Review

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Advances in SMA-Based Reinforcement in Steel Structures: A Review

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Advances in SMA-Based Reinforcement in Steel Structures: A Review

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Abstract: Shape Memory Alloy (SMA) have emerged as a revolutionary material that holds the potential to change the design and construction methods of buildings and other structures. One of the most promising applications of SMAs in civil engineering is their use as reinforcements for steel structures. This paper presents the latest research progress, opportunities and challenges of SMA in the field of steel structural reinforcement, both in terms of basic components and applications. In terms of components, the construction forms and working mechanisms of Fe-SMA strips, SMA/CFRP composite patches and SMA dampers are introduced. On this basis, the application of SMA in steel structures reinforcement is introduced, and its effect is analyzed from three aspects: crack restoration, seismic retrofitting and structural strengthening. Finally, the results of the current research are summarized and the shortcomings are analyzed, hoping to provide a reference for the research of SMA in the field of steel structures reinforcement.

Keywords: steel structure; shape memory alloy (SMA); reinforcement; review

1. Introduction

Steel structures play an indispensable role in modern society due to their high strength, good light weight, plasticity and durability [1]. However, steel structures can be deteriorated due to factors such as corrosion, fatigue or accidental loading under long-term service conditions. United States Federal Highway Administration has shown that fatigue is one of the main causes of steel structure's failure and more than 80% of steel structures fail due to fatigue[2]. Moreover, fatigue is typically catastrophic to the structure and can result in significant economic and human losses[3,4]. Traditional reinforcement methods including crack stopping holes, adding steel plates, welding, etc. can be used to strengthen structures, but they have some disadvantages such as increased weight, difficulty in application, and susceptibility to corrosion and fatigue damage[5]. Therefore, the researches for more efficient and economical reinforcement techniques have been a popular area of civil engineering in recent years[6].

Shape memory alloys (SMA) as a new smart material, have been widely used in medical and aerospace applications[7–9]. In recent years, it has also been introduced into the field of civil engineering by many scholars due to its cost-effectiveness and unique properties. One of the highlights is the research and development of various SMA-based components and devices. In addition, many scholars have introduced SMA into the field of structural reinforcement. While searching for new reinforcement techniques, it is hoped that the reinforced structure can satisfy the demand of bearing capacity and have certain seismic toughness. This paper takes the SMA-based reinforcement in steel structure as the theme, reviews the research results, opportunities and challenges at the present stage from three aspects, namely, material properties, SMA-based components and technology, and application of SMA-based reinforcement, in the hope of providing references for the further research of SMA in the field of reinforcement in` steel structure.

2. Material properties of SMA

Low-temperature stable martensite and high-temperature stable austenite are the two main phases of SMA, the fundamental characteristic of SMA is the reversible transition between martensite

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and austenite[10]. Additionally, SMA will exhibit the shape memory effect and the superelastic effect by different triggering mechanisms. These two effects and the damping effects are the main reasons why SMA are used in civil engineering[11].

2.1. Shape memory effect

The shape memory effect is the ability of a deformed SMA to return to its initial shape after a certain thermal activation. The characteristic temperatures of shape memory effect include:

(1) A_s (Austenite Start Temperature): The temperature at which the transformation of martensite to austenite starts.

(2) A_f (Austenite Finish Temperature): The temperature at which the full transformation of martensite to austenite.

(3) M_s (Martensite Start Temperature): The temperature at which the transformation of austenite to martensite initiates.

(4) M_f (Martensite Finish Temperature): The temperature at which austenite fully transforms to martensite.

Figure 1 shows the shape memory effect of SMA. It should be noted that SMA transforms from twinned martensite to detwinned martensite under stress at temperatures below M_f, the deformation of the SMA does not disappear completely with the disappearance of the stress (With residual deformation). However, the detwinned martensite will transform into austenite if the material is heated above A_f. On this basis, SMA changes again from austenite to twinned martensite by lowering the temperature below M_f. At this point, the deformation of the SMA is fully restored (Residual deformation disappears).

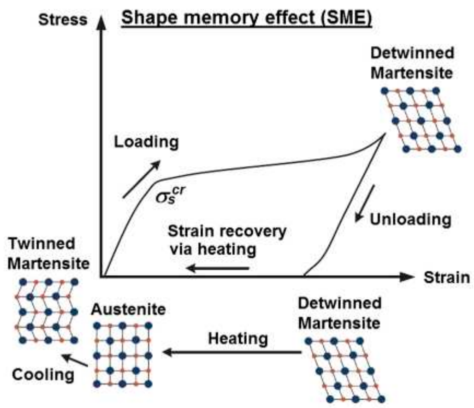


Figure 1. Shape memory effect of SMA[11].

2.2. Superelastic effect and damping effect

While the shape memory effect aforementioned is induced by temperature, the next superelastic effect is induced by stress at a constant temperature greater than A_f. The characteristic stresses of superelastic effect include σA_s, σA_f, σM_s and σM_f.

Figure 2 shows the superelastic effect of SMA. It can be seen that the initial state of SMA is austenite. The SMA starts martensitic transformation when the loading stress reaches σ_{Ms}, at which time the Young's modulus of the SMA is significantly reduced. Subsequently, when the loading stress reaches σ_{Mf}, the SMA finishes the martensitic transformation into the hardening stage. It is worth noting that when the SMA enters the hardening stage, its Young's modulus increases significantly. On this basis, the SMA transforms from martensite to austenite when the stress is unloaded to σ_{As}. And the SMA finishes the transformation from martensite to austenite when the stress is unloaded to σ_{Af}. Finally, when the stress disappears, the deformation of SMA automatically recovers completely, and its recoverable strain is as high as 8%～10%. In addition, it should be noted that the above loading and unloading cycles form hysteresis loops that is resulting in the dissipation of energy, which is the damping effect of SMA.

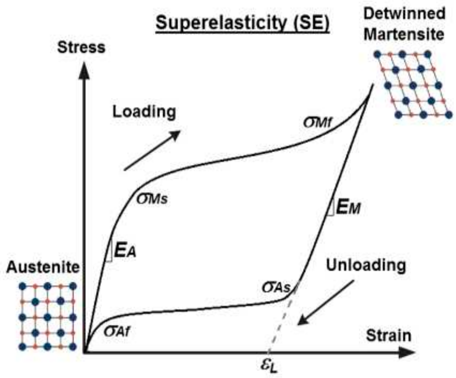


Figure 2. Superelastic effect of SMA[11].

Currently, dozens of shape memory alloys have been discovered, the most valuable in civil engineering of which are Cu-based SMA, iron-based SMA(Fe-SMA) and Ni-Ti SMA [12]. The key characteristics of SMAs commonly used in civil engineering are shown in Table 1. It can be seen that Ni-Ti SMA and Cu-based SMA have lower A_f (austenite at room temperature) and higher recovery strains, so they are often used to improve the limited-displacement and re-centering capabilities of structures by superelasticity effect[13]. Fe-SMA is often used to strengthen structures by shape memory effect[14].

Table 1. Key characteristics of SMAS.

Alloy	Elastic modulus（GPa）	σM_s (MPa)	recovery strain (%)	A_f(℃)	Type	Reference
$Ni_{50.02}$-$Ti_{49.98}$	62.5	401	6	-10	Wire, cable, bar, plate, spring	[15,16]
$Ni_{47.45}$-$Ti_{37.86}$-$Nb_{14.69}$	20	250	3.2	22		[17]
$Cu_{71.9}$-$Al_{16.6}$-$Mn_{9.3}$	31.2	210	7	-39	Wire, cable, bar	[18]
$Cu_{87.68}$-$Al_{11.7}$-$Be_{0.62}$	32	230	2.4	-65		[19]
Fe_{17}-Mn_5-Si_{10}-Cr_4-Ni_1-Vc_{63}	165	396	3.5	162	Bar, strip, plate	[20]

3. SMA-based components and technologies for reinforced steel structures

Currently, many scholars are focusing on the development and research of new SMA-based components and devices, and have already achieved more results. Representative components or devices in the field of reinforcement for steel structures include Fe-SMA strips, SMA/CFRP composites patches and SMA-based damper or brace.

3.1. Fe-SMA strip

3.1.1. Reinforcement mechanism

Fe-SMA is often used to replace steel plates for structural reinforcement due to its low price, corrosion resistance and stable mechanical properties[21–23]. Fe-SMA strips are commonly used component in the field of steel structural reinforcement, the schematically illustrated strengthening procedures of Fe-SMA strips are shown in Figure 3[24]. First, pre-straining was applied to the Fe-SMA strip (step 1), which was subsequently unloaded to a stress-free condition (step 2). Afterwards, the Fe-SMA strip which is obtained from step 2 was connected with the steel beam (step 3) and heated until the temperature reached A_f (step 4), subsequently cooled(step 5). Due to the anchorage, the shape memory effect of the Fe-SMA strips is restricted (deformation of the strip is restricted), thus providing tensile stresses to the steel beam.

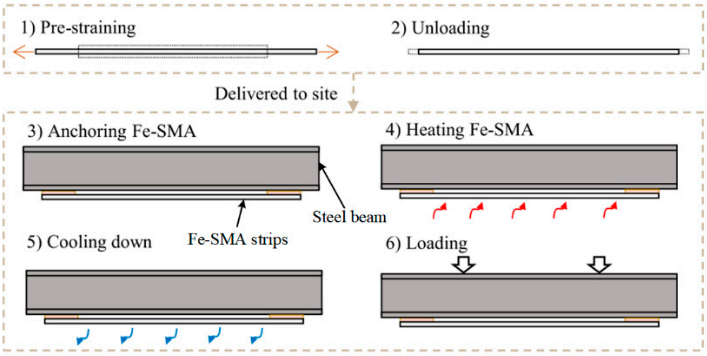


Figure 3. Strengthening procedures of steel beams using Fe-SMA strips[24].

3.1.2. Mechanical properties

The method described above is known as the prior activation method and is often used to repair structural cracks and improve the bearing capacity of structures. The method has received much attention from scholars in recent years due to the convenience of applying prestress to the structure[25].

Fatigue properties is one of the most important reasons for determining whether a component can be used in a reinforced structure, so many scholars have conducted experimental studies on the fatigue performance of Fe-SMA strips. Ghafoori[26] studied the fatigue properties of Fe-SMA strips under high cyclic loading and proposed a safe design formula for Fe-SMA strips as pre-stressing elements. The experimental results show that Fe-SMA strips have very good fatigue properties. Marinopoulou et al.[27] conducted fatigue tests of Fe-SMA strips under prestressing conditions, and the recovered stress of Fe-SMA strips decreased by about 2% compared with that before the test. Hosseini et al.[28] investigated the effect of multiple thermal activation on the pre-stress of Fe-SMA strips and showed that although the pre-stress of Fe-SMA strips subjected to cyclic loading was reduced, it could be restored to its original level by means of secondary thermal activation.

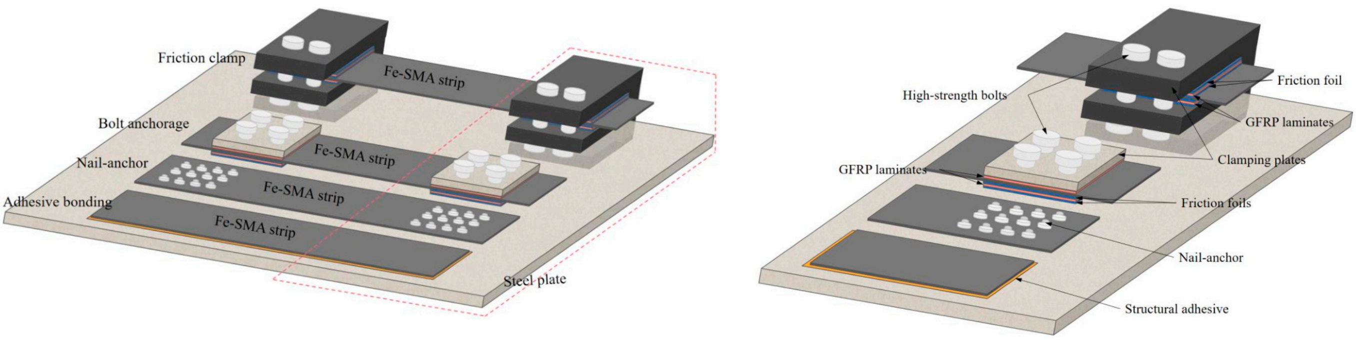
In addition to the fatigue properties, the pre-strain length and activation temperature of Fe-SMA strips have received much attention from scholars because they are related to recovery stresses of Fe-SMA strips. Izadi et al.[29] found that the recovery stress of Fe-SMA strips could reach 430 MPa at the pre-strain of 2% and the activation temperature of 260 °C. More data on the recovery stresses of the Fe-SMA strips under different experimental conditions can be found in Table 2. It can be seen that the activation temperature of Fe-SMA strips is within 160-400 degrees Celsius, which is acceptable for steel structures, but the activation temperature should not be too high for concrete structures, otherwise it may lead to the destruction of the mechanical properties of the concrete. In addition, the size and pre-strain of Fe-SMA strips have an effect on the optimal activation temperature, so the specific parameters of Fe-SMA strips and activation temperature should be determined by experiments in practical applications.

Table 2. Recovery stress of Fe-SMA strips under different experimental conditions.

Alloy	Size（mm）	Pre-strain (%)	Activation Temperature (℃)	Recovery Stress（MPa）	Reference
Fe-17Mn-5Si-10Cr-4Ni-1Vc	0.7×3	4	225	380	[30]
		4	160	330	
	0.9×3	4	160	580	[31]
	1.7×14	4	160	266	[32]
	—	4	160	350	[33]
	1.5×10	2	160	372	[26]
	1.7×25	2	160	177~200	[34]
	0.8×52.5	2	260	406	[35]
	1.5×100	2	160	292	[36]
		2	180	330	
Fe-28Mn-6Si-5Cr-0.53Nb-0.06C	—	4	397		[37]
Fe-28Mn-6Si-5Cr	—	3	300	255	[38]
Fe-18Mn-8Cr-4Si-2Ni-0.36Nb-0.36N				185	
Fe-Mn-Si alloy	1.5×20	2	160	308	[39]
		4	160	348	
	1.5×15.8	≈3	155	268~295	[40]

3.1.3. Connection and activating Methods

The reliable connection between Fe-SMA strips and parent steel components is required when strengthening structures. Connecting methods that have been proposed include: bolt anchorage, nail-anchor, friction clamp and adhesive bonding[29,41,42], as shown in Figure 4[43].



(a) (b)

Figure 4. Connection methods between steel plate and Fe-SMA strips[43].

Where, Izadi et al.[35] proposed a mechanical anchorage system for the anchoring of Fe-SMA strips to steel plates or steel beams (as shown in Figure 5.) and verified the effectiveness of the system by fatigue tests. The results show that the parent structure under this system has better integrity with the Fe-SMA strips and the Fe-SMA strips exhibit very excellent fatigue performance. Fritsch et al.[44] used nails to anchor Fe-SMA strips to steel beams and experimentally analyzed the effectiveness of different nails and their distributions. Wang and Li[45–47] proposed a two-component epoxy adhesive SikaPower-1277 to bond the parent structure with Fe-SMA strips in order to minimize the damage of the parent steel structure. Furthermore, thermal activation methods for Fe-SMA include flame-spraying gun, infrared heating, electric heating furnace, electric ceramic, electrical resistance heating[34,48–50].

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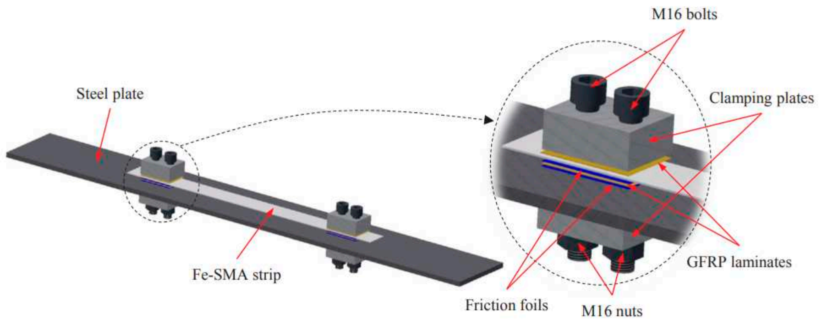

Figure 5. Components of the mechanical anchorage system developed for SMA-to-steel joints[35].

3.2. SMA/CFRP composite patch

3.2.1. Reinforcement mechanism

The effectiveness of pre-stressed Carbon Fibre Reinforced Polymers (CFRP) panels for reinforcing steel structures has been demonstrated by a number of studies[51–55], but how to conveniently apply prestress is a big challenge. To solve this problem, some scholars have proposed the concept of SMA/CFRP composite patches[56], NiTi-SMA wires are frequently employed in these studies, and the term "SMA wire" refers to NiTi-SMA wire unless specified otherwise. Fabrication and reinforcement procedures for SMA/CFRP composite patch are shown in Figure 6[57,58]. First, pre-straining was applied to the SMA wires (step 1), which was subsequently unloaded to a stress-free condition (step 2). Afterwards, the SMA wires which is obtained from step 2 and CFRP materials were glued together to form the SMA/CFRP composite patches (step 3). Then anchored the SMA/CFRP composite patch to the steel beam and heated until the temperature reached A_f (step 4), subsequently cooled (step 5).

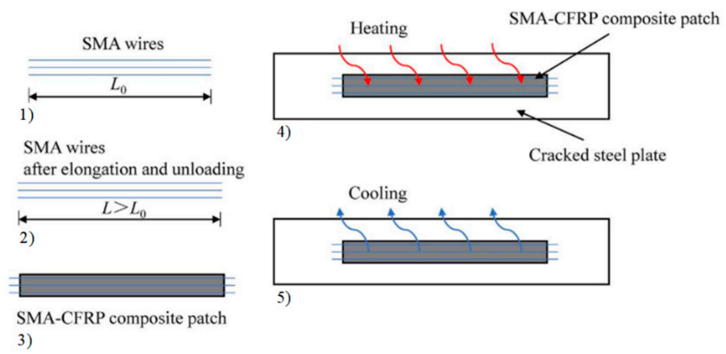

Figure 6. Fabrication and reinforcement procedures for SMA/CFRP composite patch[57].

Currently, there are two types of SMA/CFRP composite patches, one as shown in Figure 6, where the SMA is fully composite with the CFRP by means of a bonding adhesive. The patch can only be heated by electric current, and the heat resistance of the bonding adhesive needs to be considered. The other is shown in Figure 7, the advantage of this system is that the activation section is exposed and the heat resistance of the epoxy resin does not need to be taken into account when heating the section[59,60].

Figure 7. SMA/ CFRP composite prestressed strengthening system[59].

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3.2.2. Bonding performance between SMA and CFRP

It can be seen that the SMA/CFRP composite patch does not require large tensioning equipment and its prestressing is applied to the structure using the shape memory effect of SMA. However, effective bonding between SMA and CFRP is a prerequisite for the patch to work properly. Currently, epoxy resin is commonly used as an adhesive between SMA and CFRP, and many studies have demonstrated its effectiveness[57,61–65]. Furthermore, Zheng et al.[66] bonded SMA wires to CFRP with epoxy resin and experimentally investigated the bonding performance of the patches, and the results showed that a reasonable selection of the number of SMA wires could effectively avoid the debonding of the two. El-Tahan et al.[67] showed that the patch can be effectively prevented from debonding by increasing the anchorage length between SMA wire and CFRP. In addition, Gu et al. [68]pointed out that debonding between SMA and CFRP in SMA/CFRP composite patches is the main reason for the degradation of their mechanical properties, and in order to solve this problem, they proposed the idea of fabricating new specimens with orthogonally embedded SMA wires and sandwiched two-dimensional SMA film lattices, which is expected to solve the debonding risk.

3.2.3. Mechanical properties

In order to prove the effectiveness of this method, many studies have been conducted. Yang et al. [69] investigated the fracture behavior of SMA/CFRP composites using bending and charpy impact tests. Their findings indicated that incorporating SMA alloy into conventional composites enhances the ductility and impact resistance of the hybrid composite. Gu et al.[68] showed that embedding SMA wires into CFRP can effectively improve the energy absorption capacity and toughness of CFRP. Abdy et al.[61]developed a self-prestressing CFRP/SMA composite patch and verified its effectiveness through tests, as shown in Figure 8. The results demonstrate that it can be used as simple and effective solutions to significantly enhance the fatigue life of cracked steel structures. Furthermore, El-Tahan et al.[70] proposed an SMA/CFRP composite patch and investigated its fatigue properties experimentally, which showed that the patch retained more than 80% of its prestress after undergoing 2 million loadings. Deng et al.[71] also compared SMA/CFRP composite patch , CFRP sheet and SMA patch reinforcement through experiments, and the results showed that SMA/CFRP composite patch was better. Russian et al.[72] investigated the effect of surface preparation on the effectiveness of SMA/CFRP composite patches for reinforcing steel structures. The results show that smoother steel surfaces resulted in less effective reinforcement with SMA/CFRP composite patches.

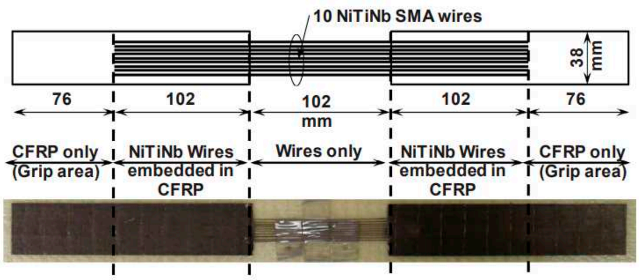

Figure 8. SMA/CFRP composite patch which is developed by Abdy[61].

3.3. SMA-based damper and brace

SMA dampers can provide stiffness and are usually used in conjunction with anti-lateral brace. SMA dampers typically utilize the superelastic and damping effects of SMA to provide energy dissipation to a structure while reducing its lateral displacement and providing the ability to self-centering[73]. Liu et al.[74] designed a tension-compression SMA damper and obtained its characteristic parameters through tests. The experimental results demonstrated the distinct effectiveness of SMA dampers in reducing displacement and acceleration responses of structures. Han et al.[75] proposed a NiTi-SMA wires-based damper capable of tension, compression, and

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torsion simultaneously. Qiu et al.[76] proposed a new type of damper, which combines SMA elements with steel dampers based on bending steel plate. Ma et al.[77] proposed a new SMA-based damper mainly consisting of pre-tensioned SMA wires and two pre-compressed springs, the damper shows both good energy dissipation capacity and re-centring capability. Sui et al.[78] proposed a novel SMA-based damper making use of SMA wire as shown in Figure 9. It can be seen that the SMA wire is always in tension whether the damper is in compression or tension. Qiu et al.[79] proposed an SMA-based anti-buckling damper by combining SMA bolts with a variable friction mechanism, as shown in Figure 10. It can be seen that whether the damper is in tension or compression, the SMA bolts is in tension, as shown in Figure 10(b). Thus effectively avoiding the problem of SMA bar buckling. Jia et al.[80] proposed an innovative double SMA damper system. In the proposed system, double SMA elements with different phase transition temperatures are arranged in parallel. Fang et al.[81] proposed a shear damper based on Fe-SMA, as shown in Figure 9. In comparative tests with mild steel damper it was found that Fe-SMA dampers offer improved ductility and fatigue properties.

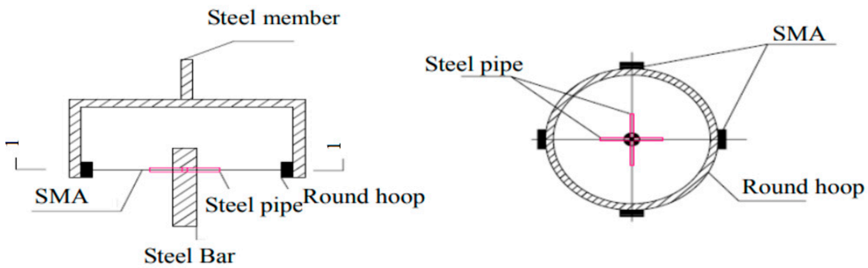

Figure 9. SMA damper[78].

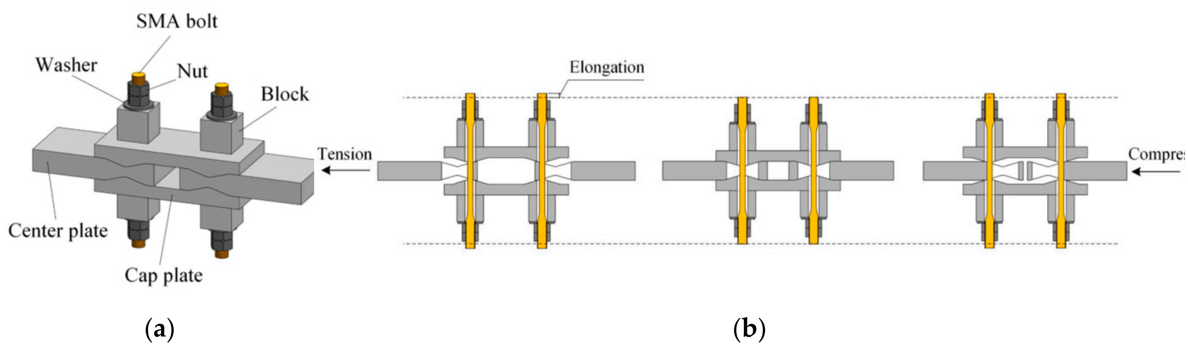

Figure 10. SMA slip friction damper[79]: (**a**) Configuration; (**b**) Sliding mechanism under axial loading reversals.

In addition, the SMA-based self-centering restrainers has also made great progress in research. Miller et al.[82] used SMA bars in BRB to reduce the residual deformation of the brace, as shown in Figure 11. It was found that the brace had good energy dissipation and self-centering ability, and the self- centering ability was related to the SMA bars. Yang et al.[82] evaluated the performance of hybrid seismic bracing with a core consisting of SMA wires and energy-consuming struts, where the SMA wires were designed to be within a maximum strain of 6%. Numerical analysis shows that the frame structure with hybrid damping bracing can have similar energy dissipation capacity as the BRB bracing system, and at the same time, it has better self-centering capacity. Shi et al.[83] propose a brace based on SMA cables, and the cables are configured within bracing system in a way that they are only subjected to tensile loads regardless of the loading direction of the bracing itself. Ozbulut et al.[84] proposed a method to optimize the design of SMA-based braces, using which the best SMA parameters can be obtained. In order to prevent buckling of SMA rods during compression, Cao et al.[85] proposed an anti-buckling system and designed long-stroke SMA restrainer(LSR), as shown in Figure 12. Numerical simulations demonstrate the effectiveness of the anti-flexing system, and the LSR exhibits excellent displacement-limiting and self-recenting capabilities.

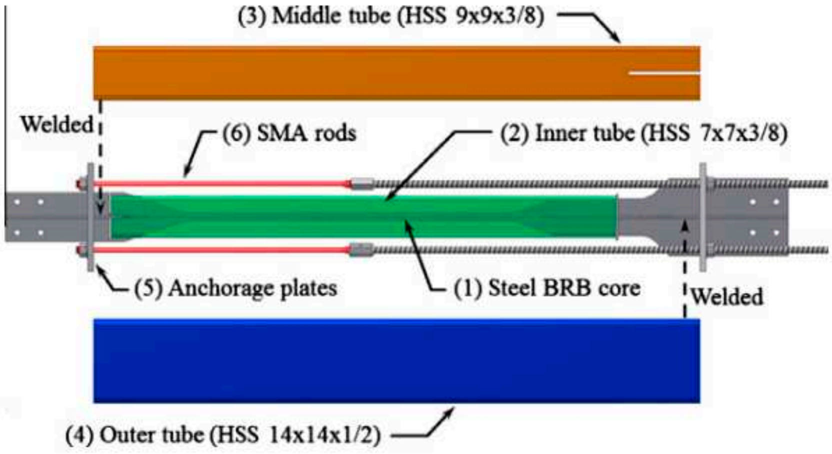

Figure 11. Self-centering buckling-restrained brace behavior[82].

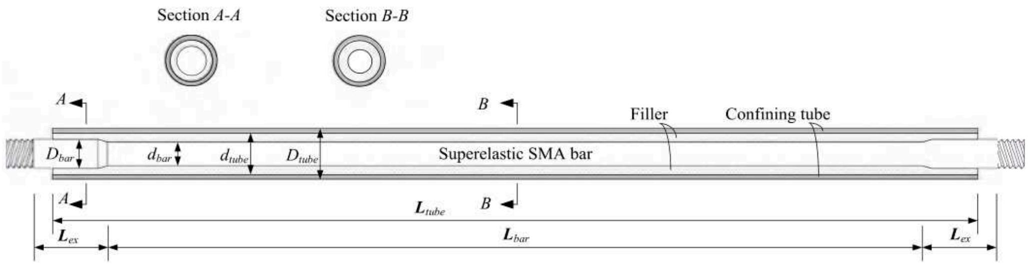

Figure 12. Long-stroke SMA restrainer[85].

4. Applications of SMA-based reinforcement in steel structures

The effectiveness of SMA-based components and technology in steel structures reinforcement needs to be demonstrated in its application. One notable example of SMA engineering applications is the practical reinforcement of cracked diaphragm cutouts on the Sutong Bridge. This application demonstrates the real-world effectiveness of SMAs in addressing structural issues and enhancing the durability and safety of critical infrastructure. This section discusses the application of SMA in the field of steel structures reinforcement from three aspects: crack repair, seismic retrofit and structural reinforcement.

4.1. Crack Restoration

Fatigue cracks in steel structures can potentially lead to structural damage and failure. SMAs can be employed to repair these cracks by applying force in the affected area to close the crack and maintain its stable state, preventing further crack propagation. Qiang et al.[86] proposed a Fe-SMA plates covering crack-stop holes method, and the repair process was shown in Figure 13. Pre-strained Fe-SMA patches were first applied to the reinforced area and then thermally activated the Fe-SMA patches to repair the cracks using the shape memory effect of SMA. The results show that the fatigue notch factor is reduced by 66.36% by bonding the Fe-SMA plate, and can be further reduced by about 14% after activating Fe-SMA. Izadi et al.[41] investigated the crack repair effect of Fe-SMA strips by tests. The experimental results showed that Fe-SMA strips significantly increased the fatigue life of the specimens and the stresses generated by the activated Fe-SMA strips could completely limit the development of fatigue cracks in the parent structure.. In addition, Izadi et al.[42] used Fe-SMA strips to retrofit fatigue-cracked riveted connections in steel bridges. The results show that the crack development can be effectively inhibited and the load-bearing capacity can be increased by activating the SMA strips.

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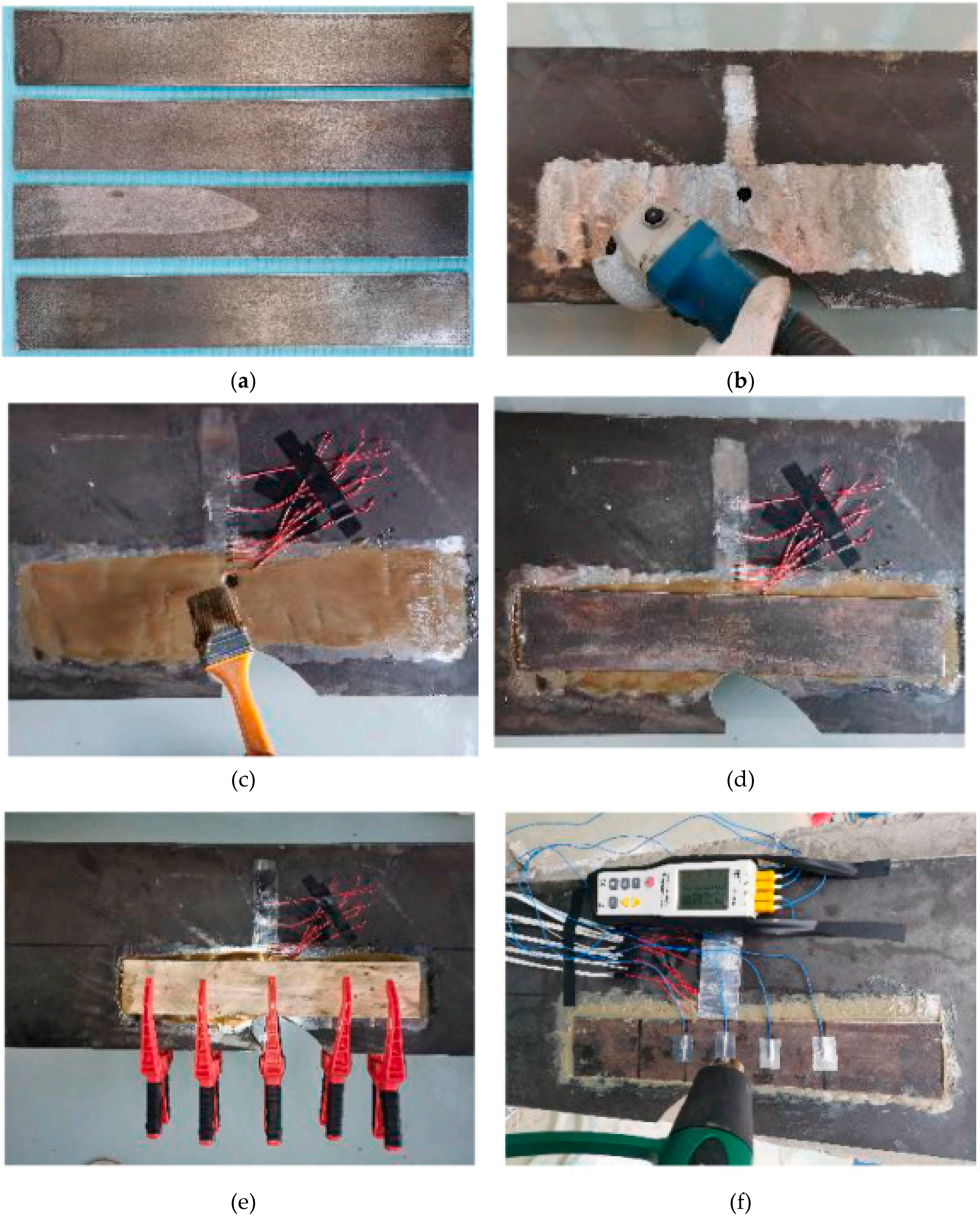

Figure 13. Repair process of the Fe-SMA strips covering crack-stop holes[86]: (**a**) Prepare pre-tensioned Fe-SMA strips; (**b**) Polish and clean the steel strips; (**c**) Apply structural adhesive; (**d**) Bond Fe-SMA strips; (**e**) Pressurized maintenance for five days; (**f**) activate Fe-SMA strips with hot air gun.

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Zheng et al.[87] comparatively analyzed the effectiveness of SMA wire reinforcement, CFRP reinforcement, and SMA/CFRP reinforcement through experimental studies in crack restoration of metallic structures, as shown in Figure 14. The results showed that the fatigue life of the members reinforced with SMA wire and CFRP increased by 8 and 1.7 times, respectively, compared with that of the unreinforced members, while the fatigue life of the members reinforced with SMA/CFRP increased by 15-26 times. Kean et al.[88] investigated the factors affecting the reinforcement effect of SMA/CFRP composite patches by fatigue tests. The results showed that the factors affecting the reinforcing effect of steel and include the amount of SMA, Young's modulus of CFRP, crack type and crack width, and the reinforcing effect of the edge-cracked specimen was better than that of the center-cracked specimen. Qiang et al.[89] proposes two repair methods of the CFRP sheets and SMA/CFRP composite patches on the basis of crack-stop holes to repair cracks of the diaphragm cutouts. Fatigue tests showed that the fatigue notch factor of CFRP and SMA/CFRP patches decreased by 12.28% and 30.76%, respectively, compared to the placement of stopcrack holes only. Deng et al.[90] experimentally investigated the reinforcing effect of SMA/CFRP composite patches, the results show that the SMA/CFRP composite patch can increase the fatigue life of the parent structure by about 8 times compared with the control specimen, which is much better than using SMA or CFRP reinforcement alone.

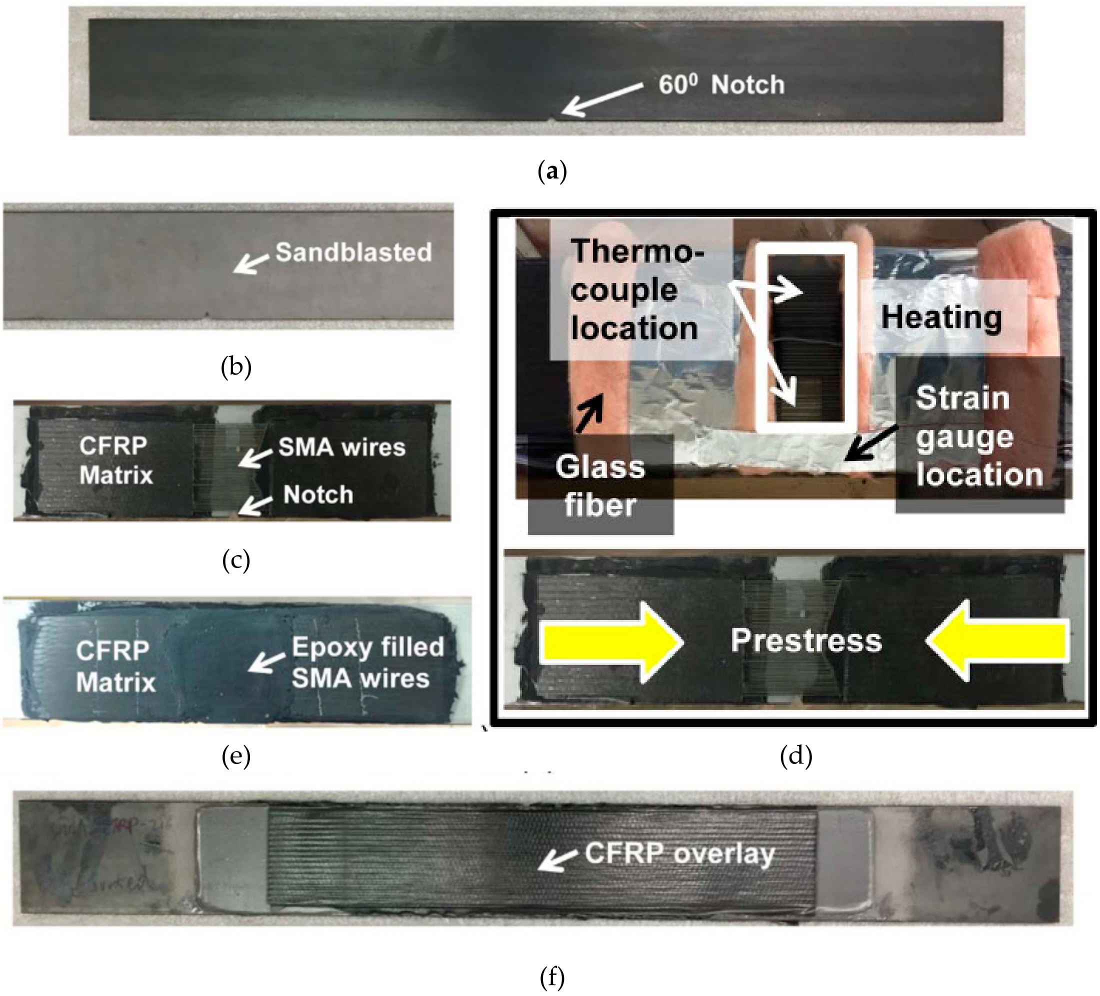

Figure 14. Process of strengthening steel plate with SMA/CFRP patch[87]: (**a**) Notched steel plate; (**b**) The plate surface after sand-blasting and cleaning; (**c**) SMA wires are placed; (**d**) The SMA wires were activated after the epoxy cured for 7 days; (**e**) The exposed SMA wires were covered with a structural epoxy paste after activation; (**f**) Two layers of HM carbon fiber were overlaid on top of the SMA wires.

4.2. Bearing capacity reinforcement

The first practical engineering application of Fe-SMA strips in the reinforcement of a bridge structure was in the metallic girder of a historical roadway bridge in Petrov nad Desnou, Czech Republic where pre-strained Fe-SMA strips were reinforced to the steel girders, as shown in Figure 15. The results showed that Fe-SMA strips can effectively improve the force on the lower flange of the steel girder and increase the yield strength and ultimate bearing capacity of the steel girder[91]. Furthermore, Deng et al.[92] used SMA/CFRP composite sheets to improve the flexural stiffness of notched steel beams.The four-point bending test results showed that compared with the unreinforced beams, the ultimate load and flexural stiffness of the SMA/CFRP composite reinforced beams increased by 79.2% and 57.9% respectively, basically equal to the sum of the effects of SMA reinforcement alone and CFRP reinforcement alone. Hosseinnejad et al.[93,94] increased the bearing capacity of steel beams by arranging prestressed SMA tendons outside their bodies. The analysis results show that the arrangement of SMA tendons increases the structural load carrying capacity more than the arrangement of steel tendons, and the pre-stressing is conveniently applied.

Figure 15. Historic steel road bridge [91]: (**a**) 3D view; (**b**) Damage point 1; (**c**) Damage point 2; (**d**) Installation of the Fe-SMA strips.

4.3. Seismic Retrofitting

One of the important applications of SMA is the seismic retrofit of steel structures. Researchers have investigated the use of SMAs as energy dissipation and limiting devices in seismic systems.

Xing et al.[95] simulated the seismic response of a steel frame with SMA dampers, and the displacement and acceleration of the structure was reduced by at least 50%. Li et al.[96] proposed a double X-typed SMA (DX-SMA) damper and it is installed in a frame-typed bridge pier, as shown in Figure 16. The results of the time-history analysis show that the installation of DX-SMA increased the overall displacement-limiting capacity of the structure and reduced the residual displacement of the structure. Lv et al.[97] combined SMA with TMD to develop a new damper, called SMAS-TMD, and the seismic performance of the frame equipped with the SMAs-TMD is analyzed by shake table tests. The results show that combining SMA with TMD can effectively suppress the detuning phenomenon that often occurs in classical optimal TMD. Qiu et al.[98] placed a SMA-based innovative self-centering damper on steel frame then the earthquake excitations were applied to the structures.

Numerical results show that the displacement response of the structure equipped with SMA-based dampers is significantly reduced compared to the original structure.

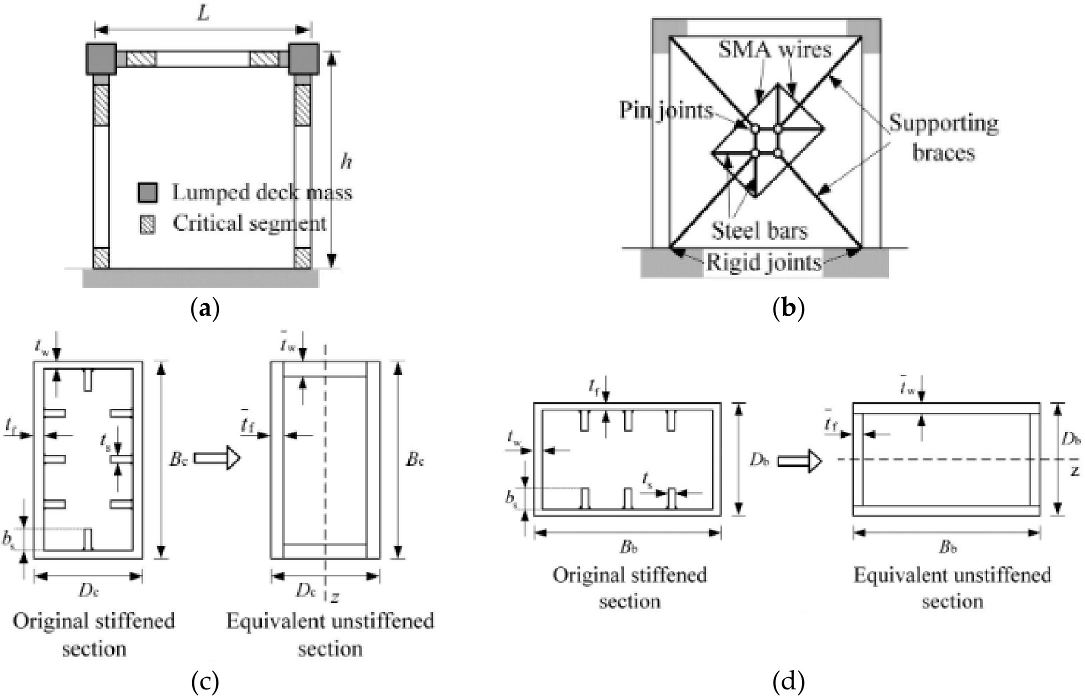

Figure 16. Model of bridge pier[95]: (**a**) Main frame; (**b**) Bridge pier with DX-SMA damper; (**c**) Column section; (**d**) Beam section.

Asgarian et al.[99,100] compared and analyzed the seismic performance of steel frames equipped with SMA braces and BRB. The result shows that SMA can improve the dynamic response of structures subjected to earthquake excitations, but the energy dissipation of structures with the BRB system was higher than that of structures with the SMA bracing system. Fahiminia et al.[101] used BRKB in two structures with different number of layers and added SMA to the core of BRKB. Subsequently, nonlinear time-history analysis of the two structures was carried out and the results showed that adding SMA to the BRKBs can reduce the residual deformations of the frames more than 50%. Vafaei et al.[102] studied the response of SMA mega brace under seismic action, as shown in Figure 17. The analysis results show that SMA braces exhibit better performance than BRB braces under near-field seismicity, but under far-field seismicity, SMA braces produce larger interlayer displacement angles. Qiu et al.[103] proposed a novel SMA brace, then the seismic performance of the frame with SMA brace was assessed by shake table tests. The results show that the structure has a good self-centering ability and the SMA bracing can withstand multiple earthquakes without repair after the earthquake. In addition, Qiu et al.[104] also proposed a design method for seismic retrofit of steel frames with SMA-based bracing, and numerical simulations were performed to validate the proposed design method. The results show that the overall seismic performance of the structure can be improved by 10%-30% with reasonable selection and arrangement of SMA-based bracing.

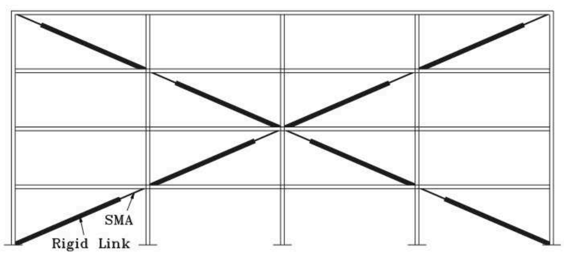

Figure 17. SMA bracing system[102].

5. Analysis and discussion

(1) At present, most of the research on SMA is based on Nitinol-SMA and has been more perfect, but the research on Fe-SMA is still in the initial stage. Although Fe-SMA is not as good as Nitinol-SMA in terms of performance and existence form, its relatively low price makes it has the potential to be widely used in practical engineering. Therefore, it is still necessary to take a step further into the basic mechanical behavior of Fe-SMA and consider the factors affecting the mechanical properties of Fe-SMA from the perspective of practical applications.

(2) The design and development of SMA-based components are mainly focused on the seismic field, but there are relatively few in the field of structural reinforcement. In fact, SMA has great potential for application in the field of structural reinforcement, and its core competencies compared to traditional reinforcement methods include: 1) Self-Adaptability, SMAs possess shape memory properties, allowing them to adapt their shape based on external temperature or strain conditions. This means that SMAs can actively apply restoring forces when the structure is subjected to external loads or deformations, enhancing the structural stability and resistance; 2) Lightweight, SMAs are relatively lightweight, so they can reinforce structures without adding excessive additional weight. This is particularly advantageous for situations where reducing loads is important, such as the maintenance and retrofitting of old or unstable structures; 3) Minimal Construction Required, SMA reinforcement typically requires less construction work compared to traditional methods. This can reduce construction time and costs, as well as minimize disruption to the original structure; 4) Excellent Controllability, the properties of SMAs can be customized through alloy composition and heat treatment to meet specific engineering requirements. This allows for precise design and tuning based on the needs of a particular project; 5) High-Temperature Performance, SMAs typically exhibit good performance at high temperatures, which is crucial for structures operating in high-temperature environments, such as industrial equipment or buildings in hot regions; 6) Self-Healing, SMAs have some degree of self-healing capability and can restore their original shape through external stimulation, reducing maintenance and repair costs. Therefore, there is still much room for research and development of SMA-based reinforcement components, both in terms of form and function.

(3) Currently, the use of SMAs in steel structures reinforcement is not very common and current research is still at the conceptualization stage, thus there is a need to intensify research in this area. In addition to the above-mentioned research and development on material properties, SMA-based components and technologies, there is a need to develop advanced construction techniques applicable to SMA reinforcement, such as SMA activation methods and connection methods. On this basis, design methods for SMA-based structural steel reinforcement should be explored, and clear design guidelines and criteria should be established to ensure the correct application of SMA in different situations.

6. Conclusions

(1) The study of the mechanical behavior of Fe-SMA under different environmental conditions needs to be strengthened, and the influence of the loading history on the shape memory effect is not well understood.

(2) The research on SMA-based reinforcement components and techniques needs to be deepened, especially for Fe-SMA-based components.

(3) Previous studies have only focused on the fatigue performance of SMA reinforcement and have not analyzed the improvement of the overall seismic performance of the structure after SMA reinforcement. Due to the characteristics of SMA, this aspect of research should also be emphasized.

(4) A rational design method is the basis for engineering applications. Scholars have verified the feasibility of applying SMA to steel structures reinforcement, but no comprehensive SMA-based design method has been proposed for steel structures reinforcement.

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