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Performance Evaluation of Concrete Structures Reinforced by Corrosion Free FRP and SMA Materials

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ABSTRACT: Fiber reinforced polymer (FRP) and shape memory alloy (SMA) reinforcement materials can potentially provide great benefits including life time cost saving, durability, safety, and post-earthquake serviceability for reinforced concrete (RC) structures. Both SMA and FRP are corrosion free. Although FRP materials are well known for their properties of being highly corrosion resistance, high strength-to-weight ratios, ease of application, and constructability, the use of SMA allows the structure to regain its original shape after load removal without any permanent large residual deformation. This paper presents a review of recent studies on structural components, such as beam-column joints that are reinforced with corrosion free SMA or FRP materials or a combination of hybrid SMA and FRP reinforcement. In summary, the presented literature review provides an insight into the ongoing research on the use of these materials for retrofitting or strengthening of RC structural components and the trends for future research in this area.

1 INTRODUCTION

Most concrete structures such as buildings, bridges, elevated highways, offshore structures, tunnels and dams are reinforced with steel bars. The deterioration of such reinforced concrete structures is mainly due to the corrosion of embedded reinforcing bars followed by the formation of cracks in concrete resulting in putting the structures out of service. For many decades, the problem of corrosion has remained an alarming issue. Likewise, the damage caused due to earthquakes is another severe issue posing a threat to safety of structures, particularly for those built prior to 1970s. Since then changes were made to the design code to prevent the newly built structures from collapse under seismic event. However, it is essential to retrofit the nonseismically designed defficient structures to prevent future damage by severe earthquakes. For many years the retrofitting of damaged buildings was carried out by traditional method such a concrete and steel jacketting to provide additional needed strength, until the use of innovative materials. More recently, many research around the world have been directed towards the use of fiber reinforced polymers (FRP) as one of these new materials, due to their superior properties, light weight, corrosion resistance, and short period and ease of installation as compared to conventional methods. Numerous researchers have worked on the use of FRP as external reinforcement for confinement, shear, and flexural strengthening (Parvin and Wang 2001; Iacobucci et al. 2003; Sarafraz and Danesh 2008; Parvin et al. 2010; Li and Kai 2011; Garcia et al. 2013). However, only few researchers have started to work on the concept of using (FRP) as internal reinforcement for beam-column joints which are critical components and their failure could result in total collapse of the structures. (Said and Nehdi 2004; Saravanan and Kumaran 2010, 2011; Mady et al. 2011; Hasaballa et al. 2011; Hasaballa and El-Salakawy 2015; Ghomi and El-Salakawy 2015).

On the other hand, Super-elastic shape memory Alloys (SMAs) are one of the kind materials capable of undergoing large deformations and returning to their original shape and position upon the removal of applied forces. As a result, the use of SMAs as structural reinforcement reduces the damage to the overall structures even after being hit by an earthquake. SMA is used in the form of sheets and strips, however, few researchers have recently used SMA as internal reinforcement bars in the plastic hinge regions where the damage can cause failure of the whole structure (Noguez and Garcia 2015; Alam et al. 2008). Such advantages from both FRP and SMA, have paved the way to start using them together as a hybrid material for strengthening RC members both externally and internally. Some studies performed on the beam-column joints consider this hybrid material to improve the overall performance of structures (Zafar and Andrawes 2012, 2012, 2014; Nehdi et al. 2010).

The use of FRP and SMA materials offers a viable reinforcement solution that is noncorrosive as oppose to traditional steel reinforcement which decays over time when exposed to harsh and alkaline environment. The aim of this paper is to provide an insight into the performance of corrosion free beam-column joints reinforced with FRP, SMA, and a combination of FRP and SMA refers to as a hybrid material.

2 NON-CORROSIVE REINFORCEMENT MATERIALS FOR CONCRETE STRUCTURES

In recent years use of fiber reinforced polymer (FRP) and shape memory alloys (SMA) in RC structures has gained popularity due to their superior material properties and non-corrosiveness. The application of these smart materials could easily replace the traditional steel reinforcement in concrete structures. Beam-column joints are one of the most critical assemblies in the structural system. Furthermore, investigations on beam-column joints are more spar as compared to beams or columns. In the following sections beam-column joints reinforced with SMA, FRP and hybrid SMA-FRP as internal reinforcement are discussed.

2.1 Beam-Column Joints Internally Reinforced with FRP Bars

Fewer researchers have investigated beam-column joints internally reinforced with FRP bars as oppose to more common application of external FRP-strengthening of joints. Most of these studies have commonly used glass fiber reinforced polymer (GFRP) material for reinforcement bars (Table 1). Said and Nehdi (2004) tested two full-scale beam-column joints, one reinforced with GFRP grid and one was reinforced with steel bars and stirrups under cyclic loading. Although the 3% minimum drift ratio requirement of ductile frame was achieved in the GFRP reinforced joint, lower stiffness and energy dissipation were observed due to elastic behavior of the GFRP material as compared to the steel reinforced joint. Furthermore, the beam tip load was as high as that of the steel reinforced joint. Because of the low stiffness of GFRP bars, the joint failure was due to the brittle behavior that led to the rupture of two bottom GFRP longitudinal bars.

On the other hand, Saravanan and Kumaran (2011) conducted experimental and numerical study using ANSYS finite element analysis software program on eighteen beam-column joints reinforced with GFRP stirrups and bars. Variables considered were bar types (threaded, sand-coated, and grooved), beam and column reinforcement ratio, concrete strength, and joint aspect ratio. Furthermore, the influence of GFRP stirrups on the joint shear strength was investigated and a design equation to predict the joint shear strength was proposed. Their study showed that compared to beam-column joints reinforced with traditional steel bars, the GFRP sand-coated reinforcement improved the load carrying capacity by almost 5%, but more importantly the deformation capacity increased by 30 to 50%. Moreover, the presence of stirrups in the joint area insured to move the failure from the joint core to the beam-column interface.

Two other experiments in 2011 were conducted by Mady et al. and Hassaballa et al. on full-scale concrete beam-column joints reinforced with GFRP bars and stirrups when subjected to seismic loading to explore the influence of GFRP reinforcement on the behavior of the joints. Hassaballa et al. (2011) variables of study were longitudinal and transverse reinforcement materials (steel and GFRP) and the beam's bar details (with hooks, straight, or straight with extension into a beam stub), while Mady et al. (2011) had the bar types (steel and GFRP), and beam reinforcement ratios as parameters. Both experiments had one reference specimen (longitudinal and transversal steel reinforcement), one specimen reinforced with GFRP bars and steel stirrups, and the rest were reinforced with GFRP bars and stirrups. In the experiment by Mady et al. (2011), it was observed that increasing the GFRP beam reinforcement ratio can increase the amount of energy dissipated by the joint due to inelastic behavior of concrete. However, GFRP joints of Hassaballa et al. (2011) dissipated energy lower than the amount dissipated by the control joint (steel reinforced). Furthermore, the use of GFRP as internal reinforcement in beam-column joints of both experiments, sustained 4% story drift ratio safely with no considerable damage or residual strains. Thus, the beam-column joint could retain its original shape upon removal of the seismic loads up to this drift ratio. Even though both GFRP reinforced and control joints of Hassaballa et al. (2011) failed in shear, the failure mode of GFRP reinforced joint with extended stub was observed by the formation of plastic hinge away from the column face which satisfies the design capacity concept (weak beam-strong column). Moreover, all joints exceeded their individual design capacity by an average of 9%. Table 1 shows additional details of the experiments and results.

Similarly, Hasaballa and El-Salakawy (2015) tested six full-scale GFRP reinforced exterior beam-column joint prototypes under seismic loading. The parameters of their study were concrete strength, and shear stress level in the joint. Diagonal shear cracks were observed in some of the joint specimens. For the same shear stress level, similar strains were recorded in the joints stirrups at failure even thougth the failure occured at different drift ratios. Furtheremore, the energy dissipation and ductility were higher for the joints that had lower concrete strength as compared to those with higher concrete strength. Therefore, the joints with higher energy dissipation were able to regain their original shape after unloading. Further details and results are summarized in Table 1.

Similar to the latter experiment, Ghomi and El-Salakawy (2015) performed an experiment on six full-scale beam-column joints reinforced internally with GFRP bars and stirrups under seismic loading. The joints had lateral beams on all four sides of the column. The variables considered were reinforcement materials (steel and GFRP), presence of lateral beams, joint shear stress level, and end anchorage of beam longitudinal bars (headed-end, and bent bars). Their findings revealed that in some cases, GFRP-RC beam-column joints confined with lateral beams were able to provide nonlinear behavior and nonbrittle failure, despite the expected linear behavior from FRP-RC structures. This was also due to high shear stress level in some joints, where at the same drift ratios, they were able to dissipate more energy as compared to those with lower shear stress level. Furthermore, both methods of anchorages performed well with shear stress level of 1.1 $\sqrt{f_c'}$ or higher.

2.2 Beam-Column Joints Internally Reinforced with SMA Bars

Smart materials such as SMA play an important part in the advancement and application of smart devices. These devices could be incorporated in many structures for providing functions like energy dissipation, sensing, monitoring, actuation, self-adapting, and healing of structures. Researchers noted that reinforcing structures with SMA bars provided remarkable results in terms of capability in regaining their original shape without any residual displacement after the movement (e.g. Alam and Nehdi 2008; Noguez and Garcia 2015). Alam and Nehdi (2008) were able to identify the discrepancies in moment-curvature relationships of beam-column joints reinforced with SMA and other joints reinforced with steel to predict the location of the plastic hinge, crack width, and bond-slip relationship for SMA reinforced joints when subjected to seismic loading. They studied analytically two beam-column joints, one reinforced with SMA bars in the joint hinge region coupled by steel couplers with steel bars in other regions, and another one reinforced with only steel subjected to cyclic displacement loading using finite element analysis software program and their performance was compared with experimental results of a bridge pier reinforced with SMA bars and spirals of another study (Saiidi and Wang 2006). The numerical results showed that finite element analysis tool could easily predict the moment-rotation and load-displacement curves with significant accuracy.

2.3 Beam-Column Joints Internally Reinforced with Hybrid FRP-SMA Bars

SMA-FRP hybrid reinforcement of concrete beam-column joints offers an advantage to efficiently strengthen the most critical locations in the structure by SMA and other locations by FRP materials. Experimental studies conducted by Zafar and Andrawes (2011; 2012) were mainly on the application of SMA-FRP composite as an innovative way to reinforce RC moment resisting frames (MRFs) in order to enhance their behavior in seismic conditions and to reduce their residual drifts after the occurrence of an earthquake. They observed that due to higher initial stiffness, the frame reinforced with steel experienced lower inter-story drifts (IDs) when compared to those reinforced with SMA-FRP and GFRP. Frame with steel reinforcement undergone 84% and 62% more residual IDs when compared to those reinforced with SMA-FRP and GFRP bars, respectively. For the same peak ground acceleration (PGA) value, the frame reinforced with SMA-FRP was capable to dissipate more energy as compared to the GFRP frame. SMA-FRP reinforced frames also exhibited almost negligible residual ID values as compared to the GFRP and steel reinforced frames. The study further revealed that application of SMA-FRP bars in the zones of plastic hinge of MRFs did not only improve ductility considerably, but also residual drifts and energy dissipation were improved when compared with frames reinforced with GFRP. Consequently, the overall performance of the frames under seismic loading conditions was enhanced.

Zafar and Andrawes (2014) also conducted a study on using SMA-FRP composite as a modern way to reinforce MRFs in order to enhance their seismic behavior. Numerical results showed that SMA-FRP hybrid reinforced MRF performed very well in terms of dissipating energy and accumulating lesser residual drifts. Moment resisting frame reinforced with steel was capable to resist 49% lower seismic demand (PGA) when subjected to different seismic events as compared to the frame reinforced with SMA-FRP.

Table 1. Summary of experimental work on beam-column joints internally reinforced with FRP

Beam-Column Joints	Mady et. al (2011)		Hasaballa et. al (2011)		Ghomi and El-Salakawy (2015)		Hasaballa and El-Salakawy (2015)		Said and Nehdi (2004)		Saravanan and Kumaran (2011)	
	Beam	**Column**	**Beam**	**Column**	**Beam**	**Column**	**Beam**	**Column**	**Beam**	**Column**	**Beam**	**Column**
Test parameters	Longitudinal reinforcement and stirrups types and ratios		Longitudinal reinforcement and stirrups types, and details of beam longitudinal reinforcement		Presence of lateral beams, and joint shear stress level		Concrete strength, and joint shear stress level		Longitudinal and lateral reinforcement types		Concrete strength and beam and column longitudinal reinforcement	
Cross-section(mm^2)	350x450	350x500	350x450	350x350	300x350	350x400	350x450	400x350	250x400	400x250	150x200	150x200
GFRP longitudinal reinforcement	5#19	8#19	5#16	8#16	10#16	12#16	8#16	12#16	8#16	12#16	4#12	4#12
GFRP transversal reinforcement	3 branches #13@100mm	3 branches #13@90mm+1 transversal#10	3#13@100mm	3#13@90mm	3#12 @ 100mm	3#12 @ 90mm	3 branches #12@100mm	3 branches #12@90mm	3 branches #10@80mm	3 branches #10@80mm	2#8 @ 150mm	2#8 @ 150mm
Tensile strength for longitudinal & transversal bars (Mpa)	590	#13=590, #10= 642	751		1,100		1,008		600		580	
Concrete compressive strength (Mpa)	30		32.5		42.2		51.3		_		44.15	
Load type	Cyclic loading	Constant axial load of 800 kN	Seismic loading	Constant axial service load=15% column capacity	Cyclic loading	Constant axial service load=15% column capacity	Cyclic loading	Constant axial service load=15% column capacity	Cyclic loading	Constant axial load of 600 KN	Monotonic loading	Constant axial load
Max. lateral load capacity (KN)	150		-		170		150		120		13.2	
Drift ratio at max. load lateral capacity (%)	4		4		6		6		6		5	
Specialty			200 mm long beam stub		Lateral beams as confinement		Couplers to connect bars together		Using GFRP grid instead of bars and stirrups		Steel bend couplers at the joint for GFRP bars	
Cumulative energy dissipation (KN m)	58 at 5% DR		23 at 5% DR		50		28		60		_	
Observed failure mode	Concrete crushing at 4% DR in beam plus rupture of beam GFRP bars at 5% DR		Concrete compression failure		Buckling of beam bars		Plastic hinge in the beam section followed by slippage of longitudinal reinforcement		Specimens were not tested up to failure		Joint shear failure	

Another study was conducted by Nehdi et al. (2010) using super-elastic (SE) SMA bars in the zone of plastic hinge and FRP in other zones of a steel-free beam-column joint under cyclic loading. It was found that the coupled SE SMA-FRP bars formed a force-displacement hysteresis for the beam-column joint, similar to that of steel RC joint with lower stiffness and comparable residual drift. The utilization of SMA at the region of plastic hinge of the beam-column joint was supposed to considerably reduce the residual drift due to its quality of being highly super-elastic. However, the observed distortion was likely because of the slippage of the FRP bar inside the couplers. Nevertheless, steel reinforced beam-column joints had the capability to withstand 89% of its load carrying capacity beyond the ultimate limit. Such SMA-FRP corrosion free RC structural members could have an extraordinary advantage in very harsh and alkaline environmental conditions, where less or no maintenance would be required. Furthermore, in the case of steel-RC beam-column joint specimen the plastic hinge formed at the column face. Conversely, by using SE-SMA in the joint region, the plastic hinge zone was successfully transferred away from the face of column by a distance equal to approximately one fourth of the beam depth.

3 DURABILITY FATIGUE RESISTANCE AND COST ASSOCIATED WITH FRP SMA REINFORCEMENT

Al-Hammoud et al. (2011) conducted an experimental study to examine the flexural behavior of corroded steel reinforced concrete beams strengthened with CFRP sheets under repeated loading. The results revealed that the steel bars are the controlling factor of the fatigue capacity of RC beams. Therefore, repairing the beam or replacing steel with innovative materials like FRP and SMA was the way to increase the capacity of the beam with corroded steel reinforcement. According to Al-Hammoud et al. (2011), after repairing and strengthening the RC beam for flexure with corroded steel by CFRP sheets, the fatigue capacity was higher than that of the control beam which had no corrosion. Additionally, Aidoo et al. (2004) found that the increase of the fatigue capacity was also controlled by the quality of the bond between the CFRP sheets and concrete. In another study by Ekenel et al. (2006) concrete beams strengthened with FRP laminates using two different types of bonding (epoxy and mechanical fasteners) were tested under fatigue to find that both types can be used for this purpose and the mechanical stiffeners can be alternatives to the epoxy adhesive; however, the epoxy bonded FRP beams with anchor spikes had the highest ultimate strength as compared to mechanical fasteners.

Additionally, Yun et al. (2008) performed an experiment on RC beams strengthened with near-surface-mounted (NSM) FRP. They revealed that NSM is the eminent method among others (external bonded, fiber anchored bonded, and hybrid bonded) to sustain good bond between FRP and concrete surface under fatigue loading.

On the other hand, the fatigue situation for SMA bars relates to its phase (Dolce and Cardone, 2001). For example when SMA is in austensite state (high temperature phase) then the SMA bars are able to undergo considerable deformation. If however, when in martensite state (cooling phase), SMA had no residual deformation and could provide outstanding fatigue resistance and large energy dissipation capabilities.

The combination of noncorrosive property and high strength capacity makes the FRP an outstanding material as internal and external reinforcement in RC structures. Based on a study by Benmokrane et al. (2002), the durability of FRP is related to the fiber types (carbon, glass, basalt etc.) and epoxy resin matrix used. Moreover, Micelli and Nanni (2004) agreed with Benmokrane et al. (2002) and noted that carbon fibers were more durable than glass fibers in harsh environment.

Although upfront cost of FRP materials might be higher than the steel, however, by using FRP as external and internal reinforcement, the maintenance and damage repair expenses would be reduced over the life of structures (e.g. Muntasir Billah and Alam 2012). On the other hand, while the superior properties of SMA, used as reinforcement in concrete structures, increase the capacity and ductility, and have the ability to re-center the structure to its original shape after damage, its high cost has always been a disadvantage due to Nickel and Titanium (Ni-Ti) composition in SMA. However, Janke et al. (2005) used different composite materials like Fe-Mn-Si-Cr, Cu-Zn-Al, and Cu-Al-Ni to shape the alloys. They were able to achieve comparable properties with a decrease in cost ratio which varied greatly with shape and required quantities. The ratio ranges were 1 to 10 and 2 to 20 for Cu-Zn-Al and Cu-Al-Ni, respectively as compared to Ni-Ti with cost ratio range of 10 to 100. From this analysis, a significant reduction in cost was observed when the Ti was removed and Ni was replaced with another component like Cu.

4 CONCLUSIONS

The performance of concrete beam-column joints reinforced with innovative smart and corrosion free materials such as FRP, SMA, and FRP-SMA hybrid is discussed in this paper. Based on the literature review conducted on various experimental investigations on beam-column joints the following conclusions are drawn:

- Beam-column joints reinforced with FRP, SMA, and hybrid FRP-SMA longitudinal bars and stirrups performed better in improving overall load carrying capacity as compared to the one reinforced with traditional steel bars.
- GFRP reinforced beam-column joints exhibited higher drift ratio as compared to SMA-FRP reinforced joints. However, joints reinforced with SMA-FRP bars sustained small amount of residual displacements in contrast to the ones with steel and GFRP reinforcements.
- The performance of SMA-FRP reinforced beam-column joints under seismic loading was enhanced, specifically in the plastic hinge zone region. Furthermore, considerable improvement in ductility, residual drift, and energy dissipation was observed when compared to joints reinforced with GFRP bars.
- Beam-column joints reinforced with FRP bars are likely to exhibit cracks at lower load and drift ratio than those joints reinforced with steel or SMA bars.
- Beam-column joints reinforced with GFRP bars showed similar energy dissipation to SMA-FRP joints but at higher drift level. Even though, in some cases, GFRP reinforced joints showed ductile behavior under reversed cyclic loading, the performance of traditional steel or SMA reinforced joints were superior under earthquake loading.
- To assure the occurrence of plastic hinge away from the joint following the capacity design rule (strong column weak beam concept), sufficient anchorage is needed in the FRP-reinforced joint core region. While for hybrid SMA-FRP reinforced joints, placement of SMA bars in the joint core is essential.

- FRP and SMA materials can offer unique replacement for steel reinforcement bars due to their noncorrosive property along with the high strength and small residual displacements. This will result in less repair and maintenance and lower life cycle cost.
- Strengthening with FRP and SMA helped improved the fatigue capacity as well as providing protection under harsh environment and corrosion for RC beams.
- Although the high cost of SMA limits the research in the field of strengthening of structures with SMA bars; however, replacing Ni-Ti traditional SMA with other compositions such as Cu-Zn-Al, and Cu-Al-Ni, will bring the cost down, while providing comparable results. Additionally, using FRP as external reinforcement reduces the maintenance cost in the long term.

5 RECOMMENDATIONS AND FUTURE WORK

Significant research work conducted on FRP and SMA in the past few decades has paved the way to utilize such smart materials as reinforcement in concrete structures. The most important factor for potential use of FRP and SMA is their cost which could possibly limit the larger application of such materials in the field of structural engineering. In the last decade, the price of SMA has significantly decreased up to considerable amount. It is expected that the price will further reduce once it becomes widely and commonly used like FRPs. The application of SMA in RC structures will not only increase the cost due to material, but also costs associated with equipment and labor charges. However, FRP and SMA materials have superior quality to resist corrosion. In RC structures, the use of SMA in the plastic hinge zones could reduce cracks formation. Due to the re-centering capability, SMA could regain its original shape and size after experiencing larger inelastic deformations under high seismic loadings thereby assuring serviceability and reduction in maintenance of the structure. The effectiveness of FRP and SMA is exceptional in minimizing risks to human life associated with unpredicted natural disaster events. Further research could be carried out by using FRP and SMA in structures subjected to blast and fire. Moreover, coupling SMA with FRP and steel bars could also be effective in providing ductility.

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