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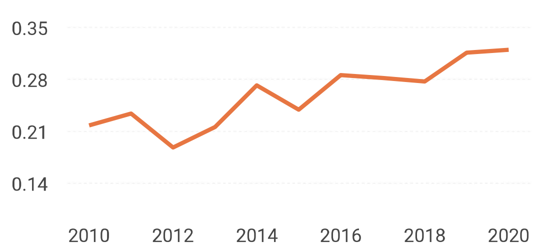

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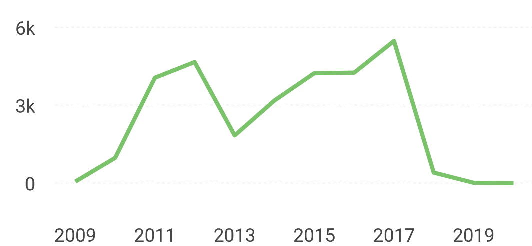

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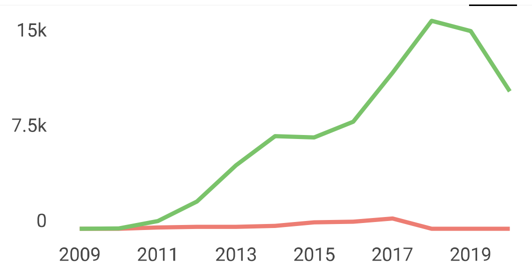

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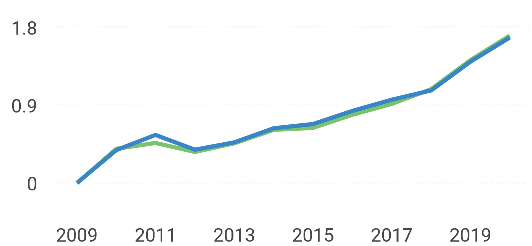

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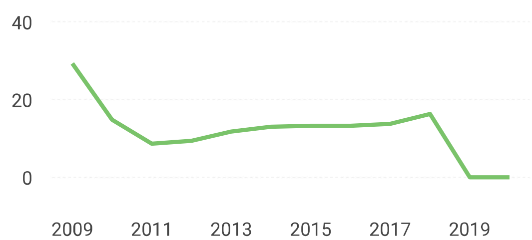

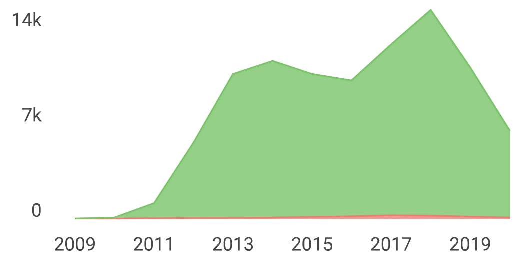

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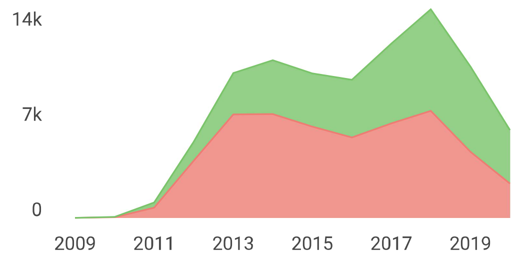

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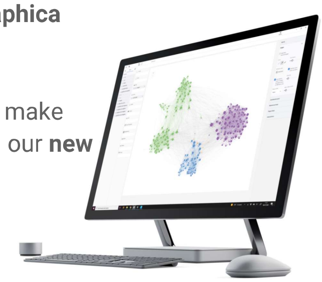

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The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)

Performance of square reinforced concrete columns externally confined by steel angle collars under combined axial and lateral load

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Abstract

Providing good ductility has become research interest in the area of seismic resistant structures. Particularly in Reinforced Concrete (RC) structure, such ductility is commonly achieved by providing good confinement. Confinement can be conventionally provided by internal stirrups, and also additional external elements which are commonly used as strengthening or retrofit works. Attaching external steel collars on concrete columns is one of many techniques in enhancing the ductility. In this study, performance of such retrofitting method is investigated through laboratory experiment. Totally five specimens are built for this investigation. The first two specimens (CS1-1, and CS1-2) are control specimens, which are conventionally confined by stirrups. The other three specimens (S1-3, S1-4, and S1-5) are only confined externally with the steel angle collars. All five specimens are tested under combined axial and lateral load. The axial load is kept constant at 30% of plain concrete axial capacity to model the gravity load. The lateral load given is according to ACI 374.1-05 quasi-static cyclic loading protocol. Lateral load resistance is recorded throughout the cyclic loading, and plotted against the corresponding lateral displacement. Results show that specimens with smaller volumetric ratio of confining element suffered brittle failure (poor ductility). Specimens with adequate confinement show good deformability and ductile failure. In conclusion, the retrofitting method by providing external steel angle collars is very promising.

Peer-review under responsibility of organizing committee of The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)

Keywords: Confinement; Cyclic Loading; Retrofit; Square Concrete Column; Steel Collar.

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Peer-review under responsibility of organizing committee of The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)
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1. Introduction

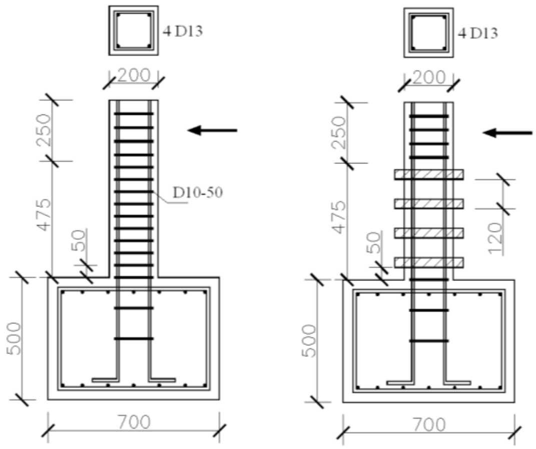
It is well recognized that good confinement will avoid brittle failure of compressed reinforced concrete (RC) members. This confinement will increase both strength and ductility which leads to higher energy dissipation capacity, thus preferable in seismic design concept [1-4]. Confinement can be provided either by conventional internal stirrups, or by external confining elements. Recently, the later approach has drawn interest of many researchers since it is more suitable for retrofit works. There are many studies which investigate the behavior of concrete members confined with such external confinements. Applying steel sheet jacketing, steel rings, and fiber reinforced polymers (FRP) are some developed techniques of this external confinement approach [5-8]. Early developments were dealing with retrofitting of circular concrete columns which were proven to be successful, since it is not very difficult to provide effective uniform confining stress. However, providing such effective confining stress in rectangular/square concrete section is not an easy task. The confining stresses tend to accumulate in the corners which cause non-uniform confining stress, making the confinement less effective. Recently, some studies have begun to address this problem. Providing external steel section collars [9-11] have been shown to be promising in retrofitting rectangular/square concrete columns. In their research, Hussain and Driver [9] used steel collars made from cutting solid steel and hollow square sections. The collars corner connections were attached by either welding or pretension high strength bolts. Grouting was provided to ensure good contact between the steel collars and the concrete column. Strength and ductility gain were evident in the research, both in monotonic compressive load test, and cyclic combined axial and lateral load test. Pudjisuryadi et.al. [10,11] used lighter steel angle collars, installed by bolting the collar corners without pretension force, and no grouting works were used. The generated confining stress was solely depended on the passive action of the steel collars when they resisted the laterally expanding concrete section. This approach was successful for the monotonic compressive load test. This paper shares further investigation of the feasibility of the approach. Some specimens are built and tested under cyclic combined axial and lateral load. Findings from the experimental works are presented.

2. Square Concrete Column Specimens

In order to investigate the performance of proposed external retrofit method under cyclic combined axial and lateral load, some specimens are prepared and built. The same normal strength concrete f_c' of 16.7 MPa is used. The cross section, and height of the specimens are set equal to 200×200 mm^2, and 725 mm respectively. The top 250 mm is heavily confined non-test region, in which middle is the application point of the lateral force. The footing to provide bottom fixity has a cross section of 700×500 mm^2. The specimens are reinforced with steels with diameter of 13 mm and 10 mm for longitudinal and stirrups, and steel angle section of 40.40.4 for the external steel collars. The strengthened non-test region and the footing are reinforced such that no failure is expected. With this set up kept constant, totally five specimens are designed with variations of confinement amount. The first two are control specimens (CS11, and CS12) which are intended to capture the behavior of conventionally confined RC column with stirrups detail according to Indonesian Concrete Design Code [12]. The confining reinforcement in the test region of specimens CS11, and CS12 are designed to meet the non-seismic (D10-150), and seismic provisions (D10-50) respectively. The other three specimens (S13, S14, and S15) are only confined externally by using steel angle collars which are intended to demonstrate the performance of the proposed retrofitting method. S13 is the specimen with the lowest volumetric ratio of steel collars, while S15 is the highest. The 40.40.4 steel angle collars are installed with uniform spacing of 180 mm, 120 mm, and 90 mm (resulting in clear spacing of 140 mm, 80 mm, and 50 mm) for specimens S13, S14, and S15 respectively. The typical control specimen (CS12), and collared specimen (S14) can be seen in Fig. 1. The summary of the specimen datas can be seen in Table 1.

3. Loading procedure

For this test, all specimens are initially loaded vertically to achieve the desired axial load (about 30% of axial load capacity expected from the strongest specimen), and kept constant throughout the test. Subsequently, a sequence of cyclic lateral load is applied to the column specimens according to ACI 374.1-05 [13]. The lateral load is applied under displacement control, with series of 3 cycles of constant drifts until failure (defined as drop of lateral resistance below 50% of its peak). The illustration of the loading protocol and the typical test setup are presented in Fig. 2. Some linear variable displacement transducers (LVDTs) are installed to measure lateral displacement, as well as to monitor the footing movement. Strain gauges are installed on longitudinal bars, stirrups, and the steel angle collars which are near the fixity where the forces are large and plastic hinges are expected to form. Specimens which survive 4.00% drift (still have lateral resistance more than 50% of its peak), are loaded further until failure.



(a) (b)

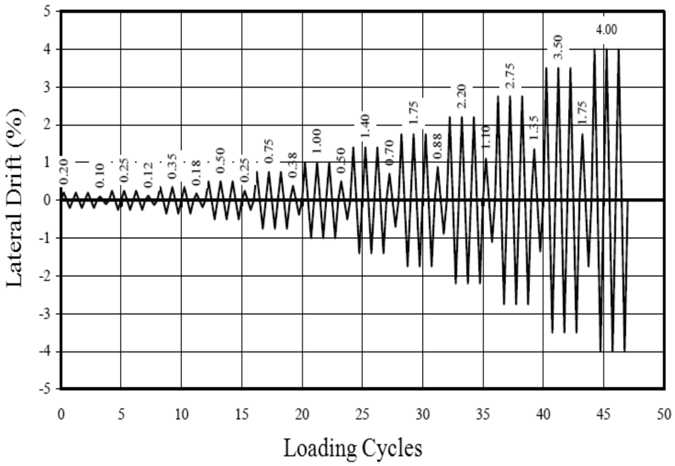
Fig. 1. Elevation view and cross section of: (a) typical control specimen (CS12 in this image); (b) collared specimen (S14 in this image).

Table 1. Important data of the specimens

Labels	f_c'(MPa)	f_y (MPa) of longitudinal bars	f_y (MPa) of stirrups	f_y (MPa) of steel angle collars	Longitudinal Bars - ρ	Internal confinement (vol.ratio)	External confinement (vol.ratio)
CS11	16.7	487	388	-	4 D13 – 1.33%	D10-150 (0.785%)	-
CS12	16.7	487	388	-	4 D13 – 1.33%	D10-50 (2.36%)	-
S13	16.7	487	-	285	4 D13 – 1.33%	-	L40.40.4-180 (4.27%)
S14	16.7	487	-	285	4 D13 – 1.33%	-	L40.40.4-120 (6.40%)
S15	16.7	487	-	285	4 D13 – 1.33%	-	L40.40.4-90 (8.53%)

4. Experimental results

To capture the overall behavior of the specimens during the test, the hysteretic lateral force-displacement (P-Δ) are presented in Fig. 3. The peak lateral load, maximum drift cycle, and other important notes of the specimens during the test can be seen in Table 2. From the two control specimens, it is observed that specimen with low ratio of confinement (CS11) suffered from non-ductile failure mechanism (diagonal failure of specimen at lateral drift of 3.50% - cycle no 41), as compared to very ductile CS12 (ductile bending damage) which survived up to lateral drift of 7.00%. Besides the longer drift capacity, more importantly, CS12 did not show significant strength loss which leads to much larger energy dissipation capacity. Specimen S13 showed poorer performance if compared to S14 and S15 which is expected. Diagonal crack failure was observed on specimen S1-3, but it already has much better overall performance than control specimen CS11. It can survive until lateral drift of 5.00% (cylce 51) before failure. Specimens S14, and S15 showed very similar performance. Both specimens survived until lateral drift of 7.00% (cycle 59), and show ductile bending damage mechanism. The tests were stopped because the lateral load resistance have dropped below 50% of their peak. The images of specimen damages can be seen in Fig.4.



(a)

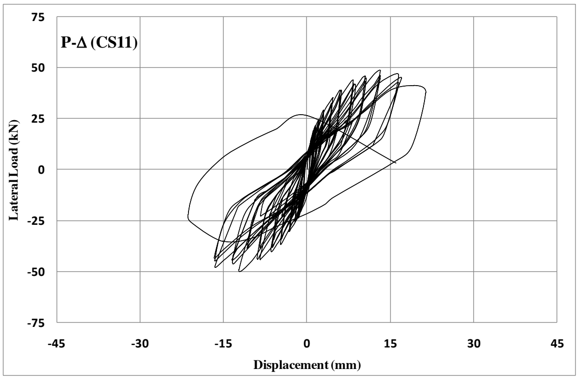
(b)

Fig. 2. (a) the lateral loading protocol; (b) illustration of typical test setup.

Table 2. Summary of the test results

Specimen Labels	Peak Load (kN) Push / Pull	Δ_y (mm) Push / Pull	Δ_u (mm) Push / Pull	μ_Δ Push / Pull	Maximum Drift (cycle)	Failure Mechanism
CS11	48.2 / 49.0	5.46 / 5.45	18.9 / 16.0	3.5 / 2.9	3.5% (41)	Brittle diagonal failure.
CS12	52.5 / 48.9	5.38 / 6.35	21.9 / 25.1	4.1 / 4.0	7.0% (57)	Ductile bending damage.
S13	48.5 / 61.2	5.46 / 3.25	23.9 / 25.8	4.4 / 8.0	5.0% (51)	Brittle diagonal failure.
S14	65.0 / 70.0	4.47 / 5.23	20.3 / 32.7	4.5 / 6.3	7.0% (59)	Ductile bending damage.
S15	65.2 / 66.8	5.14 / 5.99	22.8 / 25.1	4.4 / 4.2	7.0% (59)	Ductile bending damage.

One important parameter that can be calculated from those curves is the displcement ductility μ_Δ. This displacement ductility is defined as the ratio of ultimate displacement Δ_u with respect to yield displacement Δ_y. The definition of the ductility is adopted from ACI 374.2R-13 document [14]. Yield displcement is defined at point where a line with slope of effective stiffness reach the maximum strength. This slope is defined by connecting the point of 70% strength of the ascending branch with the origin. While the ultimate displacement is taken at point where the strength has dropped to 80% on the descending branch. There were no significant differences in the ductility if the ultimate point is defined as explained, except indication of unsymmetric damages of specimens S13, and S14. This means that the specimens still behave relatively similar until the resistance dropped to 80% of the peak. But if one is interested in the total cummulative dissipation energy capacity, it is clear that CS12, S14, and S15 showed much better results since they could survive much more cycles with larger lateral drift.



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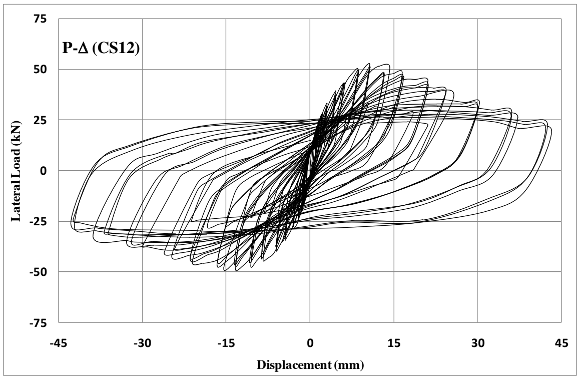

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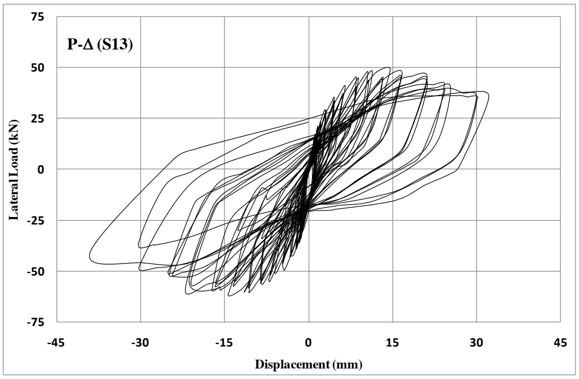

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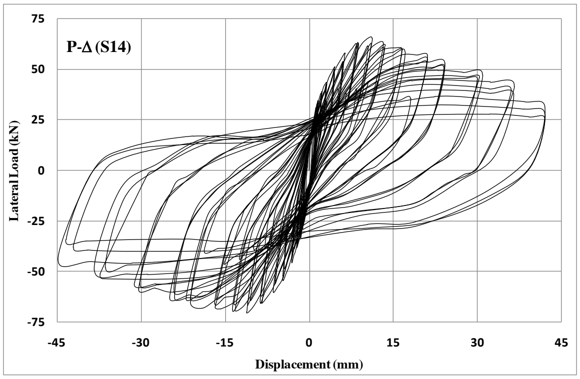

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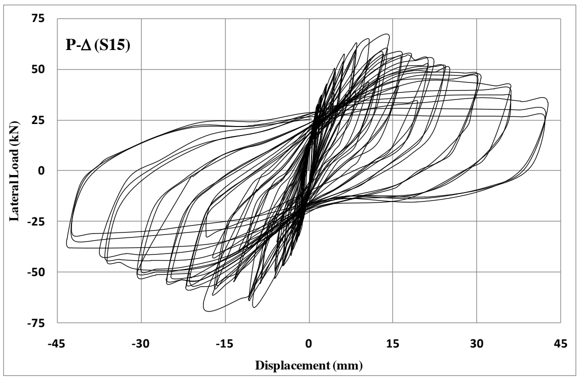

(e)

Fig. 3. Lateral force-displacement hysteretic curve of the specimens: (a) CS11; (b) CS12; (c) S13; (d) S14; (e) S15.

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

Fig. 4. Damaged specimens (a) CS11; (b) CS12; (c) S13; (d) S14; (e) S15.

5. Concluding remarks

A set of five column specimens were tested under combined axial and quasi-static cyclic lateral load. By observing the experimental result, some conclusions can be made as follows:

- Specimens with external steel collars as external confining elements show promising results. The lateral load-displacement hysteretic curves of retrofitted specimens (S1-3, S1-4, and S1-5) show much improved behavior compared to deficiently confined control specimens (CS1-1).
- CS1-1 (specimens with internal confinement not conforming to seismic provisions) failed at 3.5% lateral drift with brittle diagonal failure. The least collared specimens (S1-3) failed at 5.0% lateral drift with slightly ductile behavior, but diagonal crack pattern was still observed (clear spacing of steel collar is about 140 mm which is still greater than half of specimen dimension of 100 mm).
- The control specimen CS1-2 which is confined by internal stirrups conformed to seismic provision showed very ductile behavior. It survived until 7.00% lateral drift, and the damage was characterized by ductile bending plastic hinge at the fixity region. This behavior is generally matched by specimens S1-4, and S1-5. Both specimens were also survived until 7.00% of drift with ductile bending plastic hinge failure mechanism.

Acknowledgements

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