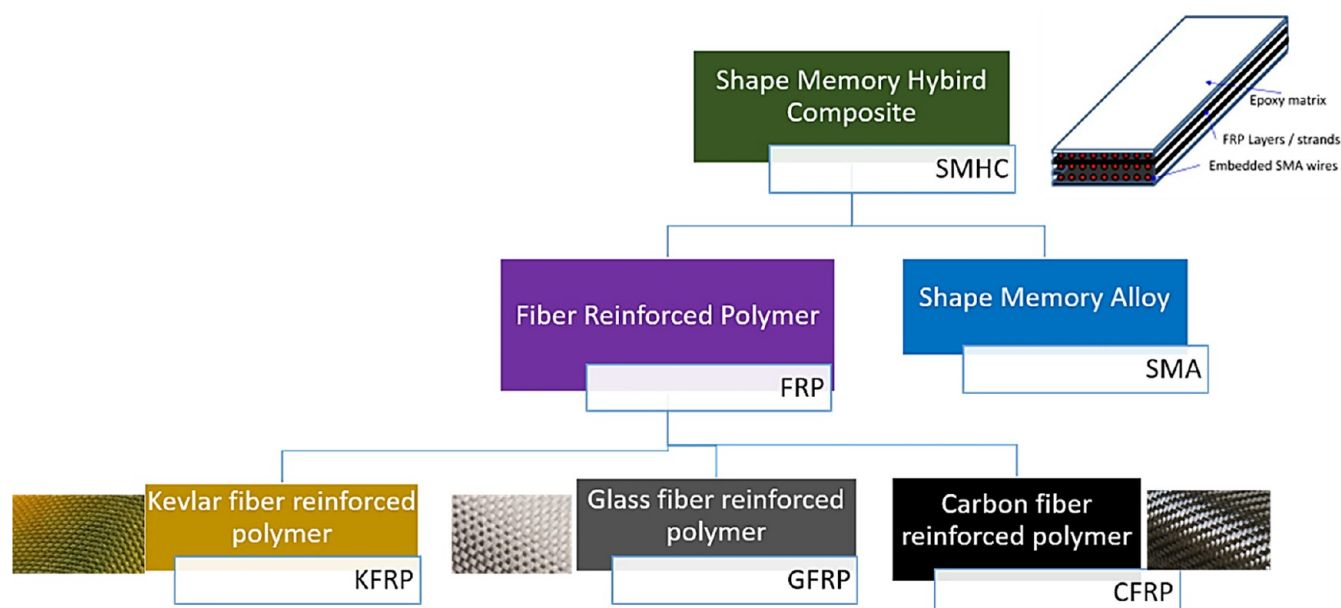


Figure 11. Flowchart of shape memory hybrid composites.

Table 1. Shape Memory Alloy (SMA)-Based Composites for Various Engineering Applications

matrix	reinforcement	treatment	processing technique	results	ref
epoxy resin	glass fiber and NiTi SMA wires	acid and nanosilica particles treatment	symmetric (center) and asymmetric SMA positioning, fabricated by VARTM	flexural and impact performance are dependent on interfacial bonding that can be enhanced by nanoparticles	54
epoxy resin	carbon fiber and NiTi wires		filament winding technique, NiTi wires prestrain to 6%	7% increase in first natural frequency and 100% increase in damping ratio were observed for NiTi (with 6% prestrain) implanted CFRP shafts	55
epoxy vinyl resin	glass fiber and superelastic NiTi SMA wires	sand-polished and acetone-cleaned	between layers of glass fiber, fabricated by VARTM	fatigue life of SMHC > twice higher than GF composites	56
epoxy resin	carbon fiber, NiTi SMA wires	prestressed SMA-CFRP composite patch used in steel plates	sheet of SMA strands integrated in multiple CFRP layers, to form SMA-CFRP composite	fatigue life increased to 2.7 (for normal modulus CFRP) and 6 (for HM CFRP)	57
epoxy resin	glass fiber + NiTi SMA wires	HNO ₃ and 2 wt % nanosilica coating using PVD	SMA wires embedded between glass fibers, fabricated by VARI process	treatment enhanced interfacial bonding strength, flexural strength, flexural modulus and failure strain	58
epoxy resin	superelastic NiTi wires		different volume fraction of SMAs fabricated by hand lay-up	increased damping, high recovery strains and high failure strain	59
epoxy resin	carbon fiber and superelastic NiTi SMA wires	SMA wires polished	manufactured using the VARI method, using carbon fibers and SMA wires embedded between bottom two layers	enhancement in toughness and energy absorption capability	30
epoxy resin	Kevlar fiber, NiTi SMA sheet, NiTi SMA wire		hand lay-up method, stacking sequence, Kevlar/Kevlar/Kevlar, Kevlar/SMA sheet/Kevlar, Kevlar/SMA wire/Kevlar	SMA sheet-reinforced Kevlar epoxy composite has 117.84% greater flexural strength, reduced deformation and increased absorbed energy for low velocity impact, than the plain Kevlar epoxy composite	60

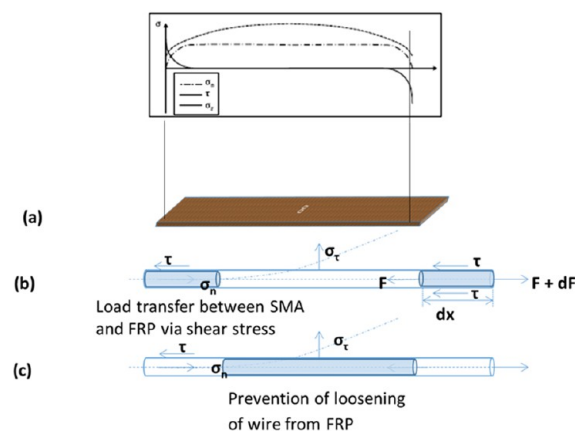


Figure 12. Different areas of active hybrid composite: (a) stress profile along the sample, (b) outer areas for load transfer via shear stress, and (c) center area for radial force in the wire. Redrawn with permission from ref 63. Copyright 2019 IOP Publishing.

increase in the diameter of the SMA wire improves the bonding due to an increase in the interfacial area. An improvement in interfacial adhesion was found by treatment of SMA wires with sulfuric acid (H₂SO₄). The SMA wires were etched with H₂SO₄ for 1 h and degreased with isopropyl alcohol for 20 min and then washed with distilled water and dried in an oven. Schrooten et al. reported that a thin oxide layer provides the best interfacial bonding.⁶⁸ Gapeeva et al. investigated the interfacial bonding of the SMA polymer interface and showed that the bonding can be improved by electrochemical etching.⁶⁹ The etched pits increase the wire's surface area, resulting in an improvement of the interlocking between the wire and the polymer. Hector et al. patented a method for improving the interfacial bond between SMA and the polymer.⁷⁰ They showed that pretreatment of the NiTi SMA wires by immersion in aqueous solution of 3% HF and 15% HNO₃ solution (until visible removal of the oxide coat) and afterward soaking in 5% phenyl phosphonic acid with ultrasonication for 20 min appreciably improved the adhesion of wires with the olefin matrix.

Lei et al. treated the SMA wires' surface by sanding, acetone cleaning, and ultrasonic cleaning before being embedded in the host matrix.³⁸ Figure 13 shows the SEM micrograph of the interfacial bonding between the wires and matrix leading to an increase in tensile strength of the hybrid composites (as shown in Figure 7).

The damage mechanics in the case of tensile failure include SMA fiber debonding and fiber fracture, as shown in Figure 14.⁵¹ It can be observed that the characteristics of the composites are highly dependent on the quality of the interface. Better interfacial bonding results in a better combination of properties of SMAs and FRPs, resulting in better strength of the hybrid composites.

Mechanical indentation techniques are also found to improve interfacial bonding as experimented by Yuan et al. They used sparse and dense indentation to improve the interfacial bonding of SMA smart composites, as shown in Figure 15. The dense indented SMA wire is found to have better bonding, resulting in better tensile and recovery properties compared to those of the sparse indented wire.⁷¹

The different techniques to improve the interfacial bond strength for SMA-reinforced composites as reported by Bhaskar are summarized in Table 2.⁷²

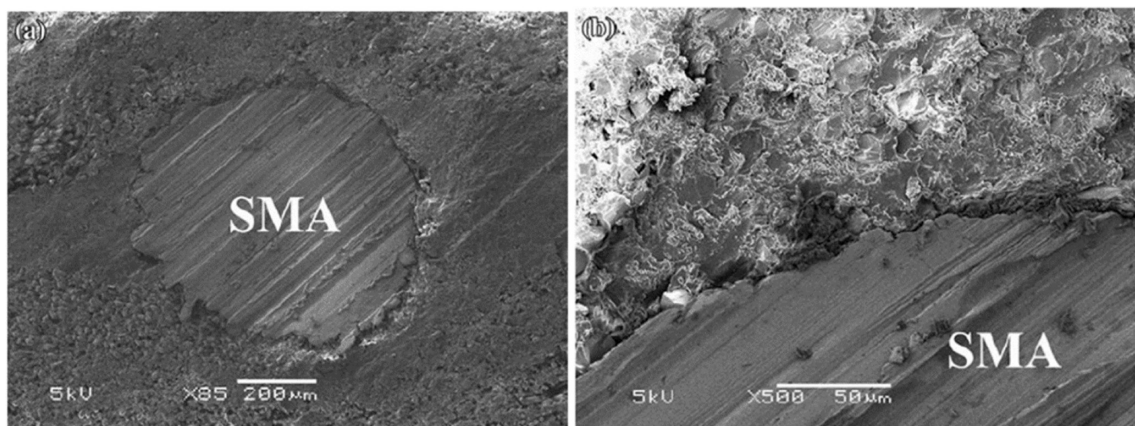


Figure 13. SEM images of interface between SMA wire and glass/resin matrix. Photograph courtesy of Lei et al.³⁸ Copyright 2013.

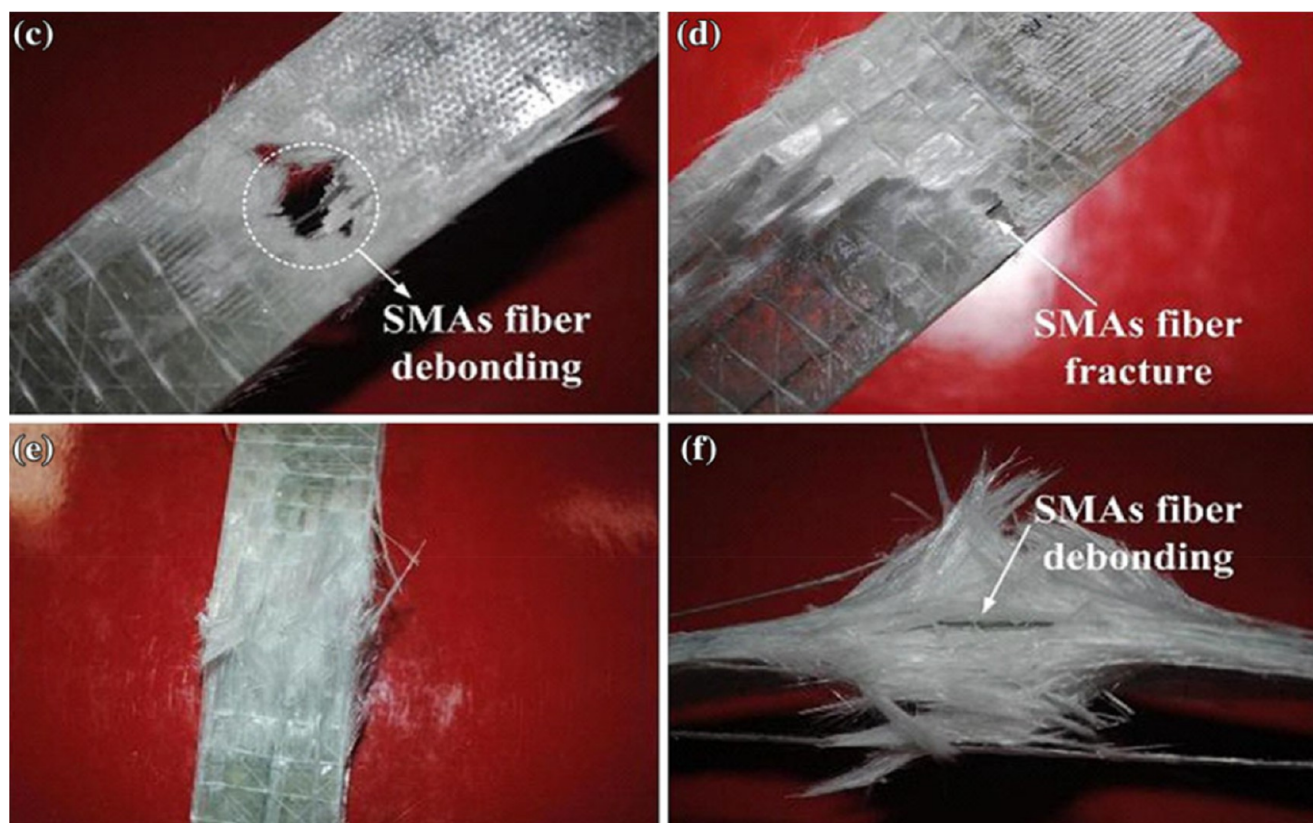


Figure 14. Tensile failure damage mechanics of the SMA/GFRP composite indicating the SMA fiber fracture and debonding. Photograph courtesy of Lei et al.³⁸ Copyright 2013.

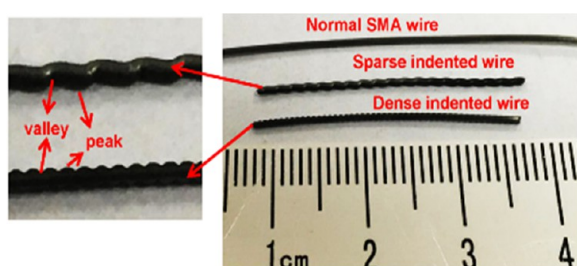


Figure 15. Sparse and dense indentation methods to improve interfacial bonding. Reproduced with permission from ref 71. Copyright 2016 Elsevier.

Table 2. Relative Bonding Scale (in Increasing Order from 1 to 5) for Conventional Surface Treatments of SMAs to Improve Interfacial Bonding Strength in a Composite Material⁷²

treatments	relative scale for bonding improvement
sandblasting	4
torsion-induced roughness	5
silane adhesives	3
electrochemical coatings	2
hand grinding	2
acid etching	1

3. APPLICATIONS OF SHAPE MEMORY HYBRID COMPOSITES

Shape memory hybrid composites have various applications in different industries such as aerospace, automotive, marine, structural, and robotic fields, where they are used to improve delamination resistance in composites, impact and vibration damping, seismic protection of structural components, crack closure, damage tolerance, shape morphing, and fabrication of self-deployable structures for structural and space-based applications. The concept of integration of SMAs into FRPs has also been used for structural and acoustic vibration control as done by Saunders et al. and Zhang et al.^{73,74} Some of the application areas are discussed below.

3.1. Delamination Damage Reduction in Composites.

Composites as laminates have usually strong in-plane mechanical properties, but they suffer from through-thickness delamination under impact loading that has been an issue in their applications as a structural material. Superelastic SMAs when stitched to the FRP composites reduce the delamination on impact as they absorb the impact energy and undergo stress-induced martensitic transformation and return to the austenitic phase on removal of stress. Thus, the energy is absorbed rather than allowing delamination propagation in composites, resulting in improvement of the impact strength and reduction in the delamination area of SMA hybrid FRP composites compared to composites without SMAs. Also, since the process is isothermal, there is no requirement of energy input (as heat) as in case of shape memory effect. Lau et al. investigated the delamination damage behavior of SMA-stitched, glass fiber–epoxy laminates (prepared by resin transfer molding) under low velocity impact.⁷⁵ They found improvement in damage resistance as well as tensile strength of the SMA/GFRP composites compared to the unstitched composites. They also proved theoretically a decrease in delamination energy of superelastic SMA-reinforced glass composites due to energy absorbed by the superelastic wires. Also, the natural vibration frequency and damping ratio of the SMA-reinforced composites in stitched configuration were improved compared to that in the unreinforced composites, resulting in better resistance to low velocity impact. Such studies can be of vital importance to the application industry of FRP composites, especially in aerospace and other transport industries, where BVID cannot be detected easily, but they cause appreciable reduction in fracture strength of composite materials.

Vachon et al. investigated the delamination propagation in SMA-stitched carbon fiber epoxy laminates (16 plies) by low velocity impact (ASTM D7137) followed by compression after impact (CAI, ASTM D7137).⁷⁶ Also, the theoretical analysis showed reduction in delamination energy compared to that in the unstitched composite plates. Figure 16 shows the stitched configuration of NiTi SMAs in Kevlar fiber and carbon fiber composites.

A 7% reduction in the delamination area under impact (energy 1 J/mm) was observed for the SMA-stitched composite in comparison to unstitched composites. The SMA-stitched composites were also found to have better CAI strength.^{77,32} Further research in this area is still required with different thicknesses of stitched composite structures, wire volume fractions, and stitching forces.

Ciampa et al. presented a novel shape memory FRP composite utilizing tufted SMA (shape memory NiTi) filaments in carbon-epoxy laminates, schematically represented in Figure

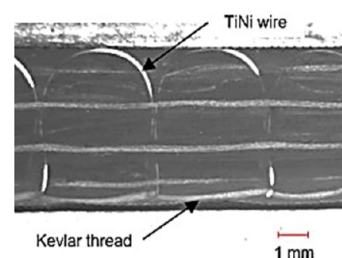


Figure 16. SMAs stitched to Kevlar and carbon fiber composites. Photograph courtesy of Cohades et al.⁵³ Copyright 2018.

17.⁷⁸ The study of interlaminar delamination shows that SMA tufts improve the fracture toughness of the composites by creating a bridging zone in the delamination area. Upon heating of the SMAs, SME is activated that partially closes the delamination. Figure 17 shows interlaminar fracture toughness with and without SMA tufts with increasing delamination length. It shows a rapid increase in toughness with delamination propagating through the tufted composite before fracture. It is found that the main toughening mechanism is the large-scale bridging process zone formed by SMA tufts behind the crack front.

The SMA tufts helped the development of reinforced composites that both resist the delamination and assist crack closure by damaging mechanisms such as impact or overloading.

3.2. Impact and Vibration Damping Applications. The intrinsic damping capacity of the shape memory and superelastic SMAs has been under the research umbrella to improve the impact properties of the composite materials. Both shape memory and superelastic SMAs are used for improving damping and impact resistance. In the case of shape memory alloys, the martensitic phase has glissile interphases and deform in the direction of applied load. As the interphases are mobile, their movement and friction between the interphases dissipate a large amount of energy, thus damping out the impact load. On heating, the material returns to the austenitic phase.^{32,79} In the case of superelastic SMAs, the material transforms to stress-induced martensite on application of stress and returns to austenite on load removal, thus damping the impact load.^{32,80} Figures 4 and 18b show the energy hysteresis during loading and unloading that represent the energy dissipated as heat during the reverse transformation.

Carbon-fiber-reinforced polymers (CFRPs) are extensively used in different research industries, but they have poor impact resistance due to which local impact leads to delamination and fiber matrix debonding. Sometimes the damage is barely visible (BVID) but can lead to delamination or crack initiation and thus reduction in mechanical properties.^{81,82} The BVID is primarily caused by falling tools or equipment that collide with ground handling vehicles.⁸³ According to the Boeing standard, the visibility threshold is from 0.01 to 0.02 in. dent depth from a distance of 5 feet.^{83,84} According to Airbus, the visibility threshold is from 1.2 mm dent depth at a distance of 1 m for BVID.^{83,85}

Damage tolerance deals with evaluation of damage growth and residual strength of the material. A residual strength test is determined to check the ability of the material to withstand design loads by applying fatigue loads to the damaged component. In case of aircrafts, it demands that BVIDs should not grow for the determined lifetime of the aircraft and visible impact damage (VID) in the structure should not grow under fatigue loading for a period of two inspection intervals. This

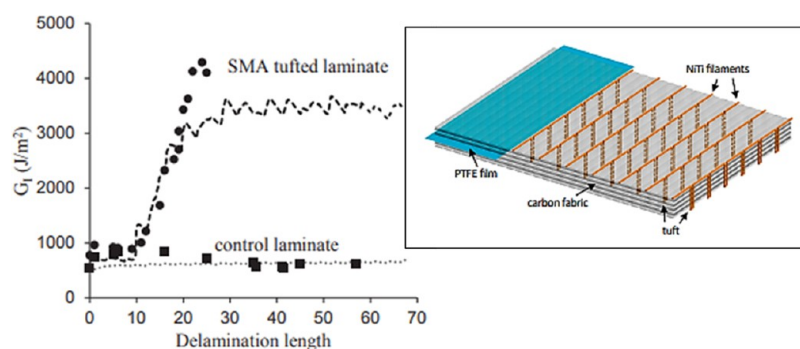


Figure 17. Measured and calculated interlaminar fracture toughness with delamination length. Reproduced with permission from ref 78. Copyright 2021 Elsevier.

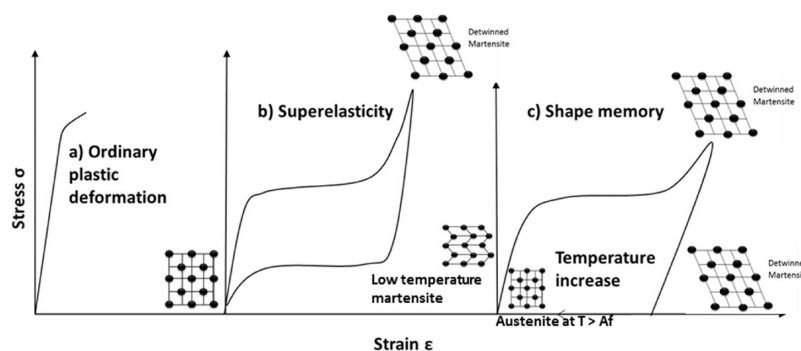


Figure 18. Tensile stress–strain diagram for loading and unloading of shape memory alloys: (a) $T \gg A_f$, (b) $T > A_f$, and (c) $T < M_f$. Redrawn with permission from ref 32. Copyright 2018 Elsevier.

criterion is often used for determination of inspection intervals for aircraft components.⁸³

SMA's reinforcement in FRP composites remains at a nearly high constant stress level over large recoverable strain and has high failure strain, which leads to better performance compared to other metals.⁸⁶ Wang et al. also established improvement in damage tolerance and impact resistance of GFRP laminates.⁸⁷ They found that deformation can be recovered largely for low and medium impact energies, while for high impact energy, the damage is irrecoverable as the SMA wires break resulting in irrecoverable damage. Over the past decades, substantial research has been done to improve the impact resistance of CFRPs. Gu et al. investigated the impact resistance of NiTi SMA wires integrated in CFRPs, using a drop weight impact test.³⁰ An improvement in energy absorption capacity of CFRP composites was found at 10 J of impact energy that is attributed to the stress-induced martensitic transformation (SIM), reversible deformation, and hysteretic energy dissipation of the superelastic wires. The impact and vibration damping ability of SMA-reinforced glass fiber composites (GFRPs) was studied by Verma et al.⁸⁸ The energy absorption and vibration damping capacity of the SMA/GFRP composite are found to be better than unreinforced GFRP composites. The vibration damping ratio of SMA/GFRP is better below the ballistic limit, i.e., 65 m/s, above which SMA fiber pullout is observed, resulting in a decrease in damping capacity. Meo et al. also investigated the impact response and damage resistance of the SMA-reinforced hybrid composite structure under low velocity impact.⁸⁹ The damage resistance and ductility of the hybrid composite laminates are found to improve upon reinforcing with SMA wires owing to their large failure strain and recoverable strain upon unloading. The energy damping behavior of the shape

memory and superelastic alloys is under study by different research groups globally. The damping of martensitic phase in shape memory materials is due to the mobile nature of martensitic variants. When elastic waves travel through the materials, the friction between the glissile interfaces releases a large amount of energy, resulting in high intrinsic damping of the martensitic phase especially in transformation temperature range.⁴⁵ Gupta et al. investigated the damage after low velocity impact response of SMA-embedded GFRP composite laminates and found that integration of SMA wires in the bottom layers of the composites is more effective at reducing delamination.⁹⁰ Also, compressive load-carrying capacity of the hybrid composites after impact is found to improve.

In the case of superelastic materials, the damping is due to the stress-induced martensitic transformation in the isothermal condition that reverts back to the austenitic phase on unloading (Figure 18b). The energy is dissipated due to hysteretic nature of the transformation, and it behaves as a passive damper.⁴⁵ However, at still higher temperature above M_d , there is a limit when stress-induced martensitic transformation will not occur, where the stress required to form SIM is greater than that needed for slip deformation, and thus plastic deformation occurs. Thus, SIM occurs in the range of $M_s < T < M_d$. Above M_d , the stress–strain V_s curve is shown in Figure 18a, which shows ordinary plastic deformation. Thus, superelasticity occurs above A_f and below M_d .⁹¹ The stress–strain curves of the shape memory and superelastic alloys is shown in Figure 18 to get insight into the impact and damping response of these materials.

Bachmann et al. investigated the passive damping of open rotor composite fan aircraft blades to overcome the vibration and noise issue by comparing SMA wire-based and piezoelectric shunt circuit-based integrated damping systems.⁹² These were

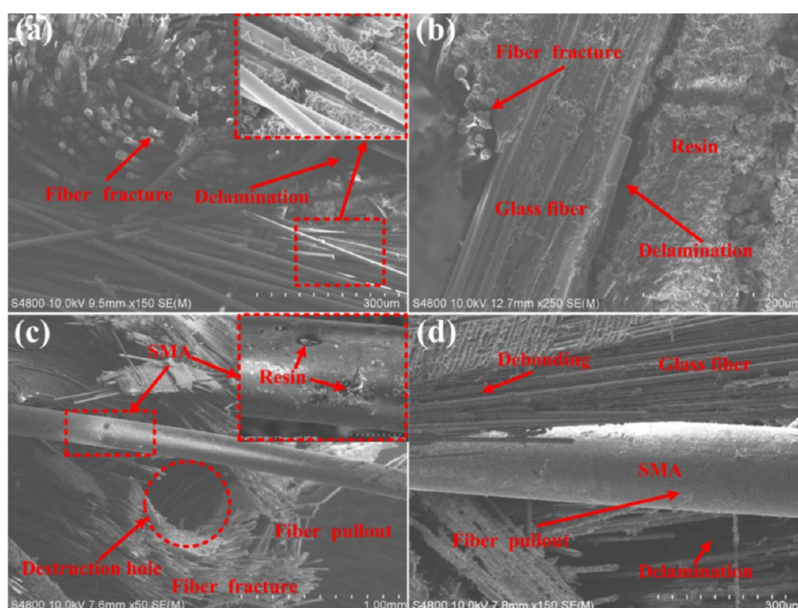


Figure 19. (a,b) Microscopic damage morphology of GFRP under impact of 20 J and (c,d) microscopic damage morphology of SMA/GFRP under impact of 20 J. Reproduced with permission from ref 94. Copyright 2021 Elsevier.

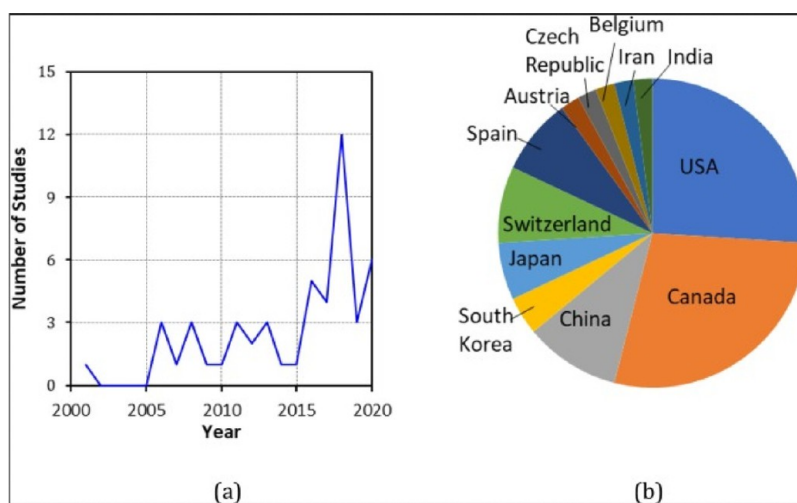


Figure 20. Data representing experimental studies on the strengthening and self-centering of SMA integrated RC structures organized by (a) year and (b) country. Photograph courtesy of Raza et al.⁹⁵ Copyright 2022.

compared with the undamped CFRP composite plates. They propose a process for integrating damping devices into a composite fan blade. Both SMA and piezoelectric elements were found to improve the system damping significantly as compared to the CFRP composite plate. Zhang et al. investigated the vibration analysis of SMA-reinforced CFRP. It was observed that the natural frequency of the hybrid composite depends on volume fraction of SMAs. Also, it was observed that for wires in the austenite phase, the natural frequency of the SMA–CFRP composite is almost twice that of unreinforced CFRP, while the natural frequency increased by 1.8 times for woven SMA–CFRP.⁹³ Thus, both the woven configuration and phase of SMAs play roles in vibration control of structures.

Figure 19 shows damage morphology of glass fiber epoxy laminate (a,b) and SMA-reinforced glass fiber epoxy laminate under impact of 20 J (c,d).⁹⁴ The impact performance is found to improve on integration of superelastic SMAs in GFRP provided better interfacial strength. The damage mechanics on

impact loading include matrix fracture, fiber fracture, delamination, fiber pullout, and debonding.

It was observed that the impact failure of superelastic SMA-based SMAHCs absorbed more energy than GF/epoxy laminates due to the remarkable energy absorption capacity/hysteresis of SMAs.

3.3. Seismic Protection Applications. The loading and aging effects in structural components with environmental factors such as force, time, and temperature degrade the reinforced concrete (RC) structures and can cause significant performance and safety concerns. Shape memory alloys offer a solution to the issue owing to their unique properties of superelasticity resulting in recovery of inelastic strain upon stress/heating (SME). SMAs can help to reduce permanent deformations and take part in self-centering and thus damage reduction in RC structures. Also, SMAs can improve the mechanical strength of RC structures to resist high loads and reduce damage.⁹⁵ Figure 20 shows experimental work being

done on strengthening and self-centering of RC structures modified by integrated SMAs.

Figure 21 shows a schematic of different anchoring methods of SMAs to RC structures.¹⁸ Figure 21a shows incorporation of

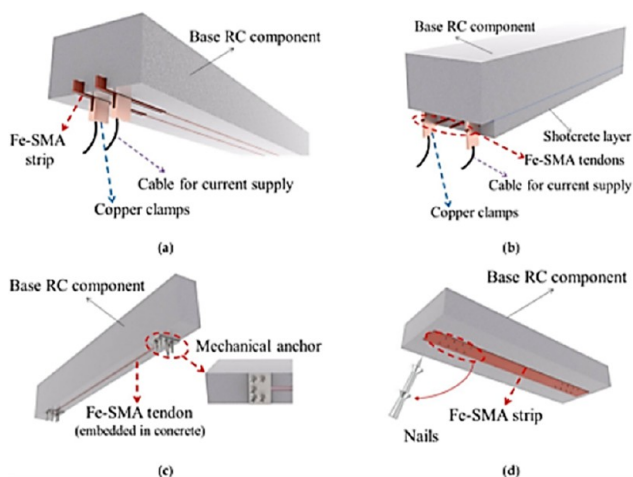


Figure 21. Illustration of different anchoring mechanisms for SMA strip strengthened RC components: (a) near-surface mounted reinforcement (NSMR); (b) shotcrete method; (c) NSMR expansion anchor method; (d) nail-based method. Photograph courtesy of Zhang et al.¹⁸ Copyright 2022.

an Fe-SMA strip into the base RC component and the cables connected to SMA for activation and prestress generation on resistive heating of cables by current. For on-site recovery, a new anchoring method is proposed employing shotcrete, as shown in Figure 21b.⁹⁶ The prestressed Fe-SMA tendons are installed beneath the beam with an additional layer of cement (shotcrete), covering the SMA strips. After sufficient curing, resistive heating is induced by the current. Feasibility studies with this anchoring technique conducted on flexural and shear strengthening of RC beams revealed effective improvement in the flexural and shear resistance of the beams.^{96,97} Also, beam

deflections, crack density, and the crack widths were all found to be reduced.

Zafar et al. studied the seismic response of SMA–FRP-reinforced concrete frames using superelastic wires under seismic loading compared to steel-reinforced concrete structures based on damage accumulation and residual drifts.⁹⁸ SMA-reinforced structures are found to perform better compared to steel-reinforced structures in terms of damage accumulation due to their ductility and superelastic response, thus dissipating energy due to hysteretic action of SMAs and returning to their original state upon unloading. This recentering feature is found to be important in moderating the effects of sequential earthquake hazards. Liu et al. designed SMA superelastic springs as the damper in a base isolation system of a multistory building.⁹⁹ They modeled and checked the response under real earthquakes comparing SMA springs versus ordinary elastic springs and found that SMA springs are more effective in controlling maximum and residual deformation of the protected structures. The damping behavior is also investigated by Wierschem et al. for SMA–FRP composites in concrete structures to improve structural damping due to improved ductility and damping capacity.¹⁰⁰ Indirli investigated the prototypal antiseismic device consisting of SMA–CFRP composites using NiTi wires and found SMA provides an undamaged CFRP behavior during all seismic sequences, with the additional benefit of recentering of the wall.¹⁰¹ An investigation on tensile cyclic behavior of SMA/FRP composites as done by Daghash et al. showed recovery of large strains upon unloading, an increase in ductility, and damping of the hybrid composites.⁵⁹ Thus, the research conducted on SMA-reinforced hybrid composites shows that such smart hybrid materials play a significant role in seismic protection applications. More research in this area is required for feasible integration of such systems in buildings that are prone to seismic activities or near the endangered seismic zone.

3.4. Crack Closure Applications. The use of SMAs has also been investigated for healing of cracks and improvement in delamination resistance in composite materials. In such cases, SMAs are integrated transverse to the crack propagation direction as stitches.³²

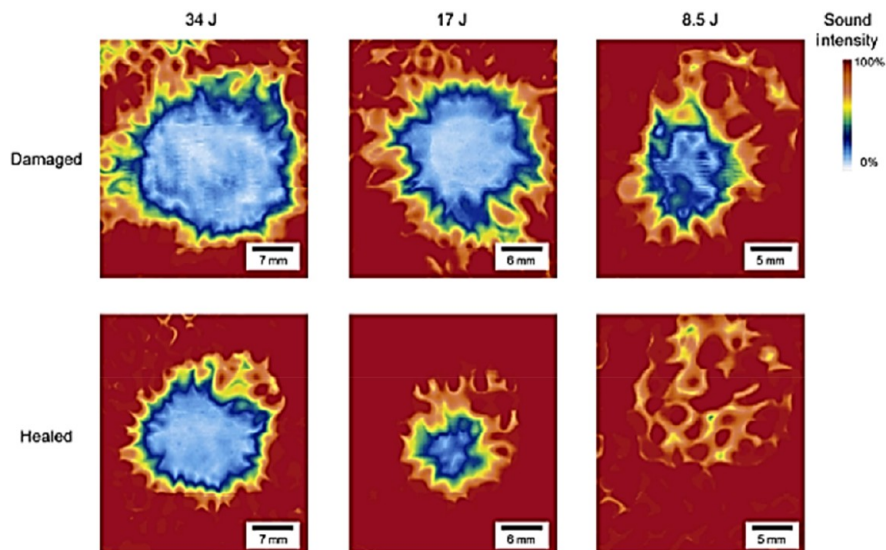


Figure 22. C-scan images of GF-epoxy-PCL FRP specimens containing SMA wires after impact (Damaged) and followed by a thermal cycle of 30 min at 150 °C (Healed) for impact energies of 34, 17, and 8.5 J. Reproduced with permission from ref 53. Copyright 2018 Elsevier.

Cohades et al. investigated the crack closure behavior of SMA wires stitched through-thickness of stacked glass-fiber-reinforced polymer with an epoxy polycaprolactone (EP-PCL) matrix after low velocity impact (17 J). The SMA wires on thermal actuation introduce compressive loads to the longitudinal cracks, resulting in crack closure by about 200 μm .⁵³ Further, the compressed cracks are filled by expansion of the vascular network by the molten polycaprolactone. This results in highly effective healing as cooling occurs. SMA wire-stitched composites showed damage area recovery of 85% after 150 °C heat treatment, which is a 55% improvement in damage recovery compared to unstitched composites. The C-scans of the damage as well as damage recovery after healing in SMA-reinforced GF-epoxy-PCL FRP specimens are shown in Figure 22.

Zheng et al. investigated the repair of fatigue-sensitive steel elements by reinforcing the samples with SMA/CFRP composites.¹⁰² They found that average fatigue lives of reinforced samples were 26.4 and 15.3 times those of the unreinforced samples at stress ranges of 155 and 217 MPa, respectively. Numerical investigation to simulate fatigue crack growth in steel elements patched with SMA/FRP composites using finite element analysis SMA wires also showed increased critical crack length for fracture.¹⁰³ Further, the SMA/FRP patch is found to substantially delay the failure. Investigation of the SMA/CFRP composite for strengthening of fatigue-sensitive metallic structures was also done by Zheng et al.¹⁰⁴ They used NiTiNb SMA wires that could generate 400 MPa recovery stress upon thermal loading and remain stable over a wide range of temperatures and applied compressive stresses near the crack. The SMA/CFRP system was able to withstand 80% of the recovery stress, after up to 2×10^6 loading cycles, as long as maximum applied stress was below the onset of debonding. Thus, SMA/FRP patches proved to be a promising technology for rehabilitation of fatigue-sensitive structures.

3.5. Shape Morphing Applications. Morphing structures can be defined as panels that are capable of self-directed shape change in response to some external stimulus. Such structures are gaining research interest in the fields of aerospace, space, automotive, and robotics industries since they can switch between shapes for optimum performance of the structure.¹⁰⁵ SMAs possess superelasticity and a high power-to-weight ratio, which make them predominantly suitable for the design of adaptable structures.¹⁰⁶ For morphing applications, SMAs are integrated on the non-neutral axis of the hybrid structure. The contraction of SMA elements during activation that may be provided by resistive heating leads to bending deformation or shape morphing of the structure. A schematic of the SMA–FRP actuator in comparison to the mechanical actuator is shown in Figure 23. Reduction in mechanical parts results in smart

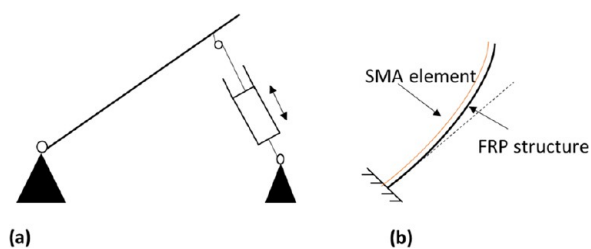


Figure 23. Comparison of actuation mechanisms: (a) conventional mechanical actuator; (b) SMA hybrid actuator. Redrawn with permission from ref 107. Copyright 2013 Sage Publishing.

configuration with weight efficiency, design simplicity, and fuel efficiency in the case of morphing structures of aircraft. The fuel consumption of aircraft is given by the following expression.¹⁰⁷

$$F = c_T \frac{C_D}{C_L} W \quad (2)$$

where c_T is the specific fuel consumption, W is the aircraft weight, C_D is the drag coefficient, and C_L is the lift coefficient. Design of morphing wings can help to improve the C_L to C_D ratio, thus reducing fuel consumption.

When SMA-based composites are used for shape morphing structures, the shape memory effect is primarily utilized in morphing by applying temperature stimulus that can be simply provided by resistive heating.

When a prestrained wire is integrated into a composite, a strain is created in the composite due to the difference between elastic properties of the host and the recovery stress in the wire, given (in one dimension) by

$$\varepsilon(T) = \frac{V_w}{1 - V_w} \frac{\sigma_w(T)}{E_c} - \alpha_c(T - T_0) \quad (3)$$

where T_0 is the thermal load start temperature, E_c is the Young's modulus of host composite, α_c is the thermal expansion coefficient of host, and V_w is the wires' volume fraction. The stress in the composite by the wires, $\sigma_w(T)$, can be obtained through modeling or from a stress–strain curve of a single wire from where recovery can be obtained directly.³²

SMA-based actuated structures are being investigated extensively to reduce complexity of structures and weight efficiency for various research industries.¹⁰⁸ Jung et al. developed a smart air intake structure for aircrafts utilizing a SMA-embedded composite structure.¹⁰⁹ For the aircrafts industry, morphing structures enable optimized aerodynamic performance such as during takeoff, cruising, and landing for improved fuel efficiency. Improved aerodynamic performance is also desired in the automotive industry for fuel saving and improved performance of land vehicles. Sellitto et al. presented case studies to numerically analyze the actuation of the trailing edge of a spoiler (aerospace contextual) and the deformation of a rear upper panel utilizing SMA-based smart devices. The maximum force that can be achieved, displacement, and the operating temperature can be controlled by composition and geometry of the adopted SMA wires.¹⁰⁸ Hübler et al. manufactured and modeled a thin walled carbon-fiber-reinforced polymer sheet with integrated SMAs for bending. They observed 25% deflection of the reinforced composite.¹¹⁰ Ruotsalainen et al. designed a control system using SMA actuator operated airfoil.¹¹¹ SMA wire actuators were embedded into FRP composite structure to bend down the trailing edge. Actuators were activated by Joule heating to control the shape. They proposed the feasibility of using optical fibers sensors and thermocouples for temperature measurement, in active FRP composite structures. Hübler et al. discussed the aerodynamic applications of active SMA-driven FRP structures and designed and simulated an active airfoil.¹¹² They proposed that SMA–FRP actuators were better replacements of common actuators as they offer reduction in number of parts, mechanics, and couplings, thus reducing the complexity of the structure. The SMA–FRP structures for aerodynamic applications also have reduced design-space requirements, lightweight potential, and morphing that allows surface deflection to improve aerodynamic efficiency and performance by design of multiwinglets or active

trailing edge control of aircrafts. To optimize the aerodynamic drag requirements switching between multi- and single-winglet design would help for cruising and takeoff or landing.^{113,114}

Baz et al. investigated the shape control of glass fiber composite beams using NiTi flat strips experimentally and numerically and showed that the shape of the composite beams can be effectively controlled without compromising their structural stiffness, as shown in Figure 24.¹¹⁵

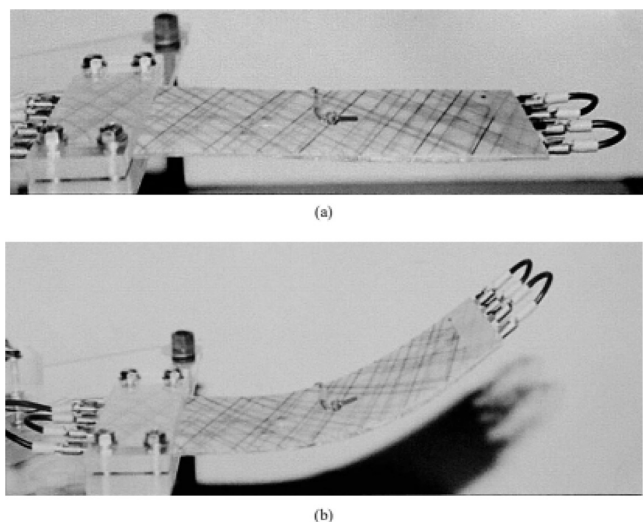


Figure 24. Photograph of GFRP beam reinforced with SMA strips: (a) initial unactivated position and (b) activated position. Reproduced with permission from ref 115. Copyright 2000 Elsevier.

Shape morphing if properly controlled and integrated in vehicle manufacturing industries from land vehicles to aerospace can revolutionize industrial research. In this world where energy saving issues are becoming vital and fuel resources are reducing, this state-of-the-art green technology can be implemented commercially to play a role.

3.6. Self-Deployable Structures. Space structures such as solar battery panels are large structures that need a foldable configuration at launch. A metallic hinged foldable configuration adds weight to the structure. Composite structures on the other hand offer high stiffness and strength at low weight can be better candidates for aerospace structures.¹¹⁶ Lan et al. worked on a shape memory releasing mechanism of smart arrays of solar cells.¹¹⁷ Figure 25 shows SMA-based automated foldable solar

panels that work with the shape memory effect by utilizing heat from solar energy, as developed by Yun et al.¹¹⁸ They worked on tracking solar energy to maximize energy output. Results from simulations show a large cross-sectional area perpendicular to sunlight, providing a 60% increase in electricity production over 1 day.

The reliability of space-based composite structures in a space environment can be studied by the work done by Baluch et al.^{119–122} Todoroki et al. proposed a partially flexible foldable structure using SMA wires embedded in the CFRP composite.¹²³ The embedded SMA wires' compactly folded composite panel structures without loading and Joule heating of the SMA wires enable self-deployment of the composite structure. Pollard et al. developed a SMA wire-reinforced CFRP deployable structure.¹²⁴ They mapped force profile numerically and experimentally through deployment path of a 450 mm radius, deployable elastic composite shape memory alloy-reinforced (DECSMAR) boom.

The research shows the potential of SMA-based composites in self-deployable structures. The significant feature of the deployable structures is that it does not need mechanical actuators that consume more space and add weight to the system. Thus, the smart structures can be a better substitute of the mechanical systems used in deployment systems.

4. CONCLUSIONS

FRPs are used in many research applications due to their good weight efficiency, corrosion resistance, and fatigue resistance. Their mechanical properties such as damping and vibration, brittle behavior, impact properties, fatigue resistance, and flexural resistance can be enhanced by integration of SMAs, resulting in smart hybrid composite SMHCs as SMAs have better actuation response compared to that of other smart functional materials. For actuation applications, SMAs with small hysteresis are preferred, whereas for impact damping applications, large hysteresis SMAs are preferred to dissipate more energy. 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. Also, the inherent delamination and crack propagation behavior of FRPs in stitched configuration is reduced in SMAHCs. An important issue of SMHCs is the interfacial bond strength of SMHCs that must be taken into consideration, and the SMA wires should be treated either mechanically or chemically to improve the adhesion with the matrix. Also, heat

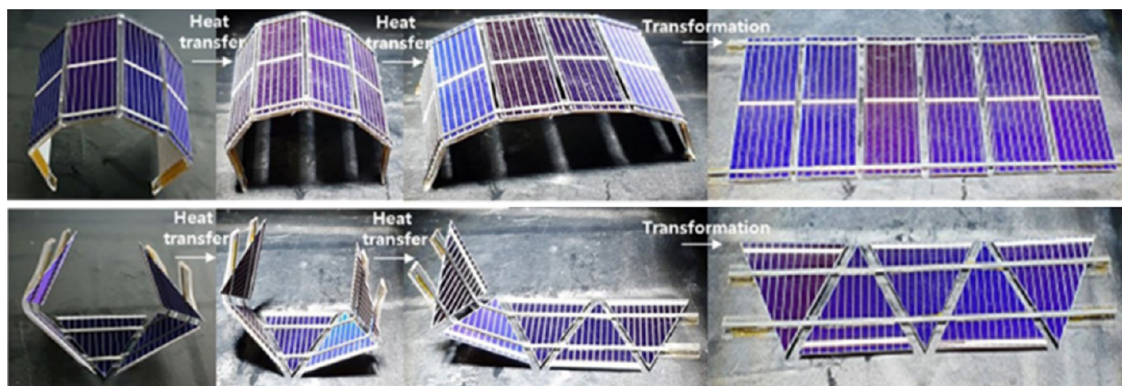


Figure 25. (a) Photographs of the transformation process of rectangular and equilateral triangular solar cells from folded to flattened configuration. Photograph courtesy of Yun et al.¹¹⁸ Copyright 2022.

transfer kinetics should be taken into account that transform the SMAs in composites that deform the laminate. In the case of shape morphing SMHCs, the stress concentration during bending of SMA elements must be taken into account to avoid failure.

Hybrid SMA–FRP composites can act as better smart actuators compared to the mechanical actuators in terms of design simplicity and weight-saving solutions for the transport industry and can lead to the development of self-deployable structures for structural and space applications and also for increasing efficiency of solar panels. SMHCs can also be used for development of shape-morphing structures for improved aerodynamics and fuel efficiency of aircrafts and automobiles and help to overcome the energy crises if commercially integrated in vehicles from automobiles to aerospace.

Thus, successful development of SMHCs has a wide range of applications in different areas and is the state-of-the-art technology as a smart composite. The future of this technology can evolve the modern world. The requirement is to take an initiative toward smart systems from conventional counterparts.

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Author Contributions

Huma Ozair conceptualized, planned and carried out the experiments, and prepared the original draft. Abrar H. Baluch contributed to the analysis and interpretation of the review. Muhammad Atiq ur Rehman validated and edited the original draft. Abdul Wadood supervised and critically reviewed the research and manuscript. All the authors provided valuable feedback and helped to shape the manuscript.

Notes

The authors declare no competing financial interest.

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