Axial strengthening of RC columns by steel encasement with direct fastening connections

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Axial strengthening of RC columns by steel encasement with direct fastening connections

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Abstract. Reinforced concrete (RC) columns are crucial structural members that sustain vertical loads. Their strength may deteriorate due to fire, corrosion of the reinforcements or design errors. In response, a new strengthening method that uses a steel encasement to increase the axial capacity and ductility of RC columns is proposed in this paper. This method is quick and convenient because direct fastening is used to assemble the system. Four columns including one control column and three strengthened columns have been tested to examine the reliability and effectiveness of the proposed method. Although direct fastening plays a crucial role in the structural performance of the proposed method, current design guidelines have not incorporated this new connection technique. Hence, extensive connection tests have been conducted to evaluate the key factors (e.g. fastener type, fastener spacing, protuberance, etc.) that affect the strength of the connections. New design equations are subsequently proposed based on the test results for shear connections that use direct fastening.

1. Introduction

Reinforced concrete (RC) columns are the main type of support used in structures to resist vertical loads [1]. They play a critical role in protecting structures, in particular, moment resisting frames, from collapse. However, the axial strength of RC columns could deteriorate over time due to three possible reasons [1-4]: (i) an increase in service load, (ii) deterioration of the construction materials, and (iii) insufficient design capacity. To mitigate the strength deficiency problem, various strengthening methods have been proposed that enhance the structural safety of RC columns. The merits and limitations of these strengthening methods will be discussed herein.

The section enlargement technique, which is also called reinforced concrete jacketing, can effectively enhance the strength and ductility of RC columns. However, the available usable floor area will be reduced due to the enlarged column sections which can cause inconvenience during usage, especially in metropolitan cities like Hong Kong where property prices are premium so residential units are smaller in size. Furthermore, this method is time and labor consuming [1-3]. To overcome these shortcomings, alternative strengthening methods such as fiber reinforced polymer (FRP) jacketing and steel jacketing have been developed.

FRP jacketing is a newer technique with a fast and easy installation process, high strength and superior durability, and has been extensively studied worldwide [5-9]. Passive confinement can occur with transverse dilation, which results in the tri-axial compressive stress state in concrete and increases in the strength and ductility of the strengthened column. However, this method is only effective in strengthening circular or square columns with round but not sharp corners [10]. Square columns with sharp corners have to be trimmed into round corners to facilitate the application of FRP jacketing.

Steel jacketing is the use of steel cages or steel encasements for strengthening purposes. It is more preferred over FRP jacketing for strengthening rectilinear RC columns. Steel cages are four steel angles welded together with a steel batten [11-12]. Nevertheless, the welding of vertical weld seams is extremely challenging and requires a high level of skill and on-site quality control. Moreover, welding can cause residual stress which could lead to premature failure. To mitigate the negative effects from welding, bolts rather than weld connections are often used in steel encasement. Furthermore, to eliminate the stress lagging between the existing columns and new steel plates, the use of post-compressed plates (PCPs) has been proposed in some of the previous studies [13-15]. However, the use of through bolts to connect the concrete column and steel jacket with the PCP method can damage the concrete. In addition, precision positioning of the bolt holes at the steel plate and concrete is required to allow the bolts to pass through. This is not easy to implement on-site.

To address the aforementioned issues existing in the previous strengthening methods, a nonconventional encasement that comprises four steel plates fixed with steel angles by using the direct fastening method is proposed in this study. Direct fastening is an effective method to quickly and easily connect two steel components. Unique hardened fasteners are driven into steel material by using a powder-actuated gun or battery-actuated gun [16]. In this approach, additional axial capacity is provided by exterior steel plates. Furthermore, the steel encasement is joined by using direct fastening which can provide some confinement to the concrete core. The shear behavior of connections that are joined by direct fastening governs the degree of confinement and hence the peak strength and the post-peak behavior of the strengthened column. When compared to other strengthening methods, the time for the erection of the steel encasement by the proposed method is extremely short. Therefore, the cost of labor can be substantially reduced.

Direct fastening is carried out by driving unique hardened fasteners into steel materials with a powder- or battery-actuated fastening tool. This connection method has been widely used for connecting non-structural components. However, the application of this joining method to structural components has not been fully explored in the literature, not to mention the availability of relevant design guides. Lu et al. [17] conducted an experimental study and proposed design equations for screwed connections, but these are not applicable to connections joined by direct fastening owing to the different anchoring mechanisms. Lu et al. [18] further examined the behavior of connections joined by powder-actuated fastening in cold-formed steel sheeting at ambient and elevated temperatures. However, their study only involved joining very thin sheets with a single knurled fastener. Hence, to facilitate the application of direct fastening, a comprehensive study that takes the effects of more variables into consideration should be conducted.

In this study, the shear behavior of connections secured by direct fastening are experimentally investigated and design expressions will be proposed. Factors such as type, number and arrangement of the fasteners, thickness of the base steel plate and fastener spacing will be considered. Furthermore, four columns are tested to validate the effectiveness of the steel encasement connected by direct fastening in improving the axial strength and displacement ductility of rectangular RC columns (with lateral dimensions of 500 mm or smaller) which are commonly found in low-rise RC buildings.

2. Connection tests

The connections between the steel plates and angles in RC columns that are strengthened by using a steel encasement system with direct fastening connections should resist significant shear force incurred from the transverse expansion due to the Poisson's effect. The load transfer process of these connections is similar to single lap joints subjected to tensile force at the ends. Therefore, single lap joints shown in figure 1 were designed and tested to study the failure process of the connections. In total, 100 samples were tested. To differentiate the different connection samples, they were properly labeled. Take for example, S275-A-4-5-6(30)-L: S275 denotes that the nominal yield strength of the steel material is 275 MPa; 'A' denotes that the sample is tested at room temperature; '4' represents the nominal diameter of the fastener; '5' signifies the thickness of the base steel plate; '6(30)' means that there are 6 fasteners with a fastener spacing of 30 mm; and 'L' means that the arrangement of these 6 fasteners is parallel to the load direction or Type 5 as illustrated in figure 1. The thickness, width and length of connected steel plate are 3 mm, 100 mm and 200 mm respectively. The thickness of the base steel plate varies from 3 mm to 6 mm while the width and length are same with those of connected steel plate.

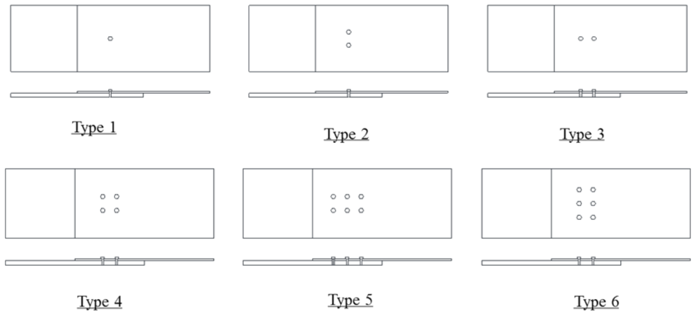

Figure 1. Configurations of the sample.

2.1. Test setup and procedure

The MTS 810 material testing system (figure 2) which has a maximum capacity of 250 kN was used to test the properties of the connection samples at an ambient temperature. Two gaskets were inserted between the upper and lower grips to allow the single shear of the connection samples (figure 3). The rate of loading was 0.5 mm/min. The testing for each connection sample was terminated when the bearing resistance was reduced to less than 20% of the maximum bearing resistance to investigate its post-peak behavior.

Figure 2. Test setup.

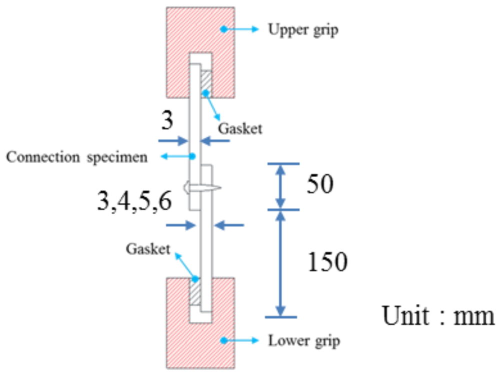

Figure 3. Assembly diagram of connection sample.

2.2. Failure modes and failure behavior

Two kinds of failure modes - bearing failure and shear fracture failure, are observed in the tests. The typical failure modes are shown in figure 4. Bearing failure results in enlarged fastener holes due to large plastic deformation and the bulging of the material around the fastener holes, which is shown in figure 4(a). The bearing resistance versus displacement (BRVD) curves of the connections are plotted in figure 5. Here, the BRVD curve for S275-A-4-4-1 is used as an example to explain the bearing failure process of this connection. In the initial loading stage, the steel plate is in an elastic region and the resistance force increases linearly with the displacement. When the steel material begins to yield, the load increases nonlinearly with the displacement, after which the bearing resistance remains approximately constant. During this stage, the holes on the steel plates are obviously enlarged and the fasteners are no longer normal to the steel plate. As a result, a pull-out force is carried out on the fasteners. The connection cannot take any force when the pull-out force exceeds the friction force between the fasteners and steel plates. Hence, the connection strength abruptly drops to zero, which is a significant shortcoming. Figure 4(a) shows the final rotation of the fasteners. The pull-out process does not occur at the same time for connections that are joined with more than one fastener, but sequentially during bearing failure. Therefore, there are inflection points on the BRVD curves when there are more than one fastener in the connection; see figure 5.

2.3. Proposed equation for bearing strength

As stated above, the connections in this strengthening method are expected to resist shear force that results from transverse expansion due to Poisson's effect. The shear capacity of this connection should be quantified to determine the confinement effect and prevent shear fracture failure. Based on the equation in [19], a new equation is proposed, in which the effects of protuberance and knurling are separated from the bearing factor.

$$F_b = \psi_{fp} \psi_{fk} \alpha_{br} d_n t_p f_{pu} \tag{1}$$

where α_{br} denotes the bearing factor, d_n represents the nominal diameter of the fastener, t_p is the thickness of the connected plate, f_{pu} depicts the ultimate strength of the steel material, ψ_{fp} is a factor for the effect of protuberance, ψ_{fp} is equal to 1.0 for connections joined with pre-drilled holes on the connected plates while ψ_{fp} is 1.35 for connections without pre-drilled holes on the connected plates, and ψ_{fk} is included for the effect of knurling. ψ_{fk} is 1.0 and 1.17 for fasteners that are not knurled and knurled, respectively.

The normalized peak load which is tested by using the predicted peak load is presented in figure 6. The average normalized peak load is 1.04 with a coefficient of variation (CV) of 0.11 and almost all of the normalized peak loads fall within the range of 0.8 to 1.2. Hence, the maximum bearing resistance can be accurately predicted by using the proposed equation with small discrepancies.

Bearing failure is the preferred failure mode in strengthening the connection due to its superior ductile behavior. To ensure that bearing failure occurs prior to fastener shear fracture, the following relationship needs to be satisfied with the exclusion of partial safety factors:

$$F_b < F_{fs} \tag{2}$$

where F_{fs} is the shear resistance of the fastener, which can be determined through tests.

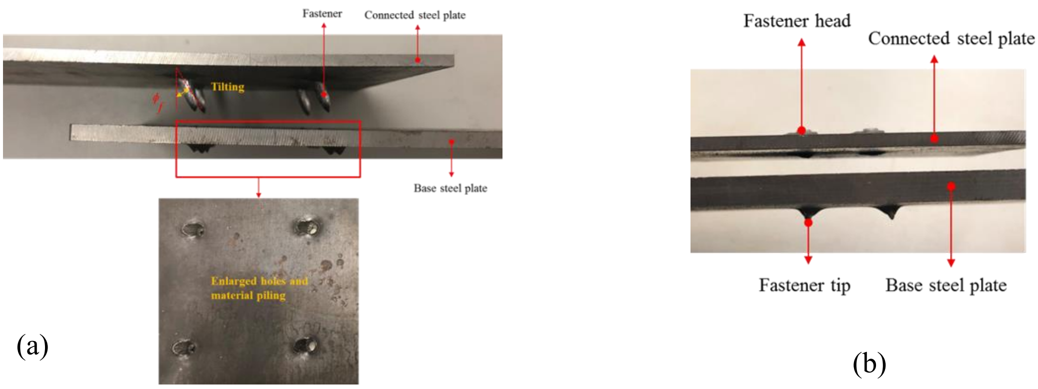

Figure 4. Failure modes: (a) bearing failure (b) shear fracture of fastener

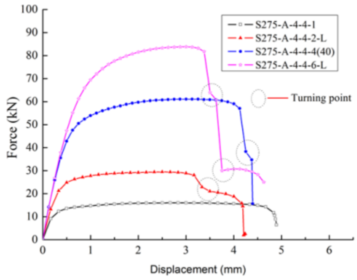

Figure 5. Shear load versus displacement of connections.

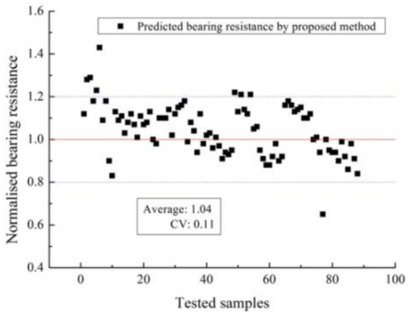

Figure 6. Comparison between predicted and tested peak loads.

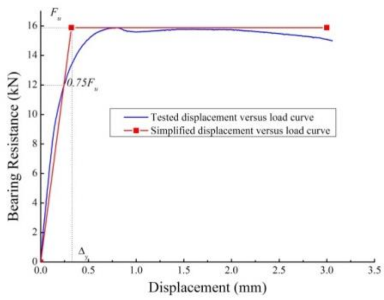

Figure 7. Simplified bilinear curve.

2.4. Proposed equation of effective stiffness

The finite element method (FEM) is an effective numerical tool for analyzing composite structures. This approach can be used to simulate the structural behavior of strengthened columns by using steel encasement with direct fastening connections. To accurately simulate the structural behavior, the non-linear response of the connections secured with direct fastenings should be modeled. In this study, the non-linear bolt resistance-deformation curve is idealized as a bilinear curve as shown in figure 7. This bilinear curve is governed by the bearing capacity and initial effective stiffness. The former has been presented in the previous section while the latter is presented as follows:

$$K_{ef} = \frac{\psi_{fn}\psi_{ef} E_s t_p d_n}{l_c} \tag{3}$$

where E_s is the elastic modulus of the plates, ψ_{ef} is the effective stiffness (ES) factor which is calibrated by the tested samples, and ψ_{fn} represents the factor that depends on the number of fasteners (FN). l_c depicts the characteristic length in which deformation happens.

Owing to the fact the characteristic length is difficult to define, the effect of this parameter can be incorporated into the effective stiffness factor. Under this consideration, the effective stiffness can be rewritten as:

$$K_{ef} = \psi_{fn}\psi'_{ef} E_s t_p d_n \tag{4}$$

where ψ'_{ef} is the modified effective stiffness (MES) factor, which incorporates the effect of character length.

In total, 11 samples were used to determine the MES factor. The results are shown in figure 8. A value of 0.017 is adopted for the MES factor. The relationship between the FN factor and number of fasteners is shown in figure 9. It can be seen that the relationship is not exactly linear due to the group reduction effect. The average FN factor for each number of fasteners is adopted and given herein.

$$\psi_{fn} = \begin{cases} 1 & n_n = 1 \\ 1.4 & n_n = 2 \\ 1.9 & n_n = 4 \\ 2.1 & n_n = 6 \end{cases} \tag{5}$$

where n_n represents the number of fasteners. The FN factor for other quantities of fasteners can be determined by using linear interpolation and extrapolation.

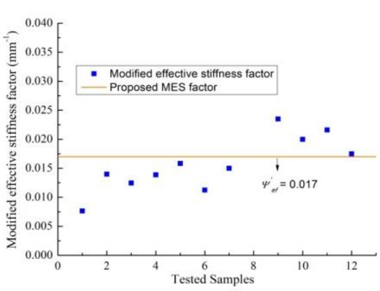

Figure 8. Modified effective stiffness factor.

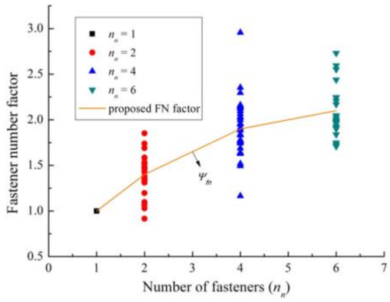

Figure 9. Factor depending on number of fasteners.

3. Column tests

The column prototype was designed based on typical low-rise RC buildings. Owing to the restriction of the testing setup, the cross-section dimensions of the original column were reduced by half. Therefore, a column with the height of 700 mm and cross-section dimensions of 200 mm × 200 mm is adopted in this test. 10 mm deformed steel rebar and 6 mm smooth steel rebar are used for longitudinal reinforcement and stirrup in the column. The target concrete strength is 30 MPa. Besides, the S275 grade steel plates with thickness of 3 mm are used for steel encasement. The size of connected steel angle in steel encasement is 60 mm × 60 mm × 5 mm. In this proposed strengthening method, four steel plates with two ends bolted to the top and bottom of concrete blocks are directly affixed to an RC column to share the axial load. Steel angles are connected to the middle part of the adjoining steel plates by direct fastening to provide passive confinement to the concrete core which can allow a tri-axial compression state in the concrete. Besides that, the vertical spacing of the angles can limit the slenderness ratio of the steel plates which is a key factor for maintaining the plate capacity. In this study, the stress lagging effect between the concrete core and external steel plates is neglected as the PCP load application method [10-13] can effectively mitigate this effect. To confirm the effectiveness of this proposed strengthening scheme, four columns including one control column and three strengthened columns were constructed and then tested; see figure 10.

The test results are shown in figure 11 and table 1. η_{P} represents the enhancement ratio of strength and η_{Δ} depicts the ductility factor. Apparently, the strength and ductility are greatly enhanced. Samples S2 and S3 have the same angle spacing while S4 has a smaller angle spacing. Strength and ductility are not greatly affected between S2 and S3 as they have the same angle spacing. When comparing S2 and S4, the strength and ductility of the latter are higher. This indicates that small angle spacing is helpful for achieving higher strength and better ductility behavior as small spacing between angles can reduce the slenderness ratio of the steel plates. Under this situation, plate buckling can be delayed. Regarding the performance of the connection joints, bearing failure was not observed before the axial load decreased to 50% of the peak load. This indicates that direct fastening is a reliable connection method for steel encasement.

Table 1. Test results.

Sample	Ultimate load(kN)	η_P	η_Δ
S1	1230	1.0	2.26
S2	1500	1.22	3.37
S3	1503	1.22	3.13
S4	1640	1.33	3.8

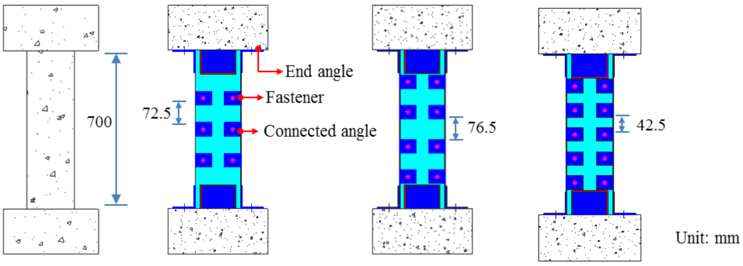

Figure 10. Strengthening arrangements of RC column.

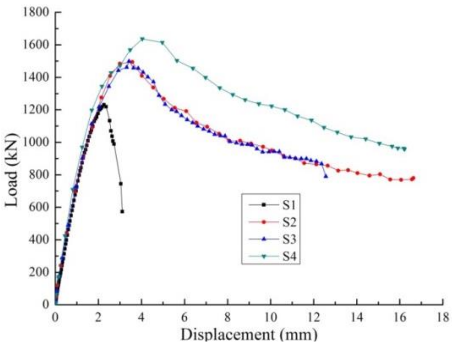

Figure 11. Load versus displacement.

4. Conclusion

This paper presents an experimental study on direct fastening connections and column strengthening by using steel encasement with direct fastening connections. The findings from this study are summarized below:

(1) An empirical equation has been proposed to predict the shear capacity of connections joined by direct fastening associated with bearing failure. The predicted strength can be used to quantify the confinement stress on the concrete core. Furthermore, by designing the shear failure load to be higher than the other failure modes, shear fracture failure of fasteners can be prevented in column strengthening applications.

(2) An equation for predicting the effective stiffness of the connection is proposed, in which the group effect is incorporated. Together with the empirical equation for predicting the shear capacity of connections, a simplified bilinear curve can be determined for simulating the behavior of the connections jointed by direct fastening.

(3) Compared to the control column, the strength of the strengthened columns (S2, S3, S4) is increased by 22%, 22% and 33% respectively and the ductility is improved by 49%, 38% and 68% respectively. This shows that the steel encasement with connections that are joined with direct fastenings can effectively improve the axial load capacity of RC columns.

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