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Simplified Nonlinear Analysis of RC Columns Exposed to Lateral Loads

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Abstract

In this study, the monotonic and hysteretic behavior of poorly detailed reinforced concrete (RC) columns under lateral loads is simply modeled by SAP2000. It has been shown in literature that the flexural, reinforcement slip and shear deformations is contributed to lateral deformation. The monotonic and hysteretic responses of RC columns due to each of these deformations, were determined. Under pushover loading, deformations due to the flexural, reinforcement slip and shear deformations were summed up to create monotonic behavior of the column. The load-deformation curve from the monotonic model were used to create backbone curve of hysteretic pivot model. The monotonic and hysteretic lateral load-displacement curves obtained in this study were compared with the results obtained from experimental studies. It has been shown that SAP2000 and experimental results were in good agreement and the behavior of poorly detailed RC columns are simplified by SAP2000 instead of using the complex analysis methods.

Anahtar Kelimeler: Weak column, Flexural deformation, Shear deformation, Reinforcement slip, SAP2000, Monotonic model, Hysteretic model

Yanal Yüklere Maruz Kalan Betonarme Kolonlarin Basit Nonlinear Analizi

Öz

Bu çalışmada, zayıf detaylandırılmış betonarme kolonların yanal yükler altındaki monotonik ve histeretik davranışı SAP2000 ile basit bir şekilde modellenmiştir. Eğilme, donatı sıyrılması ve kesme deformasyonlarının yanal deformasyona katkıda bulunduğu literatürde gösterilmiştir. Bu deformasyonların her biri için RC kolonların monotonik ve histeretik tepkileri belirlenmiştir. İtme yükü altında, eğilme, donatı sıyrılaması ve kesme deformasyonlarından kaynaklanan deformasyonlar, kolonun monotonik davranışını oluşturmak için toplanmıştır. Monotonik modelden alınan yük deformasyon eğrisi, histeretik pivot modelin omurga eğrisini oluşturmak için kullanılmıştır. Bu çalışmada elde edilen

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monotonik ve histeretik yanal yük-deplasman eğrileri deneysel çalışmalardan elde edilen sonuçlarla karşılaştırılmıştır. SAP2000 ve deneysel sonuçların iyi bir uyum içinde olduğu ve zayıf detaylandırılmış RC kolonlarının davranışının karmaşık analiz yöntemlerini kullanmak yerine SAP2000 tarafından basitleştirildiği gösterilmiştir.

Keywords: Zayıf kolon, Eğilme deformasyonu, Kayma deformasyonu, Donatı kayması, SAP2000, Monotonik model, Histeretik model

1. INTRODUCTION

In many countries, there are many reinforced concrete (RC) buildings not designed in accordance with modern seismic design codes. Majority of these buildings were built 1970's. According to the research conducted after the past earthquakes, the main reason for the collapse of concrete buildings is the poorly designed RC columns. Usually, these columns have transverse reinforcement with 30 cm spacing and 90-degree end hooks. So, the column shows non-ductile behavior and is suddenly exposed to the risk of collapse [1].

Columns are the most critical structural element in reinforced concrete structures. The flexural, reinforcement slip and shear deformations is contributed to lateral deformation of RC columns. The deformation models are shown Figure 1 [2].

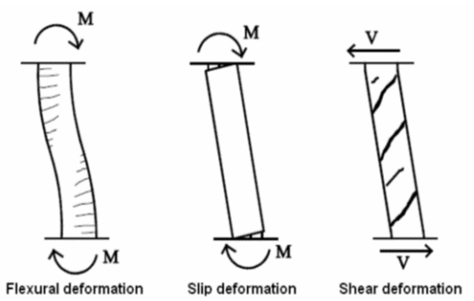

Figure 1. Lateral deformations components [3]

The flexural behavior of RC columns has been widely studied and issues related to performance assessment are generally well-known. However, behavior of the reinforcement slip has been not well-defined and are still an active research subject. Alsiwat and Saatcioglu [4] suggested bi-linear bond stress. Constant elastic bond stress was used prior to yielding of the bar and friction bond stress was used as the bar encountered plastic deformation. In a study by Eligehausen et al. [5] bond stresses are related to reinforcement slip along the bar, as opposed to regional stresses. Since the local slip is related to bond stress, this model is more complex than the other models [6-8]. Therefore, this problem cannot be solved in one step and an iterative technique was used to solve the problems. This procedure is quite complex and is not easy to implement. The shear force-shear displacement response of RC columns has also been widely studied. The 1974 SEAOC Recommended Lateral Load Requirements [9] incorporates the column shear strength equations given in the ACI 318-71[10]. However, the concrete contribution to shear strength equals to zero for axial stresses less than $0.12f_c$ is not taken into the consideration (f_c= compressive strength of concrete). The California Department of Transportation (Caltrans) [11] accepts the transverse reinforcement contribution proposed by SEAOC and the concrete contribution depends on the displacement ductility, axial load and confinement. Sezen H. [1] tested four RC columns and proposed a partial linear model for shear force-shear displacement. Patwardhan [12] developed a shear force-deformation model based on MCFT (Modified Compression Field Theory) [13]. This model is similar to the model proposed by Sezen H. [1] but maximum stress is constant until the beginning of load loss.

The relationship between the load-deformation curve of monotonic loading constitutes the backbone curve for the hysteretic response. This curve defines a strength limit for the cyclic response. Clough [14] proposed a simple elasto-plastic hysteretic model including stiffness deterioration for hysteretic flexural behavior. Bi-linear curves serve as primary envelopes. The reloading branches are aimed at the previous maximum response point to simulate degradation of stiffness. Takeda et al. [15] suggested that corrections in the distorted stiffness model should be taken into account considering the deterioration of the stiffness due to the increasing damage caused by the reinforced concrete structures subjected to seismic motions. This model was shown in Figure 2. Soleimani [16] presented a hysteretic model in which the reinforcement slip deformation was modeled by the rotational springs. The hysteretic model for reinforcement slip proposed by Alsiwat and Saatcioğlu [4] assumes that the rotation is due to the extension or slip of the reinforcement in the adjacent element. The model includes bi-linear primary envelopes and unloading and reloading branches. This model was shown in Figure 3. In the hysteretic model proposed by Roufaiel and Meyer [17] the shear effect is included in the moment-curvature hysteresis cycles. The shear effect depends on the degree of pinching. The model proposed by Kabeyasawa et al. [18] was used to analyze the flexural and shear deformations of RC wall elements by means of three vertical line elements. This model was shown in Figure 4.

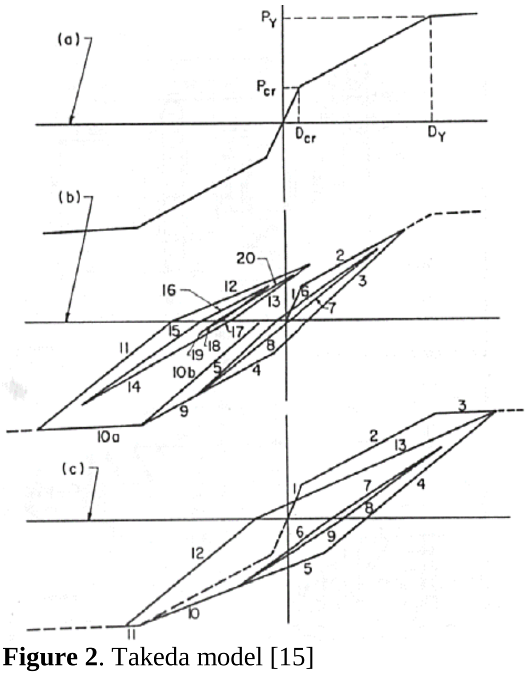

Figure 2. Takeda model [15]

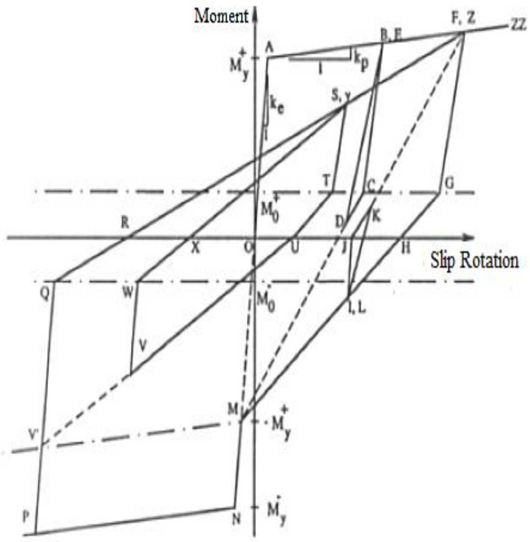

Figure 3. Alsiwat-Saatcioglu model [16]

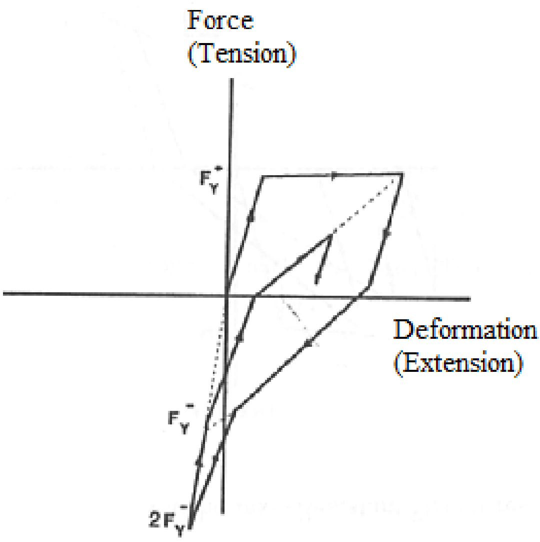

Figure 4. Kabeyasawa model [18]

Pivot model is similar to the Takeda model but has additional parameters to control the degrading hysteretic loop. The main novelty of this method is using a pivot point to which unloading path is directed. Further details of the model may be found on Dowell et all. [19]. This model was shown in Figure 5.

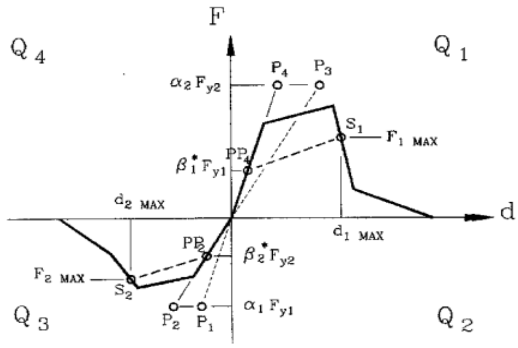

Figure 5. Pivot model [19]

In this study, the flexural, reinforcement slip and shear deformations will be modeled under monotonic and hysteretic loadings to predict the total lateral deformation of the poorly detailed RC columns by SAP2000 [20]. SAP2000 was chosen in this study because it is a general purpose and easy to use structural analysis program. First, each deformation type will be modeled separately and lateral deformation of the poorly detailed RC column will be predicted due to each deformation type. Then these three models will be combined to form a general model capable of predicting lateral deformation of the poorly detailed RC column.

2. SELECTED EXPERIMENTAL STUDY FOR MODEL VERIFICATION

Details of the experimental program of the behavior of full-scale building columns subjected to gravity and earthquake loads, isolated from a complete building frame, by Sezen H. [1] are presented. The column examples and boundary conditions are shown in Figure 6.

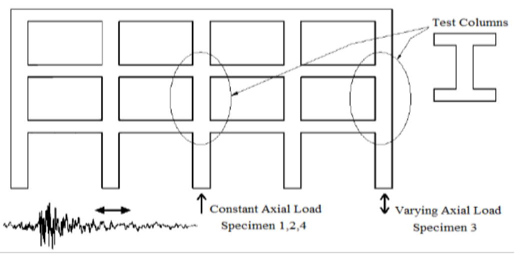

Figure 6. Idealized building frame subjected to lateral earthquake and gravity loads [1]

The experimental program by Sezen [1] includes testing of four columns with insufficient transverse reinforcement under various combinations of axial and lateral loads. Test columns connected to rigid upper and lower beams were tested in double curvature. The rigid end beams at the top and bottom of the column are 228 cm long, 76 cm deep and 66 cm wide. The top beam simulated a rigid system, while the base beam simulated a rigid floor system or a rigid foundation.

Test columns have 46 cm*46 cm cross-sections. The open height of the columns is 295 cm. In the columns, is used $\phi28$ and $\phi10$ reinforcement for longitudinal and transverse reinforcement, respectively. The transverse reinforcement is spaced at 31 cm equal intervals. The column section and reinforcement details are shown in Figure 7.

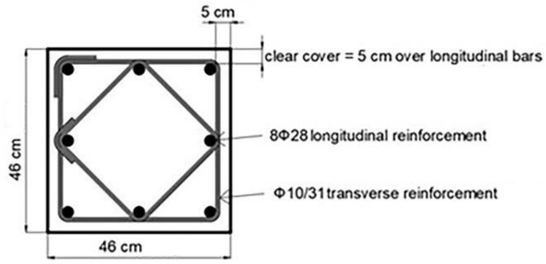

Figure 7. The column section details [1]

The Specimen 1, 2 and 4 were tested under -667 kN, -2668 kN and -667 kN constant axial load, respectively. Specimen 3 was tested under varying axial load from +2668 kN to -250 kN.

Average concrete strength was obtained from cylinder tests for each column. The determined concrete strength was 20.6 MPa. The concrete strengths of Specimen-1, Specimen-2, Specimen-3, Specimen-4 were 21.1 MPa, 21.1 MPa, 20.9 MPa, 21.8 MPa, respectively. The yield strengths are 434.4 MPa and 475.7 MPa for the longitudinal and transverse bars, respectively. [1]

3. MATERIAL MODELS

In this study, the nonlinear material models of concrete and steel are used in analysis. Mander [21] and Vecchio & Collins [13] models were used for confined and unconfined concrete under compression and tension, respectively. These models were selected based on mostly used models in the literature. It is hoped that this selection strategy will help readers to grasp the topic easily. The confined and unconfined concrete behavior models were shown in Figure 8. Unconfined and confined concrete compressive strengths and corresponding strain values were shown Table-1.,

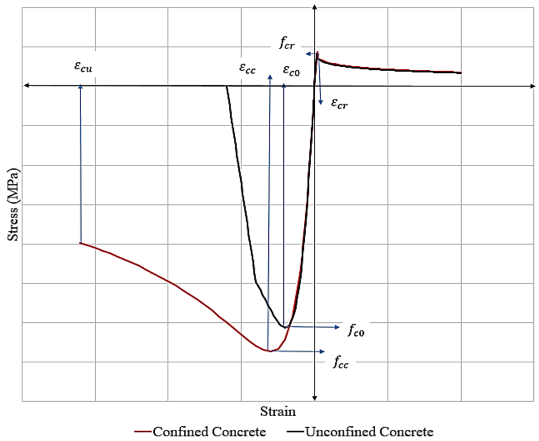

Figure 8. Model of concrete behavior under compressive and tensile stress

Notation: f_{c0} = the compressive strength of unconfined concrete, ε_{c0} = strain of corresponding to the unconfined concrete (0.002 can be assumed) f_{cc}= the compressive strength of confined concrete, ε_{cc}= the strain at the maximum compressive strength of confined concrete, ε_{cu}= ultimate strain of confined concrete, ε_{cr} = the cracking strain corresponding to uniaxial cracking strength of concrete, f_{cr}= uniaxial compressive strength of concrete.

Table 1. The confined-unconfined concrete compressive strength and strain values

Column	f_{c0}	f_{cc}	ε_{cc}	ε_{cu}
Specimen-1	21.09	23.20	0.003	0.0165
Specimen -2	21.09	23.20	0.003	0.0165
Specimen -3(c)	20.89	22.99	0.003	0.0167
Specimen -3(t)	20.89	22.99	0.003	0.0167
Specimen -4	21.78	23.89	0.003	0.0111

Notation: Specimen -3(c) is tested specimen under -249 kN axial load, Specimen -3(t) is tested specimen under +2668 kN axial load

The reinforcement steel tension model is based on the strain-hardening model. In this model, the stress increases linearly up to the yield deformation. Slope of the yield region was selected as 2% of the elastic modulus. The material is then hardening to reach the ultimate deformation value. Also, the steel compressive stresses are reduced due to buckling effect using Inoue & Shimizu model [22]. This model is shown that in the Figure 9.

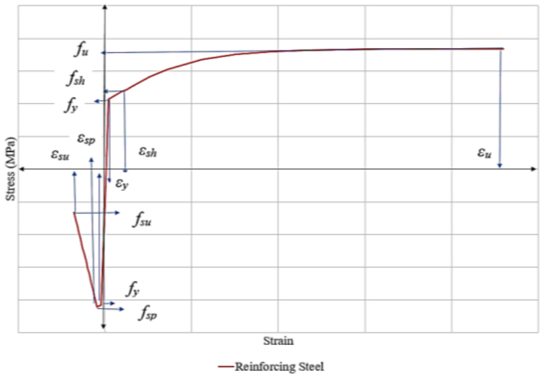

Figure 9. Reinforcing steel model

Notation: ε_{sh}= strain at the beginning of strain hardening, ε_u= strain at maximum strength, ε_{sp}= spalling strain, f_y= yield strength of longitudinal bar, f_{sh} = strength at the onset of strain hardening, f_u= maximum strength.

4. LATERAL DEFORMATION COMPONENTS

4.1. Deformation Components of Monotonic Behavior

Total lateral deformation of RC columns is the sum of the reinforcement slip, shear and flexural deformations. The flexural deformations can be predicted by the moment curvature analysis. The SAP2000 was used to obtain the moment-curvature analysis.The columns were modeled in Section Designer module in SAP2000 and moment-curvature relationships were obtained. The moment-curvature relationship was used to determine the curvature distribution along the column height. In the elastic region, there is a linear relationship between the moment and the curvature. In inelastic region, the curvature is summed up along the plastic hinge length. After yielding, flexural deformations are calculated as shown in Equation 1.

$$\Delta_f = \Delta_{f,y} + (\phi - \phi_y) L_p (a - \frac{L_p}{2}) \qquad (1)$$

where $\Delta_{f,y}$ = the flexural deformation at the yielding, ϕ = the curvature and ϕ_y= curvature at the moment of yielding, a= $L/2$ [23]. L_p= plastic hinge length ($h/2$) [24].

Sezen [1] developed an analytical model to predict the moment-rotation relationship of the RC section due to the reinforcement slip. In the proposed model, reinforcement slip can be calculated as shown in Equation 2.

$$slip = \frac{\varepsilon_s l_d}{2} \quad for\ \varepsilon_s < \varepsilon_y$$
$$slip = \frac{\varepsilon_s l_d}{2} + \frac{(\varepsilon_y + \varepsilon_s) l_d^{'}}{2} \quad for\ \varepsilon_y < \varepsilon_s \qquad (2)$$

where l_d and l'_d = the development lengths for the elastic and inelastic portion of the bar, respectively,

ε_s =the deformation of the loaded end of the bar,
ε_y=steel yield strain. The rotation due to reinforcement slip can be calculated from Figure 10 as shown in Equation 3

$$\theta_s = \frac{slip}{d - c} \qquad (3)$$

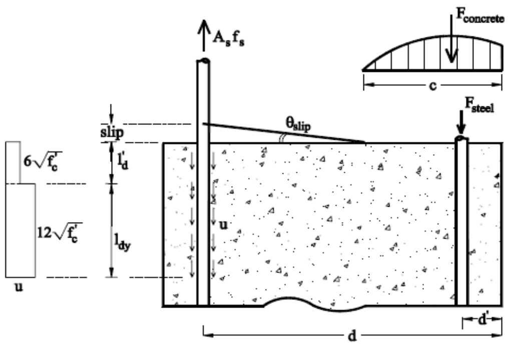

Figure 10. Rotation due to reinforcement slip [1]

where d= the effective depth, c= the depth of compression block. Lateral displacement caused by reinforcement slip be calculated as shown in Equation 4 [1].

$$\Delta_s = \theta_s L \qquad (4)$$

The shear deformations can be the governing failure mechanism of the RC columns that are not designed in accordance with seismic codes. Shear deformations in poorly designed RC column can be large percentage of total deformations. So, they should be taken into the account in analysis of the deformation capacity [1].

In this study, the shear deformation model is based on Patwardhan model [12]. Patwardhan model was based on MCFT [13]. Patwardhan's model is shown in Figure 11.

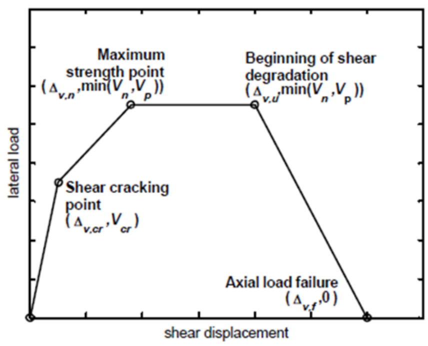

Figure 11. Patwardhan lateral load-shear model [12]

Aforementioned three deformation components are summed up to predict the total response of RC column subjected to lateral loading. The deformation components can be simply added until the maximum strength of RC column is reached. The column deformations are governed based on category selection in post-peak behavior. There are five categories depending on the comparison of the yield, flexural and shear strengths of the column. The lateral load corresponding to the initial yield of the tension bars and the lateral load corresponding to the peak moment are defined as the yield strength and as the flexural strength respectively. The shear strength can be calculated as shown in Equation 5 [25].

$$V_n = k(V_c + V_s)$$
$$V_c = \left(\frac{6\sqrt{f_c^{'}}}{a/d} \sqrt{1 + \frac{P}{6\sqrt{f_c^{'}} A_g}} \right) 0.8 A_g \qquad (5)$$
$$V_s = \left(\frac{A_{sp} f_{yw} d_c}{s} \right)$$

where V_c = concrete contribution to shear strength, V_s= steel contribution to shear strength, *a/d* = aspect ratio, A_g= gross area of column cross section, *k* = displacement ductility factor, A_{sp}= transverse reinforcement area, f_{yw}= transverse reinforcement yield strength, d_c= effective depth.

By comparing V_n, V_y, V_p each column can be classified into one of the following five categories as defined in Setzler [26]. The lateral response corresponding to each category is shown in Figure 12.

Category I ($V_n < V_y$): the shear strength is less than the yield strength and the peak strength is equal to the shear strength. So, shear behavior governs the post-peak behavior of the column.

Category II ($V_y \leq V_n \leq 0.95V_p$): the peak strength of the column is the shear strength which is less than the flexural strength but the flexural and slip deformations contribute to shear behavior after the peak behavior of the column.

Category III ($0.95V_p \leq V_n \leq 1.05V_p$): The shear strength is almost equal to flexural strength. So, it is easy to determine which mechanism governs the peak response. These strengths contribute to the post-peak mechanism.

Category IV ($1.05V_p \leq V_n \leq 1.4V_p$): Shear strength is greater than flexural strength and the column may collapse due to flexure. The peak strength of the column is the flexural strength.

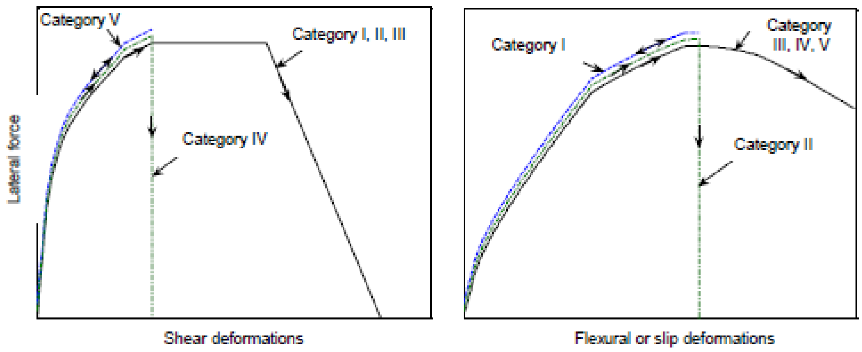

Figure 12. Flexural, reinforcement slip and shear behavior model for each category [27]

Category V ($Vn > 1.4V_p$): The shear strength is much greater than the flexural strength and the column collapses due to flexure. The peak strength of the column is the flexural strength. The flexural and slip behavior governs the post-peak behavior of the column [25].

4.2. Deformation Components of Hysteretic Behavior

Dynamic inelastic response history analysis of RC structures requires realistic conceptual models that can simulate the hysteretic behavior of these structures under seismic loads. The present state of information may not be sufficient to model each, allowing analysts to obtain reasonably accurate results from non-linear dynamic analyzes.

Numerous hysteretic models have been proposed for the seismic evaluation of structures. Among these hysteretic models, pivot hysteretic model in SAP2000 was adapted in this study [28].

The pivot hysteretic model can predict the degrading of the hysteretic loop and it is well matched with the behavior of RC elements. In this model, unloading and reverse loading are directed toward pivots points in the force-deformation curve as shown in the Figure 13. This model is commonly used for moment-rotation.

Pivot hysteretic model was selected for simulating the flexural, reinforcement slip and shear behavior of poorly detailed RC columns under lateral loads. Each hysteretic response component was analytically studied and modeled by SAP2000. The three deformation components are combined and the interaction between them are considered for a nonlinear time history analysis of RC column.

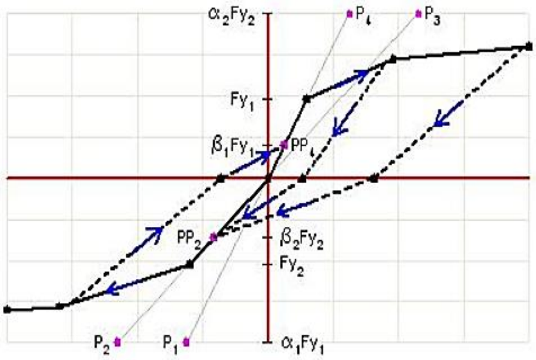

Figure 13. SAP2000 multilinear plastic-pivot model [20]

As explained above, monotonic total deformation of RC column was predicted according to the category selection. Same category selection rules were also applied in predicting total hysteretic response of the poorly detailed RC columns.

5. ANALYSIS RESULTS AND COMPARISON

The SAP2000 was used to obtain the moment-curvature relationship of the columns. According to the materials and reinforcement locations used in the experiment, the columns were modeled in Section Designer and moment-curvature relationships were obtained. In this model, different material models were defined for cover concrete, core concrete and reinforcing bars. Moment-curvature analysis was used to model plastic hinges in SAP2000. Three types of plastic hinges were created and placed separately for flexural, reinforcing slip and shear deformations. Plastic hinges for flexural deformation were placed on every one tenth of the column length. Plastic hinges for reinforcing slip and shear deformations were placed at the bottom and top of the column because maximum of these deformations was occurred at these locations. Then, push-over analysis was applied to the columns to determine monotonic deformations. Pivot hysteretic model was used to model hysteretic deformations in SAP2000. In experimental study, the loading protocol was applied for each column according to ATC-24 [29] and was used as displacement history for the columns. Then, time-history analysis was applied to the columns to determine hysteretic deformations. Category selection for each column were made according to the category intervals explained in previous section. The category selection for each column was shown in Table 2.

The monotonic flexural deformation results for specimens is given in Figure 14. The hysteretic flexural deformation results for specimens is given in Figure 15. The monotonic reinforcement slip deformation results for specimens is given in Figure 16. The hysteretic reinforcement slip deformation results for specimens is given in Figure 17.The monotonic shear deformation results for specimens is given in Figure 18. The hysteretic shear deformation results for specimens is given in Figure 19. The monotonic total deformation results for specimens is given in Figure 20. The hysteretic total deformation results for specimens is given in Figure 21.

Table 2. Column flexural-shear strength and category selection

Column	V_n **(kN)**	V_y **(kN)**	V_p **(kN)**	**Category**
Specimen-1	306.53	301.67	334.77	2
Specimen-2	410.17	311.06	326.88	4
Specimen-3(c)	409.41	308.71	324.54	4
Specimen-3(t)	222.37	223.88	272.10	1
Specimen-4	310.97	302.48	337.84	2

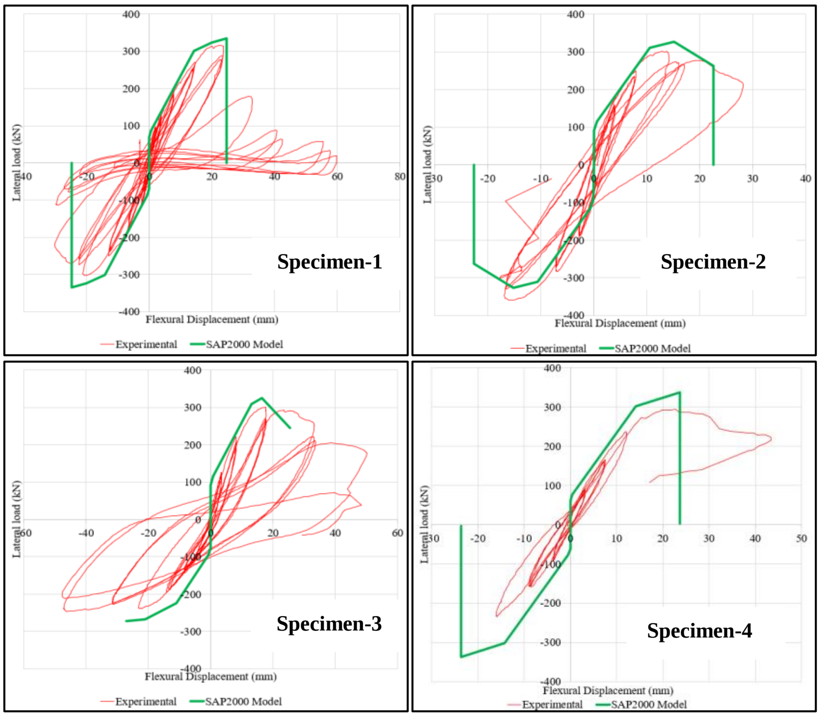

Figure 14. Monotonic flexural deformation results for specimen 1,2,3,4

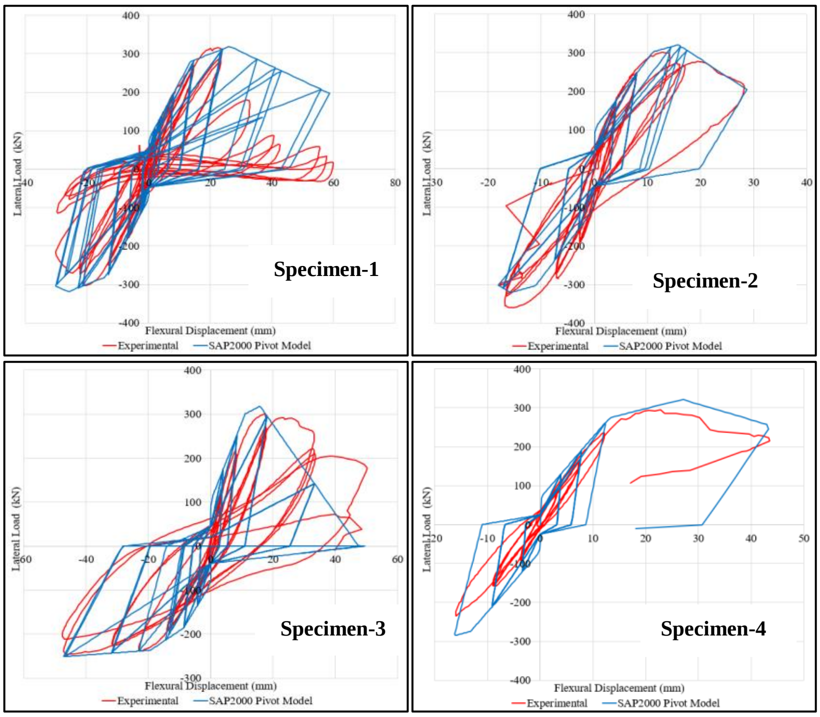

Figure 15. Hysteteric flexural deformation results for specimen 1,2,3,4

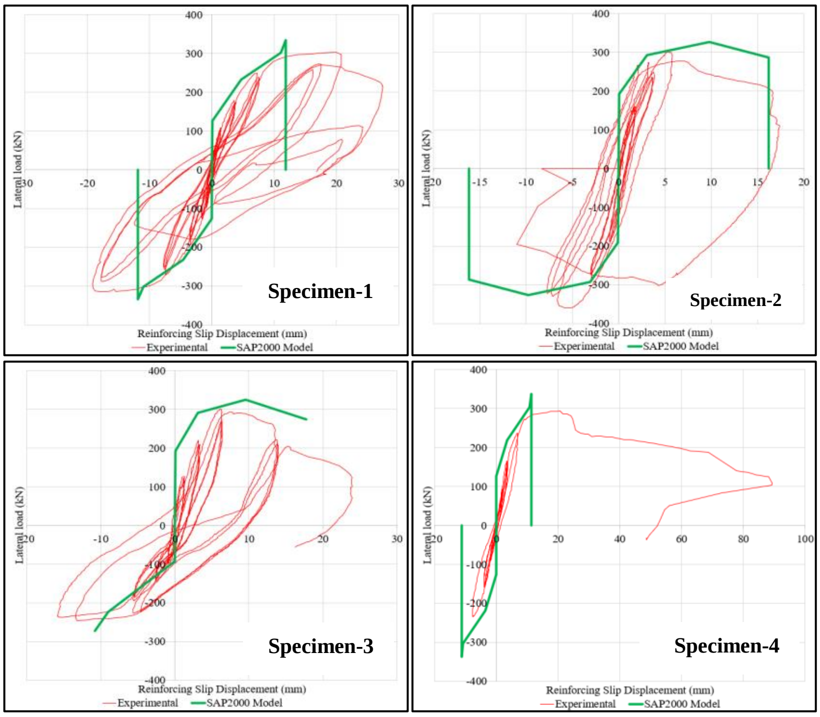

Figure 16. Monotonic reinforcement slip deformation results for specimen 1,2,3,4

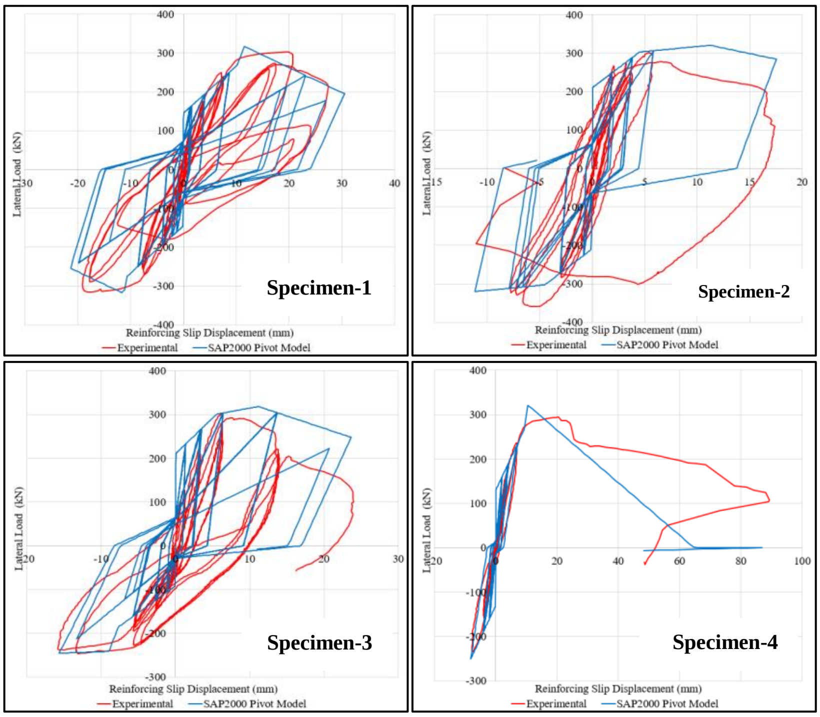

Figure 17. Hysteteric reinforcement slip deformation results for specimen 1,2,3,4

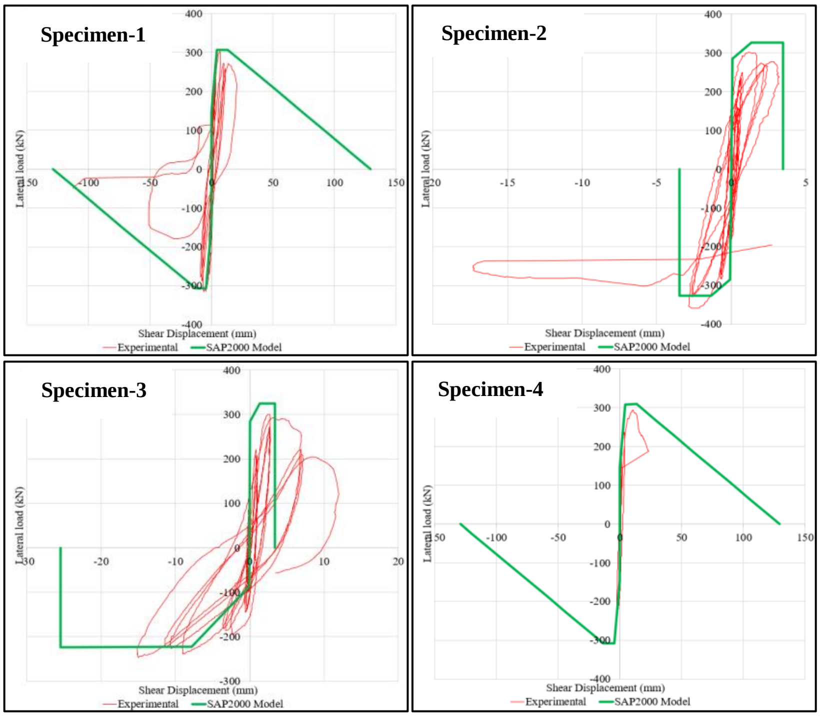

Figure 18. Monotonic shear deformation results for specimen 1,2,3,4

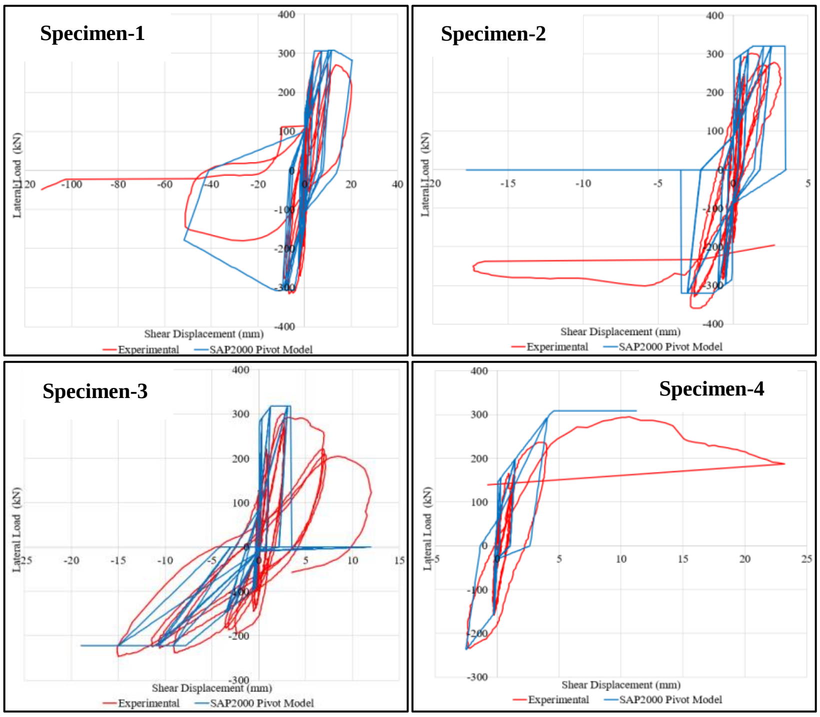

Figure 19. Hysteteric shear deformation results for specimen 1,2,3,4

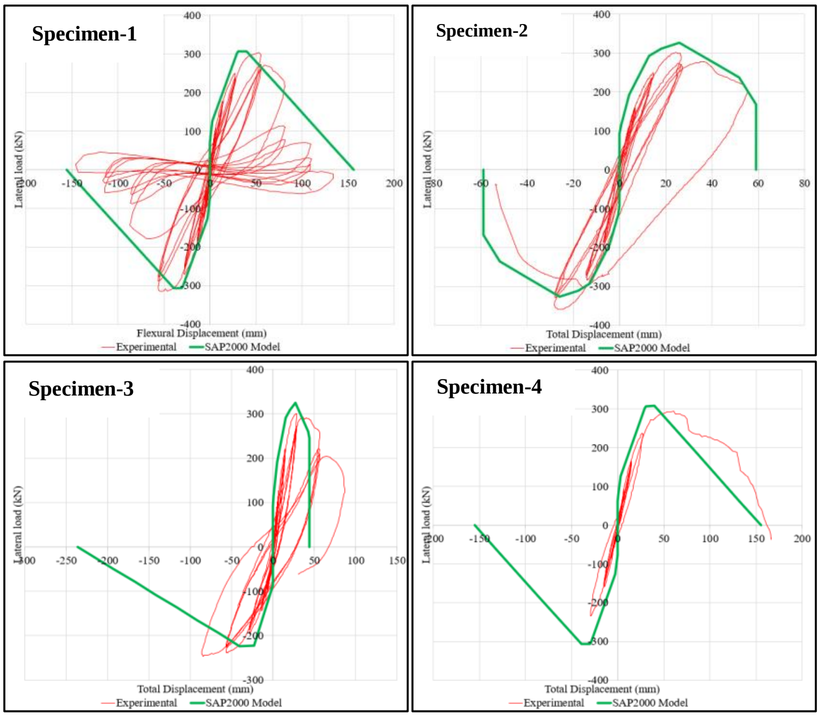

Figure 20. Monotonic total deformation results for specimen 1,2,3,4

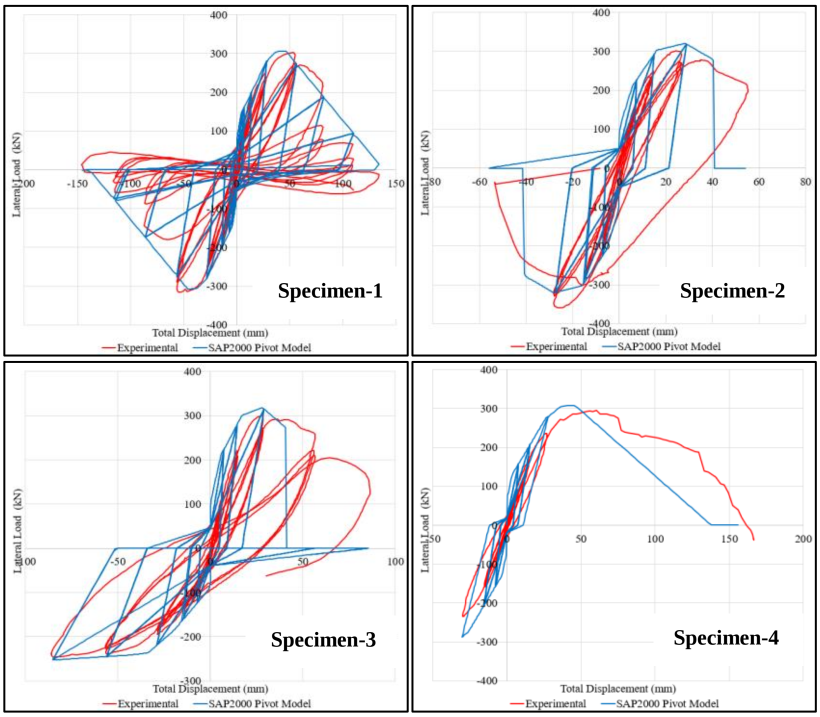

Figure 21. Hysteteric total deformation results for specimen 1,2,3,4

6. RESULTS AND CONCLUSION

The aim of this study is to predict the monotonic and hysteretic behavior of poorly detailed RC columns under lateral loads. The poorly detailed RC columns have low longitudinal reinforcement ratio, widely spaced transverse reinforcement and 90-degree end hooks. The deformation capacity of these type columns is limited. The damages observed after the past earthquakes showed that the columns in the base floor are the most critical element in non-ductile RC buildings and can cause collapse of RC building.

The four columns tested by Sezen [1] were modeled in SAP2000 program and monotonic and hysteretic analysis were performed. In the monotonic analysis, plastic hinges were created for flexural, reinforcement slip and shear deformations. Flexural plastic hinges created using moment-curvature were placed at one tenth of the columns.

Reinforcement slip hinges created according to the model developed by Sezen [1] were placed at the ends of the columns. Shear hinges created according to the model developed by Patwardhan [12] were placed at the ends of the columns. These plastic hinges were used in the RC column simultaneously to predict the total lateral deformations. In the hysteretic analysis, models for the flexural, reinforcement slip, shear and total responses were developed using the SAP2000 hysteretic pivot model. The cyclic force-displacement relationship of flexural, reinforcement slip, shear and total deformation was obtained from the corresponding monotonic responses of the column. These cyclic force-displacement relationships served as a primary backbone curve for corresponding hysteretic analysis. The monotonic and hysteretic results of SAP2000 models were compared experimental data of Sezen [1].

According to the results of this study, following conclusions could be made:

• It has been shown that complex, time-consuming shear and reinforcement slip models can be developed by simple and general-purpose SAP2000 program.

• The monotonic and hysteretic flexural, reinforcement slip, shear and total deformation models developed by SAP2000 program predicted well the experimental data for poorly detailed RC columns.

• Including tensile behavior of concrete and compressive behavior of steel modified according to buckling behavior would lead to more accurate the monotonic responses.

• Although the research is focused on modeling the behavior of poorly detailed RC columns under seismic load, the developed model can be extended to the other RC column .

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