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A study on pushover analyses of reinforced concrete columns

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Abstract. This paper proposes a realistic approach to pushover analyses of reinforced concrete (RC) structures with single column type and frame type. The characteristic of plastic hinge of a single RC column subjected to fixed axial load was determined first according to column's three distinct failure modes which were often observed in the experiments or earthquakes. By using the determined characteristic of plastic hinge, the pushover analyses of single RC columns were performed and the analytical results were investigated to be significantly consistent with those of cyclic loading tests. Furthermore, a simplified methodology considering the effect of the variation of axial force for each RC column of the frame structure during pushover process is proposed for the first time. It would be helpful in performing pushover analysis for the structures examined in this study with efficiency as well as accuracy.

Key words: performance-based design; pushover analysis; reinforced concrete column; plastic hinge.

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1. Introduction

The prevailing performance-based design method concentrates the attention on the structural behavior throughout whole life cycle of the structure. The structural behavior could not be limited in elastic state for the sake of economy when the possible severe excitation forces are considered. The analysis of the structural nonlinear behavior has been emphasized, particularly for aseismatic purpose (SEAOC Vision 2000 Committee 1995).

Generally speaking, structural nonlinear behavior excited by earthquake can be obtained via either nonlinear time history analysis or static pushover analysis. The former is one fundamental method capable of tracing dynamic responses of a structure during the whole vibration period, but it also may cost enormous computer time to conduct tedious iterative process. This drawback causes it not so popular in practical design except for some special purposes on structural investigation. On the other hand, pushover analysis method fulfills structural nonlinear analysis through a set of process composed of sequential steps of linear operation facilitates the establishment of structural capacity. It could retain the damage states of a structure corresponding to each analytical step and successfully explain the history of how the structural deterioration propagates from slight damage to ultimate state. Comparing to time history analysis, pushover analysis gives a straightforward point of view on the sequential failure process of structures, and has therefore been well accepted by structure engineers.

A well defining for the characteristic of plastic hinge would be the key point to have an accurate pushover analysis result of RC column. SAP-2000 is a widely used structural analysis computer program. It is certainly capable of performing pushover analysis (SAP2000 2002). Although SAP-2000 provided some convenient defaulted defining for the characteristic of plastic hinge of RC member, it was found that the so obtained analytical results sometimes are not satisfactory in precision point of view. In order to get a better simulation for nonlinear behavior, a program named NARC-2004 was developed (Sung and Su 2004) to conduct necessary defining the behavior of RC columns corresponding to their three different failure modes, named shear failure, bending to shear failure and bending failure, which were often observed in experiments and practical damages in earthquake. The proposed defining of plastic hinge of RC columns was used to replace the defaulted model of “M3-type” defined in SAP-2000.

The characteristic of plastic hinge is extremely sensitive to the axial load level of RC column. For a frame structure, the variation of axial force of RC column throughout the pushover process causes the changes of plastic hinge characteristic from time to time. This problem has been a trouble to engineer for a long time. A simplified methodology considering the effect of the variation of axial force for each RC column of the frame structure is proposed for the first time. It would be helpful in performing pushover analysis for the structures evaluated in this study with efficiency as well as accuracy.

Some important experimental results of RC columns performed by National Center for Research on Earthquake Engineering (NCREE, Taiwan) and Japanese Society of Civil Engineering (JSCE) were served as the materials for the necessary investigations on the proposed approach. The results of the analysis show that the proposed approach would be well to predict nonlinear behaviors of RC columns and expected to facilitate the pushover analysis of the RC structure.

2. Bend and shear behavior of RC column member

2.1 Bending behavior

The relationship between bending curvature φ_i and moment M_i of a RC member is able readily to be found from conventional calculations. For a single column member, the elastic displacement at the top of the column, δ, is given by

$$\delta = \int_0^h \varphi_i y_i dy \tag{1}$$

where h is the length of the column, and y_i denotes the distance from the top of the column to a specific section at which the curvature is in the formula. The equivalent elastic rotation θ of the column can be expressed as

$$\theta = \delta / h \tag{2}$$

The ultimate displacement δ_u at the top of the column is thus

$$\delta_u = \int_0^{h-L_P} \varphi_i y_i dy + \int_{h-L_P}^{h} \varphi_u y_i dy = \delta_e + \delta_P \tag{3}$$

where φ_u is the ultimate curvature, and L_P is the equivalent plastic hinge length (Priestley *et al.* 1996). The equivalent ultimate rotation θ_u is thus

$$\theta_u = \delta_e / h + \delta_P / (h - L_P/2) \tag{4}$$

In this way, the bending capacity of the column can then be represented by a plot of bending moment M_b versus rotation θ, i.e., ($M_b - \theta$) diagram.

2.2 Shear behavior

For the concrete of RC column members, the shear strength decreases while the inelastic displacement increases. Some recent developments (Priestley *et al.* 1994, Aschheim *et al.* 1992) provided expressions to reflect such behavior. After making some modifications referred to the study of Aschheim, the shear strength of concrete in the plastic zone of RC column is then expressed as

$$V_c = 0.53(k + F)\sqrt{f_c'} A_e \geq 0 \tag{5}$$

$$k = \frac{R_{\max} - R}{R_{\max} - 1} \geq 0 \tag{6}$$

$$F = \frac{N}{140 A_g} \quad \text{(for compressive axial force, } N > 0\text{)} \tag{7a}$$

$$F = \frac{N}{35 A_g} \quad \text{(for tensile axial force, } N < 0\text{)} \tag{7b}$$

In above equations, A_e is the effective shear area usually adopted as 80% of the total gross sectional area A_g, $R_{\max} = \theta_u/\theta_y$, and R is the rotation ductility defined as

$$R = \theta/\theta_y \tag{8}$$

where θ_y is the yielding rotation. Notice that $R \geq 1$, and V_c can be represented in terms of rotations. The total nominal shear strength of RC columns given as follows is accordingly also a function of rotations

$$V_n = V_c + V_s \tag{9}$$

since V_s, the shear strength of transverse steel reinforcement, is deemed as independent of rotations. In this case, Eq. (9) gives the relationship between shear strength and plastic rotation, i.e., $V_n = f(\theta)$.

2.3 Transformation of $V_n(\theta)$ to $(M_v - \theta)$

To investigate the resultant behavior of bending and shear for RC columns, the shear model, $(V_n - \theta)$, should be transformed to the corresponding bending one, $(M_v - \theta)$. And it would be then superimposed on the bending model $(M_b - \theta)$ to discuss the possible failure modes. The transformation is proposed as follows.

A. Under yield, i.e., $\theta \leq \theta_y$

$$M_{vy} = V_n(\theta_y) \times h \tag{10}$$

B. Ultimate stage, i.e., $\theta = \theta_u$

$$M_{vu} = V_n(\theta_u) \times (h - L_P/2) \tag{11}$$

C. Inelastic stage, i.e., $\theta_y < \theta < \theta_u$ or $1 < R < R_{\max}$

$$M_v = M_{vy} + (M_{vu} - M_{vy}) \times \frac{R-1}{R_{\max} - 1} \tag{12}$$

In this way, the shear capacity is then transferred into the coordinates, $(M_v - \theta)$, which is represented on a plot of equivalent bending moment M_v versus rotation θ.

3. Characteristics of plastic hinge corresponding to various failure modes of RC column

On the plot of bending versus rotation, the transferred shear model, $(M_v - \theta)$ is superimposed on the bending model $(M_b - \theta)$ to discuss the possible failure modes. In this way, three distinct failure modes, namely shear failure, bending to shear failure, and bending failure of RC columns can be classified as shown in Fig. 1 to Fig. 3. The precise property setting of M3 plastic hinge defined in SAP-2000 could be described as follows.

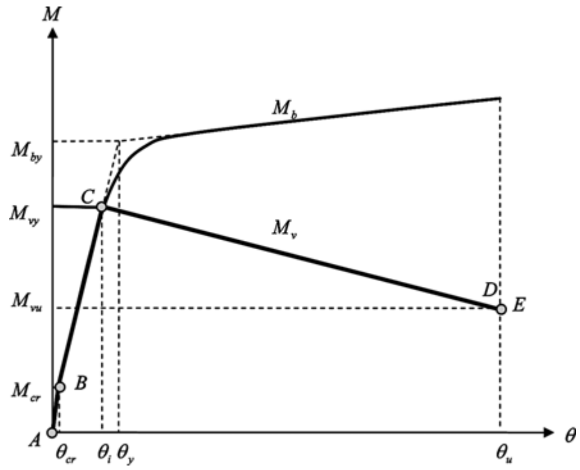

Fig. 1 Plastic hinge characteristic of RC column for shear failure

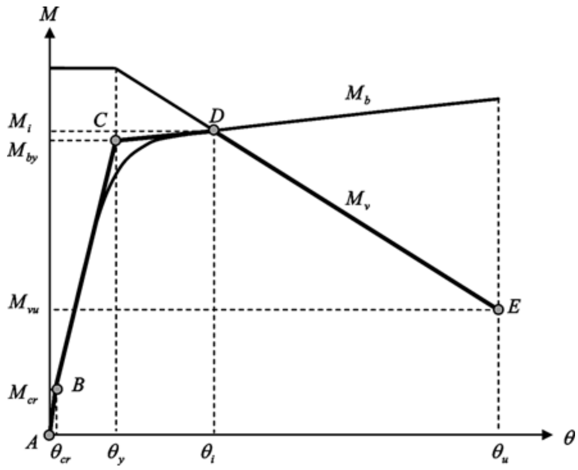

Fig. 2 Plastic hinge characteristic of RC column for bending to shear failure

3.1 Single column type

The axial force applied to the single column remains constant when calculating both bending behavior, $(M_b - \theta)$, and shear one, $(M_v - \theta)$, in the pushover process. According to Fig. 1 to Fig. 3, three distinct failure modes of RC column can be classified.

3.1.1 Shear failure mode

The $M - \theta$ diagram for the shear failure mode of RC columns is given by Fig. 1. It is seen that $M_v < M_b$ in the inelastic range, which means that the shear strength is lower than the bending one, so that shear failure occurs prior to bending failure. The characteristic of plastic hinge can be described from points A to E in Fig. 1. Point A is the original point, while point B represents the beginning of cracking of concrete with the coordinates (θ_{cr}, M_{cr}). C is the intersection point of M_v and M_b with M_v = M_{vy}, thus the corresponding coordinates are (θ_i, M_{vy}), where θ_i can be determined by setting $M_b = M_{vy}$. Finally, points D and E can be set as the same point with the coordinates of (θ_u, M_{vu}).

3.1.2 Bending to shear failure mode

The bending transfers to shear failure mode diagram of RC columns is shown in Fig. 2. Here, points A and B have the same meaning as described previously. In the present failure mode, the critical point D located at the place where M_v is equal to M_b, which separates the behavior of RC column from bending failure to shear failure. The corresponding coordinate (θ_i , M_i) can be found by solving the combined equations of behaviors $(M_b - \theta)$ and $(M_v - \theta)$. It is clearly that bending failure governs the range of rotation θ form zero to θ_i, while shear failure dominates the following range from θ_i to θ_u. On the other hand, point C can be determined from the column's bending behavior, and defined as the intersection of the elastic tangent slope after cracking of concrete to the plastic tangent slope. Finally, point E is the last point with the coordinates (θ_u, M_{vu}).

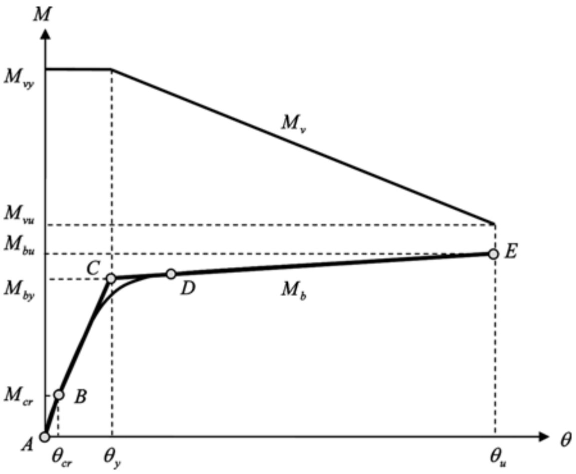

Fig. 3 Plastic hinge characteristic of RC column for bending failure

3.1.3 Bending failure mode

Fig. 3 shows the bending failure mode of RC columns. It is seen that M_v is always greater than M_b with no intersection, which means that bending failure controls whole behavior of RC columns. Here, points B and C represent the same as previous "bending to shear failure mode", while point D is the starting point of post yielding. Finally, point E is the last point with the coordinates (θ_u, M_u).

3.2 Columns in frame structure

For practical frame structures, axial forces of members may vary from time to time during the pushover process. Both bending and shear behaviors feasible to constant axial load are no longer appropriate and should be modified. In the following, a simplified methodology considering the effect of the variation of axial force for each RC column member is proposed for the first time. It would be helpful in performing pushover analysis for the structures analyzed in this study with efficiency as well as accuracy.

Step 1: Setting for the axial force at service state

Through the static linear analysis with gravity load only, the axial force P_D and bending moment M_D at both ends of structural members can be obtained. Dividing each column into two sub-columns from the location of inflection point, the length of sub-columns can thus be defined as h_1 and h_2, respectively. Since the column's height and the service axial load P_D are known, taking each sub-column as a single column, the characteristic of plastic hinge can then be determined together with the section properties, including the detail arrangement of longitudinal, transverse reinforcement, and concrete strength, etc.

Step 2: Setting for the axial force at ultimate state

Considering structures subjected to the combination of gravity load and earthquake load specified in the current building design code, the axial force ($P_D + P_{EQ}$) and bending moment ($M_D + M_{EQ}$) at both ends of members can be obtained. Then plot the point with coordinates ($M_D + M_{EQ}$, $P_D + P_{EQ}$)

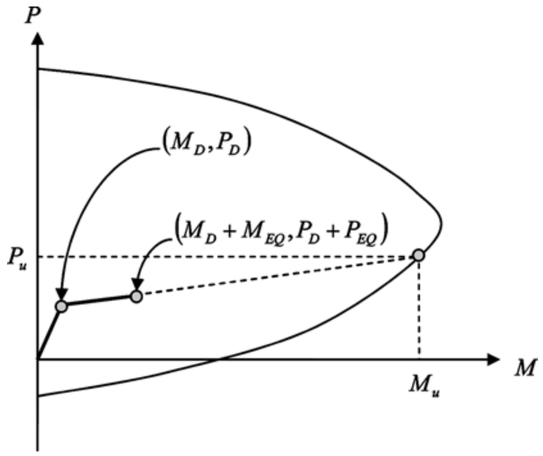

Fig. 4 Determination of RC column's ultimate axial force from P-M interaction curve

on the interaction plan of RC column as shown in Fig. 4. Extending the straight line connected between (M_D, P_D) and (M_D + M_{EQ}, P_D + P_{EQ}) to the boundary of the interaction diagram. The intersection point could be regarded as the ultimate state of RC columns under the load pattern resulted by service load and amplified earthquake load. The projection of the point to vertical axis is taken as the ultimate axial load P_u. Follow the similar process as step 1, the plastic hinge characteristic of each sub-column can then be obtained.

Step 3: Setting for the axial force varying from service state to ultimate state

The characteristic of plastic hinge for a RC member is significantly sensitive to the axial force that the member has. Accordingly, the variation of axial force of each RC column in a frame structure during pushover process causes enormous complexity in those characteristic settings. From the loading process point of view, RC columns remain elastic behavior at service state till yielding

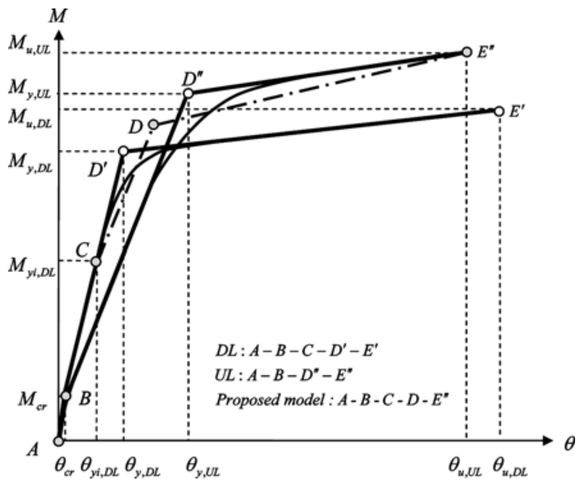

Fig. 5 Plastic hinge characteristic of RC column with varying axial load

and then trend sequentially to ultimate state as the earthquake load increases. Consequently, we proposed a simplified methodology to interpolate one characteristic with axial force corresponding to service state (DL) and another corresponding to ultimate state (UL). The interpolated characteristic of plastic hinge is then adopted for pushover analysis. The interpolation method is described as follows.

The aforementioned modeling technique is well illustrated by points *A~E* given in Fig. 5. Noting that sub-indices *DL* and *UL* are used to indicate service state and ultimate state, respectively. In Fig. 5, the path ABCD'E' is the characteristic of plastic hinge corresponding to service state; while ABD"E" corresponding to ultimate state. As usual, point $B(\theta_{cr}, M_{cr})$ represents the cracking of concrete, while point $C(\theta_{yi,DL}, M_{yi,DL})$ is the initial yielding of longitudinal steel reinforcement under service state. Point $D'(\theta_{y,DL}, M_{y,DL})$ and $D''(\theta_{y,UL}, M_{y,UL})$ are the intersections of the elastic tangent line after cracking of concrete, and the plastic tangent line under service state and ultimate state, respectively. For the proposed model, the interpolated $M-\theta$ behavior is taken as *A-B-C-D-E"*, where point *D* is set to take the arithmetic mean of D' and D'' with coordinates of $[1/2(\theta_{y,DL}+\theta_{y,UL}), 1/2(M_{y,DL}+M_{y,UL})]$, while point *E*" represents the last point under ultimate state $(\theta_{u,UL}, M_{u,UL})$.

4. Case studies of RC structure with single column type

Three cyclic loading tests of RC column performed by NCREE and JSCE are employed as the database for the investigations on the proposed approach. Table 1 shows all the data of the experimental specimens. Their corresponding characteristics of plastic hinge analyzed by NARC-2004 are summarized in Table 2.

Table 1 Considered specimens of single column

	Unit	BMR1-R	BMC1	JSCE-4
		Rectangular	Circular	Square
Concrete compression stress f_c'	MPa	22.05	26	35.9
Yielding stress of longitudinal reinforcement f_y	MPa	436.8	490.5	363
Yielding stress of transversal reinforcement f_{yh}	MPa	450.8	490.5	368
Yielding stress of tie reinforcement f_{yt}	MPa	450.8	490.5	-
Cross section	mm	600 × 750	Diameter 760	400 × 400
Height	mm	3250	3250	1245
Cover	mm	25	25	27.5
Arrangement of longitudinal reinforcement	-	32-D19	34-D19	20-D13
Spacing of transversal reinforcement within the plastic zone	mm	D10@100	D10@70	D6@70
Spacing of tie reinforcement along the long side within the plastic zone	mm	2-D10@100	1-D10@70	-
Spacing of tie reinforcement along the short side within the plastic zone	mm	3-D10@100	-	-
Spacing of transversal reinforcement within the non-plastic zone	mm	D10@100	D10@100	D6@70
Spacing of tie reinforcement along the long side within the non-plastic zone	mm	2-D10@100	1-D10@70	-
Spacing of tie reinforcement within the non-plastic zone	mm	3-D10@100	-	-
Axial load (kN)	kN	1400	1400	157

Table 2 Plastic hinge setting for considered specimens of single column

	BMR1-R		BMC1		JSCE-4	
	M/M_c	θ/θ_c	M/M_c	θ/θ_c	M/M_c	θ/θ_c
Point A	0	0	0	0	0	0
Point B	0.2154	0.1442	0.2114	0.14	0.1755	0.117
Point C	1	1	1	1	1	1
Point D	0.9916	1.6675	0.9955	1.6509	0.9671	4.8588
Point E	0.9302	6.5824	0.9818	3.6143	0.6804	6.3863
Yielding moment (kN-m)	1558926.7		1565293.1		191830.21	
Yielding rotation (rad)	0.0117		0.012		0.005842	
Immediate Occupancy (IO)	1		1		1	
Life Safety (LS)	1.6675		1.6509		4.8588	
Collapse Prevention (CP)	6.5824		3.6143		6.3863	

4.1 Study on specimen BMR1-R

The specimen BMR1-R (NCREE 1999) as shown in Fig. 6 is a single RC column with rectangular cross section. Its corresponding relationship of moment-rotation, $M-\theta$, analyzed by

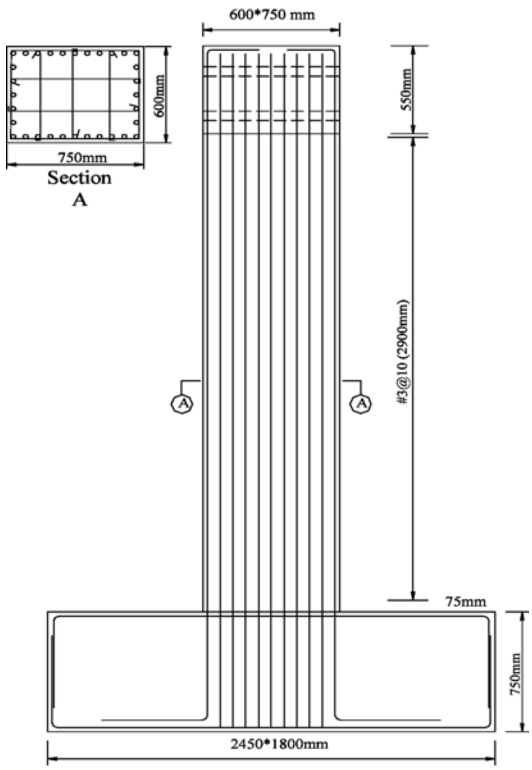

Fig. 6 Specimen BMR1-R (Chang 1999, Chung 2000)

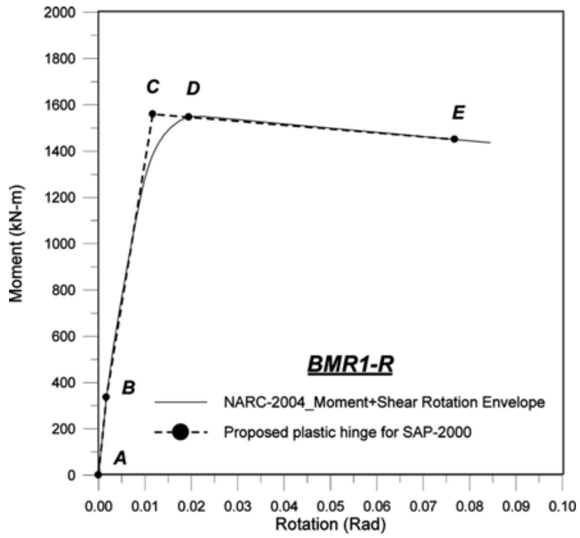

Fig. 7 Moment-rotation analysis and proposed plastic hinge property for SAP-2000N of the specimen BMR1-R

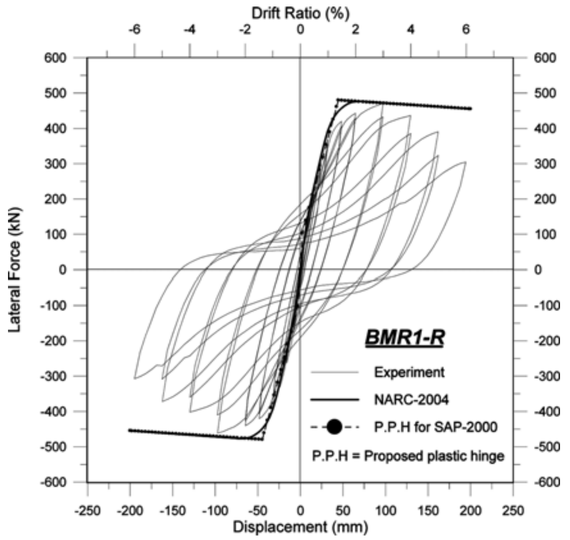

Fig. 8 Cyclic loading test and analytic pushover result of the specimen BMR1-R

NARC-2004 and the proposed setting of the corresponding plastic hinge are all displayed in Fig. 7. The results of pushover analysis performed by NARC-2004 and SAP-2000, together with the experimental hysteretic loop are all exhibited in Fig. 8. It gives evidence for the acceptable precision of our analysis to approximate the envelope of the experimental result. The effect of confinement, provided by transverse reinforcement, to concrete strength might be not so much as the expectancy. As a result, the strength capacity observed is lower than the analytical one in inelastic range. With regard to the efficiency of confinement, it is worth examining the subject more closely. Nevertheless, the analytical method we proposed provides a good accuracy for prediction of the elastic stiffness, ultimate strength, and ultimate displacement.

4.2 Study on specimen BMC1

The specimen BMC1 (NCREE 2000, 2001) as shown in Fig. 9 is a single RC column with circular cross section. Its corresponding relationship of moment-rotation, $M-\theta$, analyzed by NARC-2004 and the proposed setting of the corresponding plastic hinge are all displayed in Fig. 10. The results of pushover analysis performed by NARC-2004 and SAP-2000, together with the experimental hysteretic loop are all exhibited in Fig. 11. It is seen that the results of analyzing are well coinciding the envelope of the experimental result.

4.3 Study on specimen JSCE-4

The specimen JSCE-4 (JSCE 2001) as shown in Fig. 12 is a single RC column with rectangular cross section. Its corresponding relationship of moment-rotation, $M-\theta$, analyzed by NARC-2004 and the proposed setting of the corresponding plastic hinge are all displayed in Fig. 13. The results

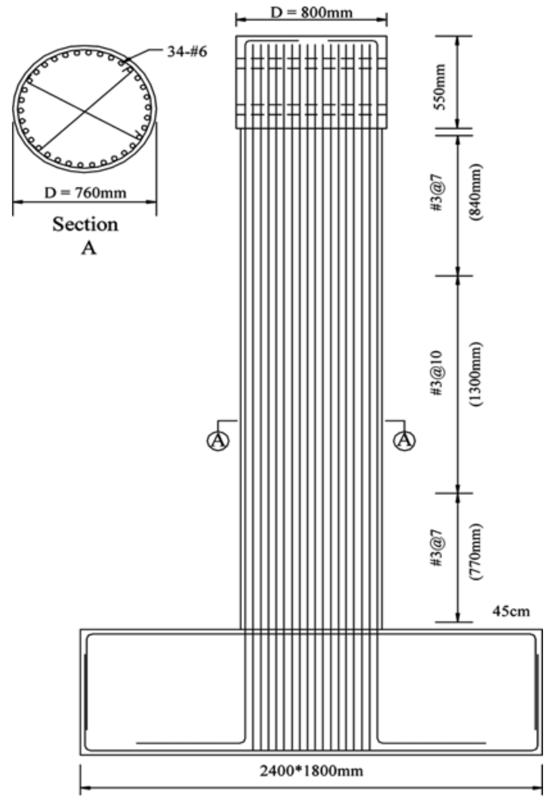

Fig. 9 Specimen BMC1 (Chung 2001)

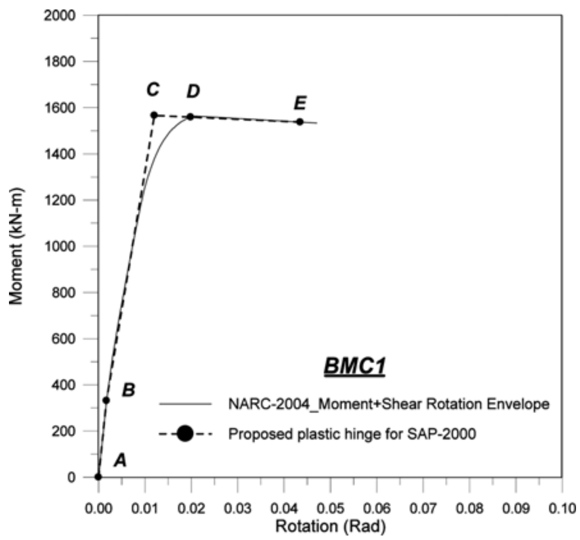

Fig. 10 Moment-rotation analysis and proposed plastic hinge property for SAP-2000N of the specimen BMC1

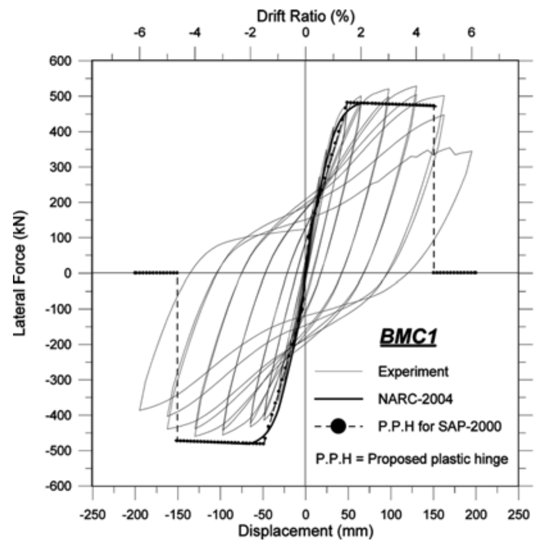

Fig. 11 Cyclic loading test and analytic pushover result of the specimen BMC1

of pushover analysis together with the experimental hysteretic loop are all exhibited in Fig. 14. Fig. 15 shows that the experimental tensile strains of the longitudinal reinforcements (at channel CH101 to CH104) are significantly close to those of the numerical analysis.

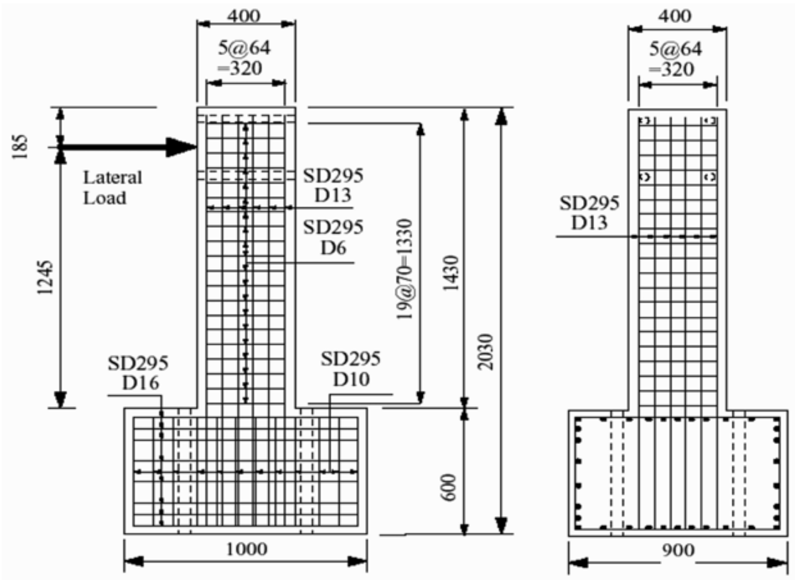

Fig. 12 Specimen JSCE-4 (JSCE 2001)

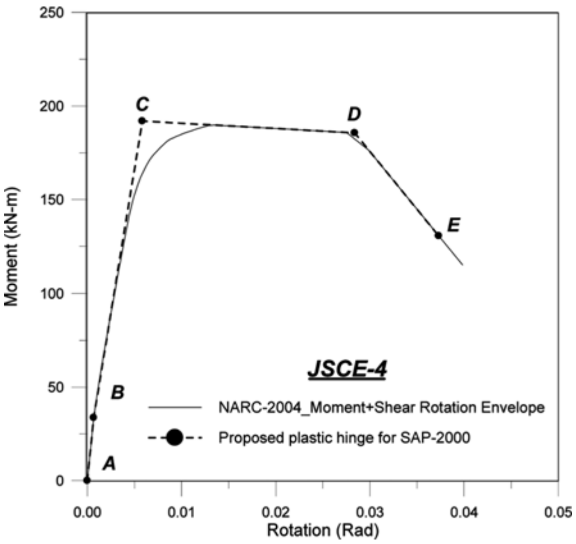

Fig. 13 Moment-rotation analysis and proposed plastic hinge property for SAP-2000N of the specimen JSCE-4

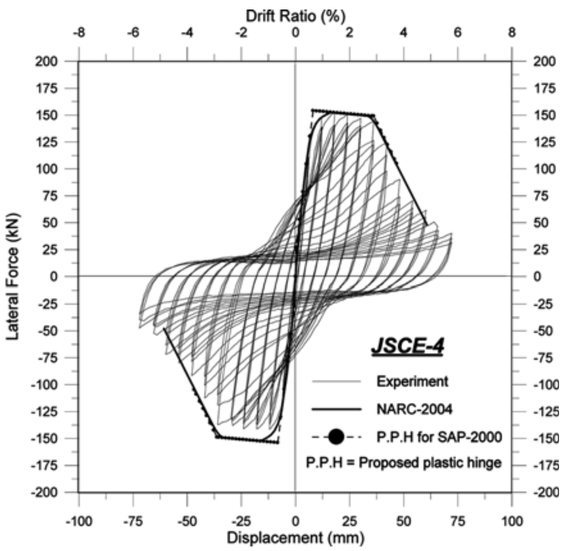

Fig. 14 Cyclic loading test and analytic pushover result of the specimen JSCE-4

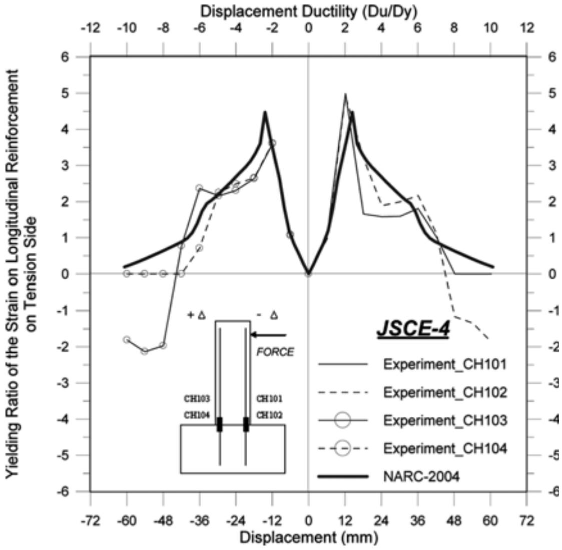

Fig. 15 Experimental and analytic tensile strains of the longitudinal reinforcements of the specimen JSCE-4

5. Case study of RC frame structure

The specimen BMDF (NCREE 2003) shown in Fig. 16 is a RC frame with two rectangular columns. As the proposed interpolation method considering the variation of axial force of frame

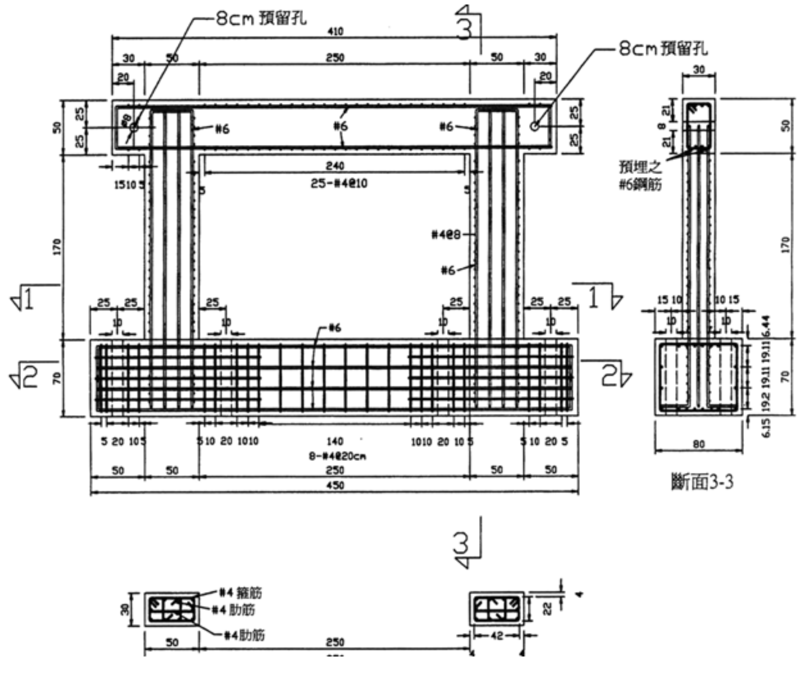

Fig. 16 Specimen BMDF (Hwang 2003)

columns during pushover process, the interpolated properties of the plastic hinge for COL1_top, COL2_top, COL1_bot, and COL2_bot are all shown in the Fig. 17. Table 3 shows three kinds of plastic hinge setting of RC members, including the axial force corresponding to service state (dash line), ultimate state (light solid line), and the interpolated result (bold solid line with circle), respectively. The results of pushover analysis using three different kinds of plastic hinge setting together with the experimental envelope of the hysteretic loop of the structure are all exhibited in Fig. 18. In which, the dash line and the light solid line represent the results of the pushover analysis for the setting corresponding to service state and ultimate state, respectively. Both the results are not well consistent with the experimental one. For the setting corresponding to service state, the result is

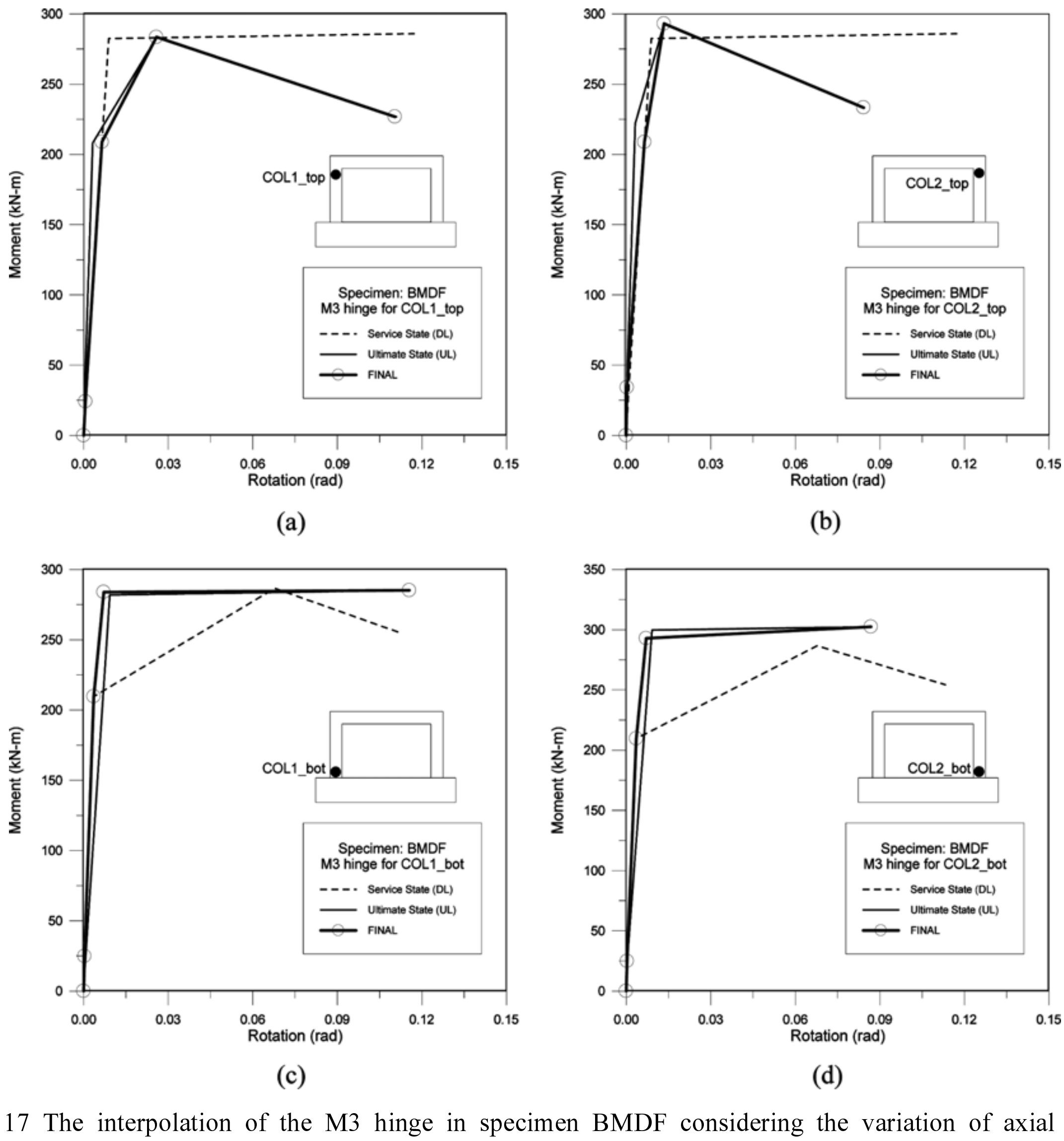

Fig. 17 The interpolation of the M3 hinge in specimen BMDF considering the variation of axial load: (a) COL1_top, (b) COL2_top, (c) COL1_bot, (d) COL2_bot

Table 3 Plastic hinge setting for specimen BMDF

	COL1_bot		COL1_top		COL2_bot		COL2_top	
	M/M_c	θ/θ_c	M/M_c	θ/θ_c	M/M_c	θ/θ_c	M/M_c	θ/θ_c
Axial load of service state (DL)								
Point A	0	0	0	0	0	0	0	0
Point B	0.1184	0.0924	0.1159	0.0967	0.1184	0.0924	0.1159	0.0967
Point C	1	1	1	1	1	1	1	1
Point D	1.3675	18.9260	1.3533	1.3609	1.3677	18.9034	1.3533	1.3609
Point E	1.2131	31.5976	1.3697	17.9387	1.2131	31.5976	1.3697	17.9387
Yielding moment (kN-m)	209.60		208.79		209.60		208.79	
Yielding rotation (rad)	0.0036		0.0065		0.0036		0.0065	
Immediate Occupancy (IO)	1		1		1		1	
Life Safety (LS)	1.3675		1.3533		1.3675		1.3533	
Collapse Prevention (CP)	1.2131		1.3697		1.2131		1.3697	
Axial load of ultimate state (UL)								
Point A	0	0	0	0	0	0	0	0
Point B	0.1139	0.0970	0.1139	0.0921	0.1541	0.0981	0.1541	0.0912
Point C	1	1	1	1	1	1	1	1
Point D	1.3541	1.3608	1.3620	7.9923	1.3493	1.3724	1.3198	4.1775
Point E	1.3698	16.8613	1.0897	34.1819	1.3623	12.9447	1.0506	26.0941
Yielding moment (kN-m)	208.1632		208.1632		222.0561		222.0561	
Yielding rotation (rad)	0.0068		0.0032		0.0067		0.0032	
Immediate Occupancy (IO)	1		1		1		1	
Life Safety (LS)	1.3541		1.3620		1.3493		1.3198	
Collapse Prevention (CP)	1.3698		1.0897		1.3623		1.0506	
Interpolation between service state and ultimate state (FINAL)								
Point A	0	0	0	0	0	0	0	0
Point B	0.1184	0.0924	0.1159	0.0967	0.1184	0.0924	0.1639	0.0451
Point C	1	1	1	1	1	1	1	1
Point D	1.3547	1.9829	1.3579	3.9730	1.3974	1.9666	1.4037	2.0647
Point E	1.3605	32.0878	1.0865	16.9920	1.4433	24.1192	1.0954	12.8971
Yielding moment (kN-m)	209.60		208.7862		209.60		208.7862	
Yielding rotation (rad)	0.0036		0.0065		0.0036		0.0065	
Immediate Occupancy (IO)	1		1		1		1	
Life Safety (LS)	1.9829		3.9730		1.9666		2.0647	
Collapse Prevention (CP)	32.0878		16.9920		24.1192		12.8971	

fine in simulating initial stiffness, but deficient in capturing the yielding and ultimate strength. On the other hand, the result for ultimate state is good for predicting the ultimate strength, whereas poor in telling the elastic behavior. Rather, the proposed interpolation method (the bold solid line in Fig. 18) gives good estimation for the elastic stiffness and also the ultimate strength as well as ultimate displacement. In Fig. 18, the analytical overestimation of shear capacity is found when

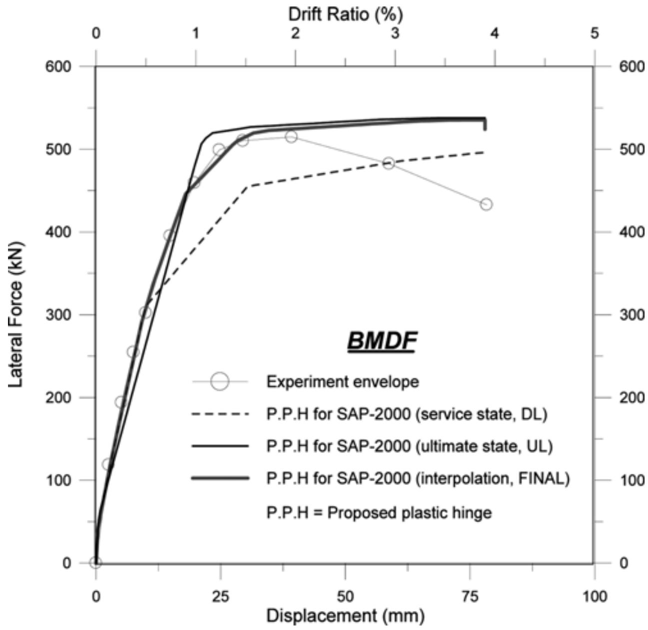

Fig. 18 Experimental envelope and analytic pushover result of the specimen BMDF

$\mu > 2.2$. It is likely caused by the slight shear cracking observed at the beam-column joint of the specimen, making the strength deterioration. The influence of joint weakening on the frame structure is not considered in this paper and is worth studying in the future.

6. Conclusions

The aim of the present research is to introduce a realistic approach with efficiency as well as accuracy to the pushover analyses of RC columns. The conclusions obtained are drawn as follows.

1. A well defining for the characteristic of plastic hinge would be the key point to have a precious pushover analysis result of RC column. Instead of the defaulted parameters defined in SAP-2000, we developed a program NARC-2004 to evaluate the characteristic with respect to three failure modes of RC column. The analytical results are found to be significantly consistent with those of experiments. The accuracy of the proposed approach has been investigated in three columns with rectangular, square, and circular section, respectively.
2. The characteristic of plastic hinge for a RC member is highly sensitive to the axial force that the member has. Accordingly, the variation of axial force of each RC column in a frame structure during pushover process causes enormous complexity in those characteristic settings. From the loading process point of view, RC columns remain elastic behavior at service state till yielding and then trend sequentially to ultimate state as the earthquake load increases. Consequently, we proposed a simplified methodology to interpolate one characteristic with axial force corresponding to service state and another corresponding to ultimate state. The interpolated characteristic of plastic hinge is then adopted for pushover analysis. It reasonably

approximates the real behavior of RC structures. Our study case of a portal frame shows that the analysis based on the axial force corresponding to either service state or ultimate state gives deficient result. Rather, our proposed interpolation method provides good estimation for the elastic stiffness, ultimate strength and ultimate displacement of the structure. It could help the grasp of the structural capacity with great efficiency as well as accuracy.

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