Proposed Methods on Enhancement of Dynamic Response of RC Frames and Soil Structure Interaction

Dina Abdulaziz 1, Ahmed Zidan 1, Metwally Ahmed 2

1 Department of Civil Engineering, Faculty of Engineering, Beni-Suef University, Beni-Suef, 62514, Egypt
2 Structural Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt

Dinaali@eng.bsu.edu.eg

Abstract. In this paper, proposed methods on enhancement of a nonlinear behavior of reinforced concrete frames subjected to cyclic load. A fully nonlinear dynamic analysis is adapted using three-dimensional finite element analysis by means of ANSYS 16.0 code. All structural elements such as footings, columns and girder are simulated in the numerical model. The concrete is assumed to be nonlinear and isotropic. In addition, some proposed methods are investigated to enhance the performance of RC frames under cyclic loading such as, cross bracing steel at the connections and at girder region as well as additional bent bars at the ends of girder. The results of analyses are presented in terms of envelope capacity, load-displacement relationship, stresses and cracks distribution. The results indicated that the provision of additional reinforcement increased the ultimate lateral capacity, ductility and introduce an additional mechanism for shear stresses for RC frame under cyclic loading. The best performance is observed when the cross-bracing is used at the top and bottom column connections whereas, the lateral capacity and displacement is increased by 12.9 % and 27.63% respectively of that computed for Control Frame. In case of cross-bracing steel at beam column connections and case of cross-bracing at beam region, the lateral capacity of RC frames is about 1.09 and 1.04 times that of control frame respectively. Furthermore, the dynamic analysis is carried out under considering the foundation soil whereas the Drucker-Prager model is used to define the stress strain behavior of soil. Besides, some significant observations on the performance of RC frames with change of the values of parametric study are presented in this paper.

1. Introduction
Extensive researches have been carried out to investigate the behavior of joints that subjected to seismic conditions in past three decades through experimental and analytical studies [1]. It is generally proposed that the performance of beam-column joints have a significant factor for the overall behavior of RC frames structures exposed to lateral load. A study of the usage of additional steel in some region of RC frame such as cross-bracing bars at the joint core, cross-bracing at beam region and bent-bars at the ends of girder introduce an additional new mechanism of shear transfer.

Several attempts have been made during the last decades to explain the behavior of RC frame under cyclic loading. Some of these attempts are based on theoretical approaches [2-7] and others on the analysis of experimental or field tests [8-11]. Literature Review shows that a number of papers have
been published on the research work done on exterior reinforced beam column joint with different innovative reinforcement patterns. The numerical reported by Sohailuddin et al. [12] illustrated the behavior of exterior beam-column joint by using four types of specimens that is simulate by ANSYS11.0. All specimens are analyzed under similar reverse cyclic loading to simulate earthquake loading in structures. They found that, the better performance was observed for specimens with diagonal bars the beam region, that produced a higher strength with minimum cracks in the joint. In addition, the usage of cross-bracing steel in beam region tends to increase in the ultimate load carrying capacity and ductility of joints for both directions upward and downward loading. Kulkarni et al. [13] proposed advanced reinforcement pattern (additional crossed inclined bars) as a solution to increase the shear capacity of the exterior beam-column joint subjected to cyclic load that is modeled by ANSYS 13.0 Workbench.

In this study, a one bay of RC frame is considered for analysis. Hence, the different types and positions of additional reinforcement (inclined bars) have been chosen for investigating the performance under cyclic loading such as, cross bracing steel at the connections and at girder region as well as additional bent bars at the ends of girder.

2. Numerical Model
The behavior of RC frame is studied by numerical analysis. The Finite Element (F.E.M) is a numerical method for solving a wide range of problems. ANSYS is finite element analysis software enables engineer to perform multiple tasks such as build computer models of the structural components, applying operating loads and study physical responses like: stress levels, temperature distributions.

2.1. Material Model
In this study, the solid element (65) will represent the concrete elements (column, girder and footing). This element is described by eight nodes with three degrees of freedom at each node: these are translations in the X, Y and Z directions. In addition, the reinforcement steel for the finite element model is assumed to be identical in tension and compression and perfectly elastic. The internal reinforcement steel is modeled using three-dimensional spar elements LINK 180, with plasticity and two nodes are required for this element. Each node has three degrees of freedom, – translations in the nodal x, y, and z directions.

The stress-strain curve for concrete is non-linear as described by Egyptian code (ECP 203) [14]. It is used to define the material behavior by a total stress- strain curve as shown in figure 1. The initial elastic modulus (Ei) of concrete material taken from the initial slope of the curve. In ANSYS program the Egyptian Code model inputs as described in table 1.

Referring to figure 1, the equation of the concrete stress $f_c$ is given by the following equation:

$$f_c = \begin{cases} f_{c^*} \left[ \frac{2\varepsilon_c}{0.002} - \left( \frac{\varepsilon_c}{0.002} \right)^2 \right] & \text{for } \varepsilon_c < 0.002 \\ f_{c^*} & \text{for } 0.002 \leq \varepsilon_c \leq 0.003 \end{cases}$$  

Where: $f_{c^*} = \frac{0.67}{\gamma_c} f_{cu}$

$f_{cu} =$ Compressive strength for concrete
$
\gamma_c =$ 1.5
$
\varepsilon_c =$ Concrete strain
Table 1. Material properties for concrete in ANSYS program

| Material Model No | Element Type          | Material Properties         |
|-------------------|-----------------------|-----------------------------|
| Concrete          | Solid-Concrete 65     | Linear Isotropic            |
| Ei, M35           |                       | 34125 MPa                   |
| Prxy              |                       | 0.20                        |
| Dens              |                       | 0.25                        |
| ALPD              |                       | 0.34                        |
| BETD              |                       | 0.005                       |
| DMPR              |                       | 5%                          |
| Shear Transfer Coefficient for an Open Crack | | 0.30 |
| Shear Transfer Coefficient for a Closed Crack | | 0.50 |
| Uniaxial Tensile Cracking Stress (M35) | | 3.5 MPa |
| Uniaxial Crushing Stress (M35) | | 35 MPa |

In Table 1; E = Initial modulus of elasticity, Prxy = Poisson ratio, Dens = Density, ALPD = Mass matrix damping multiplier, BETD = Stiffness matrix damping multiplier, DMPR= Frequency independent damping.

Moreover, the behavior of the steel reinforcement is idealized by the Egyptian Code [14] as an elastoplastic material as shown in figure 2. The reinforcing steel stress is given by equation 2 and In ANSYS16.0 the Egyptian Code model inputs as described in table 2.

\[
f_s = \varepsilon_s \times E_s \quad \text{when} \quad \varepsilon_s < \frac{\varepsilon_y}{\gamma_s} \\
\]

\[
f_s = \frac{f_y}{\gamma_s} \quad \text{when} \quad \varepsilon_s \geq \frac{\varepsilon_y}{\gamma_s} \quad \text{equation 2}
\]

Where; Es = Modulus of Elasticity, f_y = Yield Strength, \( \gamma_s = 1.15 \), \( \varepsilon_s = \) Steel Strain

Figure 1. Idealized stress-strain curve for concrete (Egyptian Code (2007))

Table 2. Material Properties for reinforced steel in ANSYS program

| Material Model No | Type of Element  | Material Properties |
|-------------------|------------------|---------------------|
| 2                 | Link180          | Linear Isotropic    |
| Ex                | 2x10^3 MPa       |                     |
| Prxy              | 0.30             |                     |
| Bilinear Isotropic| Yield Stress     | 360 MPa             |
| 3                 | Link180          | Linear Isotropic    |
| Ex                | 2x10^3 MPa       |                     |
| Prxy              | 0.30             |                     |
| Bilinear Isotropic| Yield Stress     | 280 MPa             |
2.2. Model Dimensions
In order to investigate the cyclic performance of RC frames due to additional steel in different features and shapes at joints and middle region of girder and compared by Control Case (No additional reinforcement) as shown in figure 3. In this investigation, the influence of cross bracing at two positions is studied (a) frame joints (for both beam column and foundation connections) and (b) at the middle span of girder figure 4, a, b and c. In additions, the impact of bent bars rather than the straight one on the overall response is also studied figure 4, d and e. The compressive strength of the concrete 35 MPa. The yield stress of steel bars 360 and 280 MPa are used as main reinforcement and stirrups respectively. The longitudinal reinforcement ratio is 1.5 % from concrete cross section. In addition, the spacing between stirrups in both columns and girder is 140 mm.

![Figure 2. Idealized stress-strain curve for steel (Egyptian Code (2007))](image)

![Figure 3. RC frame model steel bars detailing and dimensions: general layout of the steel bars, dimensions of specimen and details of cross-sections.](image)
2.3. Loading Condition

The RC frames are loaded at the same locations as the full-size frames. The applied loads are distributed at all nodes in the top face of the beam. Furthermore, the Fixed support is used at the bottom face of the footing.

The cyclic loading is defined as the continuous and repeated load on a structural element. The (Sin wave) function is used to simulate the cyclic load as described in Equation 3 the plot of Sin wave is illustrated in figure 5.

\[ f(t) = F \sin \omega_f t \]  

(3)

where; \( \omega_f \) = the load frequency , \( t \) = time (Sec)

---

**Figure 4.** Dimensions and reinforcement details for different enhancement methods
In the analysis, the frame is subjected to 30 cycles of cyclic load and the frequency of load function \( \omega_f \) is \( 2\pi \) as shown in figure 6. The direction of loading that used in the study are shown in figure 7.

**Figure 5.** Sin wave function

**Figure 6.** Loading history

**Figure 7.** Loading directions
3. Results and Discussion

Compared with the Control Case, the results of numerical models in terms of load-displacement curve, crack patterns and lateral capacity are presented. Figures 8 show an example of deformation for case of Model 5.

Figure 8. Horizontal displacement of Model 5 (Forward and Backward Direction)
3.1. **Ultimate lateral capacity**

The load-displacement relationships for different cases compared with control case are shown in figures 9, 10 and 11. It shows that, the best performance is observed when the cross-bracing is used at the top and bottom column connections (Model 2) whereas, the lateral capacity and displacement is increased by 12.9 % and 27.63% respectively of that computed for Control Frame. For Model 1 and Model 3, the lateral capacity of RC frames is about 1.09 and 1.04 times respectively also, the lateral displacement is about 1.20 and 1.19 times of that occurs for control frame. On the other hand, for bent bar (Model 4), the lateral capacity and displacement is increased by 3.9 % and 8.69% compared with control frame respectively. Moreover, Model 5 has the same result of Model 1. The conclusion of all results for enhancement methods are recorded in table 3.

![Figure 9. Comparison of load-displacement relations between Control Frame and Model 1, Model 2](image)

![Figure 10. Comparison of load-displacement relations between Control Frame and Model 3, Model 4](image)

![Figure 11. Comparison of load-displacement relations between Control Frame and Model 5](image)
### Table 3. Conclusion of results for enhancement methods

| Method | Improvement of lateral capacity | Improvement in ductility |
|--------|---------------------------------|--------------------------|
| Model 1 | 4 %                             | 20 %                     |
| Model 2 | 12.90 %                         | 27.63 %                  |
| Model 3 | 9 %                             | 19 %                     |
| Model 4 | 3.90 %                          | 8.69 %                   |
| Model 5 | 4 %                             | 20 %                     |

#### 3.2. Shear and principal stresses

The concept of stress is extremely important to understanding the behavior of RC frame under cyclic load. The shear behavior for RC frame structures is necessary because severe damage within a joint that lead deterioration of the overall performance of RC beam-column connections. From the analysis the maximum and minimum values of shear stresses for planes (XY, YZ and XZ) recorded in table 4 at the same load level (466 KN) that presented the failure load of Control Frame for all cases. It can be seen, for all cases of inclined reinforcement the shear stress decreases when compared with Control Frame because for these cases the loads will distributed within more elements. As shown in figures 9, 10 and 11 the maximum lateral capacity is observed for Model 2, hence, this case yields more less shear stresses among other cases.

### Table 4. Maximum and minimum shear stresses

| Specimen Details | XY | YZ | XZ |
|------------------|----|----|----|
|                  | Mx | Mn | Mx | Mn | Mx | Mn |
| Control Frame    | 1451 | -586 | 587 | -587 | 221 | -221 |
| Model 1          | 582.30 | -709.82 | 428.528 | -499.38 | 218.37 | -215.018 |
| Model 2          | 533.71 | -455.27 | 404.633 | -389.15 | 171.44 | -202.1 |
| Model 3          | 645.54 | -531.89 | 413.92 | -413.92 | 261.88 | -261.881 |
| Model 4          | 581.00 | -631.77 | 415 | -410.60 | 202.00 | -192.87 |
| Model 5          | 1260 | -759 | 447 | -504 | 279 | -250 |

Principal stresses are the maximum and minimum normal stresses on a particular plane and no shear stress. As shown in table 5, when using bracing bars, the principle stresses will decrease this means that the frame capacity is increased compared with Control Frame.

### Table 5. Maximum and minimum principle stresses

| Specimen Details | 1st | 2nd | 3rd |
|------------------|-----|-----|-----|
|                  | Mx  | Mn  | Mx  | Mn  | Mx  | Mn  |
| Control Frame    | 21562 | -1534 | 205 | -3560 | 90 | -17294 |
| Model 1          | 21014.60 | -777.38 | 275.481 | -897.76 | 111.59 | -12236.6 |
| Model 2          | 19555.60 | -883.13 | 239.552 | -1051.83 | 133.80 | -7265.92 |
| Model 3          | 20848.90 | -890.38 | 236.397 | -955.75 | 99.70 | -8586.05 |
| Model 4          | 22721.80 | -917.88 | 227.44 | -1013.91 | 107.08 | -7630.62 |
| Model 5          | 22105 | -952 | 279 | -1226 | 109 | -20930 |

#### 4. Effect of soil structure interaction

In traditional seismic design of building frame, building base is assumed to be fixed but in fact the soil beneath the structure has ability to deform. As all structures are directly in contact with the soil, interaction among the structure, foundation and soil medium beneath the foundation change the real behavior of structure. It may cause reduction in overall stiffness of structure and increases natural periods of the structure.
4.1. Description of the model
Dynamic analyses are carried out for the two different systems as follow: (1) a fixed-base structure as Control Frame and (2) frames considering the subsoil as shown in figure 12. According to El Naggar, et al. [42], the horizontal distance between soil boundaries and the depth of soil mass are assumed to be five times the footing width.

![Components of the soil-structure Model 6](image)

**Figure 12.** Components of the soil-structure Model 6

4.2. Material properties
The soil is assumed to be homogeneous or of the Gibson type, isotropic, and elastic-perfectly plastic. The model used to represent the soil behavior is that of Drucker-Prager (1952). In the Drucker-Prager model of material behavior is described by a total stress- strain curve as shown in figure 13.

![Stress Strain behavior of Drucker-Prager model](image)

**Figure 13.** Stress Strain behavior of Drucker-Prager model

To study the effect of SSI on RC frame the different values of Modulus of elasticity for soil are used as illustrated in table 6.
Table 6. Analysis procedures

| Variables Parameters | Fixed Parameters | No. of Cases |
|----------------------|------------------|--------------|
| Soil₁, $E_s = 40$ Mpa | $F_{c_u} = 35$ Mpa |              |
|                      | $A_s = 1.5\%$     |              |
| Soil₂, $E_s = 60$ Mpa | $S = 140$ mm      |              |
|                      | $\phi = 40$       |              |
| Soil₃, $E_s = 80$ Mpa | $C = 1$           | 3            |
|                      | $\psi = 0$        |              |

5. Results and discussions

The results of cyclic loading analyses, including the lateral force and the top horizontal displacement, are determined and compared for the fixed-base and the model of flexible-base resting on the soil. According to figure 16, the lateral capacity of the structures modeled with soil are always less than the lateral capacity of structures modeled as a fixed-base.

Comparing the horizontal force and top horizontal displacement of the models for the fixed-base and flexible-base resting on soil with cyclic loading as shown in figure 14, it is observed that the horizontal force of Soil 1, Soil 2 and Soil 3 decreased by 41%, 34.8%, and 34.8%, respectively, compared with fixed-base. Furthermore, the top horizontal displacement increased to 42.5% and 13.5% for Soil 1 and Soil 2, respectively, by compared with fixed-base but model with Soil 3 and model with fixed-base the lateral displacement as the same. Such a great change in the horizontal force and top horizontal displacement, and subsequently on the performance level of the model resting on Soil 1, is absolutely dangerous and safety threatening.

![Figure 14. Comparison between horizontal force and horizontal displacement for Fixed-Base, Soil₁, Soil₂ and Soil₃](image)

6. Conclusions

From the analysis and results, the following conclusions can be recorded:
1- From the numerical analysis it is observed that the usage of additional reinforcement produces an increasing in the ultimate load carrying capacity, ductility and introduce an additional mechanism for shear stresses for RC frame under cyclic loading.
2- The best performance is observed when the cross-bracing is used at the top and bottom column connections whereas, the lateral capacity and displacement is increased by 12.9 % and 27.63% respectively of that computed for Control Frame.
3- For cross-bracing steel at beam column connection and cross-bracing at beam region, the lateral capacity of RC frames is about 1.09 and 1.04 times respectively also, the lateral displacement is about 1.20 and 1.19 times of that occurs for control frame.
4- On the other hand, for bent bar, the lateral capacity and displacement is increased by 3.9 % and 8.69% compared with control frame respectively.
5- As seen in the result, when the soil structure interaction taken into account, the lateral capacity of RC frame decreases when it compared with Fixed-Support condition. When increasing the modulus of elasticity of the subsoil the horizontal displacement of the RC frames that exposed to cyclic loading decreases relatively.

6- It is observed that, the horizontal force of Soil with $E=40$, 60 and 80 MPa decreased by 41%, 34.8%, and 34.8%, respectively by compared with Fixed-Base.

References

[1] Kulkarni, S.M., Patil, Y.D., “A State-of-Art Review on Reinforced Concrete Beam-Column Joints”, Journal of Information, Knowledge and Research in Civil Engineering, ISSN: 0975 – 6744, Vol. 2, 2012.

[2] Xiaolei, H., Xuewei, C., Cheang, J., Guiniu, M., and Peifeng, W., “Numerical Analysis of Cyclic Loading Test of Shear Walls based on OpenSEES”, The 14th World Conference on Earthquake Engineering, Beijing, China, 2008.

[3] Alva, G.M.S., Canha, R.M.F., Filho, J.O., and El Debs, L.H.C., “Numerical Model for Analysis of Reinforced Concrete Beams Under Repeated Cyclic Loads”, Science & Engineering Journal, Vol 22, No. 2, pp. 105-114, 2013.

[4] Kang, H.Z., Song, X.M., Jia, K.W., Zhou, L.P., and Liu, P., “Numerical Analyses on Seismic Behaviour of Concrete-filled Steel Tube Composite Columns Based on OpenSEES Program”, Journal of Engineering Science and Technology, Vol. 6, No. 5, pp. 143-148, 2013.

[5] Scotta, R., Giorgi, P., Tesser, L., and Talledo, D.A., “Nonlinear Analysis of R/C Shear Walls Subjected to Cyclic Loadings”, 11th World Congress on Computational Mechanics, Barcelona, Spain, 2014.

[6] Sethuraman, V.S., Suguna, K., and Raghunath, P.N., “Numerical Analysis of High strength concrete with Cyclic loading using Abaqus”, Global Journal of Pure and Applied Mathematics, Vol. 13, No. 2, pp. 225-235, 2017.

[7] Jin, L., Zhang, S., Dong Li, D., Xu, H., Du, X., and Li, Z., “A Combined Experimental and Numerical Analysis on the Seismic Behavior of Short Reinforced Concrete Columns with Different Structural Sizes and Axial Compression Ratios “, International Journal of Damage Mechanics, Vol 0, No. 0, pp. 1-32, 2017.

[8] Yu, K., Huang, T., and Lu, W., “Cyclic Tests of Component of One-Story Reinforced Concrete Frame-Wall-Diaphragm Assemblage”, Department of Civil Engineering, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania, 1989.

[9] Rodrigues, H., Arède, A., Varum, H., and Costa, A.G., “Experimental Evaluation of Rectangular Reinforced Concrete Column Behavior Under Biaxial Cyclic Loading”, Earthquake Engineering & Structural Dynamics, Vol. 42, pp.239–259, 2013.

[10] Wang, T.C., Liu, X., and Zhao, H.L., “Seismic Performance of Cross-Shaped Columns with 500 MPa Grade Reinforcing Steel Bars”, Tehnički vjesnik, Vol. 22, pp.629-636, 2015.

[11] Sosa, D., Arévalo, D., Mora, E., Correa, B., Albuja, D., and Gómez, C., “Experimental and Analytical Study of Slender Reinforced Concrete Shear Wall under Cyclic In-Plane Lateral Load”, Hindawi, Mathematical problems in engineering, 2017.

[12] Sohailuddin, S.S., and Shaikh, M.G., “Finite Element Modelling of Reinforced Concrete Beam Column Joint Using ANSYS”, International journal of structural and civil engineering research, Vol. 2, No. 3, 2013.

[13] Kulkarni, S.M., and Patil, Y.D., “Cyclic Behavior of Exterior Reinforced Beam-Column Joint with Cross-Inclined Column Bars”, Journal of Mechanical and Civil, Vol. 11, Issue 4 Ver. III, pp. 09-17, 2014.

[14] Egyptian Code for Design and Construction Concrete Structures (ECP 203- 2007).