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The application of shape memory alloy technology in steel, timber and concrete connectors

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Abstract. Shape memory alloys (SMAs) are a family of functional materials with unique properties that make them ideal for use in seismic-resistant structures in civil engineering. SMAs undergo phase transformation in response to temperature and stress, enabling them to effectively absorb energy during dynamic loading cycles, thus maintaining structural integrity through their shape memory effect and pseudo-elasticity of phase transitions. This paper aims to summarize previous experiments conducted to identify the unique features of SMAs and their application advantages in steel, timber, and concrete components. Furthermore, areas where design and manufacturing can be improved to optimize the full potential of SMAs for practical and economic use during seismic forces or other dynamic loads are suggested. In conclusion, SMAs exhibit unique physical properties that make them an innovative solution for structural applications. The demand for highly reliable, seismic-resistant structures is increasing globally, and SMAs provide a reliable and economical alternative approach to satisfy this demand. The practical application of SMAs in civil engineering will contribute to the creation of new knowledge, innovative design possibilities for engineers, and safer structures for the population.

Keywords: SMA connectors, Shape memory alloys, Seismic.

1. Introduction

Shape Memory Alloy (SMA) is a unique functional material that exhibits reversible phase transformations in response to temperature and stress changes. This property makes it highly attractive as a smart material, with unique properties such as shape memory, pseudo-elasticity, and sensing capabilities. The transition between the two crystal structures of SMAs - austenite at high temperatures and martensite at low temperatures - is the key factor that gives SMAs their unique memory properties. This conversion plays a crucial role in the shape memory effect, which can be categorized into three main types: one-way, dual-pass, and whole memory effect.

The one-way memory effect refers to the ability of SMAs to restore their original shape only during the heating process. The dual-pass memory effect involves the recovery of the high-temperature phase shape upon heating and the low-temperature phase shape upon cooling. In contrast, the whole memory effect involves the recovery of both high-and low-temperature phase shapes, but with opposite orientations upon cooling, making it a highly impressive property.

SMAs also exhibit pseudo-elasticity, which allows them to restore significant deformations under external forces in the austenite state at high temperatures. However, this property is accompanied by a

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nonlinear stress-strain curve and the dissipation of energy, which should be considered when using SMAs in engineering applications.

In civil engineering, SMAs can be used as connectors in various structures, including steel, timber, and concrete. The excellent mechanical properties of SMA connectors, such as high ductility, corrosion resistance, and fatigue resistance, offer several advantages over traditional connectors.

Despite these significant benefits, further studies are still required to improve the behavior and performance of SMAs under different environmental and loading conditions. Future research should consider the development of new SMA alloys, design improvements, and innovative applications in civil engineering to improve the overall performance and behavior of SMA connectors.

This paper aims to present a summary of the use of SMAs in civil engineering, focusing on their application as connectors. The advantages of SMA in various structures, including steel, timber, and concrete, are discussed through multiple applications. Additionally, this paper also highlights potential future research directions and the various considerations that must be taken into account when utilizing SMA in civil engineering.

2. Steel connectors

2.1. SMA bolted

Superelastic SMA have the potential for mitigating damage to major structural members during earthquakes. Wang et al introduced an innovative moment connection, which used SMA bolts and plates to create a self-centering effect, reducing residual displacement after seismic events [1].

Various end-plate moment connection models were evaluated under cyclic load to determine their bending resistance and select the bending moment bearing capacity with lower bolt strength. To achieve the necessary self-centering effect, the plastic hinge was moved from the beam section to the beam-column interface, which may be accomplished using superelastic materials at the connecting interface [1]. Replacing conventional structural steel with hyperelastic SMA bolts and end plates resulted in a significant reduction in residual displacement after an earthquake, meeting ductility requirements, as well as having excellent energy consumption and sufficient stiffness [1].

Further numerical studies demonstrated that adjusting the ductility required control of elongation, and the distance between the top and bottom outermost bolt rows affected the ductility level. Using a mix of high-strength bolts and SMA fasteners such as Nitinol was deemed more cost-effective, as high-strength steel bolts would lead to significant loss of preload force, reducing the stiffness and seismic performance, when the deformation of the bolt position connection is significant [1].

Thin end plates allowed yield before the bolt breaks, resulting in a stronger ductile failure mode with increased energy dissipation capacity, but led to higher residual deformation and inferior connection re-entry capacity. A thin-plate end plate (iron-based SMA) might be used in parallel with the SMA bolt in the connection to provide compensation. Such a new connection system possessed superior energy dissipation capacity, enough strength, stiffness, a stronger ductile failure mode, and re-entry property [1].

In conclusion, using superelastic SMA in moment connections exhibited promising results for reducing damage to major structural members during seismic events. The studies conducted by Wang et al. are crucial for optimizing and advancing the use of these materials in the construction industry.

2.2. SMA plate

Moradi and Alam conducted a study on the use of SMA plates in steel beam-column connections. The researchers used a 3D finite element analysis to examine the impact of SMA plates on the structural properties of beam-column connections, comparing the results to existing experimental findings. The study evaluated the effectiveness of incorporating SMA plates on both beam flanges and webs and the addition of steel flange plates to enhance reentry capacity and prevent plastic hinge formation within the SMA length [2].

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The study found that the implementation of SMA plates in beam webs contributed to a reduction in residual drift angles [2], while the addition of beam flange plates had a relatively insignificant impact on connection behavior under bending loads. Additional steel flange plates were found to reduce plastic hinge formation within the SMA material, significantly increasing reentry capacity [2].

By preventing local buckling of the beam segment, SMA plates effectively stabilized the hysteresis of the connection. However, SMA connections showed a lower energy dissipation capacity due to the flag hysteresis of the material. As a result, they consumed 8% to 58% less total energy than steel connections. An important consideration for the widespread application of SMA plates is their cost, manufacturing constraints, and the choice of appropriate welding or joining methods. The study recommends the use of lower-cost SMA plates, such as iron-based alloys, to decrease costs and improve mechanical processing, making this technology more feasible in construction structures.

To summarize, the study suggests incorporating SMA plates in the beam web to reduce residual drift angles and prevent local buckling. Although beam flange contribution under bending loads is relatively more significant, the addition of SMA plates in the web and beam flange may not significantly alter connection behavior. By including steel flange plates, plastic hinge formation can be reduced, significantly increasing reentry capacity. SMA plates are effective in preventing local buckling of the beam segment, resulting in a more stable hysteresis without compromising strength [2]. While the proof-of-concept study demonstrated the potential of SMA plate technology in advancing innovative connection technologies, cost and manufacturing constraints require further consideration for wider application. Future studies could explore the use of low-cost SMA plates, such as metal-based alloys, which offer improved mechanical processing and material adaptation. The results of the study could prove beneficial for earthquake engineering experts, requiring further exploration in building structures to address current deficiencies [2].

2.3. SMA rods

Schwarze, R. and their team conducted a research project on a novel partially constrained connection prototype that utilized copper-based SMA rods as energy dissipators in beam-column joints. This connection was designed to provide an end-plate connection between a rectangular hollow steel beam and a broad flange steel column, using four 3mm-long CuAlBe rods as austenite rods to prestress the beam end plates to the column flange [3]. Although preliminary numerical simulations did not indicate a significant enhancement of the structure's response to seismic loads by adding CuAlBe rods to beam-column connections, further study of the analytical results from various frame structures is needed before drawing definitive conclusions about the application of SMA connections in moment-resistant frames [3]. In conclusion, Schwarze, R. and their team highlight the potential of utilizing copper-based SMA rods as energy dissipators in beam-column joints, providing a noteworthy innovation for designing end-plate connections between rectangular hollow steel beams and broad flange steel columns.

3. Timber connectors

The structural integrity of a wood construction is closely linked to the performance of the nodes within it. Enhancing the properties of traditional nodes can have a profound impact on the performance of the entire structure. With the development of multi-storey buildings using wood as a structural material, there has been a growing interest in the effects of dynamic and cyclic loads, particularly wind-induced vibrations in large structures. When it comes to seismic design, wood constructions have shown two distinct advantages: low seismic mass and ductile connection. There are two primary ways in which SMAs can be utilized in wood connection systems: as bolts to connect wooden members, or in glulam friction beam-column connection structures using SMA strips. In conclusion, enhancing the performance of nodes in wood construction is a crucial step in improving the overall structural integrity of the construction.

3.1. SMA bolted

Traditional pin-type fasteners have been used to attach wood in construction for centuries. The strength and load-deformation response of a pin connection depend on factors such as the embedding strength of the wood, the yield moment of the fastener, and the geometry of the connection. Different failure mechanisms can occur in double shear connections, with the specific type of damage varying based on the connection's design [4].

The thickness of the wooden parts and the diameter of the pins also play a role in determining the connection's strength. Other material parameters such as the embedding and bending strength are vital to consider when developing robust connections. Additionally, friction and the rope effect between the middle and side parts of bolted connections can influence the load-deformation behaviour. While the application of SMA bolts presents both challenges and prospects in wood engineering, they offer a promising avenue for energy absorption and minimal damage to the wood. However, their bending can pose a challenge to the connection's stiffness and carrying capacity, which must be compensated for by local incisions. Preliminary tests comparing SMA bolted connections to steel bolted connections have shown that the former demonstrates excellent reversible properties. Future studies will focus on optimizing SMA connections to increase their stiffness and minimize plastic damage.

Modelling the mechanical behaviour of SMA bolted connections remains a significant challenge due to the large friction and deformation effects. To overcome this hurdle, researchers will combine theory and experiment to investigate performance and durability in dynamic shock and fatigue cases. Modifications to the design will also be explored to improve the geometric properties of connections.

Beyond the technical context, cost is also a consideration in using SMA as a building material. Currently, iron-based SMA is a more economical choice over NiTi alloys. Despite their lower performance, iron-based SMA shows promising potential. Developing alloy technology specific to building components could lead to high-performance and low-cost connections in the future [4].

In conclusion, SMA bolted connections are an exciting development in wood engineering with the potential to improve upon traditional pin-type fasteners. Considering the multiple factors that influence connection strength and deformation behaviour is essential to maximize their efficiency.

3.2. SMA strips

Heavy timber structures are gaining popularity in the construction industry. However, designing beam-column connections that are both resilient and maintainable is challenging due to the physical properties of wood. Traditional methods are faced with the risk of decay and bending, making the goal of achieving optimal beam-column connections difficult. This paper presents a novel solution that utilizes SMA tapered glulam for friction beam-column connections (FCs).

SMA, a metal alloy that changes shape in response to heat and stress, provides pseudoelasticity that shows great potential for wood structural connections. The FC connection method involves using SMA strips and formwork plywood to reinforce beam-column joints. Four FCs with SMA bars underwent cyclic testing that compared their performance with that of a typical beam-column connection (CC). The testing demonstrated that the FC connection areas suffered no damage, with minimal tension damage to some SMA strips. This highlights the improved durability and maintainability that SMA-based connections offer.

Analysis of the performance differences between FCs with SMA and typical glulam beam and column connections showed that SMA's friction mechanism and pseudoelasticity resulted in superior performance for FCs. FCs with SMA exhibited improved energy dissipation capacity and had less residual deformation. Furthermore, self-centering effects were stronger due to SMA's pseudoelasticity.

Structural-level numerical analysis was conducted to determine how implementing SMA ribbon concrete in the FC structure enhances seismic performance. Simulation results revealed that the SMA friction connection preserved the dynamic response frame structure during high-intensity earthquakes while significantly reducing peak drift and residual deformation [5]. Thus, using the glulam friction beam-column connection structure with SMA strips improves the seismic performance of heavy wood structures.

Although the proposed connection method has potential advantages for frame structures, further study is needed. We aim to enhance SMA strip connection techniques to mitigate possible tensile failure, study SMA's long-term properties in conjunction with parallel grain wood creep, and investigate the properties of SMA-containing FCs to further improve this innovative connectivity technology.

In summary, the glulam friction beam-column connection with SMA is an excellent method to improve seismic performance while providing better maintainability and durability. This innovative connectivity technology promotes technological progress and supports innovation in the construction field.

4. Concrete connectors

This paper focuses on the design and reinforcement techniques of anti-bending frames to improve the functionality and earthquake resistance of reinforced concrete (RC) structures with self-centering connections. Traditional concrete connections are susceptible to significant damage during earthquakes, which has led to the development of self-centering joints to minimize damage. Self-centering connections are a specialized type of RC connection where prefabricated concrete units are joined together by unbonded post-tensioned prestressing. Nonlinear deformation occurs at the interface of the prefabricated component, resulting in a complex construction process.

Conventional RC self-centering structures are often considered cumbersome and impractical to implement. To overcome these challenges, researchers have proposed integral self-centering concrete connections reinforced with innovative materials. In recent years, researchers have explored the use of fiber-reinforced polymer (FRP) and shape memory alloy (SMA) materials in self-centering structure design. SMA materials possess shape memory effect (SME) and quasi-elastic response (PE). These properties make SMA a promising candidate for seismic design of structures. However, more experimental and analytical research is needed to fully understand their potential.

To address this issue, researchers have proposed a new detail for the plastic hinge position and studied the application of SMA rods in the design of integral self-centering concrete beam-column connections. By vertically slotting the beam so that the plastic hinge area is located far away from the cylinder and redefining the plastic hinge, the strain that permeates into the joint can be minimized, thereby mitigating potential anchorage failure.

The proposed design for a self-centering concrete beam connection aims to reduce costs, enhance joint stability, and improve superelastic properties. The system consists of an integral connection of strong columns and weak beams, which minimizes the strain seeping into the nodes and mitigates potential anchorage failures. The strengths of this system are as follows:

Firstly, it reduces direct costs by using SMA rods as bottom reinforcement to achieve self-centering behavior [6]. Direct costs are decreased by 50% compared to traditional designs, where SMA rods are installed on both the top and bottom of the beam member.

Secondly, in terms of beam elongation, the elastic response of the top steel bar under positive and negative bending ensures the minimum elongation of the beam. Thus, during strong seismic movements, the cracking of the attached plate is minimized, leading to non-tearing effects [6].

Thirdly, the system adopts the method of plastic hinge displacement, which reduces the cracking and deformation of concrete joints, thus improving joint performance by shifting the plastic hinge area away from the cylinder surface.

Finally, repair costs are minimized as the system reduces concrete cracking in other parts of the joint through concentrated plastic rotation at the trough, thus reducing repair costs after seismic excitation.

The proposed detail for the system is to place the SMA rod at the bottom of the beam for self-centering under positive and negative bends. Test results indicate excellent performance under cyclic load. It outperforms traditional reinforced concrete connections by reducing the extrusion shear effect, maintaining self-centering performance, reducing joint deformation, and moving the plastic hinge area away from the cylinder surface.

Future studies could focus on enhancing the anchorage system to avoid premature failure of the SMA rod and validate its response under seismo-like motion. Trained SMA rods could also be considered to improve cumulative energy dissipation and damping performance [6]. Overall, the innovative design boasts excellent superelastic properties while reducing costs, and it is expected to become a major research direction in the field of self-centering concrete beam connections.

5. Conclusion

To sum up, all of these innovations promote technological progress and support innovation in the construction field. In spite of the fact that previous research has demonstrated the way that the utilization of SMA connections in structures can reduce financial loss and damage, as well as producing structures that meet specifications, it may not be suitable in engineering practice, at least for now, since the relatively high cost of applying SMA connections [7]. However, future research should focus on studying how to make SMA connections from a single connection to the entire structural system, with various arrangements having various structural seismic performances. Additionally, SMA connections are strongly recommended to be integrated with robust energy-consuming systems in the structure, so as to compensate for SMA connections' lower energy-consuming capacity [7]. This would benefit the re-entry behavior of SMA materials and build ready-made smart structures that are popular in earthquake-prone areas.

Finally, SMAs' unique properties of shape memory effect and super-elasticity [8] have a significant role in the field of component connection. They provide efficient and reliable solutions for a wide range of structural applications and represent a significant step in the development of structures that can withstand dynamic loads and seismic events without suffering significant damage.

In conclusion, the innovative applications of SMA technology have led to significant advancements in the design and construction of steel and timber connections. By utilizing SMAs in these connections, designers and engineers can improve resilience, efficiency, and safety in their structures, leading to truly innovative and forward-thinking designs.

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