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Modelling plastic hinge of FRP-confined RC columns

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ABSTRACT

One of the key applications of Fiber Reinforced Polymer (FRP) in structural engineering is to provide confinement to the plastic hinge region of Reinforced Concrete (RC) columns. Due to the high complexity of the problem, current research on the behavior of RC plastic hinge is largely experimental; different and even contradicting models and conclusions have been reported. This gives rise to the need for more comprehensive studies of the problem that can only be done by numerical simulations due to the high cost of experiments. This paper provides a systematic investigation of the problem using three-dimensional finite element method (FEM). The FEM model is carefully calibrated with test results and an extensive sensitivity study is carried out to ensure the consistency of the results. An extensive parametric study of various affecting factors is carried out to study the problem and develop an improved model of the plastic hinge length. The accuracy of the model is verified with test data. It is found that both the lengths of the rebar yielding zone and the curvature localization zone increase first and then decrease as confinement increases, while the length of concrete crushing zone keeps decreasing with the increase in confinement. It is also found that the length of curvature localization zone should be considered as the physical plastic hinge length. A model of minimum jacketing length is developed for the first time, together with the improved plastic hinge length model, both of which can be conveniently used in engineering works.

1. Introduction

Fiber Reinforced Polymer (FRP) is widely used in construction industry due to its high strength, low weight and good durability [1]. One of the key applications is to provide confinement in plastic hinge region of Reinforced Concrete (RC) columns, which not only improves the load carrying capacity but also provides sufficient deformability/ductility for RC columns [2,3]. The plastic hinge length L_p is critical for retrofitting and structural design of FRP-confined RC column. While rehabilitating old structures L_p needs to be known for determination of jacketing length and thickness. On the other hand, the calculation of ultimate displacement and ductility requires the knowledge of L_p.

Due to the high nonlinearity of materials and complex interactions between constituent materials, the plastic hinge problem of RC members is complicated and has largely been investigated experimentally. Results reported in the literature are often inconsistent and even contradictory. Priestley et al. [4] and Elsanadedy and Haroun [5] showed that L_p of a confined RC column is smaller than that of an unconfined RC column, while Ozbakkaloglu and Saatcioglu [6] showed that L_p of FRP-confined columns is larger than that of RC columns. Other researchers suggested that L_p of FRP-confined columns be equal to that of a normal RC column [7,8]. Gu et al. [9] and Jiang et al. [10] concluded that L_p of FRP-confined columns first increases and then decreases with the increase of the confinement ratio. There is no consensus among researchers on the quantification of L_p so far. Therefore, further investigations of the problem are needed.

Many plastic hinge length models for conventional unconfined RC columns have been proposed [11–20], while few L_p models have been proposed for FRP-confined RC columns. Gu et al. [9] proposed a discontinuous model of L_p based on analytical study and regression of test results:

$$L_p = (0.08L + 0.022 f_y d_b) + \begin{cases} 3.028\lambda_f L & 0 \leqslant \lambda_f < 0.1 \\ \left(0.51 - 2.3\lambda_f + 2.28\lambda_f^2\right)L & 0.1 \leqslant \lambda_f < 0.5 \end{cases} \tag{1}$$

where λ_f is the confinement ratio defined as the ratio of confinement pressure f_l to concrete strength f_c; L is the length of a cantilever column (from support to the point of contra-flexure of a

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Nomenclature

A_g	gross cross-sectional area of column
A_{st}	cross-sectional area of stirrups
b	column width
c	concrete cover thickness
d	column depth or diameter
d_b	diameter of longitudinal reinforcement
E_f	elastic modulus of FRP jacket in hoop direction
E_s	elastic modulus of reinforcement
E_{sh}	hardening modulus of reinforcement
f_c	unconfined concrete compressive strength
f_{cc}	confined concrete compressive strength
f_l	confinement pressure
f_t	concrete tensile strength
f_y	yield strength of reinforcement
f_u	ultimate strength of reinforcement
G_f^I	fracture energy of concrete
h_b	crack band width
I_1	the first effective stress invariant
$I_1'^p$	the first effective plastic strain invariant
J_2	the second effective deviatoric stress invariant
$J_2'^p$	the second effective deviatoric plastic strain invariant
k_1	ratio of strain at start of strain hardening to yield strain
k_2	ratio of strain at peak stress to yield strain
k_3	ratio of ultimate strain to yield strain
k_4	ratio of peak stress to yield stress
K_{co}	c/d_b
K_{st}	combined confinement effect parameter of stirrups and FRP
$K_{stirrup}$	confinement parameters of stirrups
K_{frp}	confinement parameters of FRP jacket
L	length of a cantilever column
L_p	equivalent plastic hinge length
L_{pc}	length of significant curvature localization zone
L_{sy}	maximum length of rebar yielding zone
L_{cs}	length of compression zone where $\varepsilon_c > 0.002$
L_{cc}	length of compression zone where $\varepsilon_c > 0.006$
L_{pb}	additional plastic hinge length due to yield penetration into base
l_s	distance between spring elements
n	axial force ratio
n_b	number of longitudinal reinforcement
N_c	f_cA_g
n_f	number of FRP layers
r	corner radius of cross-section
$2r/b$	cross-sectional shape factor
r_e	E_f/E_s
S_{st}	spacing of stirrups
t_f	thickness of FRP jacket
α	dilation rate
ε_{co}	unconfined concrete compressive strain at peak stress
ε_{cc}	confined concrete compressive strain at peak stress
ε_{cr}^t	concrete tensile strain at peak stress
ε_t	axial strain of concrete at tension face
ε_c	axial strain of concrete at compression face
ε_v^p	plastic volumetric strain of concrete
ε_s^p	plastic shear strain of concrete
ε_s	steel strain
ε_y	yield strain of reinforcement
ε_{fu}	fracture strain of FRP jacket
σ_s	steel stress
θ_u	ultimate drift ratio
τ	bond stress
τ_{max}	maximum bond stress
ϕ	curvature
ϕ_y	yield curvature
ϕ_u	ultimate curvature
λ_f	confinement ratio
ψ	dilation angle
$\backepsilon$	eccentricity

column); f_y and d_b are the yield strength and diameter of longitudinal steel bars, respectively. It can be found from the model that the plastic hinge length shows an increasing and then decreasing trend as confinement ratio increases. They concluded that the increase in L_p relates to the increase of the cross-section moment capacity caused by FRP confinement and the decrease in L_p relates to the increase of frictional bond between concrete and longitudinal bars which has an adverse effect on the stress transfer length of longitudinal bars.

Jiang et al. [10] considered the shape of column on confinement effectiveness, which affects L_p of FRP-confined RC columns. Their model is a modified version of the model proposed by Gu et al. [9]:

$$L_p = (0.08L + 0.022f_y d_b) + \left(\frac{2r}{b}\right)^{0.72} \begin{cases} 3.028\lambda_f L & 0 \leqslant \lambda_f < 0.1 \\ \left(0.51 - 2.3\lambda_f + 2.28\lambda_f^2\right)L & 0.1 \leqslant \lambda_f < 0.5 \end{cases} \tag{2}$$

where r is the corner radius of cross-section; b is the column width and $2r/b$ defines the cross-sectional shape factor.

Another model of L_p allowing for FRP confinement was recently proposed by Youssf et al. [21]:

$$L_p = 0.8\lambda_f L + 0.022f_y d_b \tag{3}$$

In this model, the plastic hinge length increases linearly with confinement ratio. The hoop strain distribution along the column height is used to determine L_p. The height above the column footing where the recorded FRP hoop strain values are larger than 1/3 of the maximum recorded strain is considered as L_p. This definition assumes a relationship between the hoop strain and the length of plastic hinge. However, plastic hinge length is often related to yield of longitudinal bars and the rebar yielding zone is not directly related to lateral dilation or hoop strain of columns [9,10].

Previous studies on finite element modelling of FRP-confined RC members have focused on the strength and ductility of structural members [22–25] and few concerned the plastic hinge modelling. This paper aims to investigate the plastic hinge problem of FRP-confined RC columns in greater detail through finite element method (FEM). The FEM model is first calibrated with test results. After that, parametric studies of the plastic hinge length are carried out in order to better understand and quantify L_p. Finally, an improved model of L_p for FRP-confined RC columns is proposed and the accuracy of the proposed model is verified.

2. Finite element modelling and implementation

General finite element software ABAQUS [26] is used in this work. The constitutive models involve concrete, steel reinforcement, FRP and interfaces between concrete-steel reinforcement and concrete-FRP. Detailed modelling and the parameters are summarized below. It is noted that this work studies FRP jacketing with fibers in the hoop direction only.

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