Proceedings of 8th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8

Seismic Performance Evaluation of Eccentric Beam Column Joint of RC Frame Buildings

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Abstract

Aftermath of devastating earthquakes have shown that beam column joint of RC frame buildings has suffered severe damage which consequently interrupted the structural behavior of the buildings. Eccentric beam column joints are often constructed in towns and cities due to architectural demands and geometric constraints. Due to complexity in design and construction difficulties such joints are not given much attention. In order to investigate the effect, four RC framed buildings of story numbers varying from 1 to 4 with different joint aspect ratios are analyzed using FEA software ETABS 17.0.1. Both linear and nonlinear static analysis is performed to compare the seismic behavior of RC bare framed buildings having concentric and eccentric beam column joints in response to seismic excitation. To observe the stress variation along with eccentric distance and nonlinear behavior 3D nonlinear finite element modeling of RC beam column joints selected from buildings is carried out using finite element program ABAQUS 2017. The general objective of this research is to quantify the effect of eccentricity on energy dissipation, modal time periods, torsion, shear forces and stresses. It is observed that concentric joints perform better than eccentric joints during seismic excitation as they have higher energy dissipating characteristics. Eccentric joints are less stiff which affects the ductility behavior of the structural elements. Also higher stresses and torsional effects resulting from eccentricity reduce the shear capacity and strength of the joint and can have damaging effects on the structural response of the buildings which necessitates the need of inclusion of joint eccentricity in the analysis of eccentric beam column joints.

Keywords

Eccentric Beam Column, 3D, Capacity curve, Joint aspect ratio, Pushover analysis, ABAQUS

1. Introduction

Beam column joints are the place of junction between beams and columns. They are the most critical part of the building structures and are subjected to cyclic reversal loading due to ground motion. A beam-column joint is defined as that portion of the column within which the depth of the beam frames into the depth of column. Joints form the connecting link among the main structural elements and are weaker part in building framework which affects the performance of whole building. Beam column connections can be categorized into two groups: based on loading conditions and geometric connections respectively. Based on loading conditions they are divided into two groups: First type of joints are the one which are designed to have sustain strength under deformation along with the formation of inelastic zone and other type of joints are those which can sustain deformations without inelastic zone formation respectively.Beam column joints are the critical part of the building structures which are subjected to cyclic reversal loading due to ground motion.On the basis of geometric connections joints are grouped into three types: interior, exterior and corner [1].

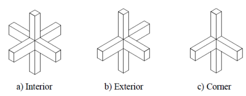

Figure 1: Types of Concentric joints

Exterior beam column joints are mostly used in the construction of moment resisting RC frame buildings. In common terms joints are basically categorized into concentric and eccentric joints. In a concentric joint the column center line coincides with the beam center line whereas in an eccentric joint either columns are

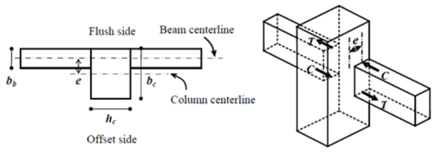

Figure 2: Eccentric beam column joint

made wider than the beams or wider beams are used. Most often the beam flushes with the exterior column faces resulting in an eccentric beam column joints. The eccentric distance between column center line and beam center line develop torsional effects in response to seismic forces [2].Nowadays eccentric joints are preferred due to architectural demands and geometrical constraints[3]. Such type of joints are subjected to torsional force and shear stresses are induced at the joint during seismic excitation. Also such joints are subjected to large deformation and large drifts. Due to brittle failure nature of joint shear the ductility behavior of building may get interrupted[4].Consequently shear capacity of adjacent concrete decreases. High flexural demands are placed at the beam column joint by beams and columns which will result in poor seismic performance of joints and also affect the seismic performance of whole building structures.

Nepal lies in highly seismically active zone and is ranked 11th in terms of vulnerability induced by earthquake hazards (UNICEF Nepal 2017) in the world. Due to deficiencies and inadequacies in structural design many buildings collapsed during Nepal Gorkha earthquake 2015.During seismic event eccentric beam column joint can lead to several hazards since it has damaging effect on strength, stiffness parameters, energy dissipation capacity and ductility behavior of the buildings. So behavior of eccentricity in beam column joint should be studied and proper design of eccentric beam column joint with proper detailing arrangements is necessary so that ductility can be developed and structure can perform satisfactorily under the action of seismic forces. Study of seismic behavior of eccentric beam column joint is a must for Structural engineers.
There are several congestion of reinforcement at the joint which imposes constructional and design difficulties. Due to which such beam column joints are not given much attention in proper design of such joints. The research work[5] performed 3D nonlinear finite element analysis of ninety eight numerical models of joint sub assemblies using MASA and an experimental study on two RC exterior beam column sub assemblies. These numerical results were validated with experimental ones compared with the different codal practices. It was found that joint sub assemblies showed yielding and diagonal shear cracking with the additional torsional cracking at eccentric joint. Maximum joint shear force was greater in concentric specimen by 26% in both experiment and numerical test results. With the increase in joint width ratio and joint eccentricity shear resistance of the joint was decreased and hence the effective joint width was decreased.

An experimental study[3] was conducted on three ¾ scale exterior RC eccentric beam-column-slab specimens and it was observed that at vicinity of eccentric joint unsymmetrical damage with the formation of diagonal shear cracks within the core region of the joint and flexural cracks on the exterior face. Also when the beam column connections were coupled with the slab/floor systems additional torsional stiffness was provided by slab and there were improvement of energy dissipation capacities, joint shear stiffness and strength in eccentric specimens. ACI 318-08/318R-05 has provided recommendations to compute effective joint width as sum of width of beam and twice the eccentric distance in case of eccentric beam column joints. According to ACI 352R-02 the nominal shear strength of joint (for joint type based on loading conditions) is given by;

$$V_n = 0.083^{\star} Y^{\star} fC^{\star} b_j^{*} h_c (Mpa) \ldots$$

Where, $Y = constant$ depend upon the type of beam column connections
fc =compressive strength of concrete
bj = effective joint width = $\frac{bb+bc}{2}$ (for concentric joints) = bb $+ \sum mhc/2$ (for eccentric joints)
$m = 0.5$ if eccentricity between beam and column center lines exceeds bc /8 otherwise 0.3 for all cases
bb=width of beam
hc =depth of column
To restrict the permissible shear force in the joints due to eccentric effect in the joint constant m is being used. It has stated that further researches are needed in eccentric beam column connections. Different experimental works have been carried out by different researchers and are validated with numerical simulations performed on finite element program to observe the eccentric effect of the RC beam column [3][5][6][7].

2. Modeling Approach

RC bared framed structures of 1 to 4 stories residential buildings with bay numbers varying from 1 to 3 in both X and Y directions are taken for the analysis in ETABS. Buildings are fixed at the bottom support. The buildings are categorized into two types: having concentric and eccentric beam column connections respectively. Floor height of the building is taken as 3m and the length of each bay in both X and Y directions is 3m. The thickness of the slab is taken as 125 mm for first two models: M1 and M2 and 200mm for M3 and M4 models. For linear static analysis 1, 2 and 3 storied buildings of bay number varying from 1 to 3 of M1 is taken. Altogether there are 24 building models for pushover analysis and 36 building models for linear static analysis.M20 grade of concrete with Young's modulus value of 22.36 Gpa and poison ratio of 0.2 and reinforcement of yield strength 500 Mpa with Young's modulus values of 210Gpa and poison ratio of 0.3 is used. Building models are categorized according to the different column and beam sizes which are as tabulated below:

Table 1: Model Details

Models	Beam size	Column size
M1	225x325	300x300
M2	250x400	300x450
M3	300x400	450x450
M4	300x500	450x600

The beams and columns of the buildings are modeled using frame elements and the slabs as thin shell element.Also the slab action has been modeled using diaphragm action. The size of various members are chosen satisfying the requirements of NBC [8][9]. Load combinations are used as per [10]. Analysis is done to accomplish the design and ductility requirement of Indian standards [10] [11][12]. The various loads used in the analysis process is tabulated as below:

Table 2: Loads on the building:

Descriptiom	Load
Concrete	$25kN/m^3$
Live load for typical floors	$3kN/m^2$
Live load for roof	$1.5kN/m^2$
Floor Finish	$1.5kN/m^2$
Wall Load	10kN/m
Parapet wall	1.5kN/m

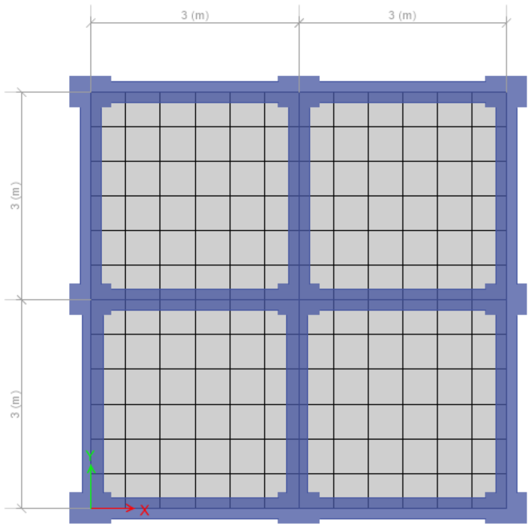

Figure 3: Building plan with Concentric joints

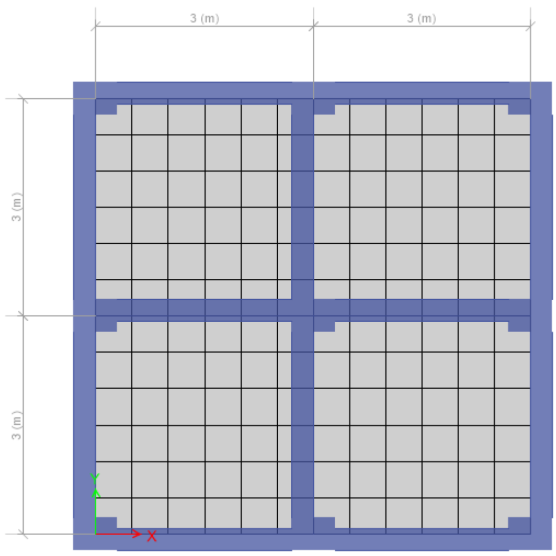

Figure 4: Building plan with Eccentric joints

2.1 Building modeling

The behavior of the purposed building is studied under static linear and nonlinear headings in response to seismic excitation. Different configurations of buildings are selected to compare the seismic behavior of buildings with eccentric and concentric joints respectively. Eccentricity is modeled in the building using frame insertion point method. Linear static analysis is performed under gravity loading. To perform nonlinear static analysis pushover analysis is performed. Static nonlinear technique is one of the techniques used in performance based design to quantify seismic structural deformations. It depicts the realistic behavior of the structure as a whole subjected to lateral forces during an earthquake event.

The structure is subjected to gravity loading and displacement controlled lateral load pattern till the structure reach ultimate state. Pushover curve is generated as the output which is the plot of base shear against monitored displacement [13].

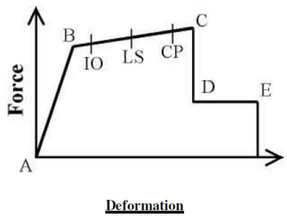

Figure 5: Pushover curve

The various performance levels are expressed as shown in the figure above. These levels determine damage limits from minor to severe from left to right location. The straight line from A to B represents elastic range, B to IO is the immediate occupancy; IO to LS is the life safety and LS to CP is the collapse prevention. If all the hinges are formed within the collapse limit the structure will be safe but after this limit the structure will collapse. The performance of the structure is desired till the collapse point. In the present work, monitored displacement value provided is equal to 4 % of building height. User defined plastic hinge properties of beams and columns are modeled and incorporated the same in ETABS. Hinges are assigned using default FEMA 356 concrete column P-M-M for columns and M3 for beams. Hinges are assigned at the 10% and 90% of the relative length.Pushover load cases are defined and unit acceleration is applied in both X and Y directions as pushover load in respective directions

2.2 Finite element modeling of joint

One fourth of beam and column length is used to simulate the behavior of the exterior beam column joint selected from the building using FEA program ABAQUS. Dynamic explicit model under quasi static displacement control condition is performed to simulate static nonlinear behavior. To observe the local failure of the joints finite element analysis is performed in this research. Concrete damage plasticity model with different damage parameters are taken from the paper [14] for concrete. An elasto plastic constitutive law for steel reinforcement is used throughout the whole geometry of the joint models and the data are obtained from ETABS. Engineering stress strain data from ETABS are converted to true stress and strain data in ABAQUS which is further input as yield stress and plastic strain data in ABAQUS. 3D two node truss elements for steel, 3D eight node brick elements for concrete and 3D four node rigid element for plate are used in this work. Tie contact is used in the inter facial region between beam and column and also between column and plate. The bond between concrete and rebar is assumed to be perfect (embedded region).Reference points and the corresponding surface is coupled using disturbing coupling constraint. Different plasticity model parameters taken for finite element modeling of concrete has been used from the work [14] [15] and are tabulated below:

The dimension of the mesh is 30mm throughout the joint model. Fixed boundary condition is applied at the bottom of column using rigid plate to avoid unwanted localized deformations at column when direct boundary conditions are applied. Push displacement of 300mm is applied at the tip of the beam using reference points. Dead load and live load are applied over the column top surface and beam top surface in the form of pressure as loadings. A uniform gravity load in the form of acceleration is applied over the whole concrete model.

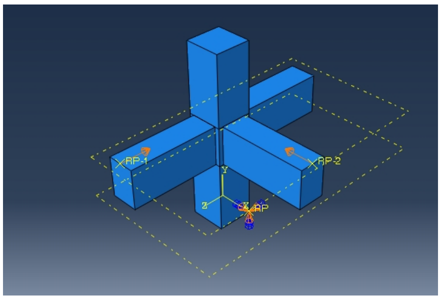

Figure 6: Finite element joint modeling in ABAQUS

3. Results and Discussion

3.1 Analytical results of buildings

• **Effect of eccentricity on energy dissipation capacities of the joint**

Nonlinear static pushover analysis is performed on G+1, G+2 and G+3 storied RC bare framed buildings with three number of bays of length of 3m in both x and y directions. The area under the pushover curve (monitored displacement vs. base shear) is computed which gives the amount of energy dissipated in the buildings during the pushover analysis. In the analysis, buildings with concentric beam column joints dissipated energy more than that buildings with eccentric joints which is in agreement with the research work [3] where it was illustrated that with the increase in joint eccentricity energy dissipation values were decreasing. The bar charts are plotted for energy dissipation values of different building models with varying story numbers as shown below. In model M1, it is observed that the energy dissipation values are more than 8% in buildings with concentric beam column joints than building with eccentric joints. In model M2 and model M3 energy dissipation values are greater than 10% in buildings with concentric joints. In model M4, energy dissipation values are nearly similar for stories 3 and 4 in both joints where these values are greater by 10 % in storey2 in buildings with centric joints than that in eccentric joints. The higher energy dissipation capacities in buildings affect the strength, stiffness and ductility behavior of whole building structure during seismic motion in response to inelastic deformations. So the buildings with concentric joints can perform satisfactorily under seismic loads. The bar charts are plotted for energy dissipation values of different building model with varying story numbers as shown below

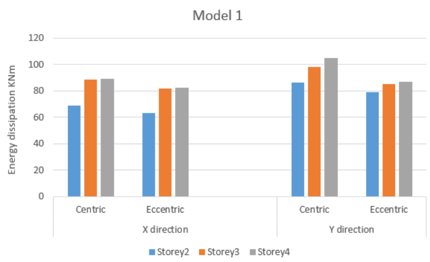

Figure 7: Energy dissipation values of building Model M1

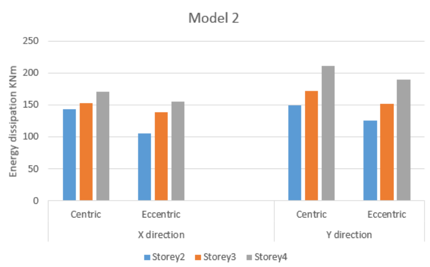

Figure 8: Energy dissipation values of building Model M2

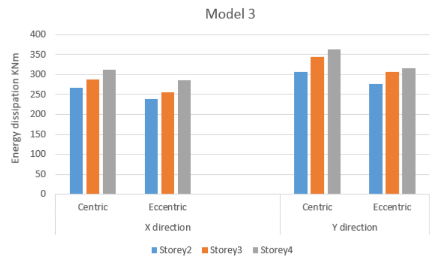

Figure 9: Energy dissipation values of building Model M3

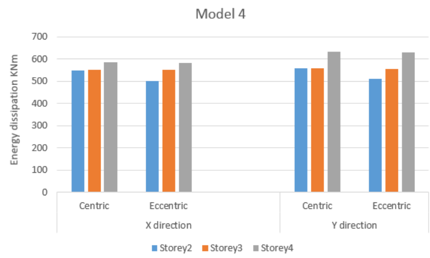

Figure 10: Energy dissipation values of building Model M4

• Effect of eccentricity on modal time periods

Nonlinear static analysis is performed on RC bare framed buildings of G+1, G+2and G+3 stories with three number of bays having length of 3m in each direction. Figure below illustrates the comparison of modal time period (seconds) in buildings with concentric joints and eccentric joints respectively. In model M1 time period values in buildings with eccentric joints are greater by 3 % than the buildings with concentric joints. In model M2 and model M3 time period values seem to be somewhat similar and slightly greater in buildings with eccentric joints. Similarly in model M4 time period values are greater by 5% in buildings with eccentric joints than with concentric joints. It is observed that the buildings with eccentric beam column joints has modal time period higher than that of concentric ones. It can also be seen from the graph that with the decrease in joint aspect ratio (Db/Dc) the modal time periods are decreasing. This may be contributed to the change in modal stiffness due to change in joint aspect ratio. Modal time period reduces with increase in stiffness. Hence eccentric ones are less stiff than concentric ones.

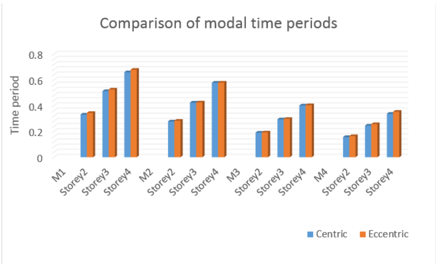

Figure 11: Comparison of Modal time periods

- **Effect of eccentricity with the increase in number of bays and stories**

Linear static analysis is performed on one, two and three stories buildings with bay number varying from 1 to 3 in both x and y directions (only symmetrical plans at a time) having bay length of 3m in each directions. Torsional moments (KNm) and shear forces (KN) are compared in the certain section of beam of buildings with concentric and eccentric joints respectively. Figures below demonstrate the graphs showing the variation of shear force and torsional moments with the variation of eccentricity respectively. From the graphs it can be observed that with the increase in number of bays and stories torsion and shear force increases in the beam. While the torsion values are greater for eccentric ones. When the full eccentricity values are applied at the joint torsion values were greater by 8% in all stories. Similarly, shear forces are greater by 6% in beam in buildings with full eccentricity values at the beam column joints being applied.

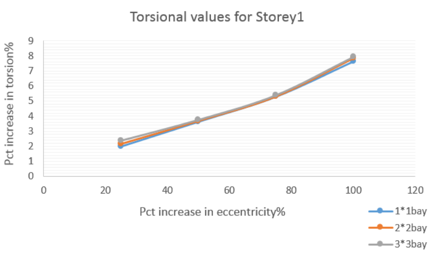

Figure 12: Percentage increase in Torsional moments with eccentricity for one story building

Figure 13: Percentage increase in Torsional moments with eccentricity for two story building

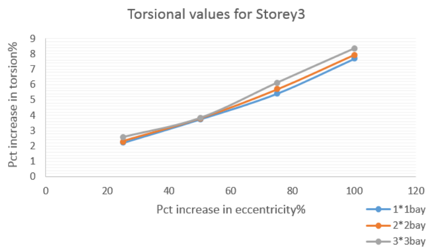

Figure 14: Percentage increase in Torsional moments with eccentricity for three story building

Figure 15: Percentage increase in Shear forces with eccentricity for one story building

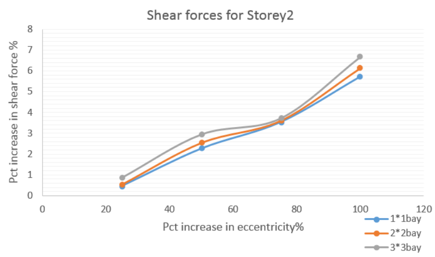

Figure 16: Percentage increase in Shear forces with eccentricity for two story building

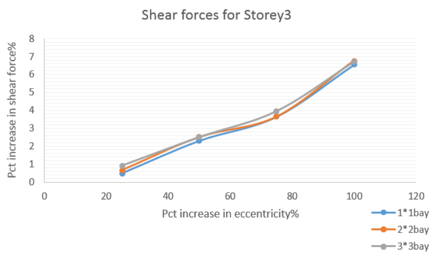

Figure 17: Percentage increase in Shear forces with eccentricity for three story building

3.2 Finite element results

Separate joint models for concentric and eccentric cases selected from building models (M1, M2, M3 and M4) have been modeled using ABAQUS 2017 .Nonlinear analysis have been carried out using dynamic explicit analysis and then maximum principal stresses are computed at the center of beam away from the joint area in separate joint models. The maximum principal stresses are compared for different values of eccentricity which can be illustrated in the graph below. Increase in stress values are in direction proportion to the increase in joint eccentricities. Stress values increased by more than 7 % with the increase in values of eccentricity by 25%, increased by more than 16% when eccentricity values increased by 50 % and increased by more than 30% when full eccentricity is applied at the joint.

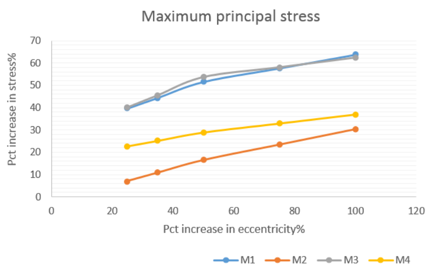

Figure 18: Percentage increase in principal stress at the center of beam with increase in joint eccentricity

4. Conclusion

The global performance of the building structures with concentric and eccentric beam column joints is enhanced using ETABS and the local performance of separate concentric and eccentric beam column joints is observed using ABAQUS and the following conclusions are made based on the results obtained:

- Torsion and shear forces in the beam are higher in eccentric joints by 8 % and 6 % respectively .This may result into high shear stresses which may lead to degradation of shear strength of the joints.

- When full joint eccentricity is applied in the beam column joints of RC framed buildings, the energy dissipation capacities decreased. Buildings with concentric joints have higher energy dissipation values. With the lower energy dissipation values, the buildings cannot perform satisfactorily under seismic loads and can disturb their ductility behavior.

- The modal time period values decreased in buildings with eccentric joints. So buildings with eccentric joints are less stiff than buildings with concentric joints.

- Stresses in the beam increased in direct proportion of increase in joint eccentricities. Stresses values increased by more than 7%, 16% and 30% with the increase in eccentricity by 25%, 50% and 100% respectively. Hence attention should be paid toward the proper design of eccentric beam column joints.

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