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NON-LINEAR BEHAVIOR OF REINFORCED CONCRETE SEMI-RIGID JOINTS UNDER LATERAL LOADS

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ABSTARCT

The main goal of this study is to investigate the nonlinear performance of concrete connections considering their actual flexural stiffness under lateral excitation. First, the joints were applied to cyclic lateral loading. From the developed experimental models, the actual relation between connections' rotation and its corresponding moment were obtained. Second, an ANSYS model was developed to determine the connections' rotation and its corresponding moment for the RC connections based on their size, concrete strength and rebar details. The connection rotation is equal that from the experimental models. The study concluded that modeling connections as rigid connections will significantly overestimate the stiffness of RC buildings and give erroneous structural responses.

Keywords: reinforced concrete, frames, non-linear analysis, semi-rigid joints.

1. INTRODUCTION

In RC buildings, the actual stiffness of connections is less than infinity (as assumed for rigid connections) and bigger than zero (as assumed for binned connections). Therefore, when these joints are subjected to lateral load exceeding their capacity, they are severely damaged. This will impose high risk on residential safety and cause financial loss. Geometric distortion is one type of RC joint failure under strong earthquake load, in which the top bars in the joint are strained in an opposite direction to the bottom bars causing these bars to slip.

This failure can be avoided by increasing the bond stress between concrete and reinforcement by increasing either concrete strength, column size or both. Beside bars slipping and joint distortion, diagonal cracks may develop earthquake excitation. Such failure can be prevented by either increasing the size of the column or increasing concrete confinement at the connection by decrease the spacing between the reinforcement ties in the column. ACI 318-14 code recommends additional methods to prevent connections failure under strong lateral load such as constructing continuous column ties around the column bars in the joint and the ratio between columns' width to the diameter of largest longitudinal bar used in the attached beam should be less than 20. Finally, the code recommends properly anchoring the longitudinal bars of the beam in the column at exterior connections. RC joints are considered as rigid joints when designing structural frames. This assumption results in assuming higher stiffness of the building than its actual stiffness.

Diverse researches on RC connections are originated in literature. Giberson [1] proposed one spring at each end of RC beam to represent nonlinear rotation at that end, however, the behavior of beam between these two springs will be elastic. Otani [2] proposed two parallel beam components model; the first component assumes linearly elastic beam and the other assumes nonlinear inelastic beam. Alath and Kunnath [3] suggested that the behavior of inelastic connection can be modeled using rotational spring with zero-length located between the adjacent members and the joint panel. Also, rigid links are assumed to connect columns and beams to allow them to rotate independently. Youssef and Ghobarah [5] used four members that are rigid and are connected by pin connections.

Despite these methods, joint deformations need to be modeled more accurately by including other factors that impact joint deformation such as the slip of beam steel bars and the joint shear deformation. The purpose of this study is to examine the behavior of RC semi-rigid connections under lateral load. First, Three specimens will be tested to obtain the connection rotation. Then, ANSYS model with 3D presentation for the RC connections was developed. The purpose of this model is to determine the moment- rotation curve for the connections based on its size, concrete strength and rebar details.

2. EXPERIMENT

2.1 Dimensions and steel details of specimens

The tested joints in this study were taken as the joints to an eight-storey residential RC building. Each storey is 3.5 m in height and 5.0 m in beam span. The connection was done based on the guidelines provided by Alva [6]. Figure-1 reveals the three specimens and their steel details. Also, in these specimens, beam reinforcements in both transverse and longitudinal directions satisfies ACI Committee 318M-05 seismic requirements.

2.2 Characteristics of Used Material

The concrete selected for the experiments was Portland Cement with 25 MPa in compression and 3.5 MPa in tension and 23,500 MPa in compression elasticity modulus. Table 1 show the mix design. Quality control specimens taken from the batches used in casting the test specimens indicated that the actual compressive strength of the concrete was 26 MPa which is slightly higher than the design strength. Finally, normal mild smooth steel with

8 mm diameter bars was used for stirrups with fy = 420 MPa.

2.3 Experiment Procedure

Figure-2 reveals the setup steps for the tested specimen. Lateral cyclic load with increasing amplitude of ±5 kN applied on the beam using hydraulic actuator. Finally, joint rotation was determined using displacement transducers. Figure-3 demonstrates joint rotation where the rotation equation is [6]:

$$\theta = \frac{\delta_1 - \delta_2}{H} \quad \dots\dots\dots (1)$$

Where δ_1 and δ_2 are the displacements given by the two transducers, while H is the transducers' distance. For all specimens, nine (9) cycles were completed with maximum/minimum values of the cyclic load amplitude reached ±65 kN. Figure-4 illustrates the loading history for this last stage up to the failure of the joint for all tested connections.

2.4 Test Observations of Specimens

As shown in Figure-5, crackswere developed at the intersection between the beam and the column and they are controlled by the beam flexural strength. Therefore, the failure first began by the development of plastic hinge in the beam, then shear cracks started to appear in the connection. Similar failure pattern was found in the literature; including Omidi and Behnamfar [7], Alva and Debs [6], and Shafaei *et al*. [8]; for the seismic designed connections. The hysteretic moment–rotation responses of the tested specimens are presented in the form of rotation versus corresponding moment applied at the joint as shown in Figure-6. Figure-6 illustrates the response of the tested specimens is a ductile moment - rotation hysteretic response. This result was expected since the specimens were designed as stated by ACI Committee 318M-14 requirement.

3. ANALYSISFOR BEAM-COLUMN CONNECTIONS

The purpose of this section is to determine the linear stiffness and the relation between connections' rotation and its corresponding moment.

3.1 Ansys Model

Concrete is modeled with Solid65 that are capable to simulate concrete cracks. On the other hand, link180 represent the reinforcement, where it's similar to a truss element that has two nodes, and each nodehas3 DOF's. The model assumes perfect bond between reinforcements and their surroundings. This assumption was based on the recommendation of many researchers such as Shafaei *et al* [8] and Alva and Debs [6] where they show that assuming prefect bond between rebar and concrete is a good and acceptable estimate for their actual bond. To provide perfect bond, both rebar and adjacent concrete were broken into the same number of connected elements.

3.2 Features of Used Rc

3.2.1 Concrete

The concrete properties are defined as (ACI 318-14):

a) Elasticity modulus for the concrete was considered as $4700\sqrt{f_c'}$ (MPa), in which f_c' is the compressive strength for concrete.
b) The ultimate axial tensile strength, or the rupture modulus, can be considered as $0.612 * \sqrt{f_c'}$.
c) Compressive strength f_c' was considered in this study to equal 25MPa.
d) Poisson's ratio, υ =0.2.
e) In this research, compression stress-strain was based on Hognestadas follows [9]:

$$f_c = \begin{Bmatrix} f_c''\left[\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right] & \varepsilon_c \le \varepsilon_0 \\ f_c''\left[1 - 0.15 * \left(\frac{\varepsilon_c - \varepsilon_0}{\varepsilon_{cu} - \varepsilon_0}\right)\right] & \varepsilon_0 \le \varepsilon_c \le \varepsilon_{cu} \end{Bmatrix} \quad \dots (2)$$

Where: f_c'' is the concrete maximum compressive stress and its calculated from Equation 3.

$$f_c'' = k_s \times f_c' \quad \dots\dots\dots\dots (3)$$

Where k_s is a function of f_c' and its equal to 0.95 for f_c' of 25 MPa. In Equation 2, the strain ε_0 is determined using Equation 4.

$$\varepsilon_0 = 1.8\left(\frac{f_c''}{E_c}\right) \quad \dots\dots\dots (4)$$

The concrete stress-strain curve is illustrated as Figure-7. The modules of elasticity value is 23.5 GPa and the modules of rupture value is 3 MPa.

3.2.2 Steel Reinforcement

The stress-strain relation of rebars is introduced as multi-linear curves in Figure-8. According to reference experimental studies f_y =420MPa forrebars.

3.3 Analysis Results

To validate the ANSYS model, the same connection tested in section three in this study was simulated using ASNYS under the same test conditions performed in the experiment. Figure-9 shows the Joint reinforcement, the equivalent stresses developed in the joint and the deflection shape at failure. Figure-9 shows cracks in the tensile region of beam then shear cracks develop in the connection. In addition, Figure-10 shows the relation between joint moment and its corresponding rotation developed by ANSYS superimposed on the experimental curves shown in Figure-6. These results support our assumption that the proposed ANSYS model is suitable to assess the relation between RC connections' rotation and its corresponding moment.

4. CONCLUSIONS

This study used experimental testing and finite element modeling to determine relation between RC connections' rotation and its corresponding moment earthquake excitation. The determined connections' stiffness's are function of their size, concrete strength and rebar details. The study determined that the flexural stiffness for the connection is similar to the value in literature. Furthermore, the relation between connections' rotation and its corresponding moment for the tested connection is similar to that found from the experiment and in the literature. This study suggests that the Design assumption of rigid joints is not accurate, because this assumption can lead to under designing of beams and columns; therefore, this study recommends determining connections' actual fixity.

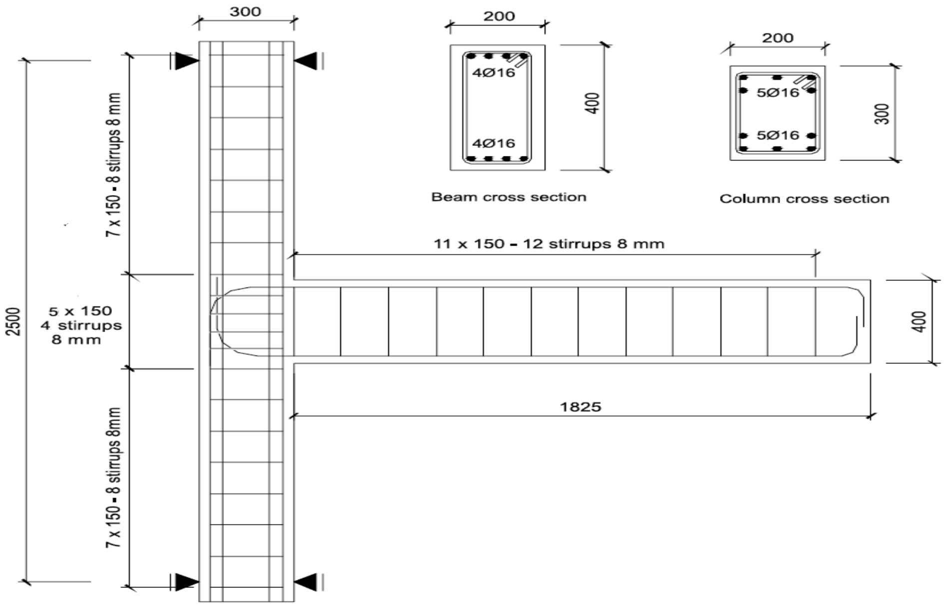

Figure-1. The geometry and dimension of the tested specimens.

Figure-2. Setup of the test specimen.

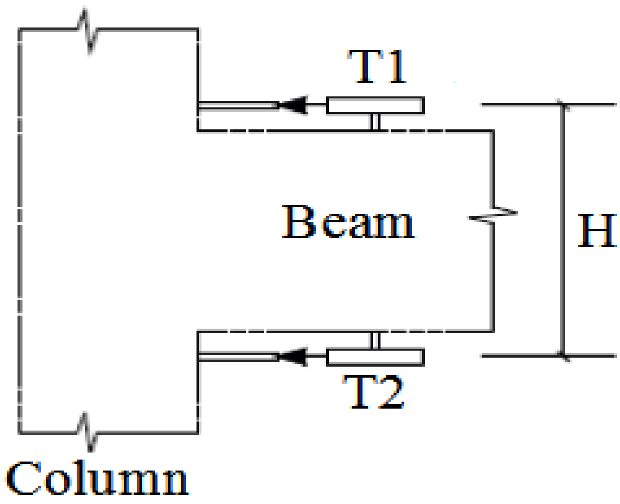

Figure-3. Displacement transducers used to evaluate relative rotations.

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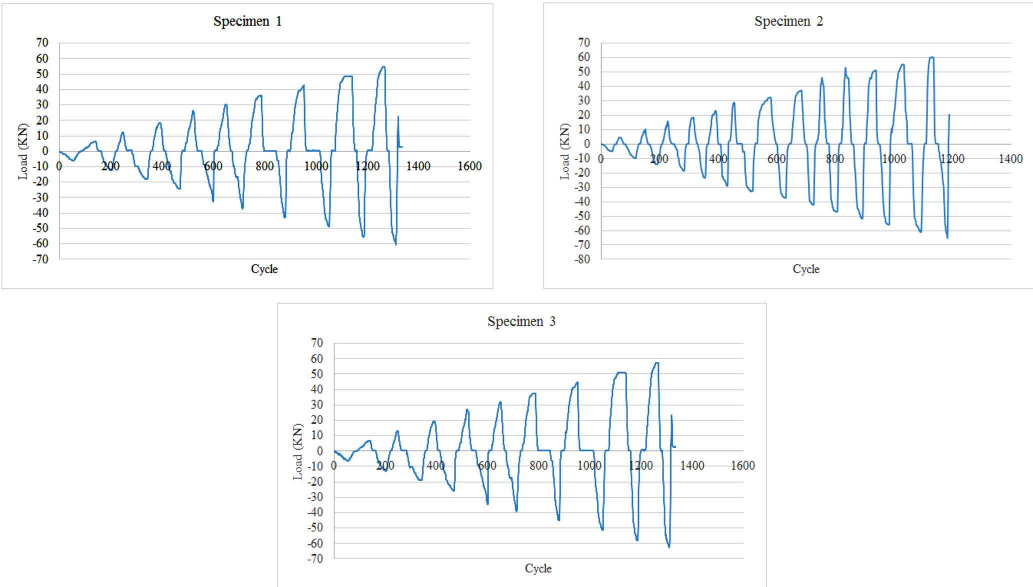

Figure-4. Lateral cyclic loading protocol.

Figure-5. Tested connection view at failure.

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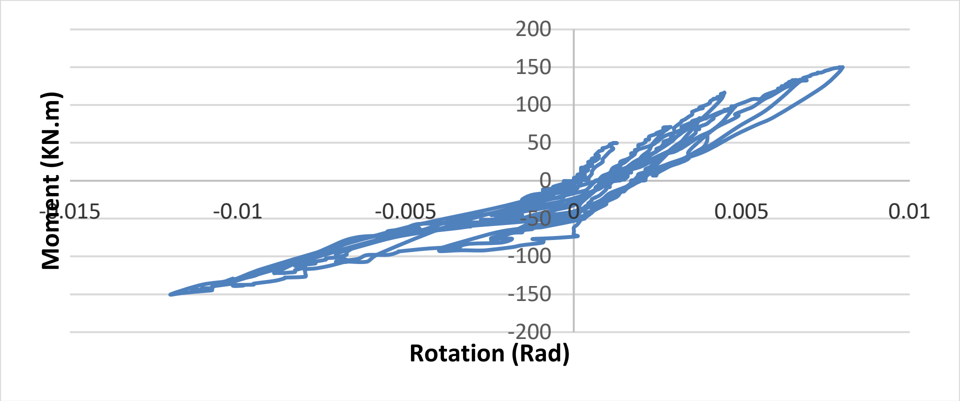

Figure-6. Relation between connections' rotation and its corresponding moment determined by the experiment.

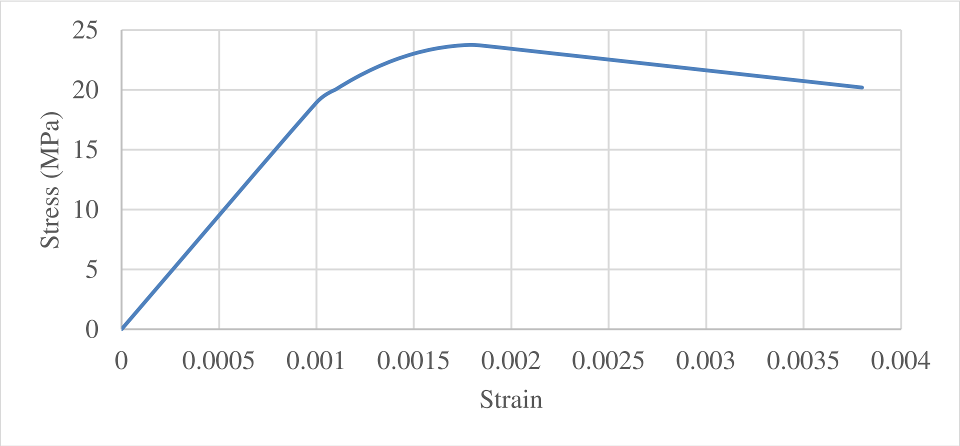

Figure-7. Stress-Strain Curve for Concrete Material.

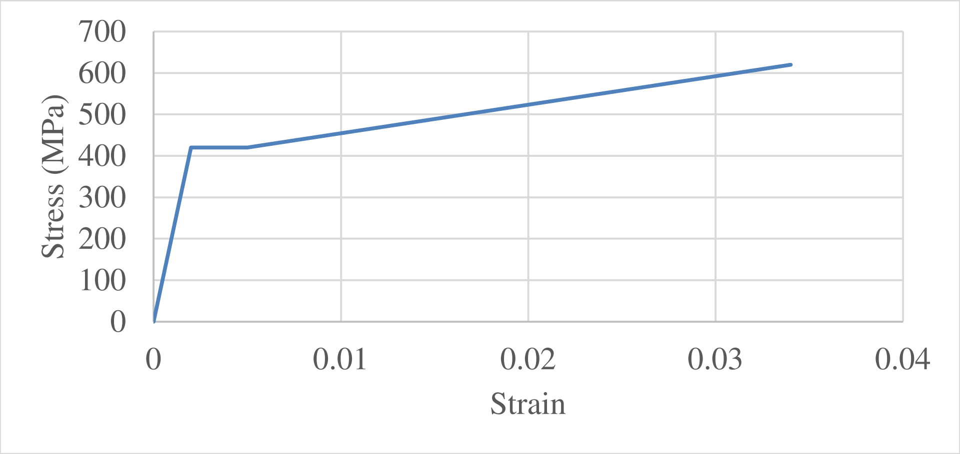

Figure-8. Stress-Strain Curve for Steel Material.

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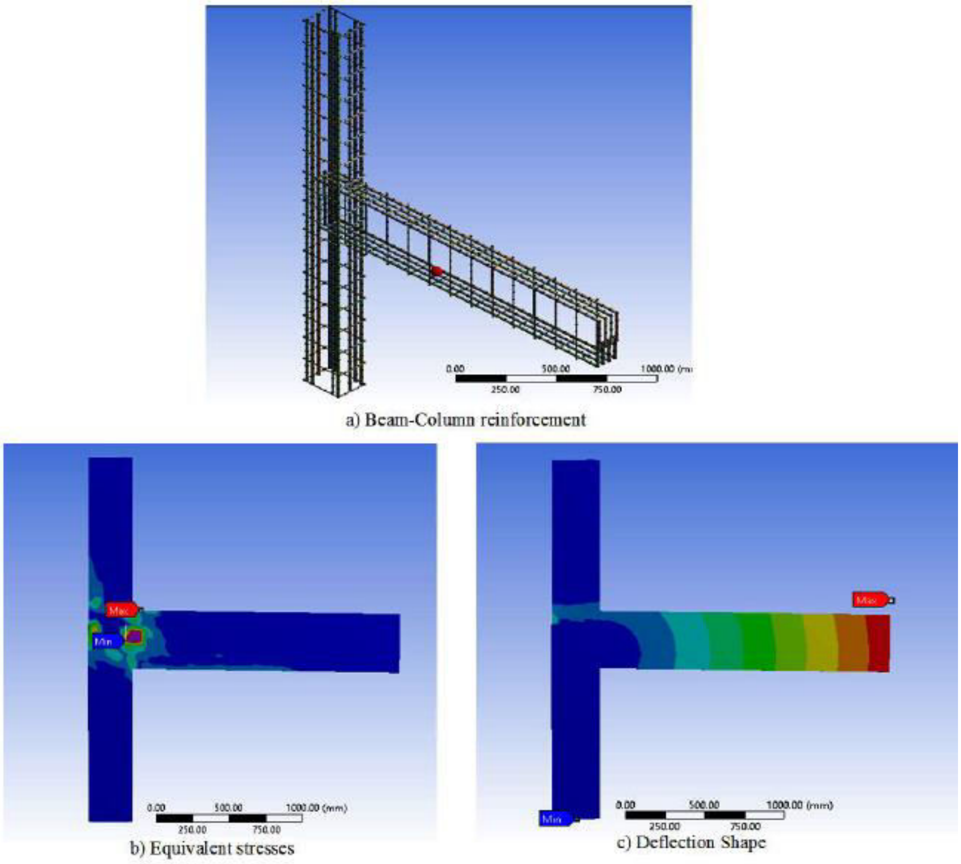

Figure-9. ANSYS Model.

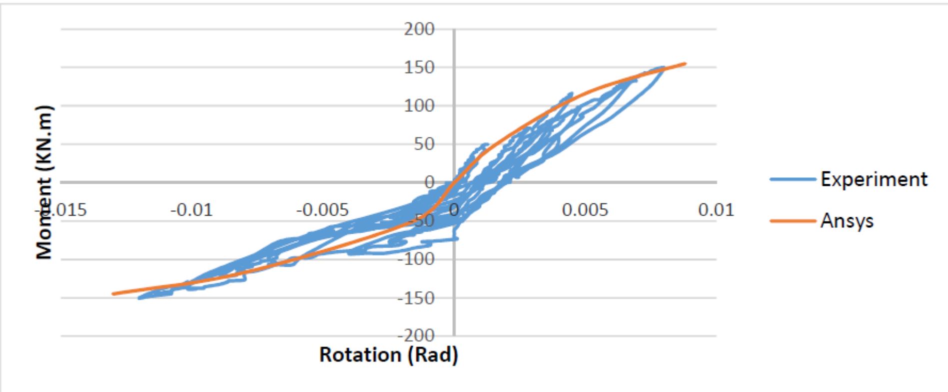

Figure-10. Relation between connections' rotation and its corresponding moment.

Table-1. CSPC mix design.

Item	Mixture Proportions (kg/m3)
Ordinary Portland cement	325
Fine Aggregate	750
Course Aggregate	1100
Water	280

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