CONSTRUCTION INDUSTRY COUNCIL
建造業議會

LABOUR- AND COST-EFFICIENT CONSTRUCTION METHOD FOR RETROFITTING RC COLUMNS WITH FRP

RESEARCH SUMMARY

Construction Industry Council

Labour- and Cost-Efficient Construction Method for Retrofitting RC Columns with FRP

Research Summary

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FOREWORD

According to the Mid-term Construction Expenditure Forecast published by the Construction Industry Council (CIC), the expenditure of Repair, Maintenance, Alteration and Addition (RMAA) work will exceed 20 billion in 2020. It is also noticed that Buildings Department is devising seismic design code. Since seismic design is not taken into account before, we are sure that considerable amount of buildings need retrofitting once the seismic design code is released. In view of the industry need, CIC collaborated with the City University of Hong Kong and initialized the research project aiming at finding an effective approach for RC column retrofitting.

The research is carried out by a research team led by Prof. Yufei WU. The retrofitting using external jacketing with fibre reinforced polymer (FRP) was adopted. Although traditional methods are still prevailing in the RMAA work, we believe that the retrofitting using FRP will become more and more popular due to its effectiveness and efficiency. CIC will work closely with all industry stakeholders to promote the technology.

Led by Prof. WU, the research team conducted a large amount of work in experimental tests and finite element analysis to produce this solid, well presented and comprehensive research report. I should like to congratulate and thank Prof. WU and all those who contributed to the research project. I also like to recommend the innovative retrofitting method to all industry stakeholders.

Ir Albert CHENG
Executive Director
Construction Industry Council

PREFACE

The need for safe and properly functioning built environment assets is of paramount importance to the successful functioning of a modern developed society such as Hong Kong. Strategies and interventions to mitigate the potentially damaging effects of seismic attacks are therefore of critical importance. The application of high-strength, light-weight and durable FRP composite materials offers a technically viable and cost effective solution, particularly to vulnerable load bearing reinforced concrete (RC) columns. While there is an increasing body of design guidance available around the world that is concerned with the retrofitting of RC columns with FRP composites, there is a need for construction-related guidelines that are informed by sound research that is specific to Hong Kong.

Congratulations to the CIC for sponsoring such an important project related to the design and installation of FRP retrofitting for RC columns. The report arising herein is supported by academically original research as well as highly practical and useful design guidance. Congratulations are also extended to the project leader, Professor Yufei Wu, as well as his able team of researchers and practitioners. Professor Wu is a world leader in the application of FRP composites to RC structures. His research on the confinement of RC columns with FRP composites is particularly well acknowledged. Since commencing his research activities in 1999, he has steadily accumulated a considerable body of knowledge and experience in the discipline. A considerable body of that knowledge and experience is contained in this report.

The analysis and design of plastic hinges in RC columns is a complex problem and our detailed knowledge of the discipline is currently quite limited. The experimental testing, numerical simulations and analytical models presented in this report go a long way towards demystifying the topic and also making it more relatable to design engineers. The relationship between physical plastic hinge length and equivalent plastic hinge length is now better understood. In addition, more accurate and rational models are proposed. Importantly, the effects of external confinement and cyclic loading are now explicitly incorporated into the models.

The design equations and constructions aspects provided in this report are conveyed in a form that are convenient for practical applications. In addition, the effective and economical construction aspects of FRP jackets are facilitated owing to the guidelines providing minimum extension lengths and jacket thicknesses. I am encouraged to see this important advancement in FRP jacketing technology, and expect the contents of this report to positively influence the practical uptake in Hong Kong.

Scott SMITH
President
International Institute for FRP in Construction (IIFC)

RESEARCH HIGHLIGHTS

The seismic design of structures will eventually be adopted in Hong Kong (HK) Special Administrative Region (SAR). Soft storey failure of columns and walls is a major problem of existing buildings in HK. Retrofitting existing reinforced concrete (RC) columns would be a major task when seismically sound construction is required. One of the most effective, efficient, inexpensive and simplest ways of RC column retrofitting is by external jacketing, particularly with fibre reinforced polymer (FRP). Jacketing can largely enhance the ductility of RC columns and thus is particularly effective in mitigating seismic damage to soft stories. However, for the flexural retrofitting of RC columns, opinions in extant literature vary in terms of the extent of jacketing required. This research project was aimed at improving the efficiency and productivity of the industry in undertaking retrofitting works by investigating the behaviour of FRP jacketed RC columns. The project involved extensive experimental, numerical and analytical studies in developing equations for evaluating the minimum required zone of retrofitting. The obtained equations have been validated by experimental testing using advanced measurement technologies, including the digital image correlation (DIC) technique.

Deliverables from the project included more efficient construction methodology of FRP jacketing to minimize labour and construction costs of the retrofitting work for required seismic level, the minimum zone of retrofitting and construction guidelines, which would lead to a higher productivity of the construction work.

NOTATION AND DEFINITIONS

A: area of an element or FRP

A_g: gross cross-sectional area of a column

A_{st}: cross-sectional area of the stirrups

b: column width

c: concrete cover thickness

d: column depth or diameter

d_b: diameter of longitudinal reinforcement

d_c: compressive damage parameter of concrete

E_f : elastic modulus of FRP jacket in hoop direction

E_s: elastic modulus of reinforcement

E_{sh}: hardening modulus of reinforcement

f_{co}: 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

$I_1^{\prime P}$: the first effective plastic strain invariant

J_2: the second effective deviatoric stress invariant

$J_2^{\prime P}$: the second effective deviatoric plastic strain invariant

k_1: ratio of the strain at start of strain hardening to yield strain

k_2: ratio of the strain at peak stress to yield strain

k_3: ratio of the ultimate strain to yield strain

k_4: ratio of the peak stress to yield stress

K_{co}: c/d_b

K_{st}: combined confinement effect parameter of the stirrups and FRP

$K_{stirrup}$: confinement parameters of the stirrups

K_{frp}: confinement parameters of the FRP jacket

NOTATION AND DEFINITIONS

L: length of a cantilever column

L_p: equivalent plastic hinge length

$L_{p\text{-}c}$: equivalent plastic hinge length under cyclic loading

$L_{p\text{-}m}$: equivalent plastic hinge length under monotonic loading

L_{pc}: length of the significant curvature localization zone

L_{sy}: maximum length of the 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_{min}: minimum jacketing length

L_{pb}: additional plastic hinge length due to yield penetration into base

$L_{cs\text{-}m}$: L_{cs} value under monotonic loading

$L_{cs\text{-}c}$: L_{cs} value under cyclic loading

l_s: distance between spring elements

n: axial force ratio

n_b: number of longitudinal reinforcement

n_f: number of FRP layers

N: number of load cycles

N_c: $f_{co}A_g$

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: tensile strain

ε_c: axial compressive strain of concrete

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_c: compressive stress of concrete

σ_t: tensile stress of concrete

σ_s: steel stress

θ_y: yield drift ratio

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 given by Eq. (5)

ψ: dilation angle

э: eccentricity

CONTENTS

1 INTRODUCTION

1.1 Background

From the historical lessons learned from past earthquakes, many earthquake experts, including Professor Robert Park, have pinpointed Hong Kong (HK) as being earthquake vulnerable, requiring emergency planning to make its buildings earthquake resistant (Park and Paulay, 2006). As a result, seismic design has recently been discussed in the Legislative Council and has subsequently been adopted. As noted by seismic experts, soft storey failure of columns is a major problem in HK. Therefore, retrofitting of existing RC columns and walls would be a major task for earthquake retrofitting. External jacketing with fibre reinforced polymer (FRP) is currently the most effective, simplest and least expensive technology for RC column retrofitting. In fact, FRP jacketing is particularly effective in mitigating seismic damage to soft storey structures by significantly increasing the ductility of the RC columns, therefore avoiding the strength degradation of structural members under very large earthquake displacement.

Flexural retrofitting of RC columns involves wrapping a layer of reinforcing material, such as FRP, to the external face of the column within the plastic hinge zone. By providing adequate confinement to a column through jacketing, the strength and deformation capacity of the concrete material can be largely increased, leading to a much improved performance of the retrofitted column in terms of both strength and ductility. FRP jacketing has been widely accepted as a highly reliable and effective construction method.

Plastic hinge failure is a typical flexural failure mode of RC columns under seismic loading. The great interest in plastic hinge primarily stems from two practical needs in engineering: one relates to retrofitting old buildings and the other lies in assessing the deformation capacity of RC columns. In view of the importance of the plastic hinge of RC columns as mentioned above, extensive investigations have been reported in the literature to quantify the plastic hinge length over which retrofitting work should be undertaken. Mostly, the focus has been directed towards predicting the equivalent plastic hinge length L_p that is used for calculating the deformation capacity of RC columns. Although numerous empirical equations have been proposed in the extant literature for predicting L_p, the accuracy (or even the definition) of L_p remains an open issue, having yet to be addressed adequately (Zhao *et al*. 2012). The high nonlinearity of materials and the interactions and relative movements between constituent materials in the plastic hinge zone further complicate the problem. As a result, studies of plastic hinges in RC members have so far been limited to experimental testing. However, the traditional method of investigating the problem through experimental testing has produced limited data, due to the long time and high cost involved in large tests. Furthermore, traditional instrumentation technologies have difficulty in obtaining accurate internal strain and curvature measurements. Therefore, the existing experimental data are incomprehensive and sometimes inconsistent, which has inhibited a good understanding of the problem. To date, the plastic hinge zone has not been well modelled and quantified. In fact, the key factors that affect the plastic hinge length have yet to be correctly identified (Zhao *et al*. 2012).

Retrofitting RC columns has been a research interest of many investigators for quite some time. Recently, investigators have developed analytical and numerical methods to study the plastic hinge zone, overcoming the limitations of experimental testing for the problem. Key factors and mechanisms that affect the plastic hinge length have been studied through experimental methods, analytical methods and the finite element method (FEM) (Gu *et al*. 2012; Zhao *et al*. 2012). These findings have provided a better understanding of the problem and the reason for the contradicting findings reported in the literature. The most recent study has led to an effective FEM methodology for studying the plastic hinge problem (Zhao *et al*. 2012; Zhao 2012). This research work is aimed at transferring the theoretical work into practical engineering applications by developing construction methodology and guidelines for retrofitting RC columns with minimum labour and construction costs.

1.2 Aims and Objectives

The major aims and objectives of this project are the following:

1. Quantification of the physical plastic hinge zone in a column/wall over which jacketing is required for retrofitting existing RC buildings subjected to earthquakes;
2. Quantification of the equivalent plastic hinge length, with which the ductility and deformation capacity of an RC column/wall are calculated for the seismic assessment of structures;
3. Provision of construction guidelines for minimum retrofitting work (labour and construction costs) of an RC column/wall; and
4. Estimation of the construction costs of the retrofitting work.

1.3 Scope

The scope of this work involves experimental, numerical and analytical studies with the following tasks:

Task 1 – Identification of the seismic design requirements in HK, and an evaluation of the vulnerability of typical HK buildings to a seismic attack;

Task 2 – Further development of an existing FEM model to allow for FRP confinement to simulate FRP jacketed RC columns;

Task 3 – Use the FEM model for a parametric study of the plastic hinge zones and develop models for calculating the minimum extent of column jacketing;

Task 4 – Develop an equivalent plastic hinge length model for calculating the deformation capacity of RC columns. This model is required for the seismic assessment of RC structures; and

Task 5 – Experimental validation of the results from Tasks 3 and 4.

2 RESEARCH METHODOLOGY

The original deliverables in the research proposal are:

1. Models for minimum jacketing design;

2. Model of equivalent plastic hinge length for the seismic evaluation of RC buildings;

3. Construction guidelines for labour and cost-efficient retrofitting works;

4. Cost evaluation method of jacketing works.

The above deliverables have been completed by experimental investigation, analytical studies and numerical simulations using an FEM model that was an extended version of the previous one.

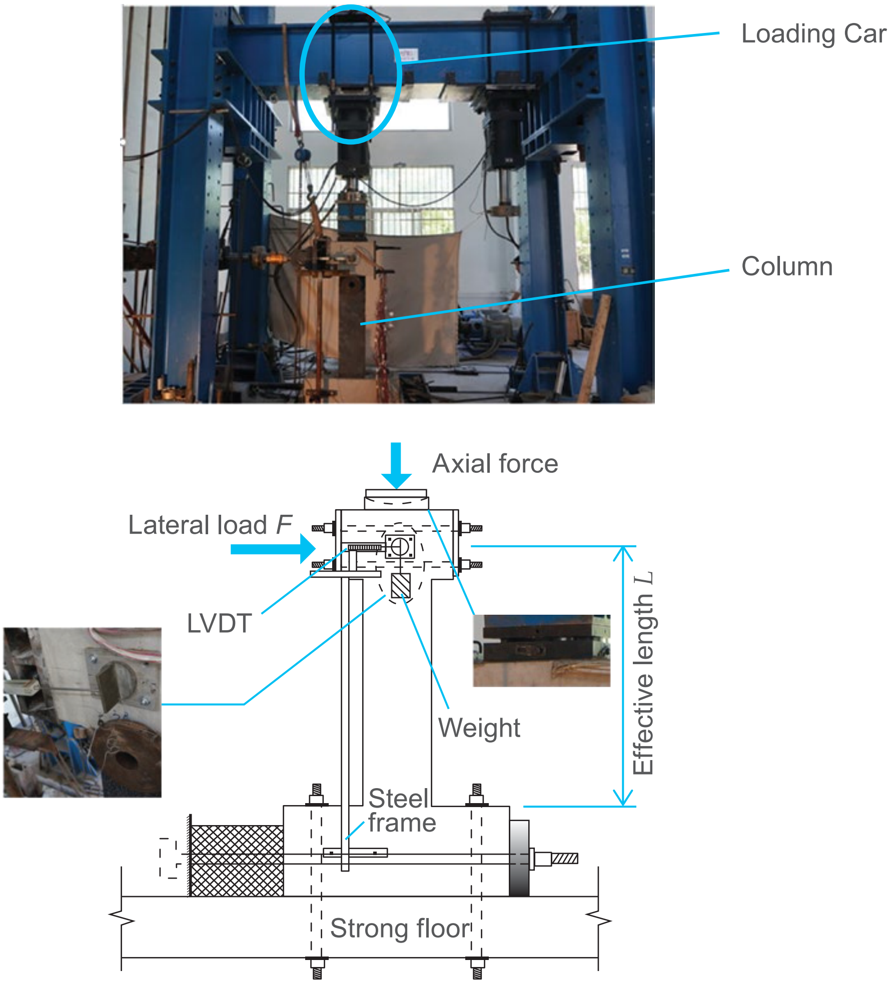
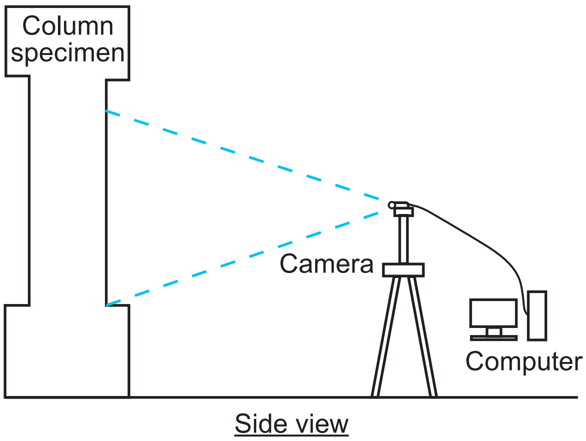
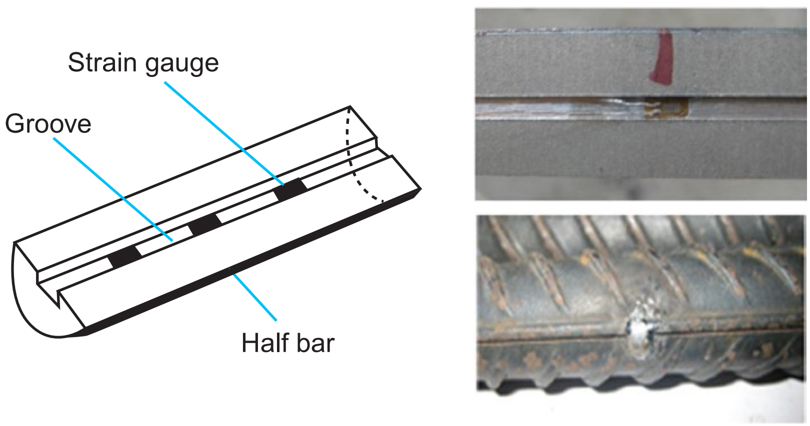


Figure 1 Typical setup of column tests

The research methodology is briefly described in this section. The RC columns with/without FRP wrapping were tested under both an axial and lateral load, as shown in Fig. 1. Digital Image Correlation (DIC) Measurement Systems (Fig. 2a) and traditional instrumentation were used to measure the strain and deformation field on the concrete or FRP surfaces so that the detailed strain field in the plastic hinge region was recorded continuously during testing. A large number of strain gauges were installed inside the steel reinforcing bars to obtain the strain distribution of the steel reinforcing bars, as shown in Fig. 2b, and to measure the rebar yielding zone without disturbing its bond with concrete. From the intensive strain measurements, the rebar yield and concrete crushing zones could be closely monitored throughout the entire loading process.



(a) DIC Measuring System



(b) Strain gauge installation in the steel reinforcing bars

Figure 2 Strain measurements

The FEM modelling and analytical studies are summarized below:

The general finite element software ABAQUS is used in this work. The reinforcement details and geometric dimensions of the columns are as shown in Fig. 3. The constitutive models involve concrete, steel reinforcement, FRP and interfaces between concrete-steel reinforcement and concrete-FRP.

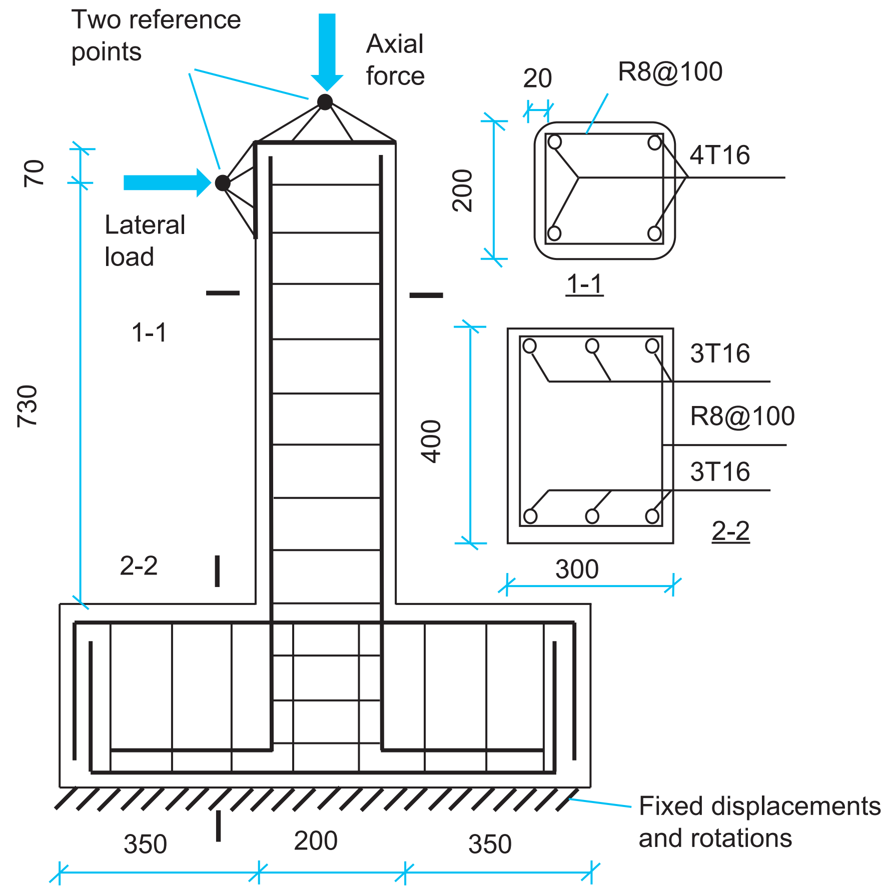
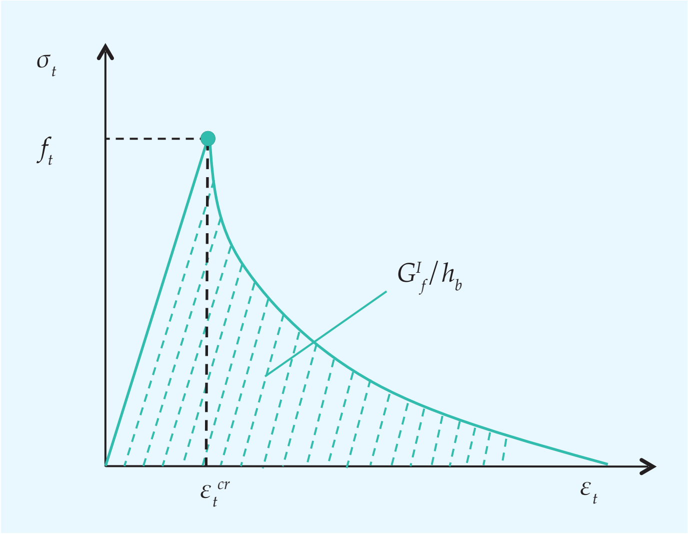
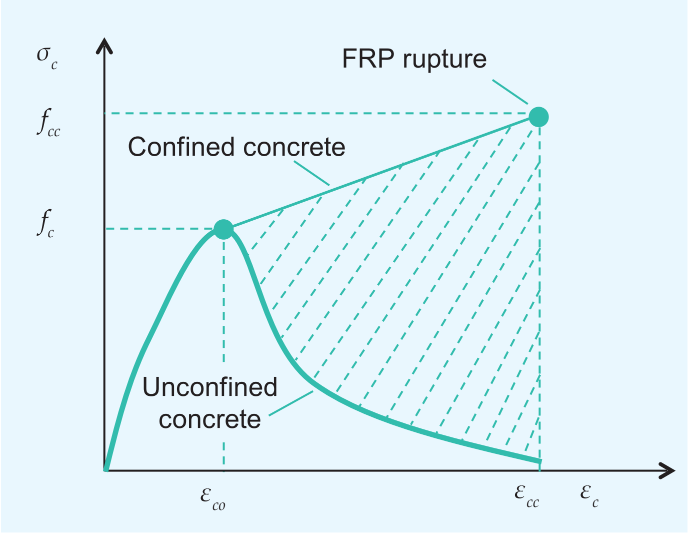


Figure 3 Specimen details (unit: mm)



(a) tension model



(b) compression model

Figure 4 Stress-strain relationship of unconfined and confined concrete

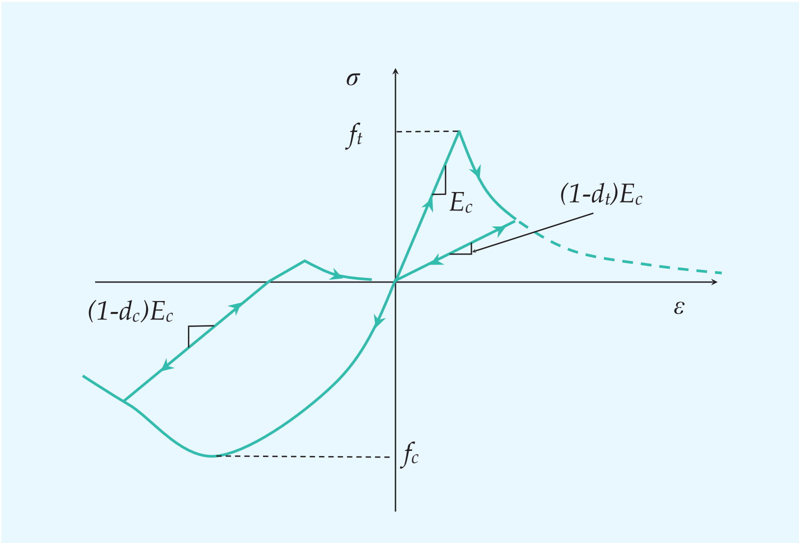
The damage-plasticity model is adopted to model the material behaviour of concrete. The ascending section of the tension relationship is assumed to be linear and the softening is assumed to be exponential. The fracture energy method is adopted for post-peak cracking of the concrete. The strain at peak stress is assumed to be 0.0001. The fracture energy for concrete is assumed to be 170 N/m, as shown in Fig. 4a.

In compression, the analysis-oriented stress-strain model by Teng *et al*. (2007) is employed for both unconfined and confined concrete, as shown in Fig. 4b. The following default plastic parameters are used for unconfined concrete in ABAQUS: 55° for the dilation angle (ψ); 0.1 for eccentricity (ϵ); 1.16 for the ratio of the initial equibiaxial compressive yield stress to the initial uniaxial compressive strength; and 0.6667 for the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian. The prediction of the stress-strain behaviour of confined concrete depends significantly on the definition of the yield criterion and hardening/softening rule and flow rule, which are very different from those of unconfined concrete due to the existence of a confining pressure (Jiang and Wu 2012; Yu *et al*. 2010). The plasticity parameters of FRP-confined concrete are defined according to Yu et al.'s model (Yu *et al*. 2010).

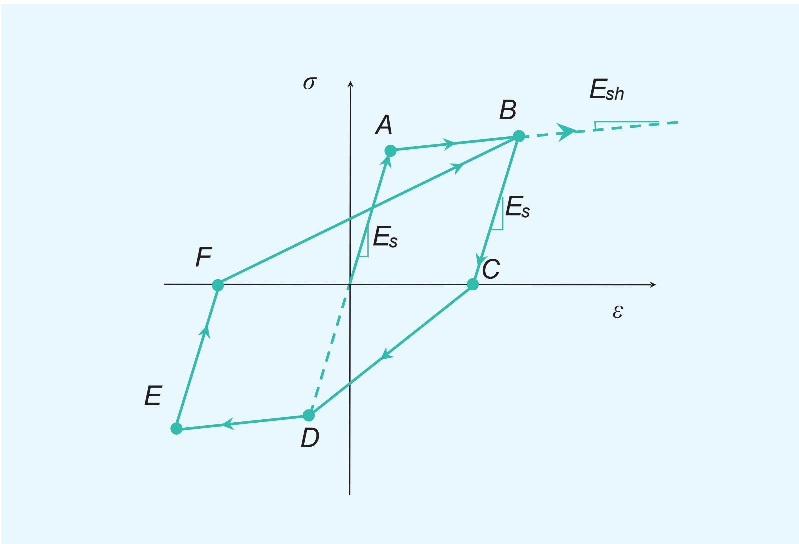
For concrete under cyclic loading, the compressive damage parameter d_c is assumed to be zero before the peak stress and is determined by the damage model proposed by Lubliner *et al*. (1989) after the peak stress:

$$d_c = 1 - \frac{\sigma_c}{f_c} \tag{1}$$

where $f_c = f_{co}$ for the concrete cover and $f_c = f_{cc}$ for the concrete core.



(a) concrete



(b) steel reinforcement

Figure 5 Stress-strain curves under cyclic loading

For concrete under uniaxial tension, the unloading and reloading paths are assumed to be linear and pointing towards the coordinate origin (Chen *et al*. 2010) (Fig. 5a). Therefore, the damage parameter d_t can be defined by

$$d_t = 1 - \frac{\sigma_t}{E_c \varepsilon_t} \tag{2}$$

where ε_t is the tensile strain.

Default values of the stiffness recovery factors w_t = 0 and w_c = 1 are adopted in the FEM model. It is noted that negative or decreasing values of the calculated plastic strain are not allowed in ABAQUS. If this kind of error occurs, the tension/compressive damage parameter should be adjusted slightly.

A 2-node truss element T3D2 in ABAQUS is employed for the steel reinforcement. The bilinear model that considers strain hardening is adopted to model the stress-strain relationship of the steel reinforcement. A cyclic model proposed by Clough (1966) is employed to represent the unloading and reloading paths, as shown in Fig. 5b.

The Spring element is selected to define the nonlinear interfacial behaviour between concrete and the longitudinal tensile reinforcement. The concrete nodes and steel nodes with the same coordinates are connected by springs. A large linear stiffness is applied in the normal direction of the interface, while the unified bond-slip relationship proposed in Wu and Zhao (2013) is applied in the tangential direction to consider the nonlinear slip between concrete and steel bars.

The FRP jacket is modelled by the 4-node membrane element M3D4R and is treated as linear elastic laminar with orthotropic elasticity. A perfect bond between the FRP sheet and concrete is assumed, which is achieved by the “tie option” in ABAQUS, unless otherwise noted.

The FEM model was validated by experimental test results and subsequently used to study the behaviour of FRP-confined RC columns through a parametric study. Based on the results of the parametric study, the extents of the rebar yielding zone, concrete crushing zone and curvature concentration zone were obtained and modelled analytically and numerically. The following factors are identified to be significant in affecting the plastic hinge regions: the column aspect ratio, axial force ratio, yield strength of the steel bar, concrete strength, and cross-sectional shape of the column.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Seismic Risk of Hong Kong Buildings

As mentioned in the Background, although Hong Kong is not geographically situated within active seismic belts, the consideration of seismic-resistance is necessary. The earthquake intensity in Hong Kong is classified into three main levels: low intensity, moderate intensity and high intensity (Buildings Department 2013). The strongest recorded earthquake in Hong Kong occurred in 1918 with the epicentre located approximately 300 km away from Hong Kong, reaching a level of moderate intensity. The probability of occurrence and the corresponding estimated building damages for the different intensities are listed in Table 1 (Buildings Department 2013). The descriptions of damage levels are listed in Table 2 (Buildings Department 2013).

Table 1 Different intensities of earthquakes and the estimated building damages (Buildings Department 2013)

		Low intensity	Moderate intensity	High intensity
Probability of occurrence		50% in 50 years	10% in 50 years	2% in 50 years
Frequency of occurrence		1 in 72 years	1 in 475 years	1 in 2475 years
Estimated building damage of significance and associated % of the entire building stock suffering from damage	Moderate damage	0.27%	3.9%	16.5%
	Extensive damage	0.003%	0.19%	2.8%
	Complete damage	0%	0.003%	0.19%

Table 2 Description of damage levels (Buildings Department 2013)

Damage level	Description
Slight Damage	Hairline cracks in beams, columns and walls.
Moderate Damage	Large flexural cracks with some spalling. Large diagonal cracks in shear walls. Masonry walls may have large diagonal cracks.
Extensive Damage	Spalled concrete and buckled reinforcement in columns and beams. Visibly buckled reinforcement in shear walls. Most unreinforced elements will have suffered extensive cracking.
Complete Damage	The structure is in imminent danger of collapse due to brittle failure of the beams and columns and most of the shear walls. Unreinforced masonry walls may collapse due to in-plane or out-of-plane failure.

The above evaluations by the Buildings Department are general. For a particular building or structure, its seismic evaluation must be carried out in accordance with existing codes of practice or guidelines. When soft story or possible plastic hinges are identified, the guidelines provided in this report can be used for seismic retrofitting or jacketing of RC columns.

3.2 Parametric Study in FRP Retrofitting

In seismic retrofitting, the determination of the physical plastic hinge region for retrofitting requires knowledge of the physical plastic hinge length. The equivalent plastic hinge length is required to calculate the ductility and ultimate displacement of a flexural member. A review of extant literature shows that a satisfactory plastic hinge model is not available, and much more research is required to develop a more rational and accurate plastic hinge model.

Through experimental testing, numerical simulation and analytical modelling in this project, which were introduced in "Research Methodology", more advanced plastic hinge models have been developed, which allow for the effect of external jacketing, and hence can be used not only for the design of new RC columns but also for retrofitting existing RC columns.

The influences of some selected important parameters (i.e., FRP confinement, axial force ratio, load cyclic, etc.) on the plastic hinge length are discussed here. The parametric study was conducted by the FEM model, which was introduced in "Research Methodology". The FEM model was calibrated with the experimental results (Fig. 6) before the parametric study. During the parametric study, a particular parameter was varied while all the other parameters were fixed. Three types of physical plastic hinge lengths, i.e., the length of the concrete damage zone (L_{cs}), the rebar yielding zone (L_{sy}), and the curvature localization zone (L_{pc}), are studied.

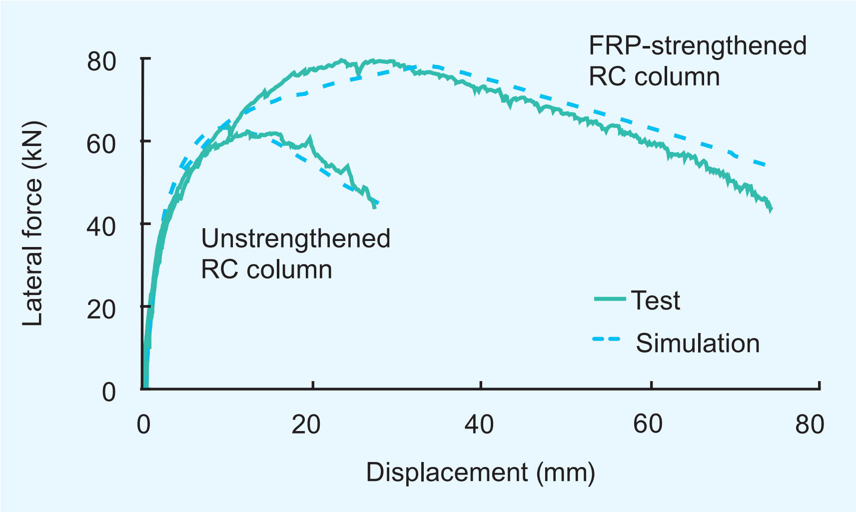


Figure 6 Calibration of the FEM model

(a) Effect of FRP confinement

FRP confinement on the development of the plastic hinge region is analysed in detail for FRP-confined RC columns in this section. Nine specimens with FRP confinement ratios ranging from 0 to 0.466 are studied. The lateral displacement is monotonically increasing under a constant axial force. The axial force is set to be $0.2N_c$, where $N_c = f_cA_g$ and A_g is the gross cross-sectional area of the column. All specimens have the same geometric dimensions and material properties. The specimen sizes are 200 × 200 × 800 mm^3 connected to a 300 × 400 × 900 mm^3 stub (Fig. 3). The corner radius of the columns is 20 mm and the effective cantilever length is 730 mm from the centre of the loading to the column base. For all specimens, steel bars with 16 mm diameters are employed as the longitudinal bars and steel bars with 8 mm diameters and spacings of 100 mm are adopted as the transverse reinforcement. The steel has a yield strength of f_y = 400 MPa, an ultimate strength of f_u = 579 MPa and an elastic modulus of E_s = 194 GPa. The reinforcement details and geometric dimensions of the columns are shown in Fig. 3.

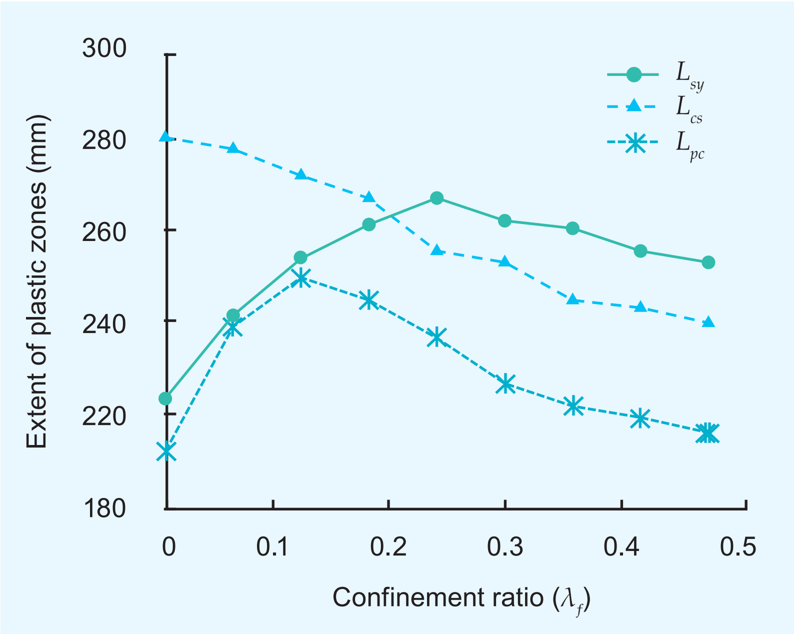


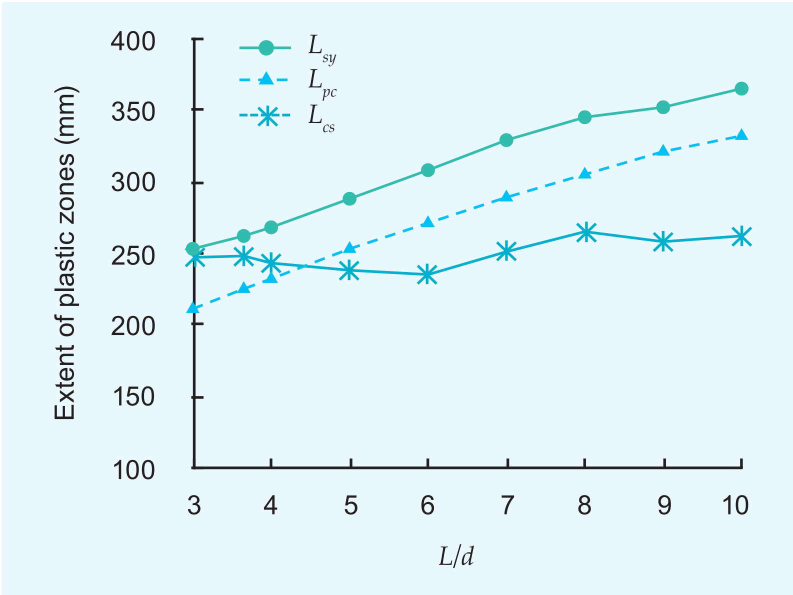
Figure 7 Effect of the confinement ratio on the plastic hinge lengths

The effects of the confinement ratio on L_{sy}, L_{cs} and L_{pc} are shown in Fig. 7. L_{sy} exhibits an increasing and then decreasing trend when the confinement ratio increases, while L_{cs} shows a descending trend. L_{pc} is governed by L_{sy} when confinement is low, resulting in an ascending trend of L_{pc}. Afterwards, both L_{sy} and L_{cs} decrease with a further increase in the confinement ratio, leading to an evidently descending trend of L_{pc}. The increase in the confinement ratio leads to an increase in the moment resistance. The increase of the moment resistance has a positive effect on the development of L_{sy} because the stress requires a longer distance to transfer in this case. As a result, the distance from the column base to the first yielding section increases, which increases L_{sy}. However, the frictional bond between the longitudinal tensile reinforcement and the concrete increases linearly with an increase in the confinement ratio, which opposes the rebar stress and has an adverse effect on the strain penetration length and hence L_{sy}. As a result, L_{sy} first increases and then decreases with an increase in the thickness of the FRP.

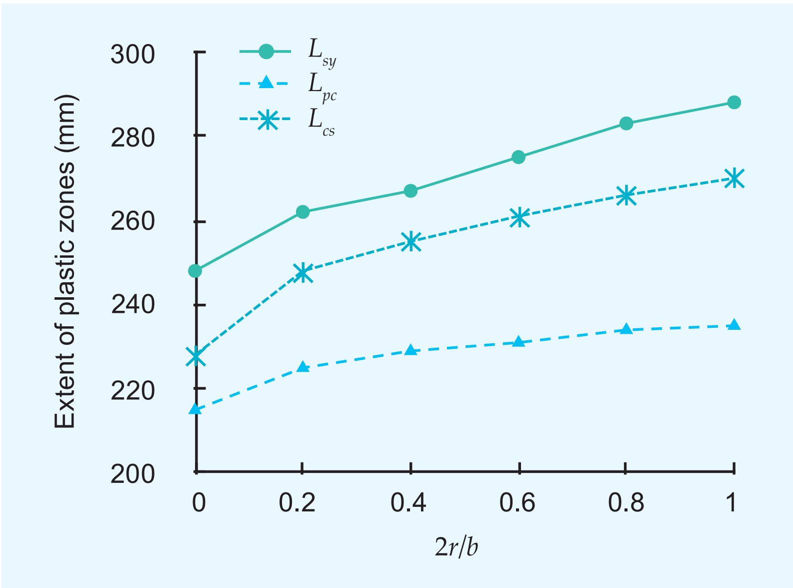
(b) Effect of geometrical parameters

The effects of column geometrical parameters, including the aspect ratio of the column L/d and the shape factor of the cross section $2r/b$, on the variations of L_{sy}, L_{cs} and L_{pc} were subsequently studied. The control specimen is confined with 1 layer of the FRP ($\lambda_f = 0.233$) and the geometric dimensions and material parameters for the control column are the same as in Fig. 3.

The aspect ratio L/d is always considered as one of the most important factors affecting the plastic hinge length in empirical models. Herein, the variation of L/d is achieved by fixing the column depth d and increasing the length L. The numerical results of L_{sy}, L_{cs} and L_{pc} as L/d changes from 3 to 10 are provided in Fig. 8a. It can be seen that L_{sy} and L_{pc} increase almost linearly with L/d, while L_{cs} remains almost constant as L/d increases.



(a) effect of the aspect ratio



(b) effect of the shape factor

Figure 8 Variation of plastic hinge zones

Fig. 8b shows the effect of the shape factor on the plastic hinge zones. It is clearly seen that L_{sy}, L_{cs} and L_{pc} all increase with an increase in the shape factor. The level of confinement is greatly improved by increasing the shape factor. For an FRP-confined RC column, the ultimate moment increases as the confinement increases. Based on the foregoing analysis, an increase in the moment capacity results in an increase in L_{sy}.

(c) Effect of the axial load ratio

To study the effect of the axial force ratio on the plastic hinge length, a parametric study was conducted by changing the axial force ratio *n* from 0 to 0.5. The effect of the axial force ratio on the variation of L_{sy}, L_{cs} and L_{pc} is shown in Fig. 9. It is clearly seen that L_{sy} exhibits a decreasing trend while L_{cs} shows an increasing trend when the axial force ratio increases. It is obvious that a larger axial force leads to an increase in the compression zone and a decrease in the tension zone, which means a larger L_{cs} and a smaller L_{sy}. The trend of variation of the curvature localization zone L_{pc} is consistent with L_{sy} when the axial force is low and consistent with L_{cs} when the axial force is high, leading first to a descending and then an ascending trend of L_{pc}.

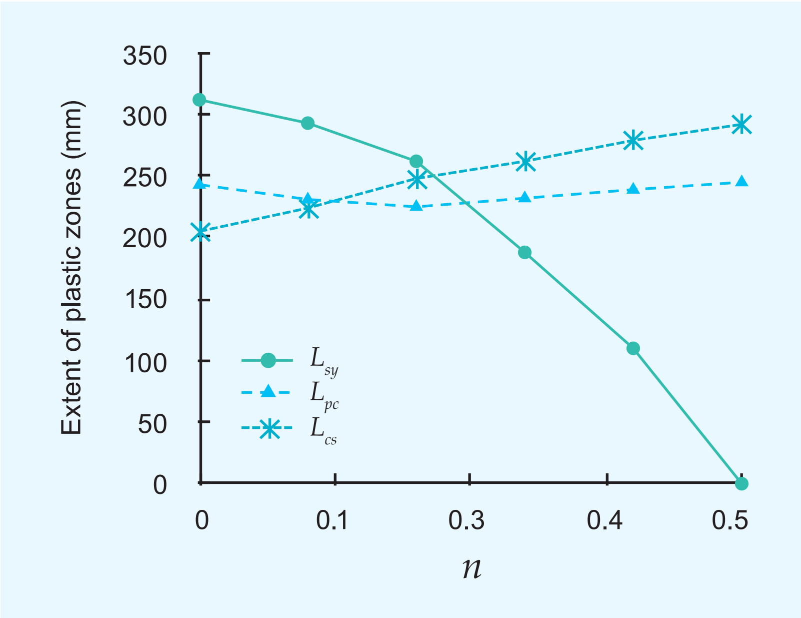
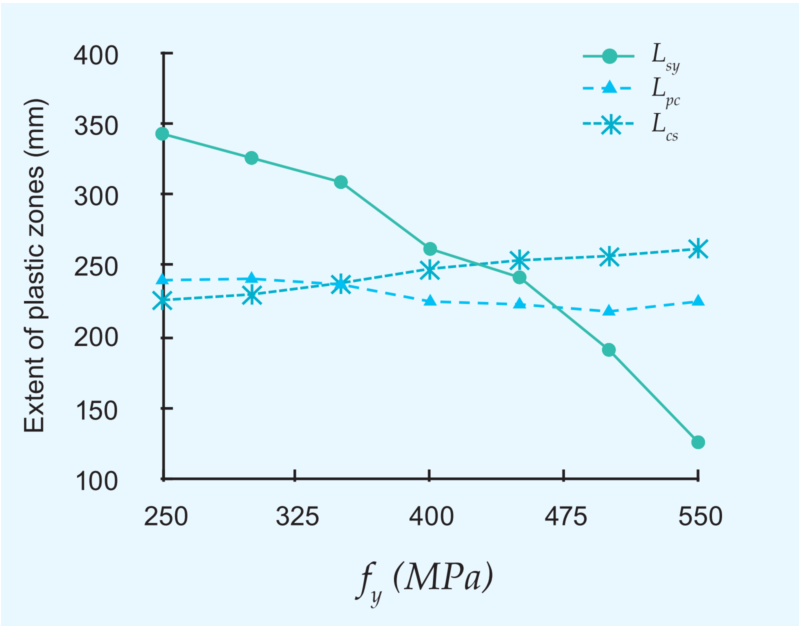


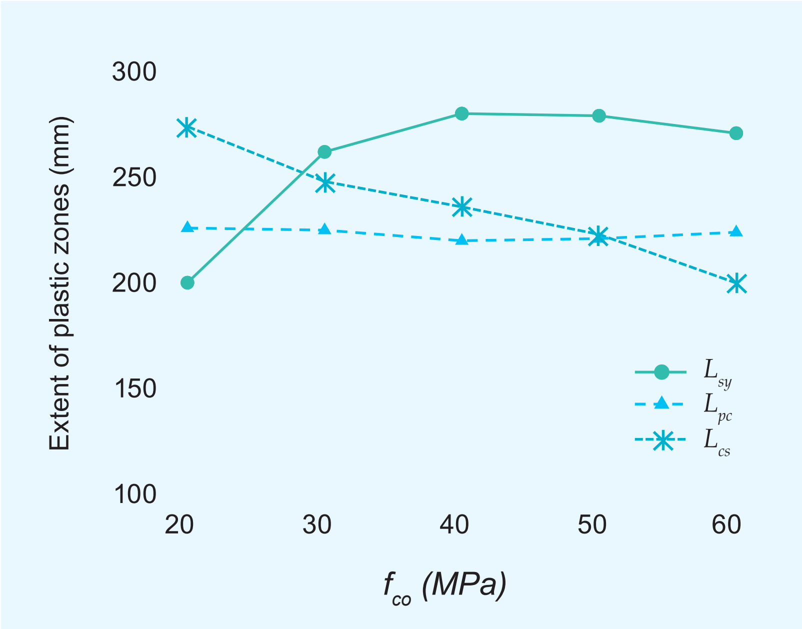
Figure 9 Effect of the axial load ratio on the plastic hinge lengths

(d) Effect of the material strength

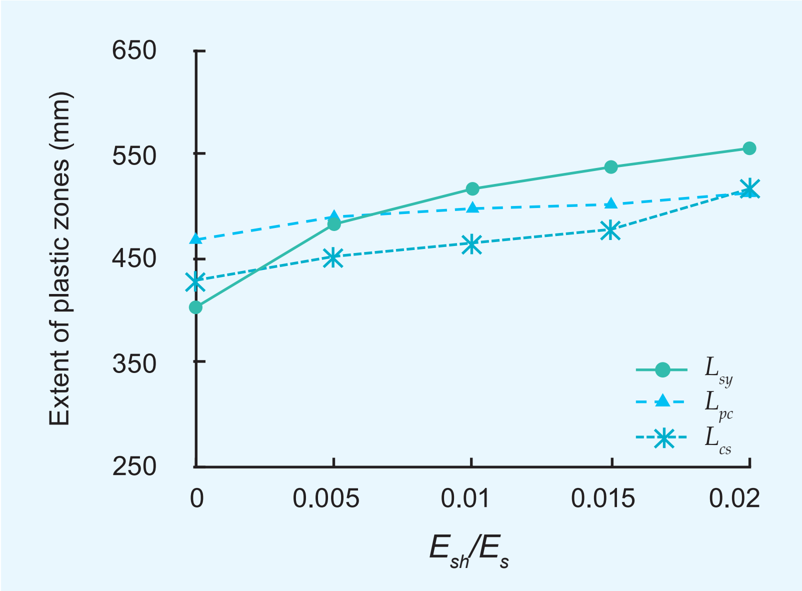
Fig. 10a shows the effect of the yield strength of steel (f_y) on the length of the plastic hinge zones. A descending trend in L_{sy} and an ascending trend in L_{cs} are observed as f_y increases. The tensile resistance is enhanced as f_y increases, leading to an increase in the area of compression zone as well as L_{cs}. However, the compression zone reaches its capacity with a larger f_y, leaving a smaller part for the steel to yield. It is also seen from Fig. 10a that f_y has almost no effect on L_{pc} due to the interaction between L_{sy} and L_{cs}.



(a) effect of the yield strength of longitudinal bars



(b) effect of the compressive strength of concrete



(c) effect of the hardening modulus of steel

Figure 10 Variation of the plastic hinge zones

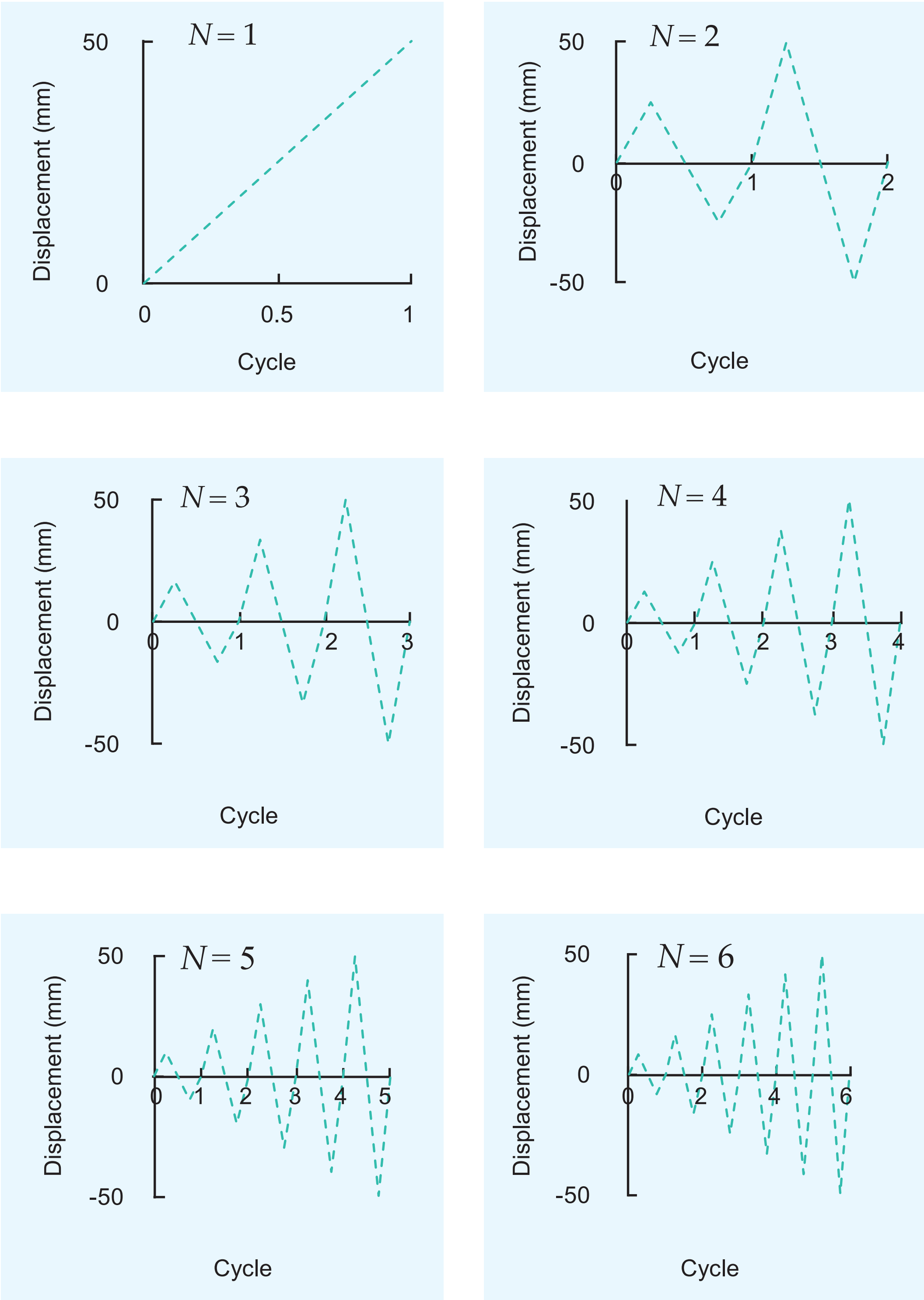
Fig. 10b shows the effect of the compressive strength (f_{co}) on the plastic hinge zones. Clear decreasing trends of L_{cs} are observed as f_{co} increases. The compression zone is strengthened as f_{co} increases, leading to a decrease in the area of the compression zone as well as L_{cs}. L_{sy} first increases and then remains almost constant. For a certain cross-section, the moment resistance of the column member increases with f_{co}. An increase in the moment capacity increases L_{sy}. However, the bond stress between the steel reinforcement and concrete also increases when f_{co} increases, which causes a reduction of the strain penetration distance. These two effects coexist and lead to the ascending and then constant trend of L_{sy}. The effect of E_{sh} on the plastic hinge zones is analysed by changing E_{sh} from 0 to 0.02E_s. The numerical results in Fig. 10c show that all the three lengths of the plastic hinge zones increase with an increase in E_{sh}. The mechanism is clear: the magnitude of the maximum steel stress of longitudinal bars beyond yielding is proportional to E_{sh}. The ultimate moment of an RC column increases as E_{sh} increases. While the yield moment is held constant, the cross-section of the first yield moves up from the column base when E_{sh} increases, leading to an increase in the extent of the plastic hinge zones.

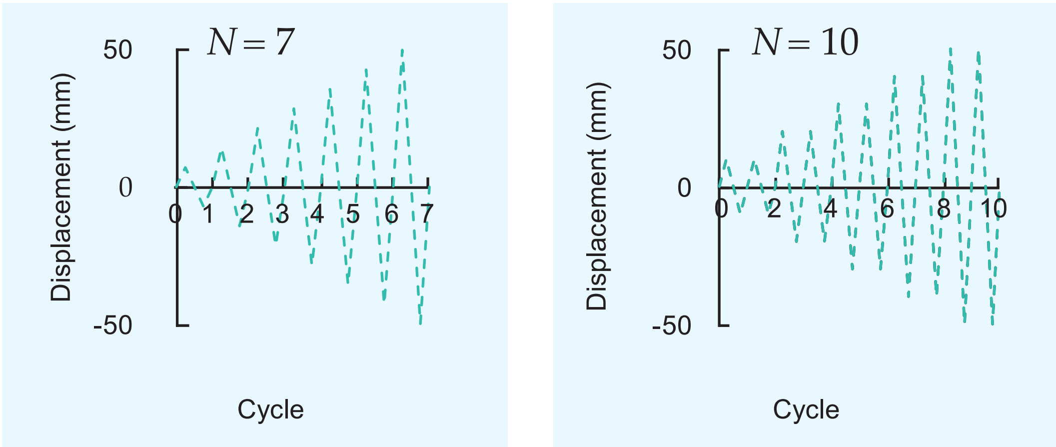
(e) Effect of loading cycles

In this part, a parametric study is conducted in order to gain a comprehensive understanding of the plastic hinge problem of cyclically loaded columns. Two square RC cantilever columns, one subjected to monotonic loading up to failure and another under cyclic loading with an increasing displacement up to 50 mm at intervals of 10 mm, are selected for the control specimens. A constant axial force is applied on the top of the columns before lateral displacement. The axial force is assumed to be 0.38N_c, where $N_c = f_{co}A_g$ and A_g is the gross cross-sectional area of the column. Both specimens have the same geometric dimensions and material properties. The specimen sizes are 400 × 400 × 1700 mm^3, connected to a 600 × 800 × 1400 mm^3 stub. The effective cantilever length is 1600 mm from the centre of the loading to the column base. The compressive strength of unconfined concrete is assumed to be 30 MPa. Steel bars with a diameter of 20 mm are adopted as the longitudinal bar and those with a diameter of 10 mm and a spacing of 100 mm are employed as the transverse reinforcement. The steel has a yield strength of f_y = 460 MPa, an elastic modulus of E_s = 200 GPa and a hardening modulus of E_{sh} = 3 GPa.

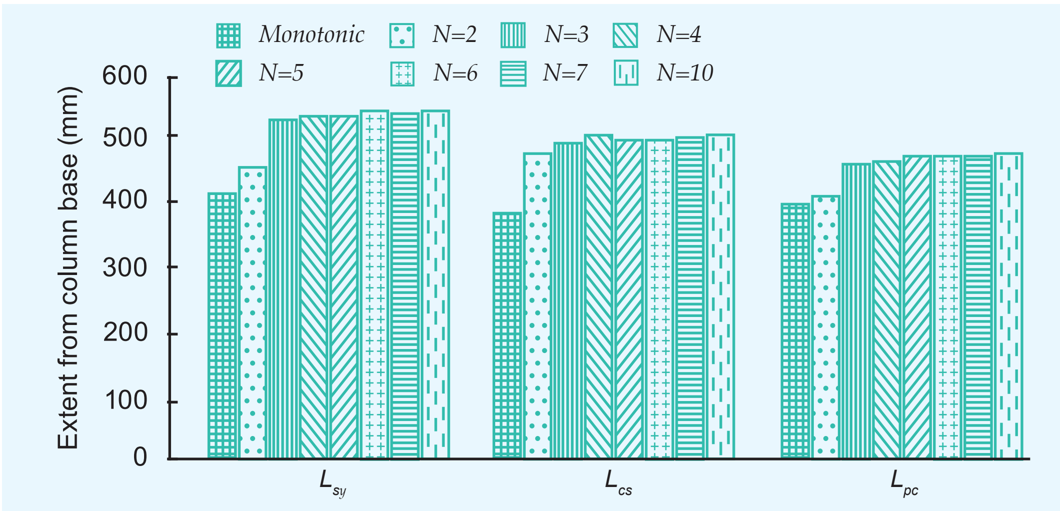
The key factors that affect the plastic hinge length include: the aspect ratio of the column L/d, the axial force ratio n, the compressive strength of concrete f_{co}, the yield strength of the longitudinal reinforcement f_y and the hardening stiffness of steel E_{sh}, and the reinforcement ratio ρs. The effects of these factors on variations of the plastic hinge zones are systematically studied. Another important parameter, the loading scheme, is studied in detail. The material parameters are the same as those in the previous section. When one factor is studied, the other factors are kept constant.

The effect of the load cycling on the plastic hinge lengths L_{sy}, L_{cs} and L_{pc} of the RC columns is studied by considering different load schemes, as shown in Fig. 11a. The cyclic displacement is applied at the column top at various displacement increments and cycles up to a fixed displacement of 50 mm. The numerical results in Fig. 11b show that the load cycle N has a significant influence on the plastic hinge zones. It can be seen that all three lengths for the columns under monotonic loading are evidently smaller than those of the column under cyclic loading. The three lengths increase rapidly with an increase in the loading cycles from 2 to 4. However, the lengths approach an asymptotical value and remain almost constant when N is greater than 5, which indicates that there is an upper limit to the plastic hinge lengths, even when N continues increasing.


N = 1
Displacement (mm)
50
0
0
0.5
1
Cycle
N = 2
Displacement (mm)
50
0
-50
0
1
2
Cycle
N = 3
Displacement (mm)
50
0
-50
0
1
2
3
Cycle
N = 4
Displacement (mm)
50
0
-50
0
1
2
3
4
Cycle
N = 5
Displacement (mm)
50
0
-50
0
1
2
3
4
5
Cycle
N = 6
Displacement (mm)
50
0
-50
0
2
4
6
Cycle



(a) loading scheme



(b) length of plastic hinge zones

Figure 11 Effect of the load cycles on the plastic hinge zones

The equivalent plastic hinge length (L_p) values can be calculated from FEM results. By analysing the variation of the equivalent plastic hinge length under cyclic loading $L_{p\text{-}c}$, it can be clearly observed that $L_{p\text{-}c}$ increases when the load cycle increases, but it approaches an upper limit. Regression analyses show that the trend of increase follows a power relationship with loading cycle N when N varies from 1 to 5, beyond which an asymptotic upper limit is reached. This relationship is given by Eq. (3a). A similar relationship for the physical plastic hinge length of the concrete damage zone (L_{cs}) is given by Eq. (3b)

$$L_{p\text{-}c} = \left[\min(5;N)\right]^{0.14} L_{p\text{-}m} \tag{3a}$$

$$L_{cs\text{-}c} = \left[\min(5;N)\right]^{0.14} L_{cs\text{-}m} \tag{3b}$$

where $L_{p\text{-}m}$ is the equivalent plastic hinge length under monotonic loading; and $L_{cs\text{-}m}$ and $L_{cs\text{-}c}$ are L_{cs} values under monotonic and cyclic loadings, respectively. For all the cases analysed in the previous parametric studies, the ratios of $L_{p\text{-}c}/L_{p\text{-}m}$ and $L_{cs\text{-}c}/L_{cs\text{-}m}$ evaluated by Eq. (3) to those from the FEM have a mean value of 0.99 (Eq. (3a)) and 0.97 (Eq. (3b)), and a standard deviation (SD) of 6.6% (Eq. (3a)) and 6.2% (Eq. (3b)). Therefore, the trend of variation of the plastic hinge length with loading cycles is well captured by Eq. (3).

3.3 Physical Plastic Hinge for FRP Jacketing

For flexural retrofitting of RC columns, an FRP jacket needs to cover at least the length of the concrete crushing zone L_{cs}, which is significantly affected by FRP confinement. Based on the parametric study, the following model of the critical plastic hinge zone L_{cs} (physical plastic hinge length for the concrete damage zone, where the concrete compressive strain is larger than the strain at a peak stress of unconfined concrete (0.002)) under monotonic loadings is obtained through nonlinear regression analyses:

$$L_{cs} = \left[1.07e^{-0.6\lambda_f} n^{0.16} \left(\frac{2r}{b} + 0.2\right)^{0.1} + 0.6\right] d \tag{4}$$

where n is the axial load ratio; r, b and d are corner radius, width and depth of the column cross-section, respectively (for circular columns, b = d and $2r/b$ = 1); and λ_f is the FRP confinement ratio, which can be calculated as

$$\lambda_f = \frac{2f_{frp}t}{bf_{co}} \tag{5}$$

in which f_{co} is the strength of concrete; and t and f_{frp} are the nominal thickness and strength of the FRP jacket, respectively.

For seismic strengthening, N is greater than 5. Substituting Eq. (4) into Eq. (3b), the concrete damage zone or minimum jacketing length can be determined by

$$L_{min} = 5^{0.14} L_{cs} = 1.25 \left[1.07e^{-0.6\lambda_f} n^{0.16} \left(\frac{2r}{b} + 0.2\right)^{0.1} + 0.6\right] d \tag{6}$$

The minimum jacketing length can be determined by Eq. (6) for FRP retrofitting work. The proposed model of Eq. (6) gives an estimation of the minimum jacketing length and thus will save construction costs for FRP retrofitting of flexural members compared to the otherwise full-length jacketing, which has been widely adopted. It is noted that the above minimum jacketing length is only applicable for flexural strengthening. The jacketing design needs to consider other requirements, such as the shear strength. For shear strengthening, full-length jacketing is usually required.

3.4 Equivalent Plastic Hinge Length for Displacement Calculation

The equivalent plastic hinge length L_p for monotonical loading cases can be obtained from FEM simulations. Extensive FEM simulations show that the confinement ratio λ_f, the column length L and the shape factor $2r/b$ have a significant effect on L_p. Using the FEM results and through regression analyses, a model of L_p is obtained as follows:

$$L_p = (0.08L+0.022f_y d_b) + 0.11\left(\frac{2r}{b} + 0.2\right)^{0.14}(e^{-1.2\lambda_f}-e^{-30\lambda_f})L \tag{7}$$

To verify the accuracy of the proposed models, the test results of the 32 RC circular columns and 20 square columns were collected. The ultimate drift ratios of all test specimens are calculated. The ultimate drift ratios of the circular specimens are also calculated using the models by Gu *et al.* (2012) and Youssf *et al.* (2015) (both applicable to circular columns only). The scatter of the proposed models is relatively small compared with the other two existing models. The average error, standard deviation and maximum error for the circular columns predicted by the proposed L_p model are 15.5%, 10.5% and 33.3%, respectively, compared with 21.4%, 14.3% and 51.3% by Gu *et al.* (2012) and 22.5%, 13.0% and 47.5% by Youssf *et al.* (2015). Thus, the proposed model reduces the error compared to other models. For FRP-confined square RC columns, the average error, standard deviation and maximum error of the proposed model are 23.9%, 22.8% and 84.2%, respectively. Again, a relatively good agreement between the proposed model and the test results is observed.

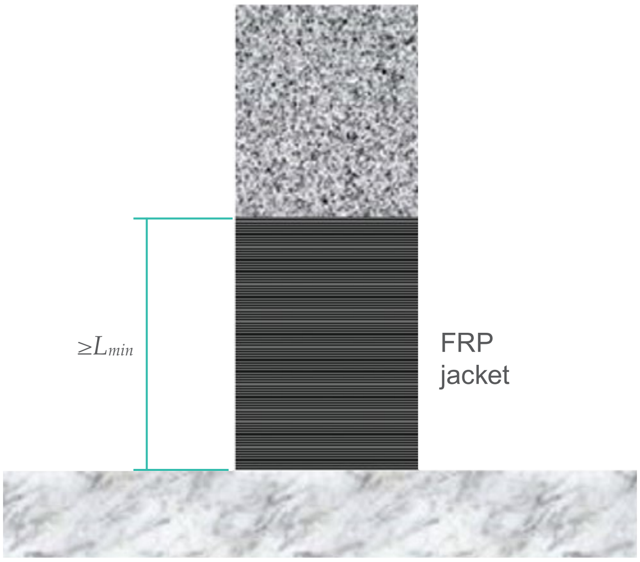
With L_p in Eq. (7), the ultimate drift ratio θ_u, can be calculated by

$$\theta_u = \theta_y + \frac{(\phi_u-\phi_y)L_p(L-0.5L_p)}{L} \tag{8}$$

where θ_y and θ_u are the yield and ultimate drift ratio, respectively; and ϕ_y and ϕ_u are the yield and ultimate curvature, respectively.

4 CONSTRUCTION GUIDELINE FOR MINIMUM RETROFITTING WORK OF RC COLUMNS

This section provides the detailed guideline of seismic retrofitting work on RC columns using FRP to minimize the retrofitting work. General guides are provided in many existing standards, such as ACI 440.2. After the Hong Kong Guide ("Guide for the Strengthening of Reinforced Concrete Structures using FRP Composites" developed by The Hong Kong Polytechnic University) is published, ACI 440.2 should be replaced by the Hong Kong Guide.



4.1 Seismic Retrofitting Design

The minimum retrofitting work, as shown in the figure above, can be designed in accordance with the following procedure:

1. Based on design requirements, such as loading and seismic demand, calculate the internal forces (including axial force, bending moment and shear force) of a particular RC column, based on Hong Kong concrete code ("Code of Practice for Structural Use of Concrete").

2. Using the calculated internal forces and/or ductility demand, design the FRP jacket thickness based on existing guidelines, such as ACI 440.2 (2008) or the Hong Kong Guide. Chapter 12 in ACI 440.2 provides design guidelines for RC column jacketing. Design examples are available in Section 15.8 and 15.9 in ACI 440.2 (2008). The design calculation will give the thickness and number of FRP layers.

3. Calculate minimum jacket length (from bottom of column), L_{min}, using the following equation.

$$L_{min} = 1.25\left[1.07e^{-0.6\lambda_f} n^{0.16}\left(\frac{2r}{\mathrm{b}} + 0.2\right)^{0.1} + 0.6\right]d$$

where n is the axial load ratio; r, b and d are the corner radius, width and depth of the column cross-section, respectively; and λ_f is the FRP confinement ratio, which can be calculated as

$$\lambda_f = \frac{2f_{frp}t}{bf_{co}}$$

in which f_{co} is the strength of concrete; and t and f_{frp} are the total thickness and strength of the FRP jacket, respectively.

4. The above calculated results provide the minimum FRP jacket.

4.2 Construction Tips

Some construction tips are provided in this section.

1. For square and rectangular columns, grinding is compulsory at every corner. The corner radius (r) should be no less than 20 mm.

2. The primary fibre direction of the FRP should be parallel to the transverse direction of the column.

3. The length of the overlap of each layer of the jacketed FRP should be no less than 150 mm.

4. The FRP jackets should be applied at the largest moment regions. If the column top is not a cantilever end, FRP jackets may need to be applied at both ends of the column based on calculations.

4.3 Estimation of the Construction Cost

The construction cost can be calculated based on the details of the FRP jacket calculated from the above procedure and using standard rates.

The following calculations are used as examples:

1. Jacketing one RC column in the plastic hinge region normally requires two workers for 2 hours to half a day. According to the government rate or other specified rate, \$R/per hour, the labour cost is HKD \$R × hours × 2 workers.

2. Material cost:

    (1) Calculate the area A of the FRP material required for one column using:

    $A = (\pi \times d \times n_f + 150)L_{min}$ for circular cross section

    or $A = [2(b+d)n_f + 150]L_{min}$ for rectangular cross section

    where 150 mm is the overlap length. Refer to NOTATION AND DEFINITIONS in the report for definitions of the notations.

    (2) Calculate the material cost. Based on the unit price of FRP, \$Q, (the price of a commonly used CFRP such as "TORAY Cloth" is approximately HKD \$75 per square metre), the material cost is \$Q×A.

    (3) Calculate epoxy resin cost

    Sikadur 300 adhesive is recommended for adhesive bonding. For small scale application, one set is required that normally cost HKD \$4200 per set. For large scale applications, the unit rate can be obtained from the supplier, say \$W/per square metre. The cost for one column is HKD \$W×A.

    (4) Others: Other materials, such as brushes, are approximately HKD \$50.00 in total for one column.

The total cost for FRP jacketing for one column is the summation of the above 4 items.

5 RECOMMENDATIONS

This research project was aimed at retrofitting RC columns with the advanced composite material FRP. For flexural retrofitting of RC columns, confinement offered by an FRP jacket can largely improve the flexural strength and ductility of the member. However, no clear construction guidelines are available in the literature for the design of minimum retrofitting work. This project provided the answer by studying the plastic hinge zone of FRP-confined RC columns through experimental, numerical and analytical studies. The following recommendations are made based on the research findings and outcomes of the project:

1. The plastic hinge zone involves a concrete crushing zone, rebar yielding zone and curvature concentration zone. These zones are all called physical plastic hinge zones. For flexural retrofitting of RC columns, the region of external jacketing is governed by physical plastic hinge zones.

2. The equivalent plastic hinge length is required for calculating the ductility and ultimate displacement of a flexural member. A satisfactory plastic hinge model is not available in the extant literature.

3. More advanced plastic hinge models have been developed through this project, which allow for the effect of external jacketing and cyclic loading. These models can be used not only for the design of new RC columns but also for retrofitting existing RC columns.

4. The plastic hinge length of FRP-confined RC columns is very different from that of normal RC columns. The lengths of both the rebar yielding zone L_{sy} and the curvature localization zone L_{pc} first increase and then decrease as the confinement ratio increases, while the length of the concrete crushing zone L_{cs} continuously decreases with an increase in the confinement ratio. Therefore, regions of FRP jacketing cannot be determined based on the plastic hinge length of normal RC columns without jacketing.

5. For flexural retrofitting of RC columns, the FRP jacket needs to cover at least the length of the concrete crushing zone, which is significantly affected by FRP confinement. A model of the minimum jacketing length allowing for this effect is developed in this work based on FEM simulation results. The model can be conveniently applied in the design of retrofitting works. It is noted that other factors, such as shear, should be considered in determining the length of the jacket. When shear failure governs, full length jacketing should be provided.

6. The length of the curvature localization zone L_{pc} is most related to the equivalent plastic hinge length. Based on the relationship between the curvature localization zone and the equivalent plastic hinge length, an improved model for the equivalent plastic hinge length is developed for calculating the ultimate displacement of columns. A new model of the ultimate drift ratio θ_u is also developed based on the simulation results that can be conveniently used for design purposes. The proposed models reduce the error and scatter in predicting column deformations, compared with existing models.

7. The loading scheme has a significant influence on the physical plastic hinge lengths. The physical plastic hinge lengths of cyclically loaded columns are larger than those of monotonically loaded ones. The physical plastic regions generally increase when the number of load cycle increases. However, this increase approaches an asymptotic value, i.e., an upper limit exists for all the three physical plastic hinge lengths.

8. Among all the parameters, the aspect ratio L/d, the number of load cycles N and the hardening stiffness of the steel bar E_{sh} have significant effects on the plastic hinge lengths. The effects of L/d and E_{sh} are more pronounced than N.

9. A simple empirical model for the equivalent plastic hinge length and concrete crushing zone under cyclic loading is developed. This is the first model reported in the literature for RC columns that accounts for the number of loading cycles. The proposed model can well capture the trend of variation of the plastic hinge length as the loading cycle changes. This model can be used for the seismic retrofitting of RC columns.

Further research work can be done on experimental testing of FRP-confined RC columns with different cross-sectional shapes to produce a more extensive database. Such a database is very much needed to provide a more comprehensive evaluation of existing models and to develop more accurate models.

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