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TESTING AND DESIGN RECOMMENDATIONS OF CONFINEMENT TO WALL ENDS WITH FRP LAMINATE AND SPIKE ANCHORS

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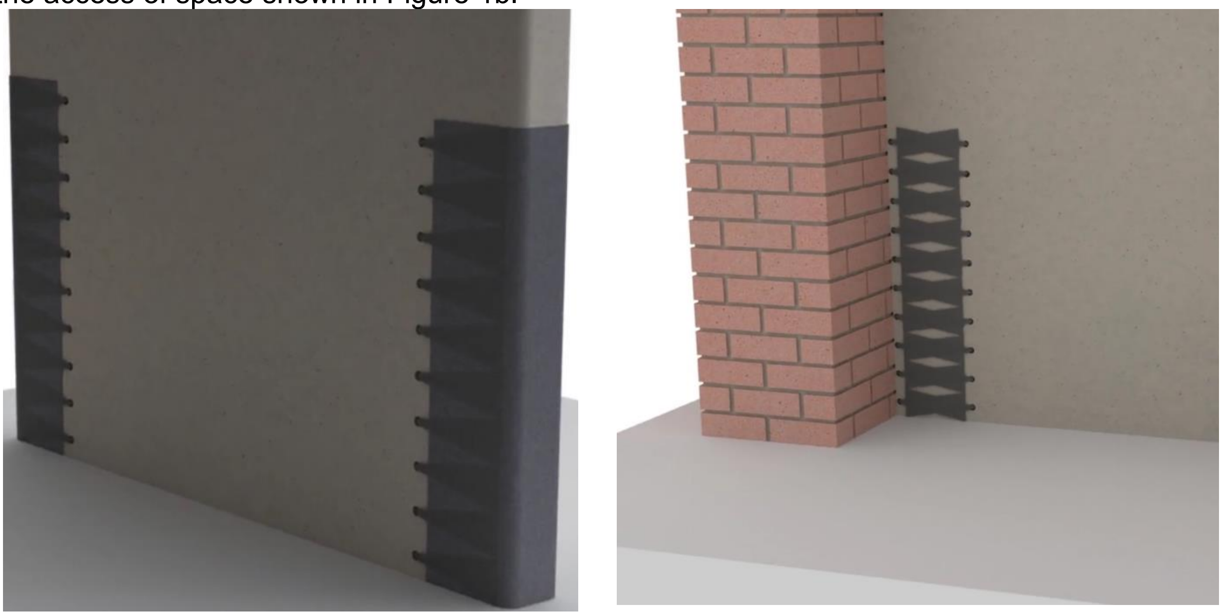
SUMMARY

Reinforced concrete (RC) structures designed before ductility requirements were developed in the 1980s may be vulnerable to seismic actions. Brittle compression failures could happen in RC walls without confinement to end regions, especially singly reinforced walls constructed during the 1970s. Strengthening is typically needed to fix this vulnerability, and using carbon fiber reinforced polymer (FRP) laminate and spike anchors is often being considered by engineers. The problem is the lack of design methodology for this confinement, mainly due to insufficient testing data. Axial compression tests were carried on 75 concrete prisms representing the end regions of RC walls, confined with FRP laminate and spike anchors to improve the compressive deformation capacity. Additional 21 unconfined concrete control prisms were also tested for comparison. Two types of confinements were tested, one being with FRP laminate and spike anchors and the other one being with only FRP spike anchors. The variables included anchor spacing, anchor cross-sectional area and cross-sectional aspect ratio of the prisms. For prisms confined with FRP laminate and spike anchors, peak strength increased significantly with decrease of anchor spacing, while failure strain increased considerably as anchor size increased. For prisms confined with only FRP spike anchors, failure strain increased as anchor spacing decreased. Design recommendations are also provided for engineers to use, based on the test results.

INTRODUCTION

Reinforced concrete (RC) walls are commonly used as lateral load resisting elements in RC structures (Paulay and Priestley 1992). RC walls constructed before introducing requirements in ductility in the 1980s are normally considered lightly reinforced and vulnerable to earthquakes according to the modern standards such as NZS 3101 and ACI 318 (NZS 2006; ACI 2019). Walls with insufficient or even no confinement for end regions are deemed prone to premature vertical bar buckling, vertical bar fracturing and concrete crushing, which limits the wall displacement capacity. Experimental studies have revealed that even doubly reinforced walls constructed according to Amendment 2 of NZS3101 (NZS 2006) can suffer premature vertical bar buckling and fracturing during earthquakes, unless enough ending region confinement such as cross-ties is installed (Lu et al. 2017; Lu et al. 2018). This phenomenon indicates that the walls designed in accordance with older version standards without requirements in ductility can be even more vulnerable. Furthermore, insufficient drift capacity caused by inadequate deformation capacity of concrete unconfined or lightly confined within end regions of various walls was observed after the 2010/2011 Canterbury earthquakes (Kam and Pampanin 2011; Shegay et al. 2020). A typical case is the singly reinforced walls built prior to the 1970s that were experimentally assessed by Dr Tongyue Zhang (Zhang et al. 2018; Zhang 2019). This type of walls was constructed with only a single layer mesh of rebars typically spaced at about 228 mm and without confinement. As a result, the walls failed in brittle manner in different ways depending on axial load ratios. Web bars fractured before corner bars did when the axial load ratio was smaller as 3.5%, due to spalling of end region concrete that exposed the corner bars. The stress in the exposed corner bars was more distributed over a longer exposed length, while the web bars were not yet exposed as much, so the strain of web bars increased more sharply and finally reached ultimate strain before the corner bars did. This action degraded the post-peak behavior, thus reducing the drift capacity. Axial failure was observed when the axial load ratio was larger as 10%. Concrete experienced premature crushing and the walls were unable to carry the axial load even at low drift levels, exhibiting poor drift capacity. These issues were a result of poor compressive deformation capacity of the end region without confinement. It should be noted that the lightly reinforced walls such as those built before the 1970s also suffer another seismic deficiency, namely that the plasticity is concentrated at one or two cracks due to low vertical reinforcement ratios, compromising the ductility and deformation capacity. However, this study focuses on the issue of inadequate end region confinement.

Various strengthening solutions have been tried over the years, such as enlargement of the end regions with new concrete columns and steel confinement. End enlargement with new concrete columns uses significant floor space, adds seismic weight to the structure, and a composite behaviour between the existing wall and the new enlargement is critical but difficult to achieve. Comparing to metal confinement, FRP is preferable due several advantages including light weight, high strength and durability. Confinement using FRP laminate and spike anchors has been considered by engineers in strengthening of lightly reinforced walls, according to feedback from industry. This kind of confinement can be used in both independent walls shown in Figure 1a and walls with end region connected with other elements that limit the access of space shown in Figure 1b.



a) Independent wall b) Connected wall

Figure 1 Confinement of FRP laminate and spike anchors to end regions of walls

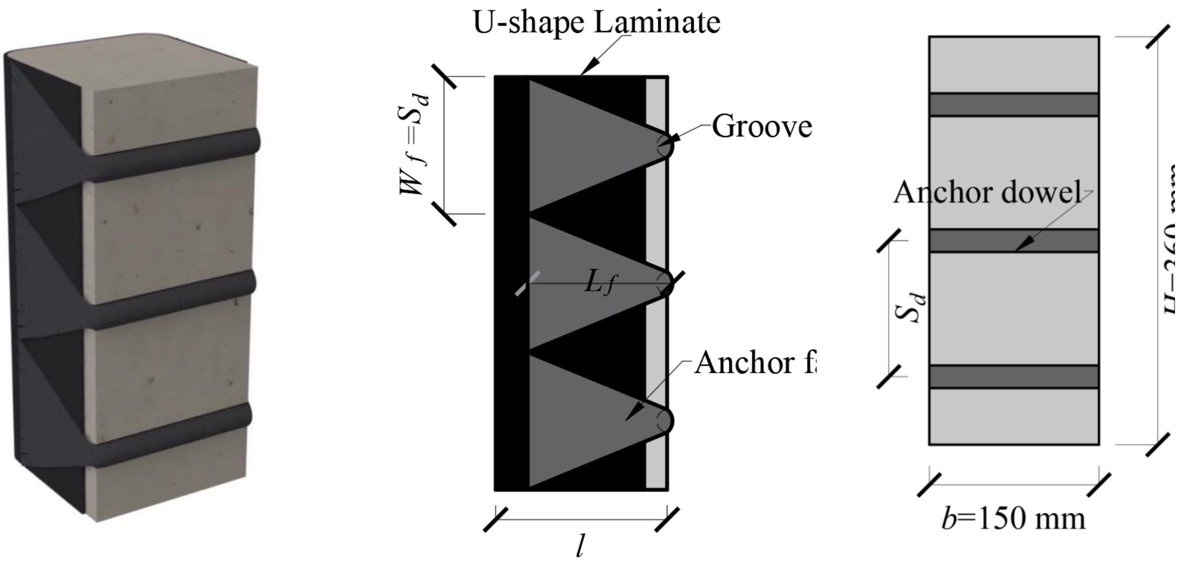
The FRP spike anchor shown in Figure 2 is made by splaying the ends of a bundle of carbon fibers into fans (del Rey Castillo et al. 2019b; del Rey Castillo et al. 2019c). The end regions of the wall can be wrapped with U-shape FRP laminates and FRP anchors installed in holes drilled through the wall thickness for independent walls, while can be confined by only spike anchors for connected walls. The part of the anchors buried in the holes are dowels, while the ends were splayed out as fans and attached to the concrete or FRP sheet. The fans must cover as much section of the laminate, and adjacent fans extent to touch each other at tips without overlapping. The fans generally cover or are covered or sandwiched by laminates to improve the bonding behavior to prevent debonding failure.

Figure 2 FRP anchor

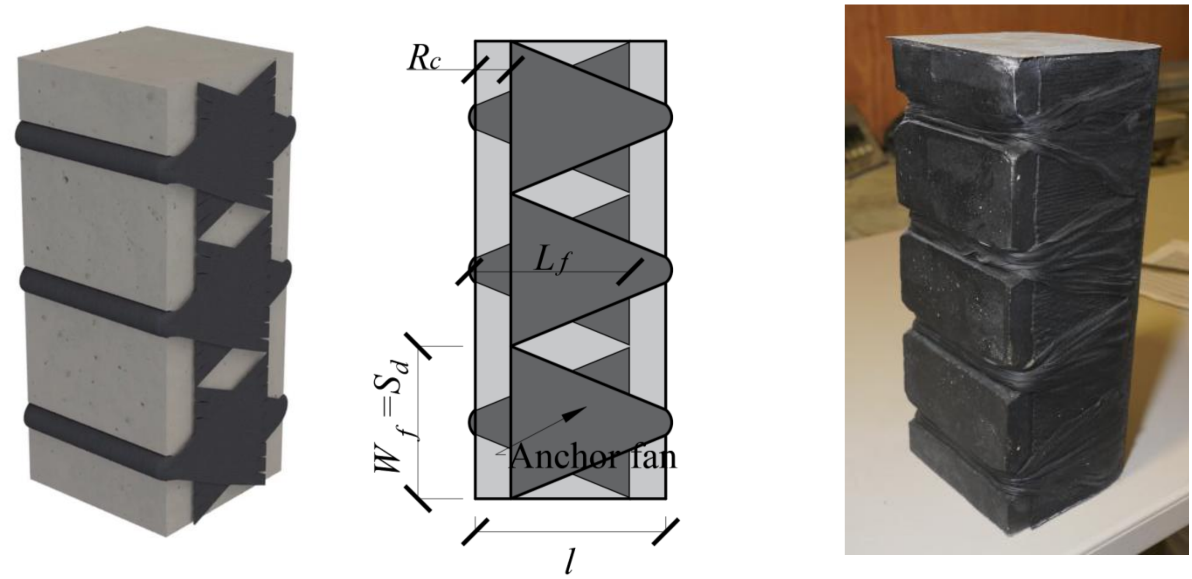
A series of static monotonic axial compression tests were conducted on concrete prisms, to study the axial behavior FRP-confined concrete with laminate and spike anchors. The prisms represented the end regions of strengthened RC walls and the test results can help understand and predict the wall behavior. This study is part of a campaign to study the strengthening method of seismic strengthening of the walls without end region confinement such as pre-1970s singly reinforced walls. The final goal of this campaign is to provide design guidelines of the strengthening method using end region confinement with FRP laminates and spike anchors.

EXPERIMENTAL PROGRAM

75 concrete prisms were tested under monotonic axial compression. These prisms included 21 unconfined prisms as reference and 54 confined prisms, using two types of confinement. One consisted in U-wrap and spike anchors shown in Figure 3a-c, while the other incorporated only spike anchors shown in Figure 3d and e. The width of the prisms (*b*) was 150 mm for all the prisms, representing the wall thickness. The length of the prisms (*l*) was one of the variables equaling to 150 mm and 200 mm, determining the cross-sectional aspect ratio of the confined zone in the wall. The height of the prism (*H*) was 360 mm for all the prisms.



a) U-wrap and spike anchors (3D)   b) U-wrap and spike anchors (Side view)   c) U-wrap and spike anchors (Front view)



d) Spike anchors (3D)   e) Spike anchors (Side view)   f) S90-28-2

Figure 3 FRP confinement of prisms

All the prisms were categorized into 26 groups with different confinement configurations as shown in Table 1, which shows the group IDs and variables in addition to the length of the prisms (l). The IDs of each group starts with letter(s), of which S is prisms with square cross-section (l=150 mm) confined by U-wrap and spike anchors and R stands for those with l=200 mm, while D means prisms confined by only spike anchors. S_d shown in Figure 3c denotes anchor spacing. A_d represents the cross-sectional area of dry anchor products. The group IDs including only letters denote unconfined prisms, while the others include the information of the variables in the format of "S_d- A_d". Each group had one or more identical tested prisms. Based on the group IDs, the prism's IDs include one more number denoting the test sequence. For example, S90-28-2 denotes the second tested prisms with square cross-section confined by laminate and spike anchors with S_d =90 mm and A_d =28 mm^2, as is shown in Figure 3f.

Table 1 Test matrix

Group ID	S_d (mm)	A_d (mm^2)	Group ID	S_d (mm)	A_d (mm^2)	Group ID	S_d (mm)
S			R			DS	
S90-28	90	28	R90-28	90	28	S90-28	90
S120-28	120	28	R120-28	120	28	S120-28	120
S180-28	180	28	R180-28	180	28	S180-28	180
S90-14	90	14	R90-14	90	14	DR	
S120-14	120	14	R120-14	120	14	DR90-28	90
S180-14	180	14	R180-14	180	14	DR120-28	120
S120-56	120	56	R120-56	120	56	DR180-28	180
S180-56	180	56	R180-56	180	56		

Concrete compressive strength was measured as 29.7 MPa (CoV=5.6%) for prisms confined by U-wrap laminate and spike anchors and 36.7 MPa (CoV=2.6%) for those confined by only spike anchors, from cylinder test following New Zealand standard NZS3112.2 (NZS 1986). FRP coupon tests were performed according to ASTM D3039 standard (ASTM 2017). The elastic modulus of dry products and ultimate strain of cured coupons of FRP laminate was measured as 234.4 GPa (CoV=8.4%) and 0.0110 (CoV=12.7%) respectively. The elastic

modulus of dry products and ultimate strain of cured coupons of FRP anchor coupons was measured as 236.4 GPa (CoV=1.3%) and 0.0118 (CoV=2.9%) respectively.
Prisms were tested using a 2000 kN compression testing machine. Digital image correlation (DIC) was used in measuring deformation of concrete and FRP, based on published methods (del Rey Castillo et al. 2019a). Three cameras were used to take photos from different sides of the prisms at a set interval for DIC, while the load readings were recorded in the photos to synchronize the load and deformation for the stress-strain curves.

Failure mode and tested curves

Two main failure modes were recorded from confined prisms, being controlled by fiber rupture in the fan near the key portion (fiber rupture) shown in Figure 4a and excessive concrete spalling (spalling) shown in Figure 4b. Fiber rupture was the most common failure mode, in which relatively longitudinal and transverse cracks were observed and the load dropped sharply once fiber ruptured, with explosive concrete crushing. This failure mode generally occurred when smaller size and more closely spaced spike anchors were used, such as all prisms in group S90-14, S120-28 and R180-14. Fiber rupture was not observed if the prism experience spalling failure mode. The load dropped sharply once excessive concrete spalled. This failure mode happened when larger size and less closely spaced spike anchors were used, such as prism S120-56-1 and R180-56-1.

a) Fiber rupture b) Spalling

Figure 4 Failure mode

The stress-strain curves of some prisms are plotted in Figure 5. The deformation capacity was significantly improved if the concrete was confined, to different degrees depending on the confinement configurations. Hardening stress-strain behavior was observed in prisms in group S90-28 with the best confinement configuration in the test matrix. The failure strains of the prisms in this group were about 0.01, which was greatly improved compared with that of the unconfined prisms of about 0.004. For prisms confined with FRP laminate and spike anchors, peak strength increased significantly with decrease of anchor spacing, while failure strain increased considerably as anchor size increased. For prisms confined with only FRP spike anchors, failure strain of increased as anchor spacing decreased.

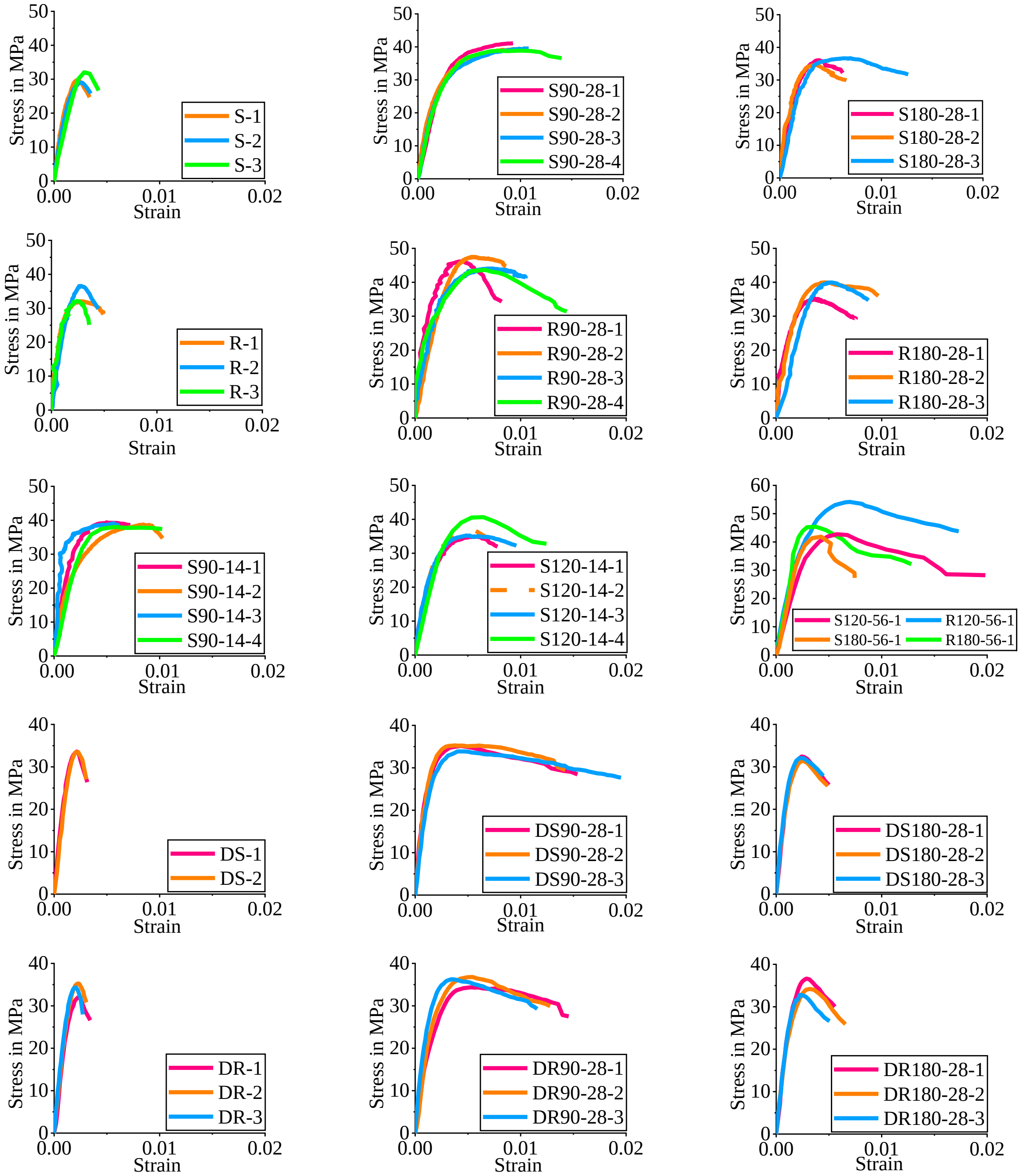


Figure 5 Tested axial stress-strain curves

DESIGN RECOMMENDATIONS

Design recommendations are given in this section based on the test results, fundamentally on anchor spacing, anchor cross-sectional area and confinement cross-sectional aspect ratio. It is suggested that the cross-sectional aspect ratio be equaling to or less than 1.5 as given by ACI 440.2R (ACI 2017). Anchor spacing can be determined based on the cross-sectional aspect ratio but should always be below either 180 mm or the wall thickness, whichever is smallest. The anchor spacing should not exceed 120 mm if the cross-sectional aspect ratio is less than or equals to 1.33, and be below 90 mm if the cross-sectional aspect ratio is larger than 1.33. The anchor cross-sectional area depends on the anchor spacing, but should always be equal to or larger than 28 mm^2 if the anchor space is 90 mm or less, and equal to or larger than 56 mm^2 if the anchor spacing is larger than 90 mm. These recommendations can change with more testing data and be validated by testing realistic walls strengthened with end regions confined by FRP laminate and spike anchors.

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