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INNOVATIVE USE OF SHAPE MEMORY ALLOYS AS REINFORCEMENTS FOR CONCRETE BEAM-COLUMN JOINTS: AN OVERVIEW

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ABSTRACT

Shape memory alloys have two unique properties of shape memory effect (SME) and superelasticity (SE) that are the ability for large inelastic deformations recovery after heating (SME) and stress removal (SE). In recent years, structural engineers used these materials in the field of civil engineering's, such as the applications of SMAs in the repair, retrofitting, and rehabilitation of concrete structures, dampers, vibration isolation systems, vibration control, and prestressing members, etc. To overcome and reduce the potential seismic risk of structures, understanding the characteristics of SMAs materials under different loading conditions is one of the critical steps. Despite the various types of researches carried out on the SMAs' structural applications, there was a need for a review of the progress of the current method in structures. To address it, a brief review of the applications of SMAs in Reinforced Concrete (RC) beam-column joints was conducted.

KEYWORDS

Shape memory alloy, SMA, Superelasticity, Beam-Column joint, Retrofitting

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1. INTRODUCTION

Beam-column joints (BCJs) are the weakest elements in RC structures (Park, 1975). The catastrophic failure occurs due to any shortage in BCJs such as lack of shear reinforcement and poor-quality concrete, especially since the structures were built before the new seismic codes were implemented. Since the 1970s, design codes have begun to implement the exacting seismic requirements for the detail of BCJ reinforcing bars. Although BCJs were still among the vulnerable members of the RC structures during earthquakes (Saatcioglu, et al., 2001). Furthermore, sufficient ductility should be the most important feature of earthquake-resistant structures because of the high cost and difficulty of building structures that behave elastically under strong ground motion. according to RC structure's conventional seismic codes, to dissipate energy, reinforcing bars are expected to yield and then permanent deformations caused by plastic properties are seen after yielding steel bars. Previous studies focused on strengthening techniques such as concrete jackets (Pimanmas and Chaimahawan, 2010; Tsonos, 2010), joint enlargement with shape modification and haunch retrofitting systems (Shafaei, *et al.*, 2014; Shafaei *et al.*, 2017; Zabihi *et al.*, 2018; Shafaei and Nezami, 2019) and fiber-reinforced polymer (FRP) wraps (Ghobarah and Said, 2002, 2008; Akguzel and Pampanin, 2012; Attari *et al.*, 2012) to prevent the shear failure of the RC BCJs without seismic details that each of which has its advantages and disadvantages. A good illustration of joint strengthening is Shafai et al (2014) which proposed stiffened steel angles and plates with prestressed cross-connections to confine actively the BCJs, which are generally used in moving the plastic joint away from column faces are very effective. However, joint enlargement techniques have their drawbacks. For instance, Beams and columns that are connected to the core of the joint carried more shear forces due to the shortening of their lengths, which may cause their shear failure, unless the additional shear force caused by the enlargement of the connection is less than the shear strength of the beams and columns. As a result, additional strengthening of beams and columns may be required in the joint area. Among these methods, one method, in particular, uses a minimal approach (i.e., focusing on a minimal design using diagonal bars to increase the shear strength of the connection core). Au et al. (Ghobarah and Said, 2002; Bindhu, Mohana and Sivakumar, 2014; Au, Huang and Pam, 2015) investigated the effectiveness of diagonal reinforcement in the connection BCJs and showed that at lower ductility factors, BCJs reinforced with diagonal bars performed better in terms of stiffness degradation and strength than specimens reinforced with horizontal bars. This proposed strengthening technique delayed the shear failure in the beam and core joint and leaded BCJs to achieve the maximum flexural capacity of the beam. Study on prestressed diagonal reinforcement in joint core was a logical development in the strengthening approach. Prestressed diagonal reinforcement can confine actively the joint core by creating the pressure in the opposite direction of the maximum principal stresses in contract to shear steel reinforcement that provides the passive confinement. Also, BCJs with active confinement show more strength to applied loading than passive confinement, especially when the concrete begins to dilate (Saatcioglu and Yalcin, 2003; Shafaei *et al.*, 2014; Suhail *et al.*, 2020).

2. BASIC CONCEPTS OF SHAPE MEMORY ALLOYS

Shape memory alloys (SMA) are known as smart materials that exhibit two special features such as a superelastic effect (SE) and a shape memory effect (SME) depending on the crystal structure of the SMAs under operating conditions. SE properties can recover inelastic strains after force removal and SME feature recover the plastic strains by heat. SMAs exist in two different phases such as martensite and austenite. The former is stable at a lower temperature, while the latter is stable at a high temperature (DesRoches *et al.*, 2004a). The martensitic phase transformation between the martensite and austenite phases produces these features. According to Fig. 1 superelastic behavior is observed at temperatures above A_f, where the entire crystal structure is in the austenite form. It is an isotherm and phase transformation process from martensite to austenite under an external load.

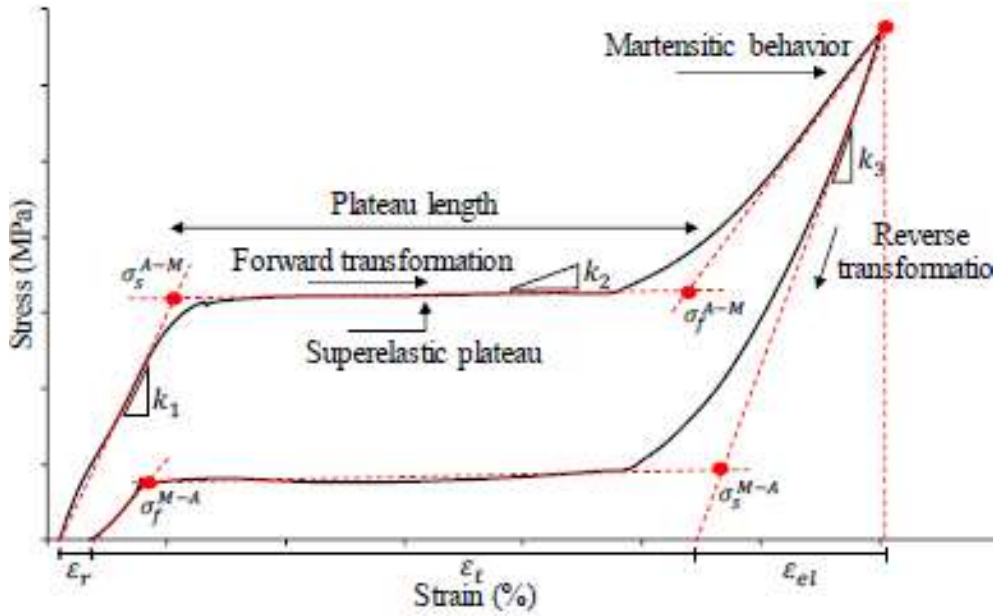


Fig. 1. Stress-strain relationship of superelastic SMAs (Burak Duran, LastName and Özgür Avşar, 2020).

Such martensitic transformation of SMAs occurs only by stress excitation at a temperature higher than the austenitic temperature (Af) of the material. At first, the austenitic alloy exhibits elastic behavior by applying the stress level up to the transformation stress (σ_s^{A-M}). If the loading continues above this stress level, the stress-induced martensitic transformation (SIM) will transform after the segregation of martensite until complete transformation occurs at the strain level corresponding to $\sigma_f{}^{M-A}$. The top plateau corresponds to martensite formation while the bottom plateau represents SIM during stress release. The entire recovery is completed in the form of flag shape stress-strain hysteresis loops through forward and reverses conversion cycles. Due to the defect generation mechanisms that occur during the martensitic transformation, a residual strain, εr, can be generated in the material during deformation, which is carried over to the next stress cycle in case of incomplete recovery (Burak Duran *et al.*, 2020).

Auricchio and Sacco (Auricchio and Sacco, 2016) illustrated the Ni-Ti SMA behavior through a simple l-D phenomenological model. DesRoches et al. (2004b) described the cyclic behavior of Ni-Ti SMA. Duerig et al. (Duerig TW *et al.*, 2013) evaluated the Ni-Ti SMA characteristics, thermomechanical treatment, and fabrication technique. Tanaka *et al.*, (2010) manufactured an iron-based SMA that showed higher a maximum superelastic strain compared with Ni-Ti SMA.

3. STRUCTURAL APPLICATIONS OF SMA REBARS IN THE BCJS PERFORMANCE

SMA is a very desirable and practical material for many civil engineering applications due to its unique material features such as SE and SME. The former refers to the ability of the material to recover large quasi-elastic strain through the removal of an applied load and the latter refers to the ability of a material to recover large "quasi-plastic" strain upon heating. Furthermore, these materials show corrosion resistance and high ductility. The SME features can provide a thermally activated rapid prestressing by using diagonal reinforcement in the joint core (Otsuka and Wayman, 1999; Yurdakul *et al.*, 2018a). Although several previous researches (Boroschek *et al.*, 2007; Cardone *et al.*, 2008; Youssef *et al.*, 2008; Zhu and Zhang, 2008; Nehdi *et al.*, 2010; Sultana and Youssef, 2016; Wang and Zhu, 2017; Yurdakul *et al.*, 2018a) have used the unique properties of SMA materials to improve the seismic performance of new RC structures, mainly as superelastic bracing systems and for the seismic strengthening of BCJs. The SE properties of SMAs can decrease the residual deformations in the plastic hinge region of BCJs. Using internal and external SMA bars instead of steel reinforcement of BCJs was proposed by many of the existing papers. The following sections listed a summary of published papers that focused on the application of SMA rebars in the RC BCJs (Raza *et al.*, 2022). papers are classified according to the years.

3.1. Using SMA rebar in the plastic hinge region

SMAs are usually used as internal reinforcement in the plastic hinge region of BCJs. A good illustration of this is Youssef *et al.*, (2008) research that focused on using superelastic Ni-Ti SMA bars in the plastic hinge region of RC BCJs under seismic loading. Fig. 2 presents the SMA reinforcement specimen detail. The residual drift ratio of SMA-reinforced joint and conventional joint with similar dimensions were 1.98% and 4.94%, respectively. The result showed that the energy dissipation decreased by using the SMA bar but the location of the plastic hinge moved away from the column faces. On the other side, the strength of both BCJs using steel and SMA bars was equal. Alam *et al.*, (2008) performed FE modeling to investigate the seismic behavior of the superelastic NiTi (55% Ni+45%Ti) SMA in BCJ. They predicted energy dissipation capacities, moment–rotation relationships, crack width and crack spacing, Bond-slip relationship, and load-displacement behavior of the proposed specimens and showed adequate agreement by experimental results. According to the data, the control specimen with fully steel reinforcements showed lower dissipation of energy and higher residual displacement compared to specimens containing SMA bars. One of the important causes of structural failure during earthquakes is related to residual displacements therefor, using SMA smart materials is a good choice due to better action than conventional counterparts. A hybrid SMA-FRP RC BCJ was proposed by Nehdi *et al.*, (2010) to ensure sufficient corrosion resistance. Two BCJs detail were considered and in one of them, steel bars were used as the whole of internal reinforcement. In another BCJ, SMA and GFRP rebars were used in the plastic hinge and the rest of the joint, respectively. Although the steel joint illustrated higher stiffness than the hybrid SMA-FRP joint, the residual drift was similar in both specimens. The remarkable value of residual drift was attributed to the slip of the GFRP bars inside the couplers. The plastic hinge location developed away from columns by using SMA rebars. Also, the hybrid BCJ can withstand 89% of its maximum load capacity even after the collapse limit (i.e., 3% floor drift). In the other research, Nahdi et al., (2011) tested an RC BCJ specimen by using Ni-Ti SMA bars in the plastic hinge. Then the damaged BCJ was repaired with concrete and subjected again under cyclic lateral loads. The result depicted that almost all permanent deformation of RC BCJ experienced under cyclic load recovered and just needs a minimum repair. In addition, the plastic hinge moved away from the column faces by using SMA and the energy dissipation capacities of the repaired and original specimens were comparable.

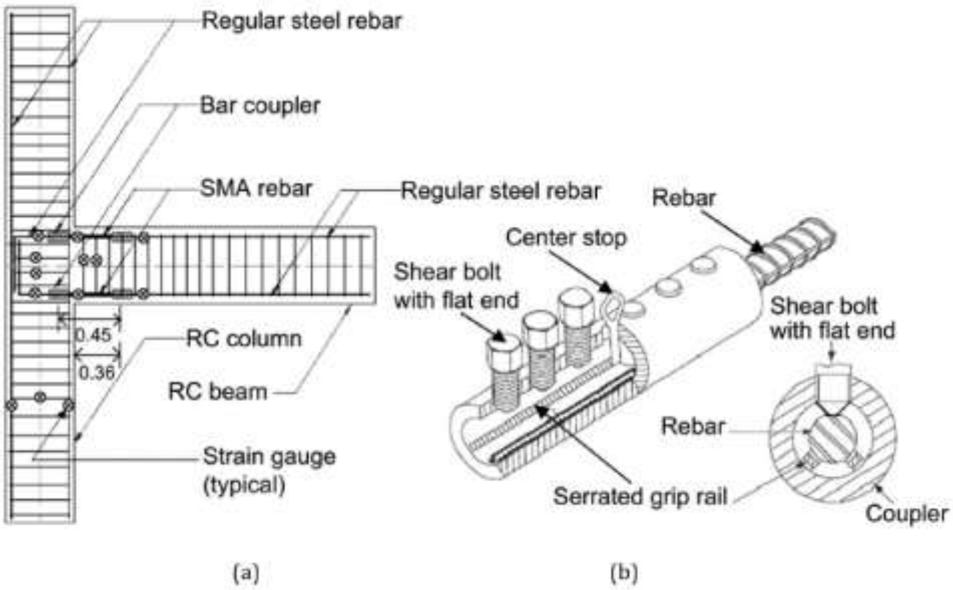


Fig. 2. BCJ Details using superelastic Ni-Ti SMA bars: (a) details of SMA and conventional steel bars, (b) coupler (Youssef *et al.*, 2008).

Jung *et al.*, (2017) suggested a new type of SMA bars according to Fig. 3 that is made by an external layer of FRP and an internal layer of a combination of SMA wire and epoxy resin. The detail of RC BCJ showed in Fig. 4 that the proposed SMA and GFRP bars were used in the plastic hinge zone and other regions, respectively. The mechanical coupler was used to connect two different bars. Using a combination of SMA-GFRP bars decreased the frame residual drift. According to the data, the residual displacement of the control specimen was 84% and 62% higher than SMA-FRP and GFRP, respectively. Moreover, the specimen with SMA-FRP showed higher dissipated energy and less damage compared to other specimens. Therefore, utilizing this proposed technique improved the seismic performance of structures.

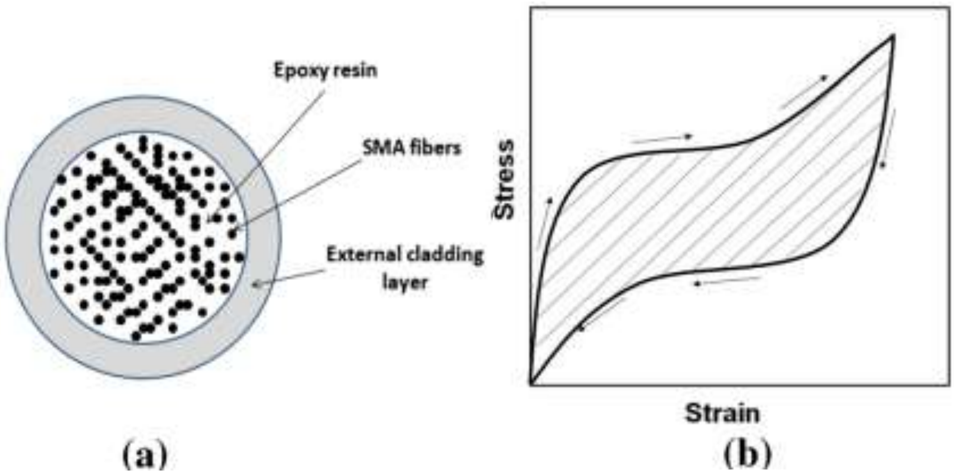


Fig. 1 a) SMA-FRP composite bar cross-section and b) superelastic SMA stress-strain hysteresis (Jung, Zafar and Andrawes, 2017).

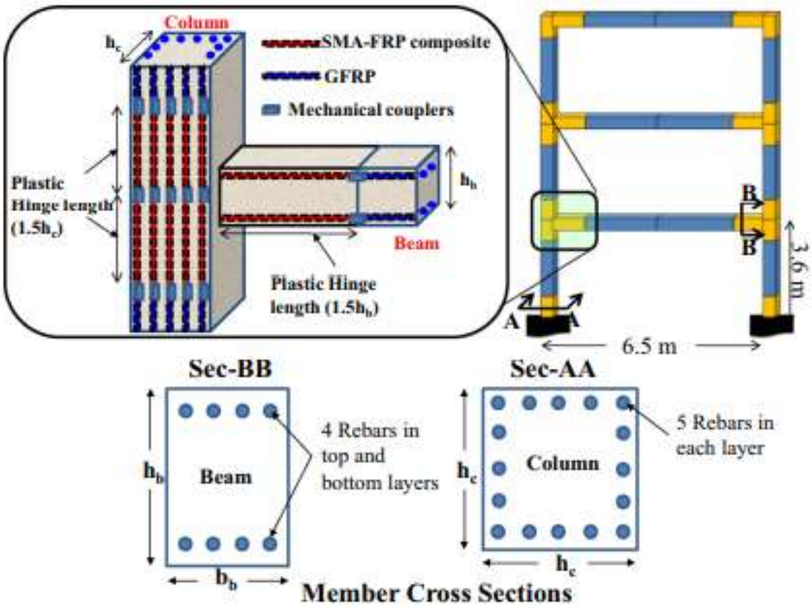


Fig. 2 Detail RC BCJ using proposed SMA-FRP composite rebars (Jung, Zafar and Andrawes, 2017).

Oudah and El-Hacha, (2017) investigated the performance of RC BCJs strengthened with superelastic Ni-Ti SMA bars. The rebars were restrained using screw steel restraints in the joints. Six BCJ specimens were considered, which SMA bars were used in four BCJ and steel bars were used in the rest of the specimens. The ultimate force capacity of steel-reinforced was much higher than its SMA counterparts which to the slippage and fracture of the SMA rebars. The experimental result showed that increasing the anchorage length rose the stiffness after cracking and decreased the final curvature of the BCJ. Oudah and El-Hacha (Oudah and El-Hacha, 2018) in the other study presented a new method to retrofit the BCJ by using superelastic Ni-Ti SMA bars at the plastic hinge. Furthermore, according to Fig. 5-a, at a distance equal to the effective depth from the beam end, a vertical slot was placed to develop the plastic hinge away from the column surface. For this proposal, three BCJs were tested consisting of a control BCJ and two BCJs that steel and SMA rebars used along with the beam vertical slot. The self-centering of SMA-BCJ showed superior performance compared to the control BCJ. In addition, using SMA rebar recovered almost all the residual displacements, minimized the pinching shear effect, decreased joint distortion, and developed the plastic hinge away from the faces of the column.

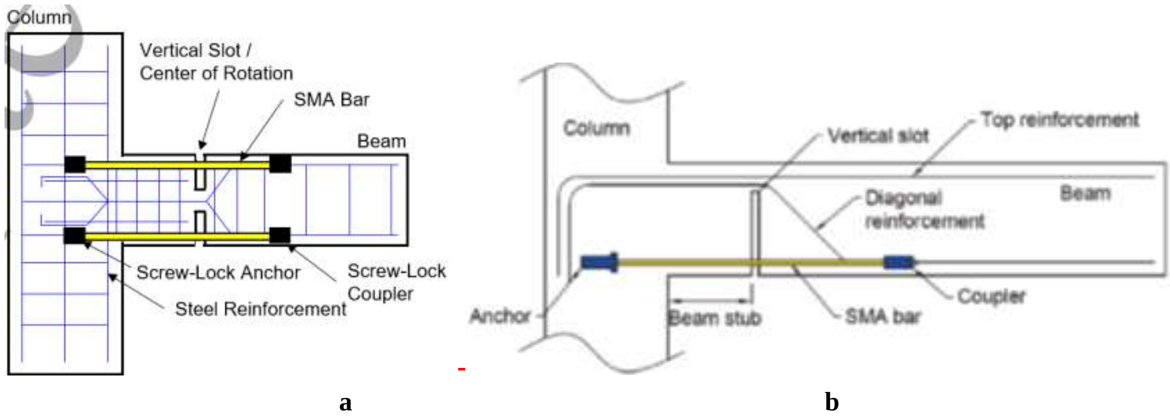


Fig. 5. Schematic of the retrofitting technique used for SMA-BCJ (Oudah and El-Hacha, 2018), (Oudah and El-Hacha, 2020).

Youssef *et al.*, (2019) performed FE analysis by Seismostruct software to model a six-story RC frame that used hybrid GFRP and Ni-Ti super elastic SMA in BCJs plastic hinge zone under pushover, astatic non-linear analysis. The target of utilizing these mentioned materials was to provide a frame with less residual displacement, appropriate strength, and initial stiffness, corrosion-free and adequate ductility. Mechanical couplers were used to link the SMA and conventional steel bars as proposed by Alam *et al.*, (2010). The analytical data showed that using the proposed technique for BCJ decreased ductility, initial stiffness, and failure load, and also experienced less displacement compared with conventional full steel reinforcement BCJ. Furthermore, they investigated the structural behavior of RC BCJs utilizing SMA and/or GFRP bars in detail through a comprehensive parametric study and developed new equations to design this type of BCJ.

Recently, As illustrated in Fig. 3-b, Oudah and El-Hacha, (2020) suggested a reinforced double-slotted SMA-BCJ for relocating the plastic joint away from the column surface and compared it with the single-slot counterpart presented in (Oudah and El-Hacha, 2018). The double vertical slots (upper and lower) were inserted at a distance equal to the effective depth of the beam away from the column. Then the superelastic Ni-Ti SMA rebars were placed in the plastic hinge region. The preponderance of this solution is consisting of moving the plastic hinge and reducing the damage to the slab connected to the beam by placing the expansion joint at the place of the vertical cracks. Furthermore, the joint self-centering response at drifts up to 14% was illustrated.

3.2. Shear strengthening of BCJ with SMAs

However, the SMA materials were used in new structures, and the application of these materials in the case of rehabilitation of damaged structures is noticeable. A good example related to using the SMA bar to strengthen externally the RC BCJ is Suhail *et al.*, (2015) paper. According to Fig. 6, they considered a pre-damaged RC BCJ strengthened utilizing SME cables. For this purpose, an elliptical cross-section was considered instead of a rectangular shape and the two steel plates were installed at the faces of the column to pass SMA cables through the holes. Cables were fixed with ended U-shape crimps sleeves. For investigating the efficiency of the suggested method, specimens were tested under cyclic load.

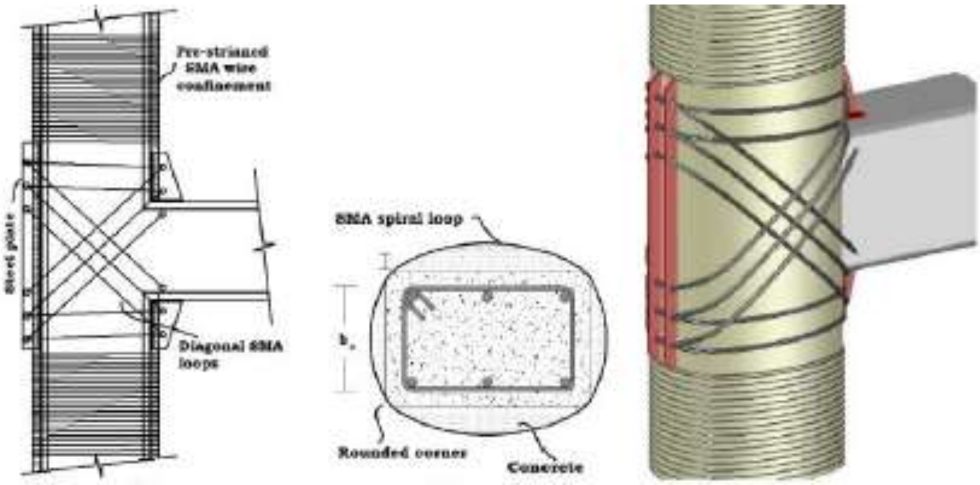


Fig. 6. RC BCJ repaired with SME wires (Suhail *et al.*, 2015).

According to Fig. 7, Yurdakul *et al.*, (2018) investigated numerically and experimentally a technique to strengthen a BCJ with a lack of shear capacity using externally bonded and post-tensioned superelastic Ni-Ti SMA bars placed diagonally. For this purpose, three BCJs were tested under axial load on top of the column and quasi-static cyclic displacement up to 8% drift ratio, in which one specimen was considered as a control BCJ and the two specimens were retrofitted with steel and post-tensioned SAM bars. The specimens reinforced with SMA rebars showed higher ultimate lateral load bearing compared with two other BCJs as illustrated in Fig. 6. In addition, the SMA-strengthened BCJ showed lower damage and ductile behavior, while the control BCJ exhibited brittle shear failure. The results showed that post-tensioned the SMA rebars to their yield capacity, enhanced the retrofitting method performance.

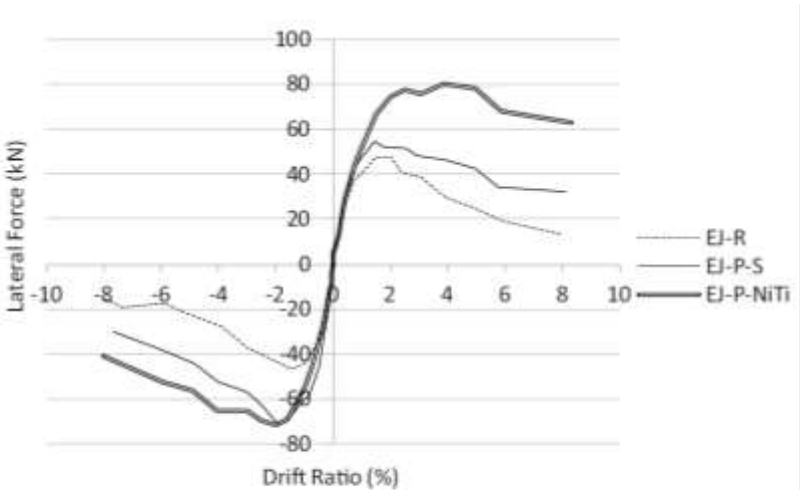


Fig. 7. Hysteresis response posh curves (Yurdakul, Tunaboyu and Avşar, 2018b).

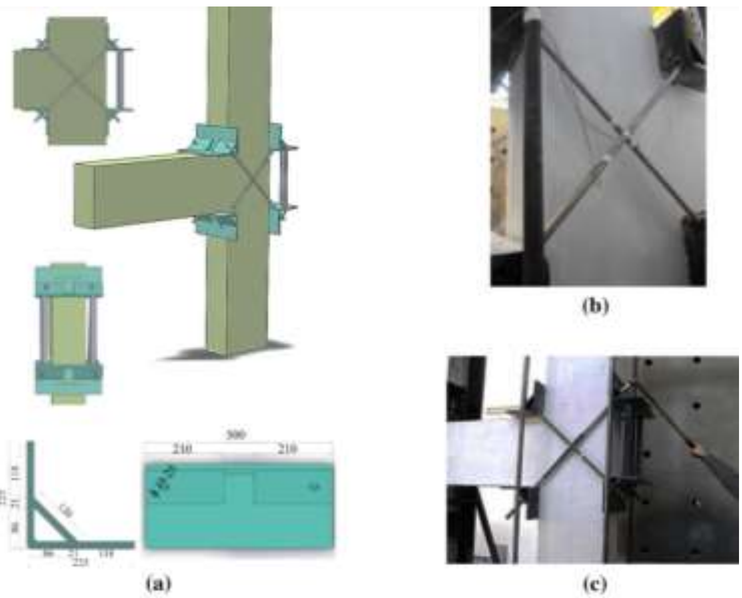
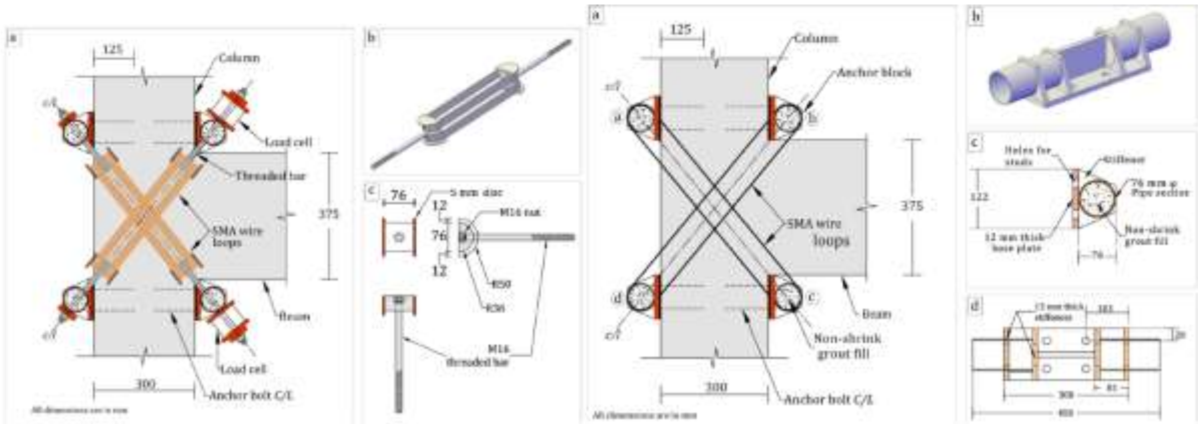


Fig. 8. Schematic representation of post-tensioned application (Yurdakul, Tunaboyu and Avşar, 2018b).

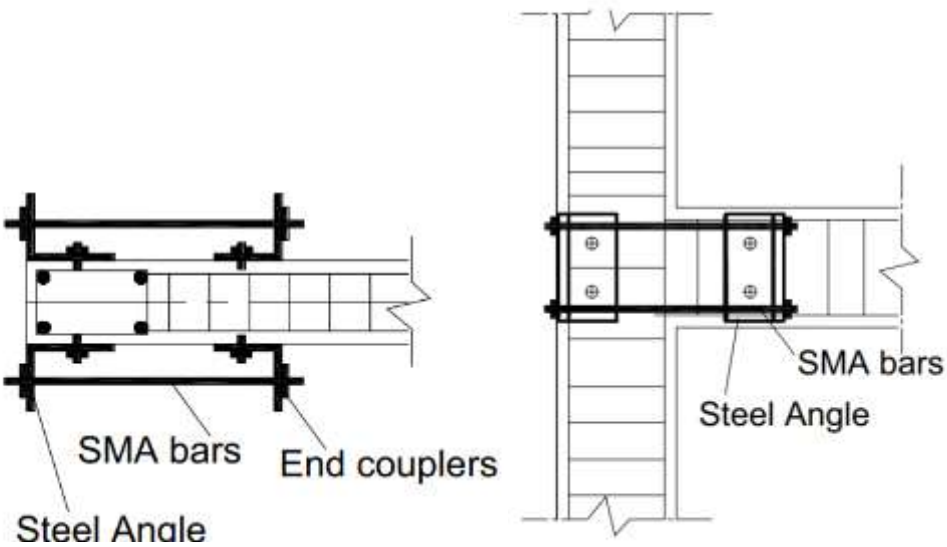
Suhail *et al.*, 2018) conducted a detailed experimental and numerical investigation of the efficiency of prestressed SMA diagonal wires in the seismic strengthening of RC BCJ with non-seismic details as can be seen in Fig. 9. Prestressed diagonal rings apply active confinement to the joint core that outperforms conventional passive confinement in terms of improved energy dissipation capacity, shear strength, and ductility. According to this research, in-plane diagonal compressive forces were applied by using prestressed Ni-Ti-Nb SMA diagonal wires that made active confinement in BCJs. Two different techniques for prestressing SMA rings were investigated, which are based on experimental studies: the first was the conventional prestressing of SMA rings by mechanical means and another refers to the fast-prestressing technique with active heat using SME of SMAs. According to the previous studies, depending on the level of confinement applied, the retrofit design the energy dissipation capacity, and the ultimate strength improved in the range of 60-70% and 20-30%, respectively. but there was no remarkable increase in ductility.



a b

Fig. 9. Schematic of retrofitting a) Initial plan b) Corrective plan (R. Suhail, G. Amato, J. Chen, 2015; Suhail R, Mccrum DP, Amato G, 2018).

lElbahy *et al.*, (2019) studied the numerical model of RC BCJ strengthened using superelastic SMA bars under a ground motion load. As can be seen in Fig. 10, external rigid steel angles and bolts were used in BCJ for SMA bars attachment. The proposed technique reduced the frame residual and maximum displacement by 50-70% and 10-15%, respectively. Furthermore, it tolerated higher intensities of an earthquake than the conventional specimen.



Elevation view **Plan view**

Fig. 10. Detail of proposed RC BCJ strengthened with SMA bars (Elbahy, Youssef and Meshaly, 2019).

Rezvanisharif and Ketabi, (2019) used Vector 2 software to investigate the performance of SMA bars at the plastic hinge zone of BCJs. They verified the experimental model of Youssef *et al.*, (2008) and considered both geometry and material nonlinearly. The result of the analytical model showed good agreement with the experimental study and can predict the cyclic response of RC BCJs using SMA-FRP composite. Moreover, a comprehensive seismic parametric study was performed according to calibrated model. They evaluated the effect of different effective variables on the seismic performance of the proposed technique. Furthermore, the seismic performance of Fe-based bars was investigated numerically and showed better behavior compared with utlizing NiTi-based SMA rebar.

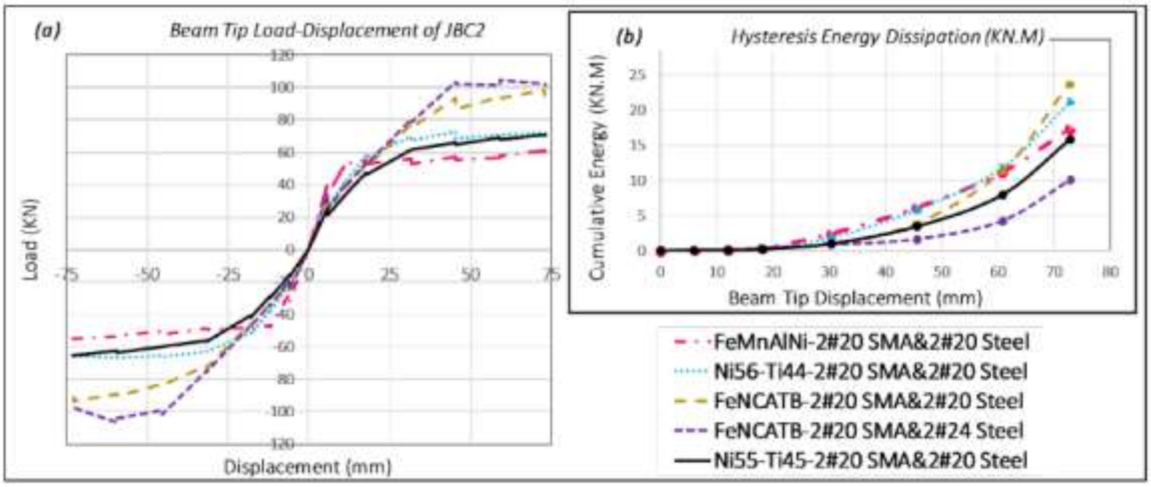


Fig. 3. Effect of SMAs type on the seismic behavior of BCJs. a) load-displacement envelop curve b) cumulative energy dissipation (Youssef, Alam and Nehdi, 2008).

Smiley et al. (Molod, 2021) tried to implement a plate of SMA alloy as an external reinforcement to increase the stiffness and ductility of the connection in numerical research according to Fig. 12. To do this, an RC BCJ was modeled in Ansys software, and loaded under a large number of random load combinations. The results of the analyses showed that the applied technique significantly increased the strength of the connection so that the cracking load of the system reinforced with the optimal SMA plate under cyclic loading was 1.4 times higher than the reference specimen. The bearing capacity of the reinforced system in the elastic region was higher than that of the non-reinforced structure, and the capacity in the plastic region was even higher. Specifically, the load-carrying capacity of the reference system at 32 mm displacement was approximately 98 kN, while the corresponding resistance value in the plateless system was approximately 66 kN. In addition, the presence of the plate led to the relocation of the plastic hinge zone from the joint to the beam span, which leads to a reduction in the risk of failure of the entire structure.

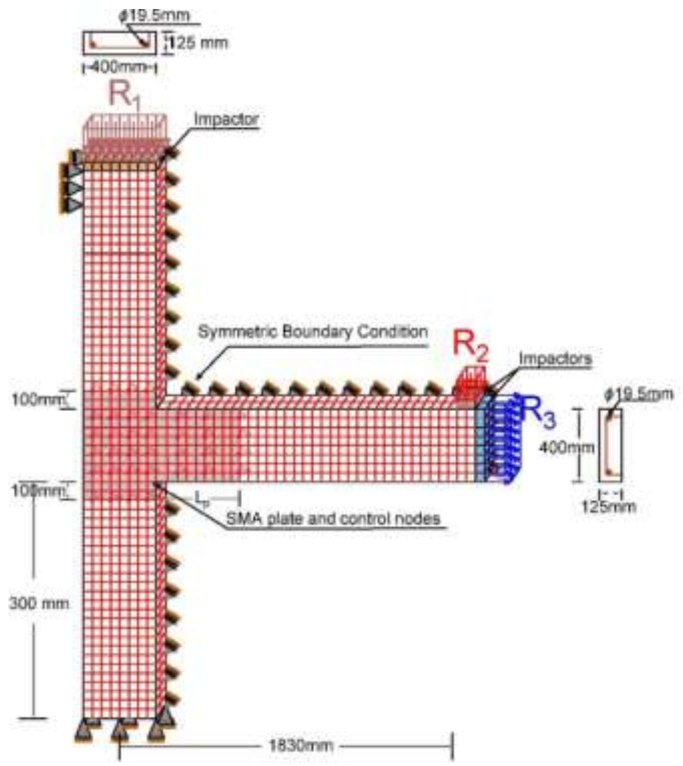


Fig. 12. RC BCJ Schematic view in Ansys (Molod, 2021).

Overall, according to the experimental previous research, using superelastic SMA rebars in BCJs decreased the residual displacements by more than 60%. Although these proposed methods dissipate less energy, the way forward could be using a combination of SMA rebars and advanced materials in the plastic hinge region. For the deficient BCJ shear strengthening proposed, using superelastic SMA rebars can improve the load capacity and ductility of the joints.

3.3. Combination of SMA rebars with advanced materials

Using internal superelastic SMA rebar instead of steel reinforcements showed low initial stiffness because the elastic modulus of normal steel bars is higher than SMAs. The solution to overcome this issue uses a combination of SAM and steel bars to maintain the expected stiffness while having the ability to partially recover the deformations. Alternatively, using advanced concrete in the plastic hinge region together with superelastic SMA can increase the energy dissipation capacity of RC BCJs and provide a high elastic modulus in the plastic joint region. Recently, researchers focused on using SMA-ECC composite materials that show extraordinary self-centering capacity, significant energy dissipation capacity, and excellent ductility. However, most previous research studied on column and beam, Qian *et al.*, (2022) presented the RC BCJ that strengthened with ECC materials and superelastic Ni-Ti SMA bars. Fig. 13 shows the five ½ scale beam-column joint.

Fig. 13. Details of the BCJ (Qian *et al.*, 2022).

Using ECC materials in the critical area of BCJs is proposed to increase the BCJs ductility. Furthermore, the SMA bars were embedded to decrease residual deformations and energy dissipation as an alternative to longitudinal bars in the plastic hinge of the beam. Self-centering performance, residual deformation, displacement ductility, energy dissipation capacity, bearing capacity, and failure modes of BCJ were relatively analyzed under a low-cycle loading test. Additionally, to investigate the effect of ECC and SMA on the seismic behavior of the BCJs, a finite element model of SMA-ECC joints was developed. The results of the study showed that ECC materials are useful for plastic hinge displacement, improving energy dissipation capacity and ductility of the structure. SMA bars can dramatically increase their self-centering capability and enable self-damage repair. SMA-ECC composite materials show a good complement to significantly enhance the self-centering capabilities, energy dissipation, and ductility, and delay the reduction of structural stiffness in the joint.

4. CONCLUSIONS

The summary of previous studies provided in this state-of-the-art paper illustrates that using SMAs can be a good choice for improving the performance of existing and new RC BCJ. In summary, the following key findings can be drawn from this study:

- SMAs bars have the benefits such as quick and easy installation, minimum long-term friction and/or corrosion losses, increased ductility, and excellent shape recovery compared to conventional steel. On the other hand, because of the high cost of these materials, the use of SMA bars in the whole of the RC structures was limited.
- Using superelastic SMA bars as internal reinforcements in new RC BCJs can reduce residual displacements by more than 90%.
- Combining SMA and FRP bars instead of steel bars can provide a corrosion-less RC component.
- Replacing steel internal reinforcements with superelastic SMA bars decreases initial stiffness due to the low elastic modulus of SMAs.
- Using advanced concrete in the plastic hinge region together with superelastic SMA can solve the low elastic modulus problem and increase the energy dissipation capacity of RC BCJs.
- A combination of steel and SMA bars or using Fe-based SMA bars can maintain expected stiffness while partially recovering deformations.

5. RECOMMENDATION

There are several recommendations related to the topic of using SMA in RC beam-column joint:

- More research is needed to evaluate the long-term durability and reliability of SMA materials in RC structures, as their performance over time is not yet well understood.
- To overcome the high cost of SMA materials, future research should explore ways to reduce production costs and/or develop alternative materials with similar properties.
- The use of advanced analytical and experimental techniques, such as finite element analysis and shake table testing, can help to better understand the behavior of RC BCJs reinforced with SMA materials.

6. ACKNOWLEDGEMENTS

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