INNOVATIVE SEISMIC RETROFITTING OF OLD-TYPE RC COLUMNS THROUGH JACKETING: TEXTILE-REINFORCED MORTARS (TRM) VERSUS FIBER-REINFORCED POLYMERS (FRP)

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ABSTRACT:

The effectiveness of a new structural material, namely textile-reinforced mortar (TRM), was investigated experimentally in this study as a means of confining old-type reinforced concrete columns with limited capacity due to bar buckling or due to bond failure at lap splice regions. Comparisons with equal stiffness and strength fiber-reinforced polymer (FRP) jackets allow for the evaluation of the effectiveness of TRM versus FRP. Tests were carried out on full scale nonseismically detailed RC columns subjected to cyclic uniaxial flexure under constant axial load. Thirteen cantilever-type specimens with either continuous longitudinal reinforcement (smooth or deformed) or lap splicing of longitudinal bars at the floor level were constructed and tested. Experimental results indicated that TRM jacketing is quite effective as a means of increasing the cyclic deformation capacity of old-type RC columns with poor detailing, by delaying bar buckling and by preventing splitting bond failures in columns with lap spliced bars. Compared with their FRP counterparts, TRM jackets used in this study were found to be equally effective in terms of increasing both the strength and deformation capacity of the retrofitted columns. From the response of specimens tested in this study, it can be concluded that TRM jacketing is an extremely promising solution for the confinement of reinforced concrete columns, including poorly detailed ones with or without lap splices in seismic regions.

KEYWORDS: confinement; FRP; lap splices; reinforced concrete; seismic retrofitting; textile-reinforced mortar (TRM).

1. INTRODUCTION

The upgrading of existing reinforced concrete (RC) structures through jacketing of columns has become the method of choice in an increasingly large number of rehabilitation projects, mainly seismic but also non-seismic. Among all jacketing techniques, the use of fiber-reinforced polymers has gained substantial popularity in the structural engineering community due to the favorable properties offered by these materials (high strength to weight ratio, corrosion resistance, ease and speed of application, minimal change of geometry). Despite all the advantages, the FRP retrofitting technique has a few drawbacks (e.g. poor behavior at high temperatures, high costs, inapplicability on wet surfaces and difficulty to conduct post-earthquake assessment behind FRP jackets), which are mainly attributed to the organic (typically epoxy) resins used to bind the fibers. An interesting alternative to FRP materials are the so-called Textile-Reinforced Mortars (TRM) [Triantafillou et al. (2006)]. These materials comprise textiles, that is fabric meshes made of long woven, knitted or even unwoven fiber rovings in at least two (typically orthogonal) directions, impregnated with inorganic binders, such as cement-based mortars. The density, that is the quantity and the spacing, of rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the textile and the degree of penetration of the mortar matrix through the mesh.

Although research on the use of textile meshes as reinforcement of cementitious products commenced in the early 1980s, developments in this field progressed rather slowly until the late 1990s. But during the past few years, the research community has put considerable effort on the use of textiles as reinforcement of cement-based products (leading to the introduction of the material commonly named “Textile Reinforced Concrete”), primarily in new constructions. Studies on the use of textiles in the upgrading of concrete structures have been limited. Most of these studies have focused on flexural or shear strengthening of beams and on aspects of bond between concrete and cement-based textile composites [Curbach and Ortlepp (2003), Curbach and Brueckner (2003)]; they concluded that properly designed textiles combined with inorganic binders have a good potential as strengthening materials of RC members. The first studies reported in the international literature on the use of textiles in combination with cement-based binders for the confinement of concrete are described by Triantafillou et al. (2006) and Bournas et al. (2007). In these studies the authors investigated experimentally the application of TRM as a means of increasing the axial capacity of plain and reinforced concrete through confinement and they compared the behavior of TRM-confined cylinders and prisms with that of specimens confined with equal stiffness and strength FRP jackets. Main conclusions were that: (a) TRM jacketing provides a substantial gain in compressive strength and deformability of plain and reinforced concrete; (b) compared with their FRP counterparts, TRM jackets may result in slightly reduced effectiveness for plain concrete and 10% reduced effectiveness for reinforced concrete prisms.

In the present study, the authors go one step further by investigating experimentally the use of TRM jackets as a means of confining poorly detailed RC columns, which suffer from limited deformation capacity under seismic loads due to buckling of the longitudinal bars or due to splitting bond failure at lap splice regions. Tests were carried out on full-scale nonseismically detailed RC columns subjected to cyclic uniaxial flexure under constant axial load. All specimens retrofitted with TRM jackets had their FRP-retrofitted counterpart, which enabled comparisons of the two systems.

2. EXPERIMENTAL PROGRAM

2.1. Test specimens and experimental parameters

A total of 13 full-scale reinforced concrete column specimens with the same geometry comprising 7 columns with continuous longitudinal reinforcement (smooth or deformed) and 6 columns with lap splicing of longitudinal bars at the floor level were constructed and tested under cyclic lateral load (Fig. 1a). The specimens were flexure-dominated cantilevers with a height to the point of application of the load (shear span) of 1.6 m (half a typical story height) and a cross section of 250x250 mm. The columns were fixed into a heavily reinforced 0.5 m-deep base block, 1.2x0.5 m in plan, within which the longitudinal bars were anchored with

90-degree hooks at the bottom. In order to represent old-type non-seismically designed and detailed columns, both series of continuous and spliced specimens were reinforced longitudinally with four 14 mm-diameter bars and 8 mm diameter smooth stirrups at a spacing of 200 mm, closed with 90-degree hooks at both ends. The geometry of a typical cross section is shown in Fig. 1b.

The specimens which were constructed with continuous longitudinal reinforcement comprised 3 columns with smooth bars (Series L0S_...) and 4 columns with deformed bars (Series L0_...). Two specimens were tested without retrofitting, as controls (L0S_C and L0_C), the second pair was retrofitted with a double-layered CFRP jacket (L0S_R2 and L0_R2), the third pair of specimens was retrofitted with an equal (to its FRP counterpart) stiffness and strength carbon fiber TRM jacket comprising 4 layers (L0S_M4 and L0_M4), while one last specimen with deformed bars was retrofitted with a lower stiffness and strength 4-layered glass fiber TRM jacket (L0_M4G).

The effectiveness of TRM versus FRP jackets, applied at the ends of old-type RC columns for specimens constructed with lap splicing of longitudinal reinforcement above the column base, was evaluated for two different lap lengths which were selected equal to 20 and 40 bar diameters, as shown in Fig. 1b. The shorter lap lengths (Series L20d_...) which were representative of RC columns constructed up to the late 1970s comprised three specimens: one specimen was tested without retrofitting as control (L20d_C), the second one was retrofitted with a two-layered CFRP jacket (specimen L20d_R2) and the third one was retrofitted with an equal (to its FRP counterpart) stiffness and strength carbon fiber TRM jacket comprising four layers (specimen L20d_M4). The corresponding specimens with longer lap lengths (L40d_ series) are L40d_C, L40d_ R2 and L40d_M4. Note that the layers in the TRM-jacketed columns were twice as many compared with their FRP counterparts, resulting in two "equivalent" confining systems, that is with equal stiffness and strength in the circumferential direction (as explained below, the fibers of the two jacketing systems in the circumferential direction were of the same type and nearly twice as many in the FRP system compared with the TRM system).

The notation of specimens is LX_YN, where X defines the lap splice length above the column base (0 for absence of lap splice – i.e. continuous reinforcement, 20d for a lap splice length of 20 bar diameters, 40d for a lap splice length of 40 bar diameters), Y denotes the type of jacket (C for the unjacketed – control columns, R for resin-based jackets and M for mortar-based jackets) and N denotes the number of layers. Note here that for specimens with smooth longitudinal bars the letter S (smooth) was added after letter X, while for the specimen strengthened with a glass TRM jacket the letter G was added after letter N. The jackets extended from the base of each jacketed column to a height of 430 mm except for the two jacketed columns with longer lap splices, where the jackets were extended to a height of 600 mm. Prior to jacketing, the 4 corners of the columns which received jacketing were rounded at a radius of 25 mm.

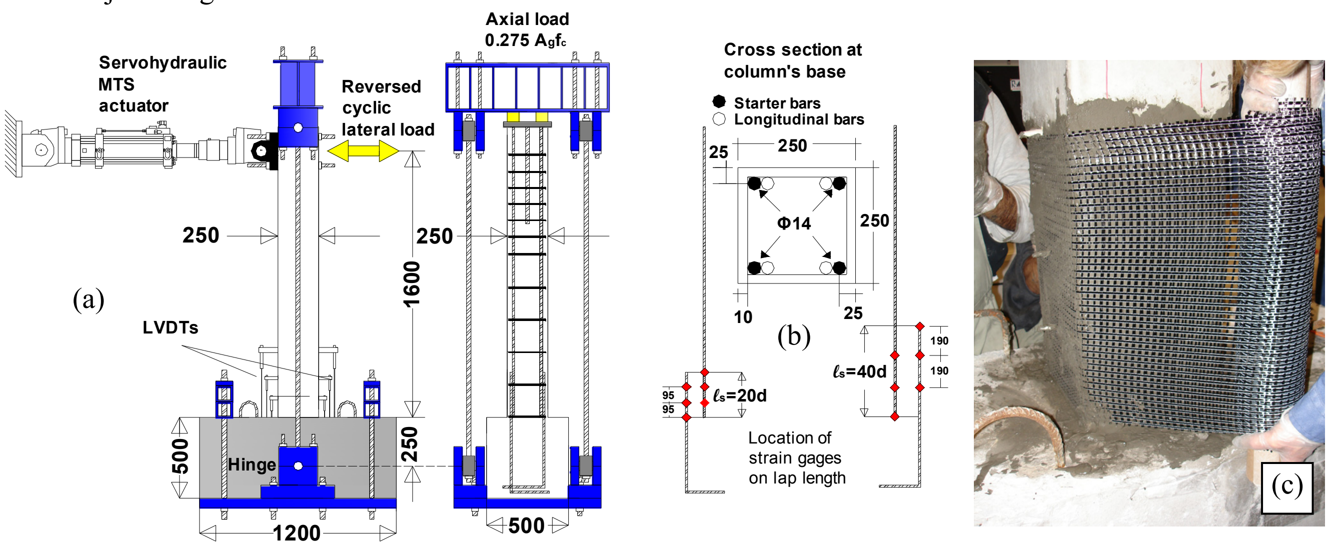


Figure 1 (a) Schematic of test setup. (b) Cross section of columns. (c) Application of TRM jacket.

2.2. Strengthening procedures, materials and test set up

The longitudinal smooth bars had a yield stress of 372 MPa, a tensile strength of 433 MPa and an ultimate strain equal to 17%, while the corresponding values for deformed bars were 523 MPa, 624 MPa and 12%. The corresponding values for the steel used for stirrups were 351 MPa, 444 MPa and 19.5%. In order to simulate field conditions the base blocks and the columns were cast with separate batches of ready-mix concrete (on two consecutive days). Casting of the columns was made with separate batches too, resulting in a mean compressive strength on the day of testing (measured on 150x150 mm cubes) equal to 30.2 MPa for specimens L0S_C, L0S_R2 and L0S_M4, 28.38 MPa for specimens L0_C, L0_R2, L0_M4, L0_M4G and L20d_C, and 25.90 MPa for specimens L20d_R2, L20d_M4, L40d_C, L40d_R2 and L40d_M4.

For the specimens receiving TRM jacketing (L0S_M4, L0_M4, L0_M4_G, L20d_M4 and L40d_M4) two commercial textiles with equal quantity of high strength carbon and glass rovings in two orthogonal directions were used. Each fiber roving was 3 mm wide and the clear spacing between rovings was 7 mm. The weight of carbon and glass fibers in the textile was 348 g/m^2 and 480 g/m^2, respectively, while the nominal thickness of each layer (based on the equivalent smeared distribution of fibers) was 0.095 mm and 0.089 mm respectively. The mean tensile strength of the carbon and glass fibers (as well as of the textile, when the nominal thickness is used) was taken from data sheets equal to 3800 MPa and 1700 MPa, respectively. The elastic modulus of carbon and glass fibers was 225 GPa and 70 GPa, respectively. For the specimens receiving FRP jacketing (L0S_R2, L0_R2, L20d_R2 and L40d_R2), a commercial unidirectional carbon fiber sheet was used, with a weight of 300 g/m^2 and a nominal thickness of 0.17 mm. For the specimens receiving mortar as a binding material, a commercial inorganic dry binder was used, consisting of cement and polymers at a ratio of about 8:1 by weight; the water:binder ratio in the mortar was 0.23:1 by weight, resulting in plastic consistency and good workability. The average flexural and compressive strength of the mortar was calculated equal to 6.51 MPa and 20.8 MPa, respectively. Finally, for the specimens receiving resin adhesive bonding, a commercial structural adhesive (two-part epoxy resin with a mixing ratio 3:1 by weight) was used with a tensile strength of 70 MPa and an elastic modulus equal to 3.2 GPa [cured 7 days at 23 ^{o}C].

Application of the mortar was made in approximately 2 mm thick layers with a smooth metal trowel. After application of the first mortar layer on the (dampened) concrete surface, the textile was applied and pressed slightly into the mortar, which protruded through all the perforations between fiber rovings. The next mortar layer covered the textile completely and the operation was repeated until all textile layers were applied and covered by the mortar. Of crucial importance in this method, as in the case of epoxy resins, was the application of each mortar layer while the previous one was still in a fresh state. A photograph of the application method of textile combined with mortar binder to provide jacketing in one of the specimens used in this study is shown in Fig. 1c.

The columns were subjected to lateral cyclic loading through the use of a horizontally positioned MTS actuator, under a constant axial load corresponding to 28% of the members' compressive strength. Displacements and axial strains at the plastic hinge region were monitored using six rectilinear displacement transducers. The instrumentation also included a total of 8 strain gages for each column with continuous longitudinal reinforcement and a total of 12 strain gages for each column with lap splices. Measurements from the strain gages on each pair of starter-longitudinal bars were used to determine strain distribution of bars and bond stresses along the splice length, while for columns with continuous bars measurements were useful to estimate the onset of bar bucking.

3. TEST RESULTS AND DISCUSSION

The response of all columns tested is given in Fig. 2 in the form of load-drift ratio loops. The performance and failure mode of all tested specimens was controlled by flexure, as expected due to their design characteristics. Key results are also presented in Table 3.1.

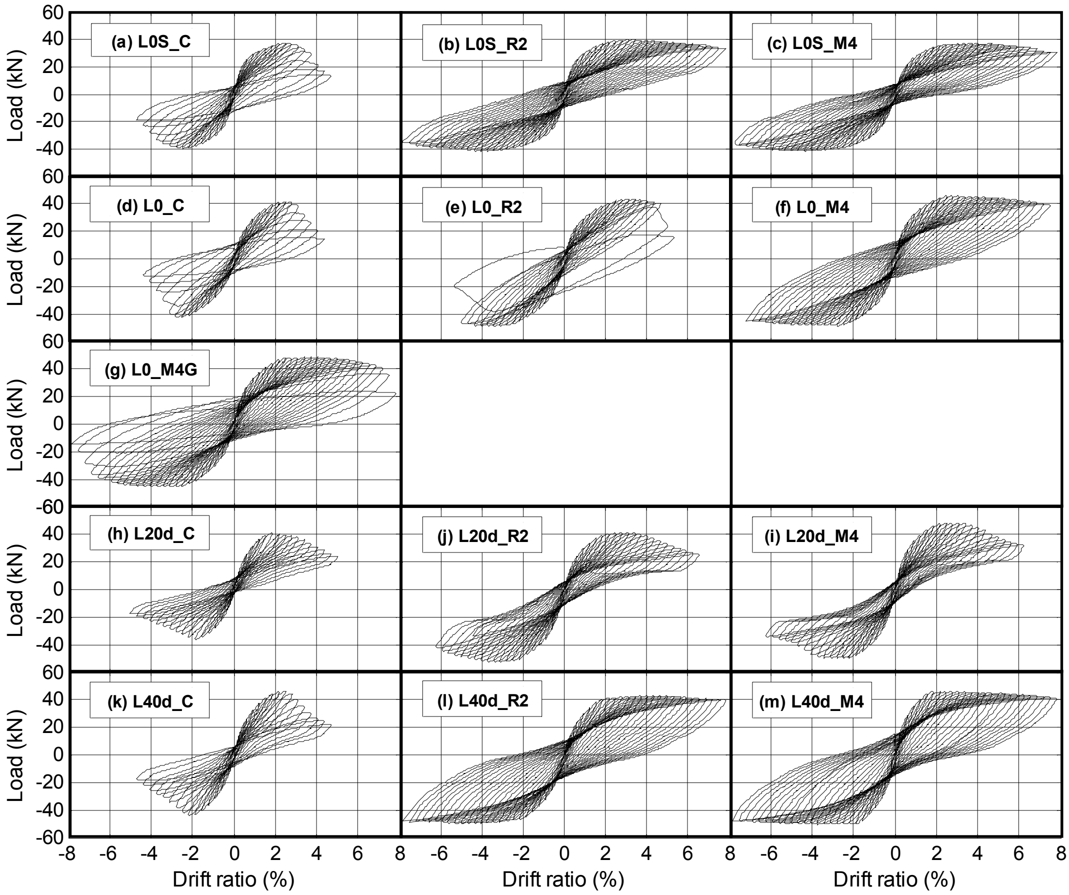


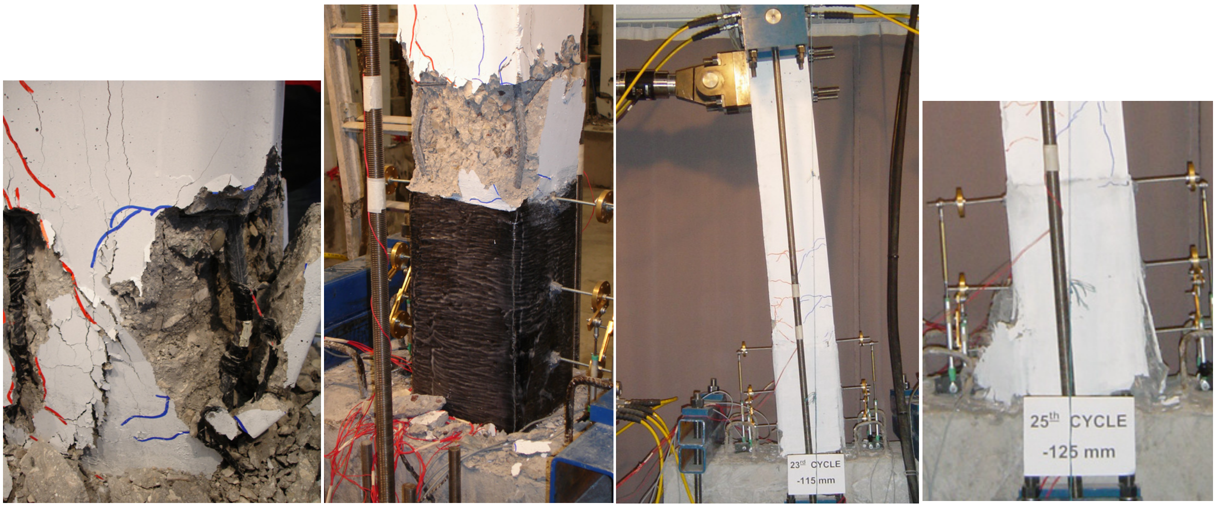
Figure 2 Load versus drift ratio curves for all specimens tested.

Table 3.1 – Summary of test results

Specimen notation	Peak force (kN)		Drift at peak force (%)		Drift at "failure" (%)		Failure Mode
	Push	Pull	Push	Pull	Push	Pull	
L0_C	41.63	-42.48	2.5	2.5	3.43	3.43	Buckling of longitudinal bars
L0_R2	43.46	-48.70	2.8	3.1	5.0	-5.31	Buckling of longitudinal bars above FRP jacket
L0_M4	45.77	-49.19	2.8	2.8	7.81	7.81	Conventional failure was not reached
L0_M4G	48.82	-45.28	4.0	2.8	7.5	6.9	Fracture of the TRM jacket due to both rebars buckling and concrete dilation
L20d_C	41.50	-36.62	1.87	1.87	4.06	3.12	Splitting bond failure followed by spalling of the concrete cover
L20d_R2	41.26	-52.86	2.81	3.12	5.31	6.25	Splitting longitudinal cracking followed by pull out bond failure of lapped bars
L20d_M4	48.46	-49.80	3.12	2.18	5.0	5.0	Splitting longitudinal cracking followed by pull out bond failure of lapped bars
L40d_C	46.21	-43.87	2.5	2.18	3.43	3.12	Splitting bond failure followed by spalling of the concrete cover
L40d_R2	42.97	-49.93	4.68	5.0	7.81	7.81	Conventional failure was not reached
L40d_M4	45.90	-50.48	1.87	3.75	7.81	7.81	Conventional failure was not reached

3.1. Specimens with continuous longitudinal reinforcement

The failure mode of the two unretrofitted specimens L0S_C and L0_C (Fig. 3a) was controlled by bar buckling above the column base, which led to direct lateral strength degradation. The outward bending of buckled bars at the columns' corners (at mid-height between the two adjacent stirrups closest to the column base) was found to be responsible for the concrete cover spalling over the lower 200 mm of the column. The attained drift ratio at failure sustained by both unretrofitted specimens L0S_C and L0_C with smooth and deformed bars was very close, equal to 3.75% and 3.43%, respectively.



(a) (b) (c) (d)

Figure 3 (a) Disintegration of concrete and bar buckling. (b) Buckling of longitudinal bars above the FRP jacket. (c) Undamaged carbon TRM jacket at end of test. (d) Rupture of glass TRM jacket due to bar buckling.

The behavior and failure mode of retrofitted columns was not dominated by longitudinal bar buckling above the column base. Based on strain gage measurements, it was concluded that bar buckling was not averted for FRP or TRM confined specimens. In fact, bar buckling initiated with a significant delay ranging between 4-8 cycles with respect to the unretrofitted columns (L0S_C and L0_C), but it was not accompanied by strength degradation. This is attributed to the fact that buckled bars under external confinement could sustain a significant portion of their compressive load after buckling, as the concrete cover remained in place and provided lateral support to bars.

The behavior of the two retrofitted columns with smooth bars was very similar (Fig. 2b and 2c), but quite different from and far better than their unretrofitted counterpart L0S_C (Fig. 2a). Member deformation capacity increased by a factor of more than two, while peak resistance was practically the same as in the unretrofitted column. Furthermore, the post peak response was quite stable, displaying gradual strength degradation. Whereas the FRP jacket in column L0S_R2 exhibited limited rupture over the lower 50 mm at 7.2% drift ratio, the TRM jacket remained intact until the test was terminated at 7.8% drift ratio.

The heavy confinement provided by the FRP jacket to specimen L0_R2 (Fig. 2e) restrained the outward bending of longitudinal bars inside the FRP jacket region. Owing to this fact the concrete cover dilation was marginal and a large amount of strain energy was stored in the confined concrete without any stress relaxation in the compression zone. This resulted in the transition of the compressive force above the FRP jacket, where buckling of the longitudinal bars finally occurred in the space between the FRP jacket's end and the next stirrup at a height of 530 mm, as shown in Fig. 3b. Similar observations of bar buckling above the FRP jacket (in regions with the bending moment is significantly lower than that at the column base) have been marked by other researchers too [Bousias et al. (2007)].

The behavior of TRM-jacketed columns L0_M4 and L0_M4G (with deformed bars) against bar buckling was favorable. Buckling was controlled, as the compressive force released from early buckled bars was carried by the surrounded confined concrete inside the TRM jackets. This is possible to occur in this confining system as TRM jackets are able to deform outwards without fiber rupture, contrary to stiffer FRP jackets in which the outward bending of longitudinal bars leads to stress concentrations and thus possible rupture. More specifically, in specimen L0_M4 the carbon fiber TRM jacket remained intact until the test was terminated at 7.8% drift ratio (Fig. 3c), while in the case of column L0_M4G fracture of the glass fiber TRM jacket (Fig. 3d) led to failure. Fracture of the jacket initiated from a limited number of fiber bundles (when the hoop stresses reached their tensile capacity) and then propagated rather slowly in the neighbouring bundles.

Finally, for specimens with deformed bars and carbon or glass fiber TRM jackets the behavior was similar, but quite different from and far better than the FRP confined and unretrofitted specimens. Member deformation capacity increased by a factor of 1.5, 2.3, and 2.1 for specimens L0_R2, L0_M4 and L0_M4G, respectively, in comparison with the control specimen L0_C, corresponding to drift ratios at failure equal to 5.15%, 7.81% and 7.2%, indicating a higher effectiveness for TRM versus FRP jackets of about 50%. Peak resistance was practically the same for all jacketed specimens and about 10% higher than that of the control specimen due to earlier bar buckling.

3.2. Specimens with lap splicing of longitudinal bars

The performance and failure mode of all specimens with lap splices was also controlled by flexure. Significant longitudinal splitting cracks developed along the splice length of lapped bars for both unretrofitted specimens L20d_C (Fig. 4a) and L40d_C (Fig. 4b) at drift ratios of 1.56% and 2.5% respectively, corresponding to peak lateral load. The length and width of the longitudinal cracks along the splice length was increasing at higher drift levels as the bond between reinforcing bars and concrete was deteriorating. As a consequence of this, the concrete under compression spalled along the lower (approximately) 100 mm and 175 mm from the base of specimens L20d_C (Fig. 4c) and L40d_C respectively, leading to substantial lateral strength degradation after peak lateral load. Contrary to control specimens L0S_C and L0_C with continuous bars, the expansive spalling of the concrete in the critical zone was not followed by buckling of longitudinal rebars for two reasons: first the compression reinforcement was double and second the quick strength degradation of the specimens associated with the extensive bond deterioration reduced the demand of the compression reinforcement to resist the applied load. The drift ratio at failure (average values for both loading directions) sustained by unretrofitted columns L20d_C and L40d_C was 3.59% and 3.28%, respectively.

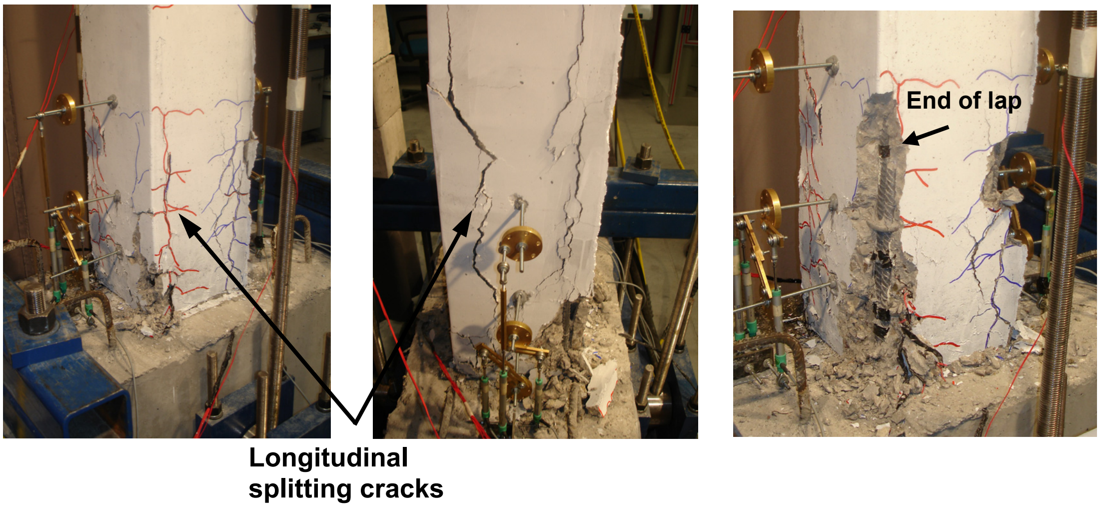


Figure 4 Longitudinal splitting cracks for specimens (a) L20d_C and (b) L40d_C. (c) Failure of unretrofitted column L20d_C.

TRM and FRP jacketed columns with either short or long lap length responded far better than their unretrofitted counterparts both in terms of strength and attained deformation at failure. Specimens L20d_R2 and L20d_M4 (with short lap lengths) sustained reversed deformation cycles up to 6.3% drift before failing due to pull-out bond failure of the spliced bars. This occured when longitudinal splitting cracks had propagated along the entire splice length; thus at that point the presence of TRM or FRP jacket had no effect on the residual splice capacity. The mean strength increase (in both loading directions) with respect to the control specimen was 20.3% and 25.6% for specimens L20d_R2 and L20d_M4, respectively, while the corresponding increase in deformation capacity was 64.7% and 38.8%. For the columns with longer lap splices, both L40d_R2 and L40d_M4 specimens behaved in an identical manner until the end of the test at a drift ratio of 7.8% (when maximum piston stroke was reached), resulting in an increase of the member's deformation capacity by a factor of more than 2.5. Peak resistance was practically the same as in the unretrofitted column, indicating that a lap splice length of forty diameters is adequate for the development of the column's strength capacity. Overall, it may be concluded that TRM confining jackets provide substantial gain in lateral strength and deformation capacity of cyclically loaded reinforced concrete rectangular columns with lap splices at the column's base. Compared with equal stiffness and strength FRP jackets, they are characterized by a slightly reduced effectiveness in terms of deformability for columns with short lap splices, while for columns with longer lap lengths the behavior of FRP and TRM specimens is identical.

4. CONCLUSIONS

The effectiveness of TRM jackets as a means of confining RC columns with limited capacity due to buckling of the longitudinal bars or due to bond failure at lap splice regions is investigated in this study. Comparisons with equal stiffness and strength FRP jackets allows for the evaluation of the effectiveness of TRM versus FRP jackets. Thirteen tests on full scale columns under cyclic uniaxial flexure show that TRM jackets are quite effective as a means of increasing the cyclic deformation capacity and the energy dissipation of old-type RC columns with poor detailing, by delaying bar buckling or by preventing splitting bond failures at columns with inadequate lap splices. Compared with equal stiffness and strength FRP, TRM jacketing has practically the same effectiveness. All test results presented in this study indicate that TRM jacketing is an extremely promising solution for the confinement of poorly detailed reinforced concrete columns in seismic regions.

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