Engineering Structures 101 (2015) 465–476

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Displacement and plastic hinge length of FRP-confined circular reinforced concrete columns

Osama Youssf [a], Mohamed A. ElGawady [b,*], Julie E. Mills [a]

[a] University of South Australia, Adelaide, Australia
[b] Missouri University of Science and Technology, MO, USA

ARTICLE INFO

Article history:
Received 22 January 2015
Revised 23 June 2015
Accepted 16 July 2015
Available online 7 August 2015

Keywords:
FRP-confined concrete
RC columns
Plastic hinge length
Ultimate drift ratio
Finite element analysis
LS-DYNA

ABSTRACT

Confinement of both existing and newly constructed reinforced concrete (RC) columns by fibre reinforced polymer (FRP) has been commonly used in recent decades. This is because of its ability to enhance the shear resistance and the ductility of the RC columns, which are the main parameters that govern the behaviour of RC columns under lateral loading. This paper presents a finite element (FE) model that was developed using the LS-DYNA program aimed at modelling the plastic hinge length (l_p) for FRP-confined RC columns. A FE parametric study was conducted to investigate the effect of FRP-confinement on l_p. Empirical models were proposed to predict l_p and the ultimate drift ratio (δ_u) for FRP-confined RC columns and the results were compared with similar previous models. The proposed FE model was able to predict the plastic hinge region and l_p value which can provide a simple way for designers to investigate the behaviour of FRP-confined columns during the design process. The proposed δ_u model reduced the average of errors (A) and standard deviation (SD) by 15.1%, 3.9%, respectively, compared to the best predictions by previous models.

1. Introduction

Reinforced concrete (RC) columns subject to seismic loading are critical structural members and many of these columns have been severely damaged or collapsed during moderate to large earthquakes due to inadequate strength, confinement, or ductility [1–4]. By enhancing the ductility of a structure, the seismic demand may decrease, leading to a more economical design, and the displacement capacity may increase, leading to an improved building performance [5,6].

In recent years, external confinement of concrete columns by fibre reinforced polymer (FRP) has become increasingly popular in the construction industry [7–12]. FRP-confinement increases the column's shear resistance and ductility because of its high tensile stiffness and strength [13,14]. FRP-confinement prevents concrete cover from spalling and increases the inelastic deformability of concrete in the potential plastic hinge region, which can increase the lateral displacement capacity of the column under seismic loads [15–19]. FRP shells provide stay-in-place formwork for new structures, and a protective shell against corrosion, weathering and chemical attacks [15,18,20]. Therefore, using FRP to confine concrete columns subject to seismic loads is an important design or rehabilitation option to consider.

The parameters that can affect the behaviour of FRP-confined columns are the column axial load ratio, the flexural reinforcement ratio, cross section shape, cross section aspect ratio in the case of rectangular sections, the column effective moment-to-shear span, the mechanical characteristics of the used FRP fabric namely, the FRP thickness, ultimate tensile strength, ultimate strain, and E-modulus [5,21,22]. Increasing the thickness and/or strength of the FRP increases its stiffness and then delays the FRP rupture [15,23]. This delays the reinforcement buckling; hence, the column ultimate displacement and peak strength increase. However, there is threshold for confinement beyond which any increase in confinement does not increase the strength or ductility of a column [22]. Furthermore, increasing the cross sectional aspect ratio for columns having rectangular columns reduce the effectiveness of the confinement. Hence, for a given confinement ratio, columns having larger cross section aspect ratio develop smaller ultimate drift compared to columns having smaller cross section aspect ratio [22].

The plastic hinge region in a member is defined as the physical region over which the member experiences inelastic deformations and severe damage [10]. The performance of a plastic hinge is critical to the deformation capacities of flexural members and hence requires extensive detailing to prevent failure of structural

* Corresponding author.
E-mail address: elgawadym@mst.edu (M.A. ElGawady).

http://dx.doi.org/10.1016/j.engstruct.2015.07.026

members from extreme events such as earthquakes. Identification of the plastic hinge length (l_p) is a key step in estimating the ultimate drift ratio (δ_u) of concrete columns. The ultimate drift ratio of a column is defined here as the ratio of maximum lateral displacement experienced by the column to its shear span. Priestley et al. [24] and Elsanadedy and Haroun [25] showed that the plastic hinge length of an FRP-confined RC column is smaller than that of a traditional RC column. However, other experimental tests have also shown that the l_p of FRP-confined columns are larger than those of traditional RC columns [15]. Other researchers reported that the l_p of FRP-confined columns is equal to that of a traditional RC columns [26,27]. Gu et al. 2010 [16] have observed an increase and then decrease in the l_p depending on the columns confinement ratio. They have related the increase in the l_p to the increase of the cross-section moment capacity caused by the effect of the FRP-confinement. This results in significant increase in the plasticity zone and hence the l_p increases. However, they related the decrease in the l_p with the confinement ratio increase to the additional frictional bond between concrete and longitudinal bars caused by the confinement pressure that able to decrease the reinforcement strains along the column height and hence the l_p decreases [16]. Hence, there is no consensus among researchers on the quantification of l_p for FRP-confined columns. Therefore, quantification of the plastic hinge zone is important, not only for the design of new structures but also for the rehabilitation of old structures [28].

Several analytical models (e.g. [21,29–31]) have been developed for estimating l_p for unconfined columns. These models resulted in a wide range of l_p values ranging from 0.4 to 2.4 of the column's diameter. However, limited studies were conducted to determine l_p for FRP-confined columns [31]. Priestly and Park [32] have proposed an analytical model for l_p estimation based on experimental observations as shown in Eq. (1). Paulay and Priestly [29] have improved Eq. (1) based on curvature integration of typical member to account for different grades of longitudinal reinforcement as shown in Eq. (2). Lu et al. [33] have modified Eq. (1) to express the length of the plastic hinge based on a regression analysis using relevant experimental results as shown in Eq. (3).

$$l_p = 0.08H + 6d_b \tag{1}$$

$$l_p = 0.08H + 0.022f_{sy}d_b \tag{2}$$

$$l_p = 0.077H + 8.16d_b \tag{3}$$

where l_p is the plastic hinge length, H is the column shear span, d_b is the longitudinal rebar diameter, and f_{sy} is the longitudinal rebar yield strength.

The first term in these equations (Eqs. (1)–(3)) accounts for column bending effect, while the second term accounts for steel tensile strain continuing into the footing due to the finite bond stress (tensile strain penetration effect), with consideration of different reinforcement grades incorporated in Eq. (2).

Bae and Bayrak [21] have conducted analytical parametric studies on the influence on l_p of various parameters using four full-scale square reinforced columns. The effect of axial load ratio, reinforcement ratio, and shear span to column depth ratio were investigated through moment–curvature analysis and the axial strain profile of the longitudinal compression bars. However, the strain penetration effect on the l_p was kept constant as it did not change with columns parameters, except for the flexural rebar diameter. Their proposed model is shown in Eq. (4).

$$l_p = \left[0.3\left(\frac{P}{P_0}\right) + 3\left(\frac{A_s}{A_g}\right) - 0.1\right]H + 0.25D \tag{4}$$

where l_p is the plastic hinge length, P is the column axial load, P_0 is the column axial load capacity, A_s is the total area of longitudinal reinforcement, A_g is the gross area of column cross section, H is the column shear span, and D is the column diameter.

Mortezaei and Ronagh [5] have proposed modifications to that proposed by Bae and Bayrak [21] (Eq. (4)) based on finite element (FE) parametric studies on FRP strengthened reinforced columns subjected to far-fault and near-fault ground motions. The parameters that they investigated were the same parameters investigated by Bae and Bayrak [21]. Eqs. (5) and (6) show their proposed models.

$$l_p = \left[0.4\left(\frac{P}{P_0}\right) + 3\left(\frac{A_s}{A_g}\right) - 0.1\right]H + 0.65D \quad \text{(For near-fault ground motion)} \tag{5}$$

$$l_p = \left[0.4\left(\frac{P}{P_0}\right) + 3\left(\frac{A_s}{A_g}\right) - 0.1\right]H + 0.55D \quad \text{(For far-fault ground motion)} \tag{6}$$

where l_p is the plastic hinge length, P is the column axial load, P_0 is the column axial load capacity, A_s is the total area of longitudinal reinforcement, A_g is the gross area of column cross section, H is the column shear span, and D is the column diameter.

Gu et al. [16] have conducted an experimental investigation on FRP-confined reinforced concrete columns subjected to seismic load using different types and thicknesses of FRP. Based on the results of this experimental investigation, Gu et al. [31], have modelled l_p of FRP-confined columns by taking into consideration the effect of confinement ratio (λ_l) as shown in Eq. (7).

$$l_p = (0.59 - 2.30\lambda_l + 2.28\lambda_l^2)H + 0.022f_{sy}d_b \tag{7}$$

where l_p is the plastic hinge length, λ_l is the confinement ratio, H is the column shear span, f_{sy} is the longitudinal rebar yield strength, and d_b is the longitudinal rebar diameter.

Measurements of l_p in previous experimental studies (e.g., [21,34,35]) were based on visual observations of the column-damage regions. Ozbakkaloglu and Saatcioglu [15,18] have introduced a physical technique to measure l_p for FRP-confined columns using the recorded FRP lateral strains during the cyclic loading. This technique is based on the intimate relationship that exists between the lateral expansion of the FRP tube and the level of damage sustained by concrete inside the tube [10]. Higher FRP-tube hoop strains correspond to the most highly damaged regions of the columns, since the concrete undergoes rapid expansion inside the FRP tube within these regions. The technique assumes that, at the ultimate column displacement, the plastic hinge region terminates at a height above the column footing where the recorded hoop strain values are below 1/3 of the maximum recorded strain. This technique was verified through measurements of column rotations and strains on longitudinal reinforcement [10,36].

By estimating l_p for a given column, δ_u can be estimated due to the good correlation between them. Paulay and Priestly [29] have proposed a model predicting δ_u as shown in Eq. (8) by conducting curvature analysis of a cantilever column. This model defined the ultimate drift ratio as the summation of two components. The first component accounts for the lateral displacement at the yielding of the steel reinforcement and the second component accounts for the plastic displacement occurring after column yielding. This model has not taken into consideration the effect of FRP-confinement on the ultimate drift ratio of a reinforced column.

$$\delta_u = \frac{\emptyset_y H}{3} + \frac{(\emptyset_u - \emptyset_y)l_p(H - 0.5l_p)}{H} \tag{8}$$