16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Modeling of Lateral Response of Reinforced Concrete Columns in Existing Buildings (ID284)

Registration Code: S-F1463087413

Modeling of Lateral Response of Reinforced Concrete Columns in Existing Buildings

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Abstract

When the reinforced concrete columns in existing frame buildings lack essential seismic details they are vulnerable to significant damage or collapse during a strong earthquake. Overall assessment of the structural performance of buildings requires accurate modeling and better understanding of axial and lateral load response of columns. This paper focuses on modeling of columns with insufficient transverse reinforcement and poor reinforcement details. They are likely to experience brittle shear failure and lose their axial load carrying capacity under large lateral loads. A macro model procedure is developed to predict the strength and displacement capacity of the columns before and after shear failure and at axial load failure. The model is being implemented and validated in the OpenSees software. The model is applied to estimate the lateral load-deformation response of previously tested columns, and the predicted and experimental data are then compared. The model considers total lateral deformation of the column to be composed of three deformation components due to flexure, shear and reinforcement slip. In the proposed model, lateral load-deformation response of the column is simulated by estimating flexural and shear deformation components separately while considering their interaction when they are combined.

Keywords: reinforced concrete; columns; shear model; cyclic shear model;

1. Introduction

Failure of one or more reinforced concrete (RC) columns may cause partial or complete collapse of an existing building especially when the columns lack essential seismic details. Therefore, the columns are the most critical components of building frames. Overall seismic assessment of buildings requires accurate modeling and simulation of lateral load response columns. Shear strength degradation and axial load failure need to be incorporated into the model if the columns are not designed to be ductile. Although, there are several available computer programs to analyze RC structures, unique modeling capabilities are needed to accurately represent their behavior. To account for the effect of poor reinforcement detailing in existing columns, researchers [1][2][3] proposed modeling techniques that involve addition of springs to the ends of RC columns.

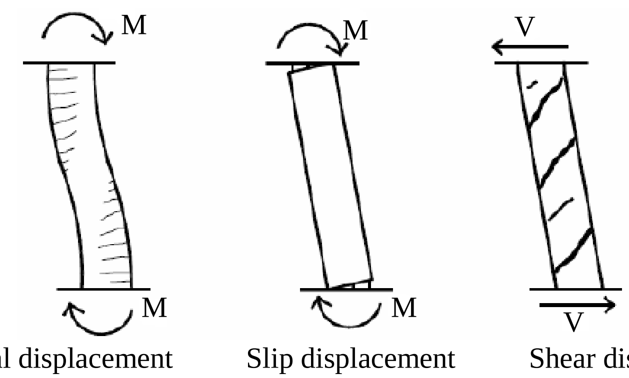

Fig. 1 - Three components of lateral displacement of a reinforced concrete column [4].

The lateral deformation of a RC column can be represented as a combination of three different displacement components: flexure, slip, and shear deformation components (Fig. 1) [4]. In this research, to model the total lateral deflection of a column, each of the three components are considered separately and then combined to simulate the lateral behavior of the column.

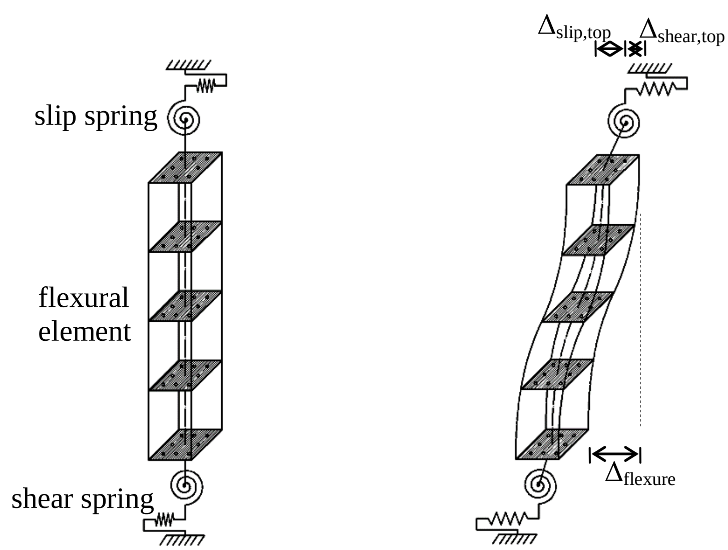

Fig. 2 – Proposed OpenSees model including deformation components (left).

In this paper, a simple model is proposed and implemented in open source software to accurately capture the cyclic lateral force-displacement behavior of a column (Fig. 2). The model is based on an earlier model by

Setzler and Sezen [4]. The model provides a convenient way to model and analyze multi-story buildings with poorly detailed columns. The Open System for Earthquake Engineering Simulation (OpenSees) [5] is used to model and analyze the column. The open source software allows for editing of the source code and adding users to own and modify the code.

In this study, a new uniaxial material is defined to simulate the cyclic shear force-displacement relationship of a RC column. OpenSees built-in materials and elements are utilized to model flexural and slip displacement of the RC column. Initially, existing models for each displacement component are applied, and then the complete model is created by combining these component models. The flexural displacement of the column is obtained from a built-in element in OpenSees. A *zero-length-element* is defined at both ends of the columns to account for shear and slip displacements.

2. Monotonic Lateral Displacement

2.1 Flexural displacement

Flexural displacement of RC elements can be determined by performing moment-curvature analysis of the fiber cross section. In order to conduct moment-curvature analysis, the constitutive material models are defined for unconfined and confined concrete and reinforcing steel. The compressive strength model for confined concrete developed by Mander et al. [6] is adapted in this research. The stress-strain relationship for unconfined concrete is also determined from Mandel et al. [6] up until the peak strength is reached. The post-peak behavior of unconfined concrete is obtained from the study of Roy and Sozen [7]. Steel stress-strain relationship is bi-linear with 2% strain hardening after yielding. In OpenSees, from the uniaxial material library, *concrete01* and *concrete04* are used for unconfined and confined concrete, respectively, and *steel01* is used for steel.

The curvature of section along the length of the RC column can be determined by fiber section moment-curvature analysis. Then, using a plastic hinge method, the lateral load-flexural deflection relationship can be calculated. The flexural deflection, Δ_f can be calculated before and after yielding using Eqs. (1) and (2), respectively.

$$\Delta_f = \frac{\phi a^2}{3} \qquad for \quad \phi \le \phi_y \tag{1}$$

$$\Delta_f = \frac{\phi_y a^2}{3} + (\phi - \phi_y) L_p \left(a - \frac{L_p}{2}\right) \qquad for \quad \phi_y \le \phi \le \phi_u \tag{2}$$

where ϕ is the end curvature at column end, ϕ_y and ϕ_u are curvatures at yield and ultimate, respectively. The plastic hinge length, L_p, is set equal to *0.5h* (*h* is depth of cross section) [8]. *a* is shear span, which is equal to length, *L* for a cantilever column and *L/2* for a column with fixed ends.

In this study, OpenSees model is created with force-based beam-column element "*forceBeamColumn*". The flexural behavior of the column is captured using distributed plasticity along the length of the column. A sensitivity analysis was performed by comparing several available forced-based and displacement-based OpenSees flexural elements with varying number of integration points. It was found that a forced-based element with five integration points was sufficiently accurate to simulate the flexural behavior a RC column.

2.2 Slip displacement

The displacement obtained from fiber section moment curvature analysis does not account for the reinforcement slip at the ends of the column. The additional lateral displacement caused by slippage of bars out of column supports or foundation should be added to flexural displacement. The slip model developed by Sezen and Setzler [9] is utilized in this study as presented in Eqs. (3) and (4).

$$slip = \frac{\varepsilon_y f_s d_b}{8u_b} \qquad \text{for } \varepsilon_s \le \varepsilon_y \qquad \text{[in psi units]} \tag{3}$$

$$slip = \frac{\varepsilon_y f_s d_b}{8u_b} + \frac{(\varepsilon_s + \varepsilon_y)(f_s - f_y) d_b}{8u'_b} \qquad \text{for } \varepsilon_s > \varepsilon_y \qquad \text{[in psi units]} \tag{4}$$

where, d_b is longitudinal bar diameter, ε_s and f_s are strain and stress in reinforcing steel, respectively, and y refers to yielding. u_b and u'_b are the bond stresses over elastic and inelastic portions of the longitudinal bar [9]. Then, the rigid body rotation at the end of the column due to bar slip, θ_s, can be calculated from Eq. (5).

$$\theta_s = \frac{slip}{(d-c)} \tag{5}$$

where d is the distance between maximum compression fiber and centroid of tension steel, and c is the neutral axis depth from the extreme compression fiber.

The slip model cannot be applied directly in OpenSees due to complexity of capturing and monitoring variables defined above during each analysis step. Thus, the slip model is simplified and represented as a tri-linear model in OpenSees. In this study, three curvature values are considered to determine slip rotation values at three points: 1) first cracking, 2) yielding and 3) ultimate slip rotation. The moments corresponding to these three points are chosen such that the area under the tri-linear model is the same as that of the continuous model (Fig. 3). Then, *hysteretic* material in the uniaxial material library of OpenSees, with default cyclic parameters, is used to model the simplified slip response shown in Fig. 3.

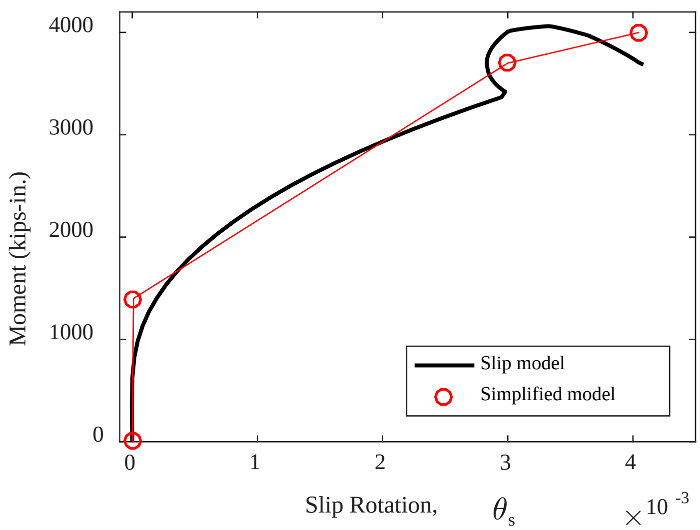

Fig. 3 - Slip model developed by Sezen and Setzler [9] applied for Specimen 1 tested by Sezen [10].

2.3 Shear displacement

In this study, shear displacement of RC columns are calculated using the model developed by Sezen [11]. The model defines four points representing four unique shear behavior of a RC column. The critical points are defined as: cracking, peak strength, onset of shear strength degradation, and axial load failure (Fig. 4).

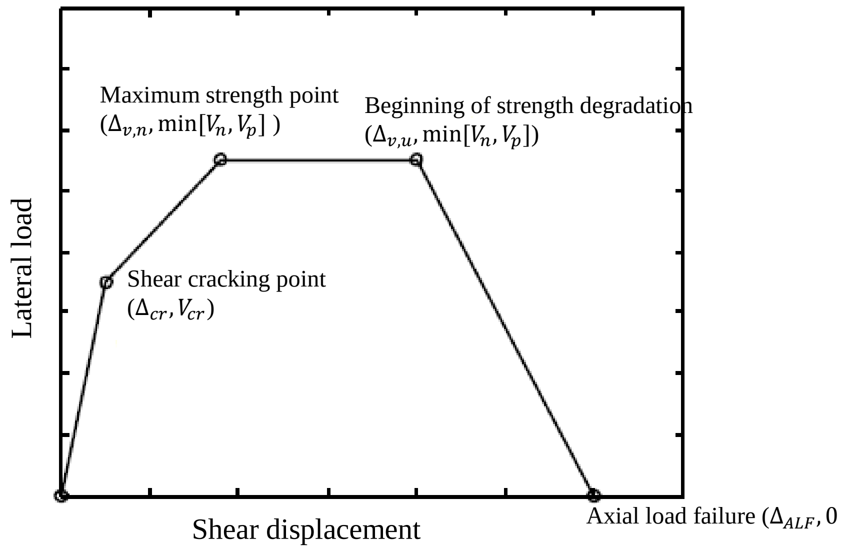

Fig. 4 - Shear model proposed by Sezen [11].

Displacement at shear cracking, Δ_{cr} is calculated from Eqs. (6) and (7) [12]. The cracking strength, V_{cr} is obtained by assuming RC column behavior is elastic up until cracking.

$$\Delta_{cr}= \left(\frac{P}{50000} + 0.0062\right) \qquad \text{[in psi units]} \qquad (6)$$

$$V_{cr} = \left(\frac{P}{50000} + 0.0062\right)\frac{GA}{L} \qquad \text{[in psi units]} \qquad (7)$$

where $\frac{GA}{L}$ is the shear stiffness and P is axial load. After shear cracking, the column has reduced stiffness up until peak strength. Peak shear strength of column, V_n and the corresponding displacement, $\Delta_{v,n}$ can be calculated by Eqs. (8) and (9), respectively.

$$V_n = k\left[\left(\frac{6\sqrt{f_c'}}{a/d}\sqrt{1+\frac{P}{6\sqrt{f_c'}\cdot A_g}}\right)0.8\,A_g + \frac{A_v\cdot f_{yv}\cdot d}{s}\right] \qquad \text{[in psi units]} \qquad (8)$$

$$\Delta_{v,n}= \left[\frac{1}{33000}\frac{f_y\sqrt{\rho_l}}{a/d\sqrt{\frac{P}{A_g\cdot f_c'}}} - 0.0006\right]L \qquad \text{[in psi units]} \qquad (9)$$

where f'_c is compressive strength of concrete, A_g is area of cross section, A_v is area of transverse reinforcement, f_{yv} is yield strength of transverse reinforcement, d is the effective depth of cross section, s is the spacing of transverse reinforcing steel, and k is a parameter to account for reduction shear strength [11]. If the peak shear strength of RC column, V_n is higher than the peak flexural strength, V_p calculated from moment curvature analysis, the peak flexural strength, V_p should be considered as peak shear strength. The shear stiffness of the column is assumed to be zero at the onset of shear strength degradation. The displacement at the onset of shear strength degradation point can be calculated from Eq. (10).

$$\Delta_{v,u}= \left(4 - 12\frac{v_n}{f_c'}\right)\Delta_{v,n} \qquad (10)$$

where $v_n(= V_n/bd)$ is shear stress at peak point. Once the shear strength degradation is triggered, the shear stiffness of the column becomes negative until the point of axial load failure, where the displacement, Δ_{ALF} can be calculated from Eq. (11) [13], where θ is the average angle of shear crack that is assumed to be 65° in this study.

$$\frac{\Delta_{ALF}}{L} = \frac{4}{100}\frac{1+\tan^2\theta}{\tan\theta + P\left(\frac{s}{A_v \cdot f_{yv} \cdot d \cdot \tan\theta}\right)} \qquad \text{[in psi units]} \qquad (11)$$

In OpenSees, to simulate shear force-displacement relationship, a new uniaxial material is created and added into uniaxial material library of OpenSees. The created material, a shear spring, includes four linear lines or regions as shown in Fig. 4. The uncracked and cracked stiffnesses and shear displacements presented in this section are used as input to generate the model.

3. Cyclic Lateral Displacement

Under cyclic loading poorly detailed or nonductile RC columns typically experience stiffness deterioration, strength degradation, pinching response, and early axial load failure. To accurately model the cyclic behavior, these effects should be included in the model. As stated above, the lateral behavior of a RC column can be represented as a combination of three displacement components. Using the same approach, cyclic response is obtained by combining the individual displacement components (Fig. 2). Cyclic flexural behavior of the column is determined from the fiber section moment-curvature analysis in OpenSees.

Cyclic lateral response due to bar slip is obtained using the default cyclic parameters of *uniaxial hysteretic* material in OpenSees. For the shear spring material, a set of cyclic rules is defined to model the cyclic shear response. In general, for shear critical or nonductile columns, once the peak strength is reached the shear spring dominates the overall lateral behavior. The proposed cyclic rules for shear behavior are defined in the next section.

3.1 Proposed cyclic shear response

A set of rules are defined to accurately simulate the cyclic shear behavior of poorly detailed or nonductile columns. The shear behavior is considered in four different phases including; elastic part (up to cracking strength, V_{cr} in Fig. 5), between cracking and peak strength (i.e., between V_{cr} and V_n in Fig. 5), peak strength to onset of shear strength degradation (between $\Delta_{sh,n}$ and $\Delta_{sh,u}$ in Fig. 5), and onset of shear strength degradation to axial load failure (between $\Delta_{sh,u}$ and $\Delta_{sh,alf}$ in Fig. 5).

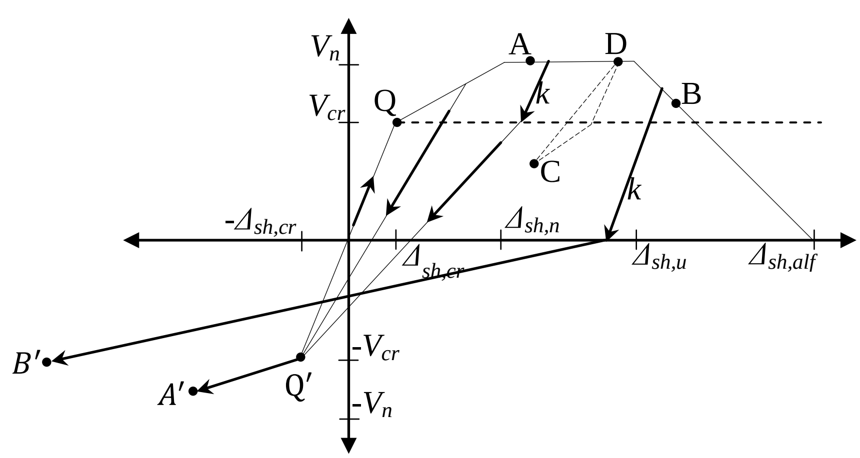

Fig. 5 - Cyclic rules for the proposed shear force–shear displacement relationship.

The cyclic loading and unloading rules are defined as a function of level of damage in the column. Initially, in the elastic part, the column behaves elastically with full contribution of shear stiffness. Once the shear cracking occurs, the unloading and loading path goes through cracking point on the opposite side (point Q'Fig. 5).

Beyond cracking point, the target is the previous peak point (point A' in Fig. 5). Point A' is symmetry of A which can be any point between cracking point (Q) and onset of shear strength degradation (after D). In the third region, (e.g. unloading starting between A and D) the unloading and loading path is modeled with three different slopes. During unloading, up to cracking level, V_{cr} the unloading path has the initial stiffness of *k*. *k* is the slope from the peak strength of a side to cracking strength of other side, from Sezen and Chowdhury [14]. In Fig. 5, this is the unloading starting between points *A* and *D* until V_{cr}. Beyond cracking force, the target is cracking point on opposite side (Q'). After reaching the cracking point (Q'), the target is the previous peak point (point A'). Finally, after the shear strength degradation starts, the path follows two different slopes. The unloading stiffness is *k* up to zero load. Beyond zero force, the loading path goes through the previous peak point (Point B' in Fig. 5). B' is the symmetry of B, which can be any point between the onset of shear strength degradation and axial load failure. In addition to these rules, if the loading is reversed without completing a cycle, for example, at point *C* in Fig. 5, the reloading goes through the previous peak point (point *D* in Fig. 5).

4. Comparison of Measured and Calculated Response

The proposed model is validated using two columns tested by Sezen [4] (first two columns in Table 1) and five columns tested by Lynn et al. [15]. Geometric and material properties of the test columns are shown in Table 1, where *b* is the width of the square column cross section, f_y and f_{yv} are yield strength of longitudinal and transverse steel, defined earlier, *P* is compressive axial load, and *s* is spacing of transverse steel. Setzler and Sezen [4] categorized RC columns into five categories as a function of yielding (V_y), peak flexural (V_p) and maximum shear strength (V_n) of the column. Category I indicates a column likely to fail in shear before yielding (shear failure) and category III column is likely to fail after yielding (shear-flexure failure).

Table 1: Geometric and material properties of test columns

Column Name		b (in.)	f_y (ksi)	f'_c (psi)	f_{yv} (psi)	*P* (kips)	*s* (in.)	Category of Column [4]
1	Specimen 1	18	63	3060	69	150	12	III
2	Specimen 2	18	63	3060	69	600	12	VI
3	2CLH18	18	48	4800	58	113	18	III
4	2CMH18	18	48	3700	58	340	18	III
5	3CLH18	18	48	3900	58	113	18	I
6	3CMD12	18	48	4000	58	340	12	III
7	3CMH18	18	48	4000	58	340	18	I

Displacement based static cyclic analysis is conducted in OpenSees. For all tested columns, up until peak strength is reached, there is a good agreement between the experimental and calculated response (Figs. 6 and 7). However, post peak behavior of 3CLH18 and 3CMH18 is not sufficiently captured. The difference comes mainly from the category of the columns. These two shear dominated columns have less ductility compared to other columns. The total displacement of the column is obtained following the rules that depend on the column category. However, during OpenSees analysis, currently these rules are not applied. That is why, the proposed model is not likely to capture the response of shear dominated columns as well as more ductile columns. The analysis results show that the response of category III and VI columns (shear-flexure failure) can be modeled better with the proposed model. As it can be seen from Fig. 7, the model appears to be less suitable for category I columns failing in shear.

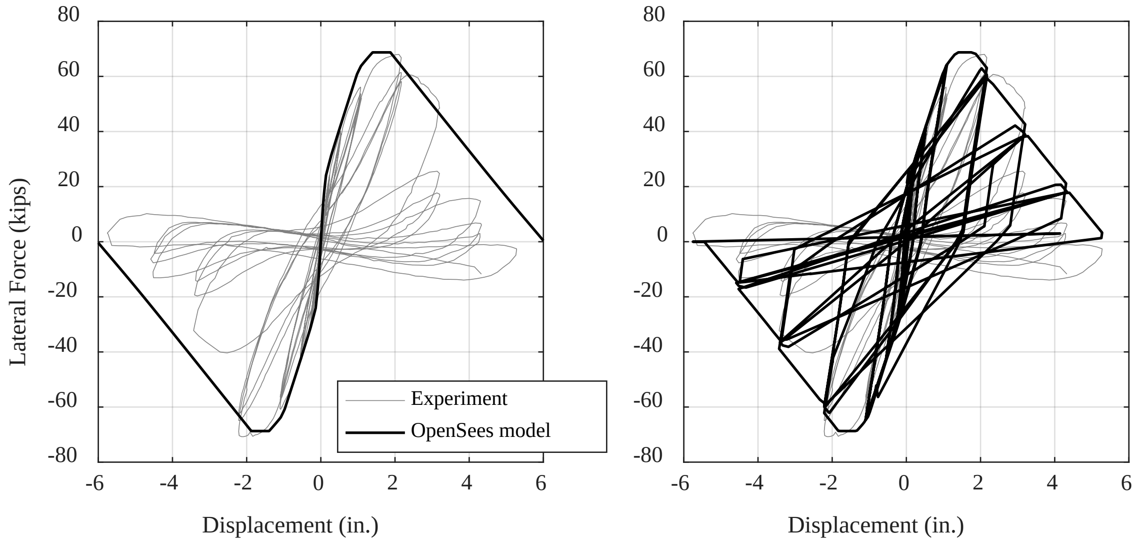

Fig. 6 - Monotonic and cyclic results of OpenSees analysis for Specimen 1 tested by Sezen [10].

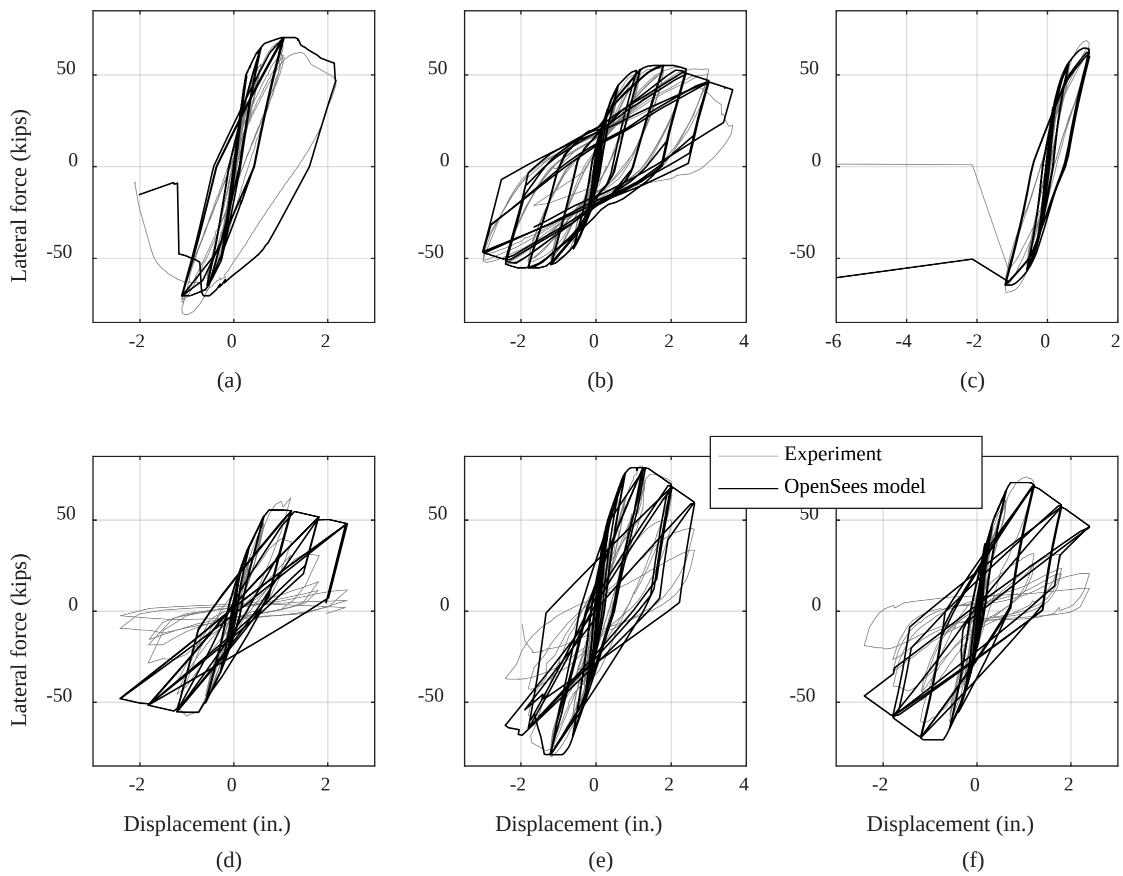

Fig. 7 - Cyclic OpenSees analysis results: a) Specimen 2, b) 2CLH18, c) 2CMH18, d) 3CLH18, e) 3CMD12, and f) 3CMH18.

5. Conclusions

Poorly detailed reinforced concrete columns are modelled and analyse using the open source software (OpenSees). In this study, a reinforced concrete column is modeled using three different elements which simulate flexural, slip and shear behavior. For flexural behavior, distributed plasticity model is used with fiber sections defined at five integrating points along the column length. Springs are placed at the ends of the column to capture the effects of slippage of bars and shear behavior. In these springs, in the lateral direction, shear behavior is modeled, while slip rotation is implemented in the rotational degree of freedom of the spring. For slip behavior, a continuous model developed by Sezen and Setzler [9] is transformed into a tri-linear model, and represented with *hysteretic* material in the OpenSees library. A new uniaxial material is also created in OpenSees to simulate shear displacement versus shear force response using the model developed by Sezen [11].

The proposed model is verified with additional six test columns. The comparison of calculated and experimental data shows that the model can accurately predict the behavior of poorly detailed columns up until peak strength. For columns with shear-flexure failure (category III and VI [4]), the proposed model can accurately capture the lateral load-displacement response after peak strength. The proposed model is currently not suitable for the columns experiencing pure shear failure (category I [4]).

6. References

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