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EFFECT OF CONFINEMENT ON PLASTIC HINGE LENGTH OF RC SQUARE COLUMNS

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ABSTRACT

The confinement effect of fiber-reinforced polymer (FRP) jacket on the plastic hinge length of square RC columns is studied through experimental testing and analytical study. Seven half-scale RC square columns with different confinement ratios were tested. The strain of longitudinal reinforcement bars and the extent of yielding were measured by strain gauges mounted inside the reinforcement bars. The variation of the strain field of the external column face was recorded continuously by digital image correlation (DIC) during a test. More rational approaches of data analysis are used for identification of plastic hinge length from measured strain fields. The obtained results show that, compared with unconfined RC columns, FRP jacketing increases the plastic hinge length when the confinement level is low, but reduces it when the confinement level is high. The analytical study shows that existing models of plastic hinge length could be inadequate in one way or another because not all important factors are included. The proposed model can correctly capture the trends but it needs to be further improved for higher accuracy when more test results are available.

KEYWORDS

Reinforced concrete, square columns, plastic hinge length, FRP, test, curvature concentration.

INTRODUCTION

Jacketing RC columns with FRP in the plastic hinge region is a popular method for structural rehabilitation. The length of the plastic hinge, L_p, should be known in order to minimize the jacketing work. Existing models of L_p cannot be used for FRP jacketing, as confinement affects the ultimate strain of concrete and distribution of bond stress between rebars and concrete, which significantly affects L_p. There is no consensus in the literature on the effect of confinement on L_p. Gu et al. (2012) studied FRP confined circular concrete columns and concluded that confinement increases L_p when it is small but reduces it when it is large. The confinement effect on L_p for square columns is not clear until now. As the confinement by FRP jacket on square/rectangular columns is quite different from that on circular columns, it is necessary to study L_p of FRP confined square RC columns.

EXPERIMENTAL PROGRAM

Test Specimen, Setup and Instrumentation

A total of 7 square RC columns were tested. Details of the specimens are shown in Figure 1 and Table 1. The yield strength of longitudinal bars and stirrups are f_y = 379 MPa and 342 MPa, respectively.

The measured average concrete cube strength was 35.2 MPa at 28 days. A carbon fiber reinforced polymer (CFRP), with the nominal thickness t = 0.167 mm, ultimate strength f_{frp} = 4080 MPa, ultimate strain ε_{fu} = 1.71%, and elastic modulus E_f = 245 GPa, was used for FRP jacketing. The thickness of FRP jackets was the only variable of the tests (see Table 1). A constant axial load was applied during the tests with an axial load ratio n = 0.35 ($n=N/f_{co}A_g$, where N is the applied axial load, f_{co} the cylinder compressive strength of unconfined concrete, and A_g the gross cross-sectional area). The confinement ratio is defined as $\lambda_f = f_l/f_{co}$, where f_l is the confining pressure calculated by $f_l = 2f_{frp}t/b = 2E_f\varepsilon_{fu}t/b$.

Table 1. Details of test specimens

Spec. ID	FRP layer	λ_f	F_{max} (kN)	L_{pr} (mm)	L_p (mm)
S1	0	0	181.1	336	333
S2	0.36	0.066	213.7	366	348
S3	0.51	0.094	227.3	337	334
S4	0.76	0.14	190.8	317	324
S5	1	0.184	212.7	266	298
S6	2	0.368	211.4	292	311
S7	3	0.552	205.6	283	307

Note: A layer less than 1 indicates FRP strips with gaps in between (Figure 2b), e.g. 51 mm wide FRP strips with 49 mm gaps = 0.51/(0.49+0.51) = 0.51. FRP strips or sheets cover the whole length of the columns.

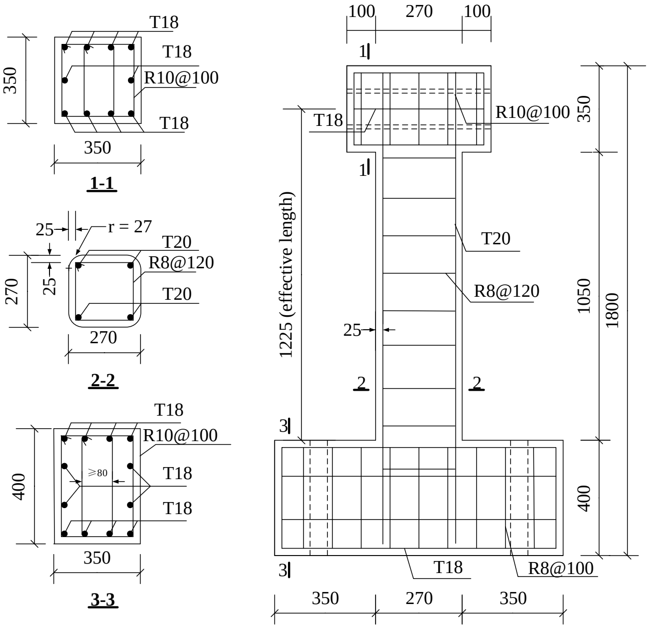
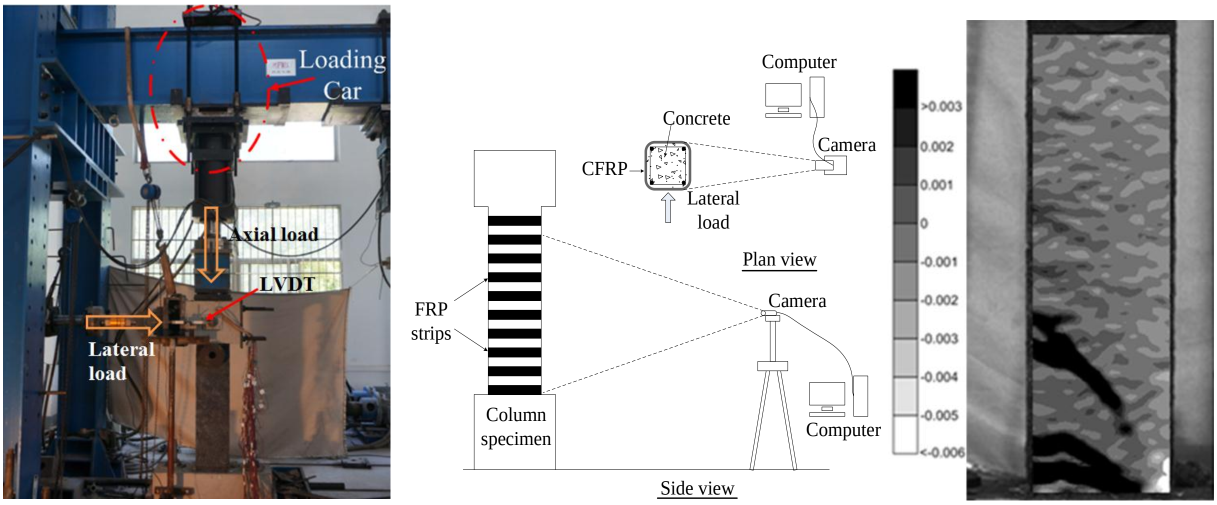


Figure 1. Test specimen (unit: mm)

The test setup is shown in Figure 2. A special loading car with four rollers was designed to allow the axial load actuator to move freely together with the lateral movement of the column head (Figure 2a). A steel spherical hinge was fixed at the top of column to maintain verticality of the axial load. As this work aimed at detailed measurement of deformation in the plastic hinge zone, a simple loading scheme was preferred. Therefore, the columns were tested under monotonically increasing lateral displacement at the top under constant axial force. A complicated loading scheme (e.g. cyclic loading) would complicate the problem and lead to less accurate measurement of strain and curvature distributions. The lateral loading rate was 1.5 mm/min. One linear variable displacement transducer (LVDT) mounted on the steel frame that was fixed to the column base was used to measure the lateral displacement of the column top relative to its base (Figure 2a). An optical instrument, digital image correlation (DIC) (Wu and Jiang 2013a), was used to capture the displacement and strain fields on the surface of the test specimen (Figure 2b) at every 5 seconds during testing. To monitor the strain of the steel bars, the four longitudinal steel bars were cut into half and closely spaced strain gauges were mounted inside the groove that was cut in the centre of the bars (Jiang et al. 2014). This kind of strain gauge installation will not affect the bond between the steel bars and concrete. Unfortunately, most of the strain gauges failed after yielding of the bars, and could not provide detailed distributions of the rebar strain during plastic hinge rotation. Therefore, the rebar strain measurement is omitted in this paper. Nevertheless, the measured rebar strain field, although incomplete, is generally consistent with the plastic hinge length calculated from DIC measurements (Jiang et al. 2014).

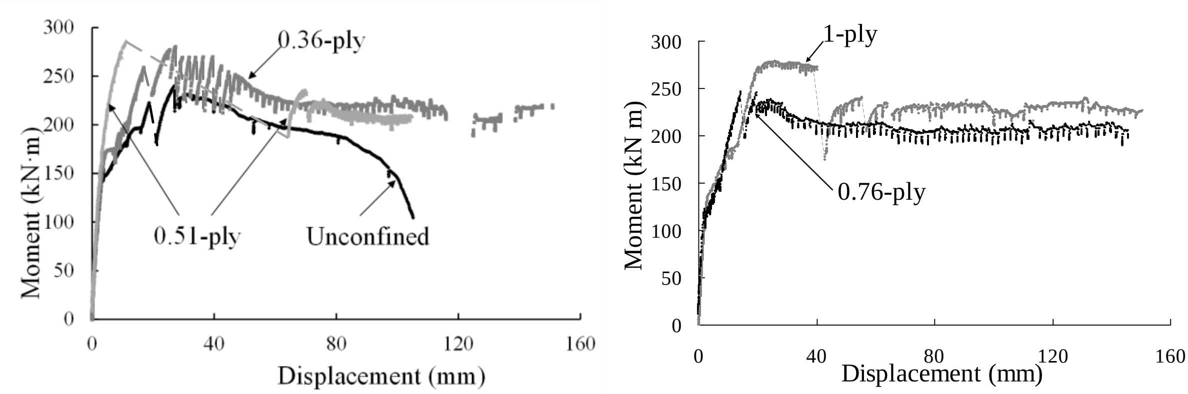
Test Results

The maximum lateral loads F_{max} of all specimens are as given in Table 1. Confined columns had a slightly higher lateral load capacity than the unconfined one. The moment vs. top displacement (M-Δ) curves of the columns are shown in Figure 3. The small fluctuations of the curves in the figure were caused by the breaks of the loading process for DIC photographing, whereas the large fluctuations were the result of the intermittent rotations of the spherical hinge at the top of the column. Although lubricant was used in the spherical hinge, significant friction existed due to the large axial force. The columns had the same stiffness in the initial loading stage. The reduced degradation and more ductile post peak response of the confined columns shows that FRP jacket effectively enhanced the concrete and prevented large degradation after the peak point. Based on a recent study by the authors, the stiffening effect of FRP jacketing on concrete is more significant for eccentrically loaded columns compared with concentrically loaded columns (Wu and Jiang 2013b).

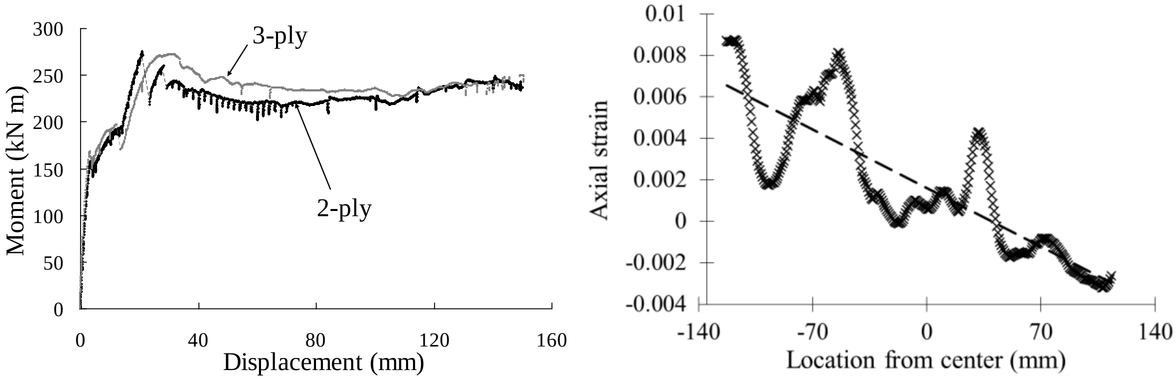


(a) Loading system (b) DIC system (c) Strain at Δ = 15 mm

Figure 2. Test setup and DIC system



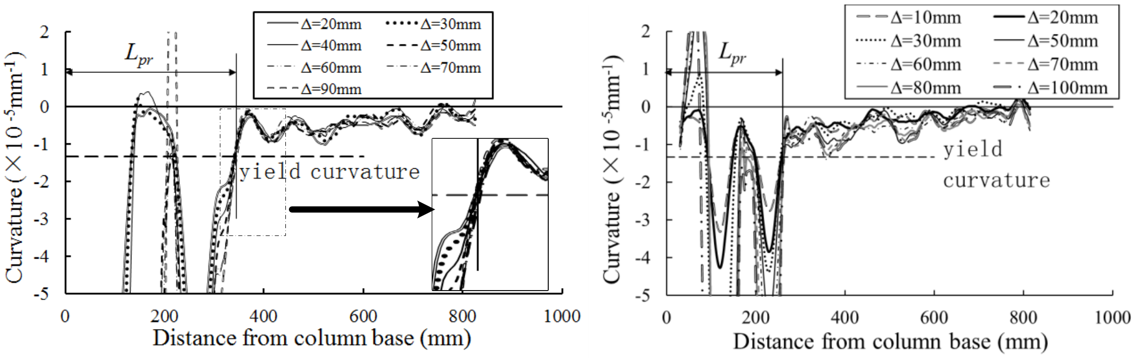
(a) Group I (b) Group II



(c) Group III (d) Cross-sectional strain distribution

Figure 3. Column responses

A typical longitudinal strain field measured by DIC on the surface of the column is shown in Figure 2c. The strain fields from DIC facilitate the calculation of cross-sectional curvatures, as shown in Figure 3d. The average effect, or a trend line that satisfies plane section assumption, can be obtained for a cross-section strain distribution. Therefore, the slope of a trend line gives the curvature. The fluctuation of strain in Figure 3d is caused by heterogeneity of concrete and local cracking. Figure 4 gives the longitudinal curvature distributions of two typical columns. Detailed results for all columns can be found in Jiang et al. (2014). Significant curvature localization is observed in Figure 4 that can be used to determine the curvature concentration zone in the plastic hinge region.



(a) Specimen S1 (b) Specimen S5

Figure 4. Curvature distributions

PLASTIC HINGE ANALYSES

Numerous models have been proposed for the equivalent plastic hinge length L_p of RC columns without jacketing. A few typical ones are given in Table. 2. The equivalent plastic hinge length is not the length of physical plastic deformation zone but a theoretical length that accounts for the plastic rotational capacity of column (Paulay and Priestley 1992). However, the equivalent plastic hinge length is closely related to the physical plastic deformation zone or curvature concentration zone.

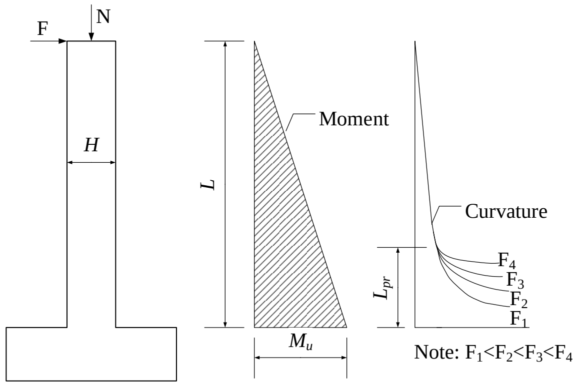
Table 2. Existing plastic hinge models

Reference	Model	Literature	Model
Paulay and Priestly (1992)	$L_p = 0.08L + 0.022d_b f_y$	Berry (2006)	$L_p = 0.05L + 0.1d_b f_y/\sqrt{f_{co}} \leq L/4$
Gu et al. (2012)	$L_p = \left(0.59 - 2.3\lambda_f + 2.28{\lambda_f}^2\right)L$ $+0.022f_y d_b \quad (0.1 \leq \lambda_f \leq 0.5)$	Ho (2003)	$L_p = \left[20n^{0.5}\left(\frac{f_{co}}{f_y}\right)^{1.5}\left(\frac{\rho}{\rho_s}\right)^{0.5} + 0.6\right]H$

Note: d_b = diameter of longitudinal bar, n = axial load ratio, ρ = longitudinal reinforcement ratio, ρ_s = volumetric ratio of transverse steel, L = column length, H = cross-sectional depth.

Determination of Plastic Hinge Length

The typical curvature distribution of a cantilever column is illustrated in Figure 5. When the lateral force F increases to a certain value and a plastic hinge forms, large and non-linear curvature occurs in the physical plastic hinge zone with length of L_{pr}. However, the curvature distribution outside L_{pr} essentially keeps elastic. Further increase in loading increases the curvature within L_{pr} but the elastic part does not change much. The point dividing the elastic and the plastic parts is essentially fixed. Therefore, the dividing point can be used to determine the physical plastic hinge length L_{pr}. The determination of the dividing point is illustrated in Figure 4a. Fluctuation of the curvature distributions in Figure 4 is caused by concrete cracking that leads to a larger curvature at cracked sections. Nevertheless, a dividing point can still be found from the curvature distributions as shown by the enlarged part in Figure 4a. L_{pr} of all columns are identified in this way and provided in Table 1. The cross-section at first yield of longitudinal bars can be determined from test results. It is noted that the cross-section at the dividing point coincides with the cross-section that first yields (Figure 4).



Note: $F_1<F_2<F_3<F_4$

Figure 5. Identification of plastic hinge length

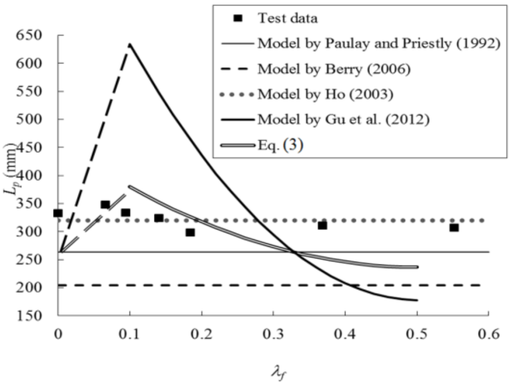


Figure 6. Comparison of plastic hinge models

To compare the physical plastic hinge length L_{pr} with the equivalent plastic hinge length L_p, the following relationship proposed by Hines et al. (2004) is used

$$L_p = 0.5L_{pr} + L_{pb} \tag{1}$$

where L_{pb} is the plastic hinge length due to yield penetration into the base that is given by the 2nd term of the Paulay and Priestly's model, i.e. $L_{pb}=0.022d_b \times f_y$. The experimental L_p from Eq. (1) as well as the results from existing models given in Table 2 are compared in Figure 6. Large differences exist between the test results and model predictions, and also among different models. Gu et al.'s model shows a correct trend but over-estimates the confinement effect. The model by Ho (2013) is the only model that considers axial load and the confinement effect of stirrups. It has been well understood in the literature that these two factors significantly affect the plastic hinge length.

Effect of FRP Confinement

As Gu et al.'s model is applicable to circular columns where jacketing is highly effective in confining concrete, it obviously overstates the confinement effect by square FRP jackets. The test results of plastic hinge length in Figure 6 also exhibit an ascending and then descending trend when FRP confinement increases, which is consistent with Gu et al.'s model. Furthermore, when the FRP confinement increases to a certain ratio, the plastic hinge length approaches an asymptotical value.

The increasing first and then reducing effect of FRP confinement on plastic hinge length is physically reasonable (Gu et al. 2012). In the increasing stage, the FRP confinement enhances the compressive strength of concrete that causes an increase of the lever arm of the resultant force in a cross-section and hence moment resistance of lower part of the column. In spite of the increase in the cross-sectional moment capacity, the yield moment does not change when confinement increases. As a result, the moment capacity increases when confinement increases, leading to a larger base moment. Hence the first-yield section moves up along the column, which increases the plastic hinge length. In the reducing stage, the lateral confinement from FRP jacketing increases the frictional bond between longitudinal reinforcements and concrete. The bond stress opposes rebar tensile stress, and hence, causes a reduction in the stress of the longitudinal bars. In the yield plateau of rebar, a small change in rebar stress causes a large change in its strain. In other words, confinement and frictional bond significantly reduces rebar strain and yielding zone, causing reduction of plastic hinge length. When the thickness of FRP jacket further increases, the confinement effect approaches an asymptotic value that corresponds to a rigid jacket. Therefore, the plastic hinge length approaches a constant value.

Revised Plastic Hinge Model

If the additional effect of FRP confinement on plastic hinge length is considered separately, Gu et al.'s model in Table 2 can be rewritten as:

$$L_p = \left[0.08L + 0.022f_y d_b\right] + \left[\left(0.51 - 2.3\lambda_f + 2.28{\lambda_f}^2\right)L\right] = L_{p0} + L_{pc} \tag{2}$$

The first term L_{p0} is the normal plastic hinge length in the original model by Paulay and Priestly (1992) and the second term L_{pc} accounts for the confinement effect. The reduction of confinement effectiveness caused by a square shaped jacket can be accounted for by the shape factor $k_s = (2r/b)^{0.72}$ (Wu and Wang 2009), where r is the corner radius and b the cross-sectional breadth. Therefore the additional plastic hinge length L_{pc} due to confinement should be revised by multiplying a factor of k_s , or

$$L_p = L_{p0} + (2r/b)^{0.72} L_{pc} \tag{3}$$

Eq. (3) is plotted in Figure 6. Compared with the test results, the trends are generally well captured by Eq. (3). However, it can also be seen in Figure 6 that the test result without confinement is closer to that predicted by Ho (2013). This is because the test columns in this work had a larger axial force than normal columns tested in other works. Therefore the axial load effect is significant, which is adequately reflected by Ho's model. Although Ho's model includes the effect of axial force, it gives L_p = 0.6H when axial force equals to zero, which cannot reflect the effect of bending moment gradient (first term in Paulay and Priestly's model) and yield penetration (2nd term in Paulay and Priestly's model). A model that can account for all these factors appropriately is unavailable in extant literature. Therefore, more experimental tests and analytical studies are needed to develop a plastic hinge length model that can adequately account for all these factors to provide a more accurate model.

CONCLUSIONS

The plastic hinge length of FRP confined square RC columns was experimentally investigated. It was found that FRP jacketing affects the plastic hinge length of the columns. Compared with unconfined columns, FRP jacket increases the plastic hinge length when confinement is small, however, reduces the plastic hinge length when confinement is high. This trend is consistent with that predicted by Gu et al. (2012) for FRP confined circular concrete columns. However, such effect on plastic hinge length is relatively smaller than that for circular columns. A model for predicting the equivalent plastic hinge length of FRP confined square RC columns is proposed from the work. Furthermore, it is found that no existing model for plastic hinge length includes all the important factors and more experimental tests and analytical studies are needed to develop a more accurate plastic hinge length model.

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