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CYCLIC BEHAVIOUR OF MECHANICALLY SPLICED SHAPE MEMORY ALLOY AND STEEL BARS

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ABSTRACT

Different types of mechanical couplers are used to splice rebars in reinforced concrete (RC) structures. The efficiency of these couplers for connecting steel rebars has been tested and reported in this paper. Recently, superelastic shape memory alloy (SMA) proves to have a great potential to be used as reinforcing bars in concrete structures in seismic areas. However, using SMA bars in entire structures is not economically feasible due to its high cost. Therefore, it is more rational to limit its use in the plastic hinge regions, whereas regular steel can be used in the other regions of the structure. The connections between SMA and steel are critical, and must be able to transfer the full force from SMA bar to steel bar. Since existing couplers have been developed for connecting steel bars, an experimental investigation was performed to determine their suitability for connecting SMA to steel bar. Commercially available screw-lock couplers were found to be unsuitable. Special treatment needs to be done to achieve the full superelastic strain of SMA while connected with steel bar. None of the available couplers provided adequate performance for SMA spliced bars. Hence, an existing coupler was modified for SMA-steel splicing.

Introduction

Bridges and buildings in seismic regions are vulnerable to collapse and severe damage during earthquakes due to excessive lateral deformations. Therefore, safety and serviceability of civil infrastructure are of great concerns in such regions. Under seismic load RC structures designed according to current seismic code are expected to behave nonlinearly and dissipate adequate energy by yielding of rebar, and thus causing permanent damage to the structure. Nonetheless, the new design philosophy intends not to cause permanent damage rather the owners/designers expect/want the structure to be retained and remained functional with minor repair works even after a large earthquake. Superelastic (SE) SMAs are unique alloys with the

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ability to undergo large deformations and return to its original shape from inelastic deformation only upon stress removal. This distinct property makes SMA a potential candidate to be used as reinforcement at the critical locations of RC structures (Alam et al. 2007a, Saiidi and Wang 2006). The use of superelastic SMA as reinforcement instead of steel in the hinge locations of beams and columns will not only help to dissipate adequate seismic energy, but could also restore the original shape of such members after seismic actions. Such SMA reinforced beam-column elements could allow structural engineers to design RC members, connections and the whole structure exhibiting little damage and mitigating post earthquake repairs. SMAs have gained increased usage in structural applications (Alam et al. 2007b). For instance, Dolce et al. (2004) used SMA bracings for seismic retrofitting of existing frames. Maji and Negret (1998) used SMA wires/tendons in prestressed concrete. Indirli et al. (2001) utilized SMA rods for strengthening structures through application of corrective post-tensioning forces. Inaudi and Kelly (1994), Clark et al. (1995) and others contributed significant analytical and experimental studies on structural response control using SMAs. Recent research in the application of SMAs in vibration control includes the work of DesRoches and Delemont (2002), Wilde et al. (2000) and others.

Since SMA is a costly material, it is not feasible to use it as reinforcement in the entire structure. Therefore, it is practical to limit its use particularly at the hinge region in conjunction with steel. However, connection of steel and SMA bar is critical. Welding might be an option for connecting SMA to steel. However, welding creates a brittle connection around the weld zone and is not effective (Hall 2003). The only option remains is the use of mechanical couplers. A number of commercially available couplers were tested with steel rebar. Based on the results, a suitable coupler was chosen for connecting SMA and steel rebar. The connections between the coupler and SE SMA bar have been modified and improved in several ways, and tested under cyclic tension. Finally, a suitable connection has been fabricated, which has been found quite effective up to the SE strain range of SMA rod.

Mechanical Couplers

The use of mechanical rebar couplers in reinforced concrete (RC) construction is a simple, swift and cost-effective method for splicing smooth and/or deformed rebar in tension and/or compression applications. Various types of couplers are available in the market for connecting rebars of the same size (regular couplers) or of different standard sizes (transition couplers). Screw lock couplers have several advantages over threaded couplers since they do not require the ends of rebars either to be threaded or specially treated. This helps them to apply readily in the construction field. No special installation equipment is required, quick and easy installation save time and money, which is ideal for new construction, rehabilitation, retrofitting, strengthening and upgrading of RC structures and its components.

Bar lock couplers used in this experiment are mechanical splices and connectors compatible with reinforcing bars that comply with ASTM A 615, ASTM A 706, ASTM A 996 (Barsplice Products Inc., 2006). They consist of smooth, shaped, steel sleeves with converging sides. Two different types of screw lock couplers have been used for connecting two different size bars: a) regular single barrel coupler (SBC) and b) double barrel zap transition coupler (DBZTC). In the SBC, the reinforcing bars are inserted into the coupler ends until it reaches the pin at the middle (center stop). Both the rebars meet head to head separated by the pin at the middle as shown in Fig. 1. In the case of DBZTC, rebars are inserted into two different slots of the coupler ends, where instead of meeting head to head, they meet in parallel as shown in Fig. 2.

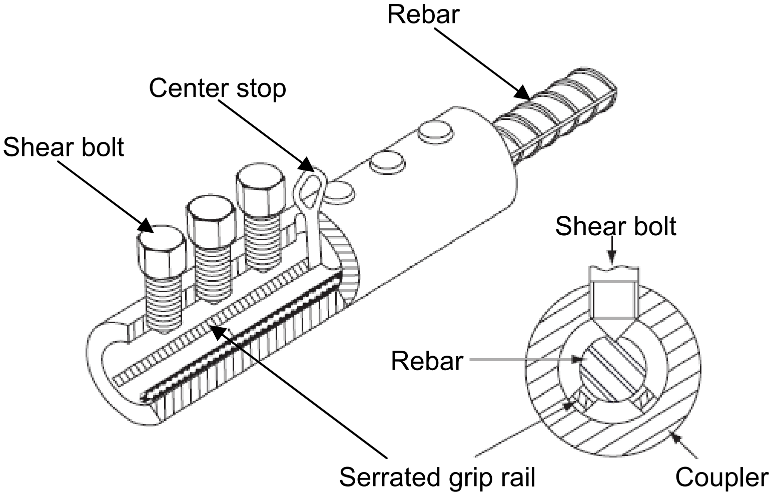


Figure 1. Single barrel screw lock coupler (Dayton/Richmond Concrete Accessories, 2006)

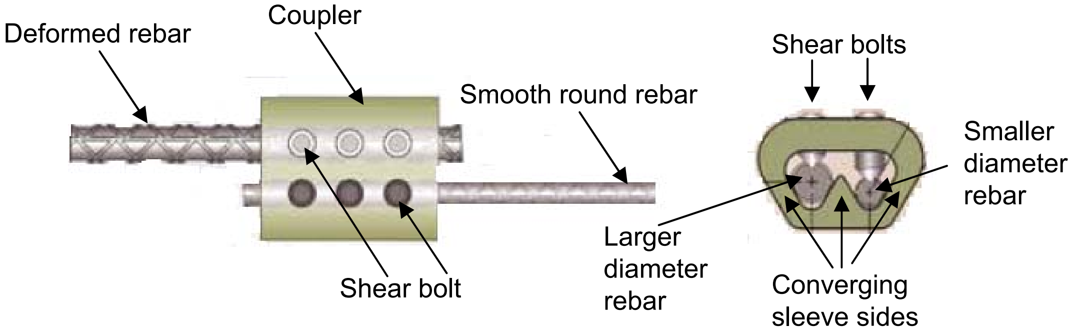


Figure 2. Double barrel zap transition screw lock coupler (Barsplice Products Inc., 2006).

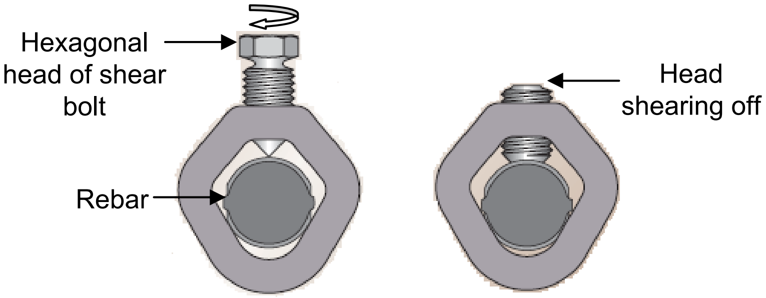
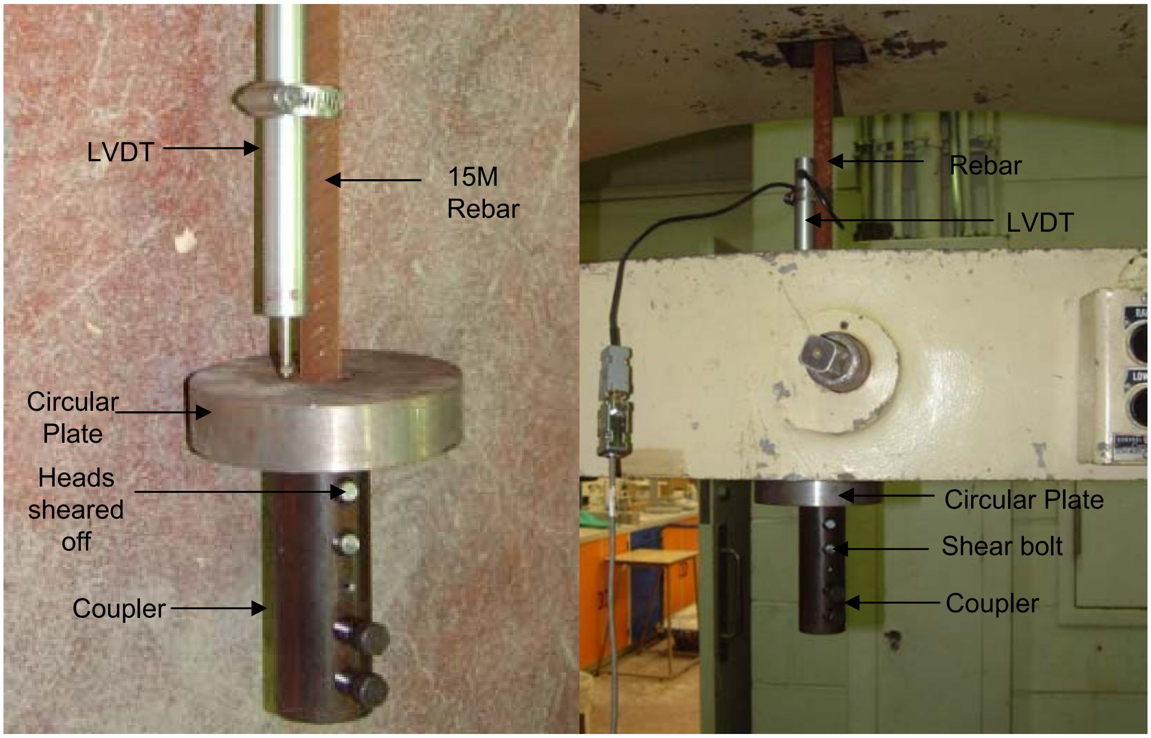


Figure 3. Screw heads shear off by the tightening torque (Barsplice Products Inc., 2006).

Both types of couplers have a series of cone-pointed hexagonal-head lock shear screw bolts arranged along the longitudinal axis of the rebar (as shown in Fig. 1 and 2). These bolts are threaded into the side of seamless tubing. The SBC has two serrated steel strips along its full length and the DBZTC has converging sleeve sides as shown in Fig. 1 and 2 respectively. During mechanical splice assembly, the heads of the shear bolts are tightened by a power or a hand-held ratchet wrench. The tightening embeds the shear bolts into the rebar surface and wedges the bar into the serrated steel strips for converging sleeve sides. Screw heads shear off (Fig. 3) when tightened to the prescribed installation torque as specified in the manual. Force from the shear bolts causes rebar deformations to interlock the rebar within the coupler wedge. Thus the resistance from the shear bolts and the wedge action results in a full positive connection for transferring tension and/or compression forces from bar to bar

Testing of Couplers with Steel Rebar

Instead of testing the whole arrangement i.e. inserting bars from the opposite end of the coupler (Fig. 2), the test was done with one bar at a time. After inserting a rebar in one end of the coupler, the screw heads were tightened and sheared off by applying the prescribed torque as described earlier. The coupler arrangement was then tested in the universal testing machine under tension only. The rebar was inserted through a thick circular plate to support the coupler against pulling the rebar in tension as shown in Fig. 4a. An LVDT attached with the rebar was placed on the circular plate to measure the bar slip in the coupler (Fig. 4 and 5). After testing the rebar, the whole test was repeated for the round bar inserting in the other end of the coupler. This arrangement also helped to avoid any unwanted coupling forced induced in the rebar specimen while testing a DBZTC coupler.



(a) (b)

Figure 4. Test set up for coupler type 1 (SBC) with deformed bar.

Test Results

Tensile strength test was performed for different rebars used in the couplers. The results are shown in Table 1. The specimens with the test set up described in the previous section were tested under tension in the universal testing machine. The results are shown in Table 2 where the specimens are designated as D-2-T1-1, R-1-T2-3 etc. The first part represents whether the rebar is deformed bar (D) or round bar (R), the second part represents diameter of the bar where 1, 2 and 3 stands for 12.75, 16 and 19.5 mm diameter bars respectively. The third part represents the type of coupler, where T1 and T2 represents SBC and DBZTC respectively, and the last digit represents the specimen number for similar kind of arrangements.

Table 1. Tensile strength test of rebars

Bar	Diameter	Yield Load	Yield Strength	Ultimate Load	Ultimate Strength
	mm	kN	MPa	kN	MPa
Round	12.75	43.2	338.4	61.5	481.7
Deformed (15M)	16.00	104.8	524.0	123.9	619.5
Deformed (20M)	19.50	132.0	440.0	195.0	650.0

Table 2. Test results for couplers

Specimen Name	Bar Diameter	Coupler Type	Yield Load	Bar Slip at Yielding	Ultimate Load	Bar Slip at Ultimate	Failure Pattern *
	mm		kN	mm	kN	mm	
R-1-T1-1	12.75	SBC	43.4	1.8	61.3	20.7	Y.R.
R-1-T1-2	12.75	SBC	43.1	1.5	61.0	18.8	Y.R.
R-1-T2-1	12.75	DBTC	42.9	1.5	61.1	32.1	Y.R.
R-1-T2-2	12.75	DBTC	42.5	1.2	61.0	19.3	Y.R.
R-1-T2-3	12.75	DBTC	43.3	1.4	60.5	36.8	Y.R.
D-2-T1-1	16.00	SBC	104.2	1.7	122.7	9.1	Y.R.
D-2-T1-2	16.00	SBC	103.6	1.8	118.0	12.8	Y.R.
D-2-T1-3	16.00	SBC	103.8	1.7	123.9	27.2	Y.R.
D-2-T2-1	16.00	DBTC	102.6	6.3	103.6	10.6	C.F.
D-2-T2-2	16.00	DBTC	103.2	4.3	104.6	7.4	C.F.
D-2-T2-3	16.00	DBTC	-	-	99.5	5.4	C.F.
D-3-T1-1	19.50	SBC	133.2	2.5	192.3	14.4	Y.R.
D-3-T1-2	19.50	SBC	131.7	2.3	195.0	11.0	Y.R.

*Y.R. means the failure occurred by yielding of the bar and C.F. means the failure occurred at the coupler by pulling the bar splice off.

Figure 5. Failure pattern of 15M rebar in SBC coupler.

The test results presented in Table 2 show that SBC couplers can produce full yield strength and ultimate strength of both deformed bars and round bars. The bar slip at yielding has been found very small, which proves to be a better connection in holding the rebars. All the specimens of SBC failed by yielding and rupture of reinforcements (Fig. 5) and thus, providing sufficient ductility. All the 15M rebar specimens with DBZTC couplers failed to produce the required ultimate strength of the rebars although the bar slip at the initial stage was relatively small. After reaching the yield point, there was no increase in the load rather it dropped suddenly and the connection failed by shearing along the rebars by the bolt screws. The tearing along the length of the failed rebar is shown in Fig. 6. In case of round rebars, two of them failed by rupture and one failed at the coupler by pulling the bar splice off.

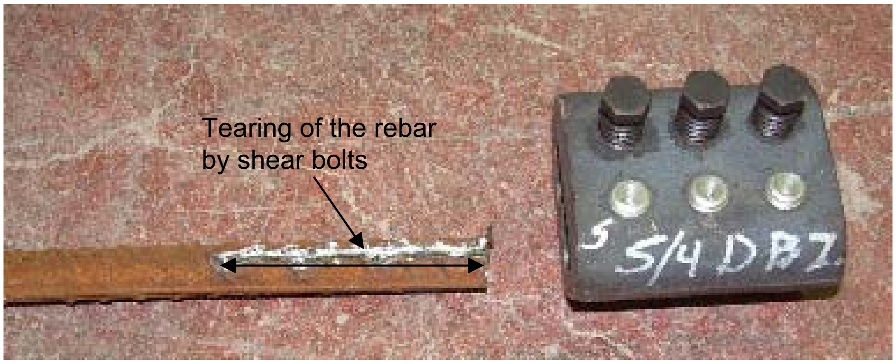


Figure 6. Failure pattern of 15M rebar in DBZTC coupler.

Testing of Couplers with SMA Rebar

Figure 7 shows the tensile strength test result of SMA rebar used in the test. Here, the first yield point is identified as 401 MPa (f_y) at 0.75% strain (ε_y). The SE strain (ε_{SE}) is identified as 6.4% at a stress of 503 MPa (f_{SE}). Its initial Young's modulus (E_y) is calculated as 62.5 GPa. In the universal testing machine (UTM), the grips' teeth firmly hold the SMA bar as the stress increased during the pullout test. This biting effect created notches on the SMA bar surfaces, which caused failure of the bar at the grip of UTM.

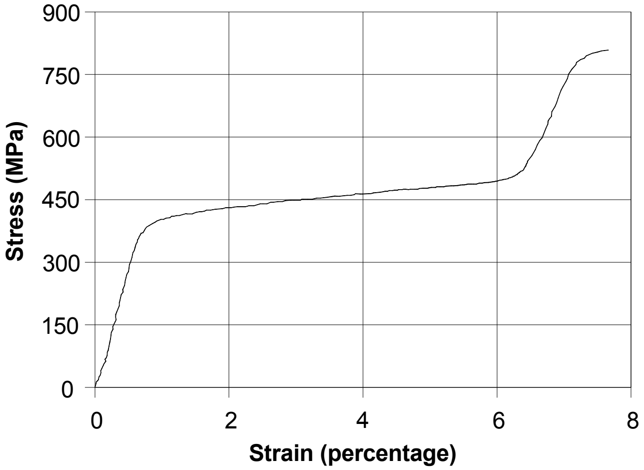


Figure 7. Tensile strength test result of SMA rebar

The regular SBC coupler was used to splice SMA bar. Here, the tightened shear bolts embed into the SMA rebar surface and apply normal force on the bar holding it into the serrated steel strips for converging sleeve sides (Fig. 3). During testing, SMA rebar failed after four cycles at a strain of 1.48%. This premature failure was due to the embedment of sharp end screws inside SMA rebar surface, which produced notches. As a result, SMA lost its strength due to its sensitivity to notches and the bar failed.

In the next attempt, the sharp end screws were flattened to avoid notch development and to increase the frictional resistance against sliding out of the bar from coupler. Therefore, two extra rows of holes were drilled through the coupler in parallel to the existing row at an angle of 45º away from the centre of the coupler as shown in Fig. 8. Nine screw locks were used to connect one SMA bar to the coupler. This arrangement was tested under cyclic tension and the result showed promising as it could produce eight cycles in the pullout test before failure of the connection. In this case the SMA bar slid out from one end of the coupler, and steel rebar on the other end experienced some slippage. Here, the SMA rebar experienced a maximum strain of 3.22%.

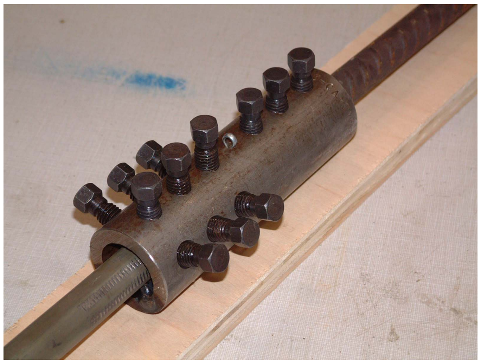


Figure 8. Modified splice arrangement of SMA rebar in SBC coupler

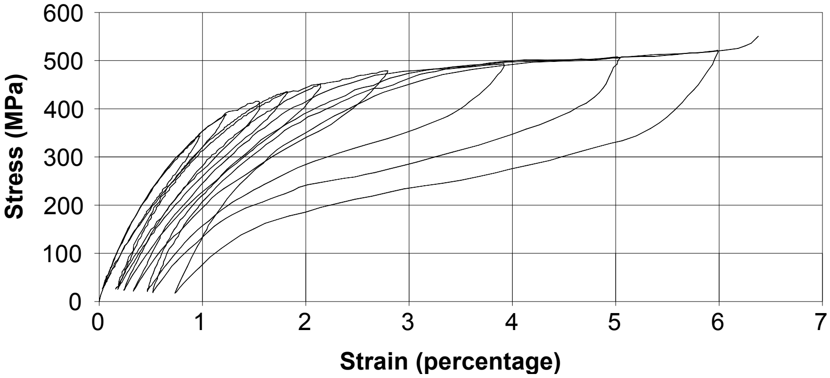


Figure 9. Cyclic tension test of spliced SMA rebar in modified SBC coupler

Similar arrangement was exercised with two extra rows of holes drilled through the coupler in parallel to the existing row are at an angle of 60º instead of 45º away from the centre of the coupler. The other difference is that the sharp ends of the screws have been flattened more, to a diameter of 3.5 mm at their edges. Cyclic tension test confirmed that this arrangement is the most effective splicing arrangement for connecting SMA bar with steel rebar. This arrangement could produce strains up to the full SE range of SMA. Figure 9 shows the cyclic tensile strength of SMA bar with this modified SBC connection. The bar experienced a maximum of 6.38%

strain and a residual strain of 0.73%. The connection was subjected to eleven cycles before failure occurred. The SMA rebar failed at the connection end of the coupler possibly due to high stress concentration and micro-crack formation at the point of contact of coupler screws, which ultimately caused formation of notches and failure.

Conclusions

Because of SMA's higher cost compared to other construction materials, use of SMA as longitudinal bar alone in the entire structure is not feasible rather it will be more practical to use it along with regular steel rebar. This paper discusses a novel approach to connect SMA with steel rebar. The objective of this study was to find out a suitable coupler for connecting SMA to steel rebar where the SMA bar will be effective beyond its SE strain range under cyclic loading. Screw-lock couplers have been found appropriate in this case since it requires no special installation equipment, or modification/special treatment for rebar. It is also quick and easy to install saving time and money, which is ideal for new construction, rehabilitation, retrofitting, strengthening and upgrading of RC structures and its components. Two types of screw-lock couplers have been tested under simple pullout test. SBC has shown better performance compared to that of DBTC in terms of load resistance and ductility. SBC also provided a direct, in-line load transfer mechanism. DBTC may also prove impractical, since this may cause congestion of the reinforcements where there is limitation in the width of concrete members.

Regular SBCs were used in the exploratory study of SMA and steel rebar connection. It has been found that regular SBCs are not sufficient to hold SMA rebar up to its full SE strain range. Several alternatives were chosen so as to modify SBC for a better performance. The best alternative came up with few modifications to the SBC, thus achieving SMA's full superelastic strain. Two parallel extra rows of shear bolts/screws at an angle of 60° from centre row (i.e. 9 screws) were needed to hold a single SMA rebar where all the screw ends were flattened to a radius of 3.5 mm. Two extra screw bolts were also used to connect the steel rebar. The modified version of SBC showed good performance under cyclic tensile test up to its superelastic strain range. The test results demonstrate that SMA possesses a great potential to be used as reinforcement at critical regions of RC structures along with conventional steel, where SMA is expected to yield under strains caused by seismic loads, which will not only be able to dissipate significant amount of energy but also potentially recover deformations at the end of earthquake. Thus, smart RC beam-column elements for buildings, and column-foundations for bridges can be built with superelastic SMA rebar, which will allow structural engineers to design connections, which will exhibit little damage and eliminate post earthquake joint repairs.

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