Simulation of reinforced concrete beam-column joints under cyclic loading

Ghaith A Al-Jumaily¹, Ammar A. Abdul Rahman²

¹Graduated Student, Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq.
gveyformr@gmail.com

²Structural Engineering, Faculty Member, Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq.
ammar.rahman@yahoo.com

Abstract. Reinforced Concrete buildings with 3 to 5 stories are common structures in Iraq. Recently and due to several earthquakes taking place at the borders and/or even inside Iraq, these structures are under the action of long-term cyclic loadings from these earthquakes. A major structural element in these RC structures is the beam-column connection which observes the energy from the earthquake shocks. Consequently, understanding the performance of these joints under reversed cyclic loading produced from repeating earthquake became necessary to understand the real capacity and behavior of these connections. One model is developed using the finite element software ABAQUS to represent a possible type of beam-column joint in any typical structure undergoing reversed-cyclic load from earthquakes. The suggested model offers a simple demonstration of the plastic mechanisms which determines joint behavior under shear loading created from repeating seismic actions. The model is subjected to reversed cyclic loading made from the peak value of actual earthquake applied at different timings after the joint reach yielding in the longitudinal reinforcement. The purpose of the study is to determine the energy and the remaining shear strength that the joint holds after it reaches the yield point after such reversed cycles. Shear capacity and deformations of the columns are calculated after each applied cycle gained from the earthquake and accumulated to know the total deformation after the cycles and to understand the response of that joint after each cycle and at the end. The results of this particular model indicate that it is suitable to be used in demonstrating the response of such type of joint undergoing cyclic loading.

Keywords: Beam-column joint, concrete compressive strength, seismic load, concrete damage plasticity, reversed cyclic loading, column transverse reinforcement, beam transverse reinforcement.

1. Introduction

In the past few years, frequent earthquake incidents took place in the zone among Iraq, Iran and Turkey. The incidents have caused some damages to structures. These damages led structural elements to collapse. One of the most dangerous elements causes the structure to collapse is the joint that connects lateral and vertical elements together. This shows the importance for researchers and structural engineers to gain a better understanding of joints performance when they are exposed to seismic loads.

Several experimental researches dedicated their work to study the seismic response of RC frames built earlier or within the 1970s which were designed to withstand only gravity loads. In general, experiments on sub-assemblies were carried out with interior or exterior beam–column joints having minimum percentages of reinforcements according to specifications. Bonacci and Pantazopoulos [1,2] analyzed the essential parameters influencing the performance of interior and/or exterior joints, such as (transverse beams action during loading, joint confinement, bond strength, axial load on the joint, and...
concrete strength), through the database that was obtainable at that time due to the results of these experiments. In FIB Bulletin n.24, additional studies regarding the interpretations of old joints behavior were concluded. Nevertheless, most of the tests were focused on the deformed bars bent in the joint, and fewer studies were associated with the hooked-end plain bars joints, and joint shear failure was present on less of them [3]. Structural designs became dependent on the numerical capabilities embraced in the up-to-date design codes for the structural analysis especially the finite element method where real response (stresses, deformations) was easily predicted. Choosing a proper finite element joint model shall be capable of incorporating the suitable material models with an accurate representation of existing boundary conditions in addition to the definition of the load combinations. Due to the difficulties in modeling of RC connections, designers aimed to ignore modeling them and depend on assumptions stated on Codes which depends on accumulated previous experience. While the steel reinforcement is basically proposed from practical recommendations derived from limited experimental tests, consequently, the amount of steel embedded inside the connection could be overestimated or simply poorly distributed [4].

2. Joint Description
The actual dimensions of the connection under investigation and its properties are those of any typical commercial building in Iraq with not more than six stories been used. The symmetry in the cross-section was not used in this analysis in order to fully visualize the model.

The structure of the connection chosen is an outer connection (exterior joint) of the typical buildings in two-dimensional representation due to size problem during running of the analysis. Dimensions and reinforcements of the connection are shown in Figures 1 and 2. The end of the column was connected with a rigid bracket.

All simulations in this work have been carried out using the commercial ABAQUS/Explicit finite element software, which has the ability to obtain the structure’s dynamic response by direct time integration of all the degrees of freedom of the model.

Figure 1. Reinforcement and cross section details of the column and the beam (Units in mm)
3. Finite Element Modeling

The beam-column was modeled using brick elements of 8-nodes. In order to make accurate analysis, the reinforcement behavior was gained using truss elements in three dimensions, they were accustomed to represent each reinforcement bar embedded into the beam and column’s concrete (inside the brick elements) with circular cross-sectional area. Models are shown in Figures 3 and 4.

Two types of materials were modeled: concrete and steel, the built-in material models that the software provides were used in this study.

3.1 Concrete Material Properties

The Concrete damage plasticity model is utilized to achieve the concrete material properties in this study. To differentiate the concrete manner out of the elastic range, plastic and specific concrete properties will be characterize in addition to the elastic properties. The initial elastic modulus and the relationship of compressive stress-strain are approximated using provisions. The tensile strength of concrete is obtained from [5], while the tensile post failure behavior is modeled by the use of an exponential expression identical to that derived by [6] as shown in Table 1 and Figures 5 to 8.

Figure 2. Dimensions of the joint (Units in mm)

Figure 3. Finite element model of the joint

Figure 4. Modeling of the joint reinforcement
3.2 Steel Material Properties

The behavior of the reinforcement bars was devised using Bi-linear elasto-plastic model. The model’s elastic input data is the Poisson’s ratio and the elastic modulus shown in Table 1.

|                | Concrete | Steel reinforcement A615 Grade 60 |
|----------------|----------|-----------------------------------|
| $E_c$          | 30588.57 MPa | $E_s$                             |
| $f_c$          | 30 MPa   | $f_y$                             |
| $\nu$          | 0.15     | $\nu$                             |
| $\gamma_c$     | 24.5 kN/m³ | $\gamma_s$                        |
| $f_t$          | 1.8 MPa  | $f_u$                             |

**Table 1:** Materials properties used in the model

**Figure 5.** Concrete compressive strength curve [6]

**Figure 6.** Concrete Tensile strength curve [6]

**Figure 7.** Concrete compressive damage plasticity parameters [6]

**Figure 8.** Concrete tensile damage plasticity parameters [6]
3.3 Boundary Conditions
The boundary conditions used in the simulation have been modeled as rigid support holding the column at the bottom to replace the point at mid span of the column. The beam's two-side surface and the column's bottom face have been restrained against two directional movements allowing the structure to move only with the direction of the load.

3.4 Reversed Cyclic Load Simulation
Seismic analysis of a typical joint in reinforced concrete building frames was carried out using nonlinear time history analysis. The direct integration method was used in the equation of motion in order to study the joint behavior under seismic action. In this study, the structural response was assessed at all steps and at the end of any step. The input data was an acceleration-time history function with a peak value of the earthquake hit Iraq-Iran border 30 km south east of Halabja city on 12 November 2017 with a magnitude of 7.3 Mw at earthquake focal point as recorded by International stations and with 4.9 Mw as recorded at the station in Baghdad was used in this work as the input cycle activity. The choice of this earthquake was for the following reasons [7]:

• To study the behavior of typical joints in Iraq during the actual recorded earthquake.

• By this Study's preparing date, The Halabja Earthquake is considered the Largest recorded earthquake in Iraq.

The acceleration-time history peak value from Halabjah earthquake of 1.1 m/s² was transferred into displacement according to the dimensions of the model taken. It was almost a 2 mm displacement. To create cycles from the same displacement induced, this displacement was repeated 6 times then doubled and repeated 3 times at timings shown in Figure 9 below. These cycles were the input loading in our model.

![Cyclic Load amplitude](image)

**Figure 9.** Cyclic loading Scheme adopted

4. Results
The following results were concluded from applying the cyclic scheme presented in Figure 9 to the joint model. The load-displacement cycles show a pure plastic range after the first loading cycle which means that the join was under plastic deformation after the first loading cycle. Then plastic range capacity increases and bulb of the capacity increased more than 4 times the original plastic capacity till last cycle where the capacity decreased rapidly showing full failure of the joint as illustrated in Figure 10.
Figure 10. Load vs. accumulated displacement response of the joint

The response showed also that first yielding was at the top reinforcement for the negative moment at the connection at the end of the first cycle (stage of loading), then the top reinforcement failed after reaching full capacity of the plastic range of the material at the end of the sixth cycle as shown in Figure 11.

Figure 11. Stresses reach yielding in top reinforcement (at the end of stage 6 of loading) (Units in MPa)

After that the bottom reinforcement of the same location at the face of the joint reached its ultimate plastic capacity and failed at the end of the seventh loading cycle as shown in Figure 12.
Figure 12. Stresses reach yielding in bottom reinforcement (at the end of stage 7 of loading) (Units in MPa)

Crushing of concrete didn’t appear during the first cycles and the deformation was limited to the yielding of the reinforcements but after beginning of cycle 7 crushing of concrete appeared clearly at the outer faces of the joint, as shown in figure 9, and the following figures until the full collapse of the joint. The following figures show several failure situations took place at the joint.

Figure 13. Stresses in concrete after the breaking of top reinforcement at the end of stage 7 of loading (Units in MPa)

Figure 14. Deformation shape when top reinforcement broke at the end of stage 7 of loading (Units in mm)
5. Conclusions

The problem of repeated cycles induced by several earthquakes taking place was drawn into attention and analyzed to study the behavior of rigid beam-column connections. The model concluded through ABAQUS managed tracing the yielding of reinforcement then crushing of concrete in acceptable sequence and reasonable timing.

It was kept on purpose to make the reinforcement in its minimum percentage so we can let the section reach higher stresses at early stages. It was clearly recognized that due to minimum percentage of reinforcement, at the end of first loading cycle, the top then the bottom reinforcements reach yielding. After several cycles, yielding continue and the section was gaining additional energy leading to larger cycles of load deformation relation until the crushing (compressive stress) of concrete reach its limits and the whole section collapse.

It is necessary to state for the official organizations, that repeating the same magnitude of earthquakes taking place at the borders between Iraq and Iran are weakening the joints of the reinforced concrete frames of the old buildings and must be followed, investigated and traced.

It is recommended that the cracks on old buildings must be marked carefully and followed after each new earthquake to see if there is progress in spreading since reinforcements cannot be seen.

6. References

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