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Exterior Beam-Column Joints Under Varying Column Axial Load

Mohammed A. Sakr[1], Ayman A. Seleemah[1], Tamer El-korany[2], Ahmad G. Saad[3]

[1]*Professor, Faculty of Engineering, Tanta University, Egypt*
E-mail: mhsakr010@yahoo.com
[2]*Assistant Professor, Faculty of Engineering, Tanta University, Egypt*
[3]*Demonstrator at Misr higher institute, Mansoura City, Egypt*

ABSTRACT

Reinforced concrete beam-column joint (BCJ) has a great role to maintain the safety of buildings under influence of seismic forces. During seismic actions, overturning moments are produced by lateral loads that are translated as axial loads in the columns. BCJ behavior changes with frame column axial load level. This paper presents BCJ behavior under varying column axial load from the tensile capacity to the compression capacity of column using finite element model (FE Model). A two dimensional (2D) FE Model taking into account material non-linearity was proposed. The proposed FE Model is verified with experimental results available in literature with varying column load level and failed in different modes. The comparison between experimental and numerical results indicates that the FE Model is able to simulate the performance of BCJs and is able to capture the different failure modes with acceptable accuracy. Moreover, the proposed FE Model is used to conduct a parametric study to investigate behavior of two specimens designed according to Eurocode recommendations under varying column load levels. An interaction diagram was introduced for each specimen expressed the behavior under varying column axial load using FE Model and equations of Eurocode. Difference in results appeared between equations of Eurocode and FE Model results in joint shear strength capacity.

Keywords: Beam column joint, Column axial load levels, Tension, Finite element model, Eurocode, Interaction diagram.

1. INTRODUCTION

In a multi-storied building, reinforced concrete beam-column joint (BCJ) is an important component of a reinforced moment resisting frame and should be designed and detailed properly, especially when the frame is subjected to seismic forces. The main role of columns is transfer vertical forces from slabs to foundations, while joints transmit moments and shears of beams into the columns. Lateral loads such as earthquake and wind produce overturning moments that make columns and joints also subjected to variable moment, shear and axial load. The variation in axial load of columns as well as joints due to overturning moments leads to a compressive axial force on one side of the structure along with tensile on the opposite [1].

Many variables such as joint dimensions, concrete strength, bond resistance, column axial load, joint shear reinforcement, column to beam flexural strength ratio, slab effects and transverse beams affected on joint performance [2-4]. Most of these variables has been incorporated in several studies and consequently guidelines for design are available in the current design codes [5,6]. However, effect of magnitude of column axial load, which is a key influencing parameter in predicting shear strength of BCJ has not been considered explicitly thus far, and its complex effects on the BCJ failure mode remained not well understood.

A few number of experimental programs have been carried out to identify the behavior of BCJs under varying of column axial load. Masi et al.[7] conducted experimental work on beam-column joints to study influence of column axial load on the behavior of BCJ; the values of axial load ratio considered were

0.15 $f_c' A_g$ and 0.3 $f_c' A_g$ (f_c'-concrete nominal strength and A_g-area of column section). The results showed that the deformation and ductility are affected by the magnitude of column axial load and the value of the axial load acting on the column can change the collapse mode and spreading damage from the beam to the joint panel. Fujii and Morita [8] showed, the increase of column axial load level from $f_c'^*A_g/12$ to $f_c'^*A_g/4$ improved the shear strength of the exterior joints nearly 10 %. Li et al.[9] studied the effect of high axial load on the non-seismically designed BCJ with or without strengthening by ferrocement jackets with embedded diagonal reinforcements. The ratios of axial load considered were 0.2 and 0.6. Test results indicate that increasing axial load to 0.6$fc'Ag$ is detrimental for the joint with and without strengthening.
Some numerical studies also have been carried out using finite element model (FE Model). Haach et. al.[10] studied joint behavior numerically using the software Abaqus[11] under the influence of different levels of column axial loads (0.0, 0.2, 0.4,0.6 and 0.8). The results showed that significant values of strain in stirrups inside the joint region were observed earlier in specimens with low column axial loads than in specimens with high column axial loads. Also they showed that column axial load generated tension stresses on beam longitudinal reinforcement; therefore, the shear force in the joint is increased by this variable. The geometry of the joints and stress level in the column were the parameters studied numerically using DIANA software to investigate the shear strength of exterior joints [12]. Results have led to empirical expressions that provide the shear strength of unreinforced exterior beam-column joints. On the other hand, a group of researchers like Vollum and Newman[13] , Bakir and Boduroglu[14] and Park et. al. [15] believe that the axial load on the column does not affect joint shear strength. The column axial load affects the behavior of joints by changing their failure modes and their peak loads especially when the beam column connection suffering column hinging [15].
The main emphasis of this research work is to investigate the effect of column axial load levels from the tensile capacity to the compression capacity on the performance of BCJs under monotonic loading. This investigation will be carried out through numerical study using FE Model. Also this paper presents an interaction diagram (ID) of BCJ that able to consider the effects of the combination of lateral and varying column axial loads besides corresponding collapse mode at each column level. The proposed ID using two ways; the first is using Eurocode equations and the second is using FE Model. The comparison between Eurocode and FE Model IDs is one of the main objectives of this study.

2. FINITE ELEMENT MODEL

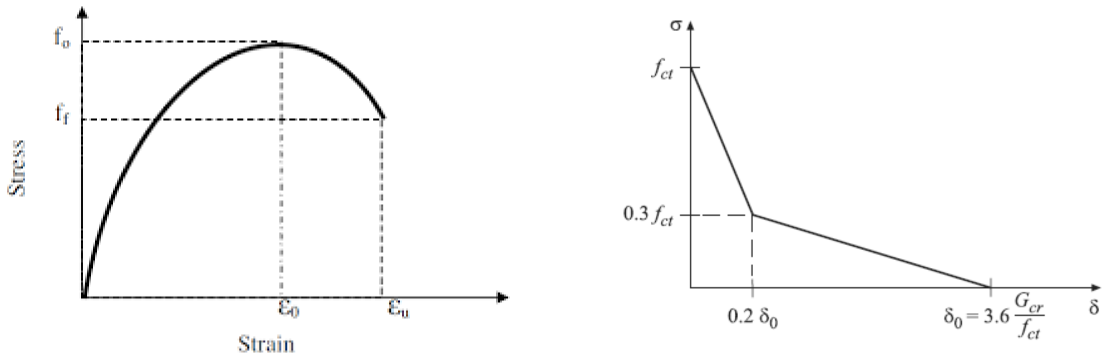
The FE simulation software Abaqus/standard[11] is used to develop 2D model taking into account material non-linearity and able to simulate the behavior of BCJs under varying column axial load. FE Model presented below delineates the modeling to simulate concrete followed by modeling of reinforcing steel and its bond behavior with concrete.

2.1. Modeling of Concrete

Abaqus allows three models to simulate the concrete behavior (a) concrete damage plasticity model, (b) concrete smeared cracking model, and (c) brittle cracking model. The concrete damage plasticity model is used in this study due to its ability in simulating the plastic properties of concrete and taking the softening behavior either in compression or in tension into consideration [17]. The main two failure modes are tensile cracking and compressive crushing [11]. The stress-strain relationship for concrete under compression is initially linear elastic until micro-crack initiation. Thereafter, the behavior becomes nonlinear as shown in Fig.1a according to Desayi [18] . Poisson's ratio for concrete was assumed to be 0.2. Under uniaxial tension the stress–strain response follows a linear elastic relationship until the value of the failure stress is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress the formation of micro-cracks is represented with a softening stress–strain response. The softening curve of concrete under tension could be represented by using the model of Hillerborg [17], as shown in Fig.1b, where f_{ct} is the tensile strength and G_f is the fracture energy of concrete. The elastic modulus, E_c, and tensile strength, f_{ct} were calculated by ACI 318-14 [5] as shown in the following equations.

$$E_c = 4700\sqrt{fc'} \qquad \text{Equation (1)}$$

$$f_{ct} = 0.33\sqrt{fc'} \qquad \text{Equation (2)}$$



a) Compression **b) Tension**

Fig.1. Uni-Axial Stress-Strain Curves of Concrete.

2.2. Modelling of Reinforcing Steel

The stress–strain curve for steel was assumed to be an elastic-perfectly plastic material and identical in tension and compression. The Poisson's ratio was 0.3. The values needed to draw the stress strain curve were the elastic modulus E_s, and the yield stress f_y.

2.3. Mesh and Bond Between Steel and Concrete

A linear plane stress rectangular (CPS4R) or triangular (CPS3) element, was used to model the concrete, the element is capable of plastic deformation, cracking, and crushing. The steel was modelled using a two-node 2D truss (T2D2) element in Abaqus, this element is also capable of plastic deformation. The embedded method with perfect bond (the embedded region constraint) between reinforcement and surrounding concrete is adopted to properly simulate the reinforcement concrete bonding interaction. Using a suitable mesh can help to reach accurate results and find narrow cracks in reinforced concrete structures, so a mesh size of 10 to 40 mm was used in this study.

3. NUMERICAL VALIDATION

FE Model described above has been validated with experimental results available in literature. A comparison of experimental results and FE Model prediction is presented next to validate its competency to envisage the failure load, mode of failure and overall behavior of BCJs. The chosen tests were Kaku and Asakusa [19], Eslami and Ronagh [20]. Experimental specimens have been chosen to cover different column axial load levels (-0.04 and 0.2), also cover different collapse modes (joint or beam).

3.1. Kaku and Asakusa [19]

Reversed cyclic loading tests were carried out for eighteen reinforced concrete exterior beam-column joints designed in accordance with the principle that yielding of adjoining beam or column preceded joint shear failure. Column axial force, amount of joint hoop reinforcement, existence of intermediate column bars, and moment resisting capacity ratio of beam to column were selected as experimental variables. The reinforcement and detailed dimensions of specimen No.13 as showed in Fig.2. The yield and ultimate stresses of the longitudinal reinforcement and transverse reinforcement, the concrete compressive strength and column load level for specimens No.13 are shown in Table.1. According to boundary conditions applied to specimen, column was simply supported at both ends and the tension axial load was applied to the column's end using a hydraulic cylinder. The column axial tension load is applied to the top of column corresponding to 4% of the compressive strength of concrete in the first step. The lateral load was applied in second step to the beam tip.

The numerical simulation agrees well with test results. The first yielding in specimen No.13 occurred in the longitudinal beam bars at 41 kN then shear failure in joint at peak load of 46 kN. Fig.3 shows the finite element analysis results of force-displacement curve which is compared with the envelope curve of the cyclic loading response, also the plastic strain distribution at peak load.

Table 1: Mechanical Properties of Steel Reinforcement.

Concrete compressive strength fc' (MPa)	Column level (v_d)	Reinforcement type	Main Bar	Yield strength	Ultimate tensile strength
46.4	-0.04	Longitudinal R.F.T. of beam in each side	4 D 13	391	594
		Total longitudinal R.F.T. of column	12 D 10	395	564
		Stirrups	R 6	250	537

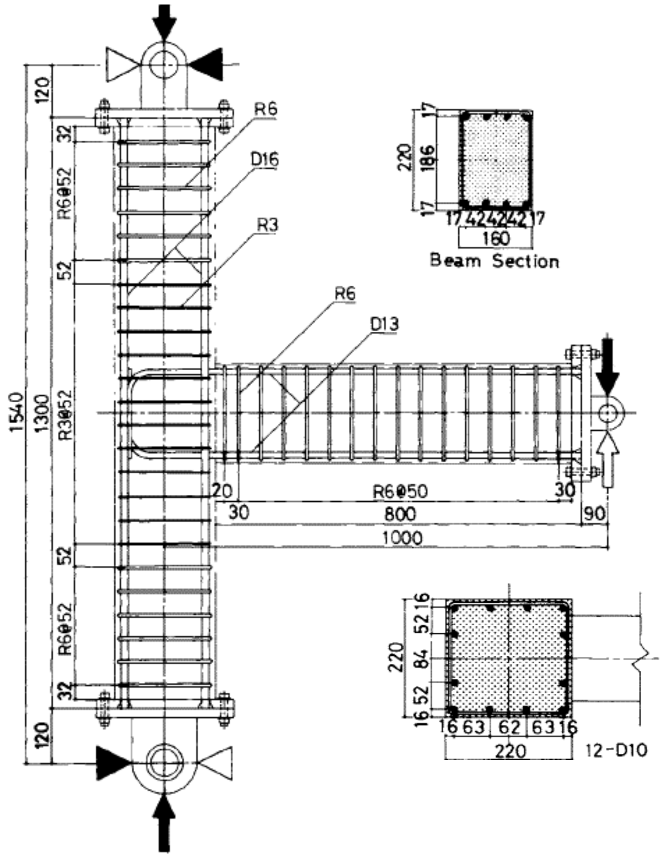
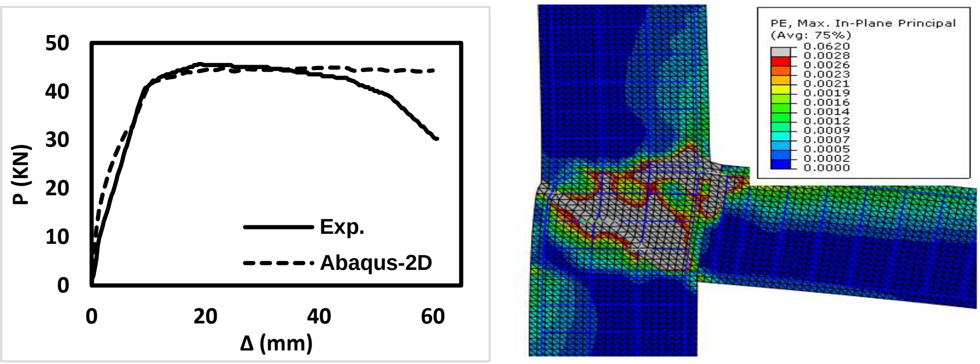


Fig. 2. The Geometry and Details of The Test Specimen[19].

Fig. 3.



(a) **(b)**

Comparison between FE Model results and experimental results:

a) Load-deflection curve; b) Numerical plastic strain distribution at peak load.

3.2. Eslami and Ronagh [20]

An exterior beam-column joint namely CS was tested under monotonic loading and the column axial load of 344 kN was applied, this axial load represents a uniform stress approximately equal to 0.2 fc' on the column section, the reinforcement and detailed dimensions of test specimen are shown in Fig.4. The mechanical properties of the steel reinforcement and concrete are summarized in Table 2.

Table 2: Mechanical Properties of Steel Reinforcement.

Concrete compressive strength fc' (MPa)	Column level (v_d)	Reinforcement type	Main Bar	Yield strength	Ultimate tensile strength
45.9	0.2	Beam and column longitudinal	10 mm	521	692
		Stirrups	6mm	545	600

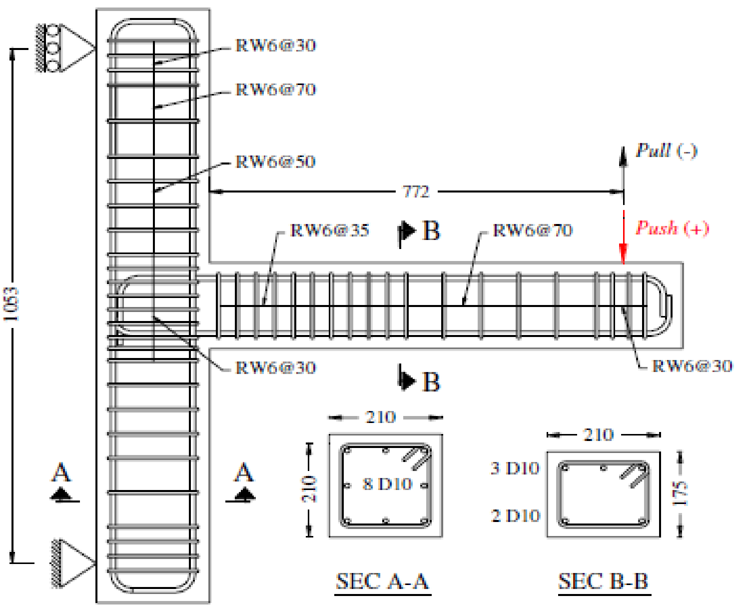
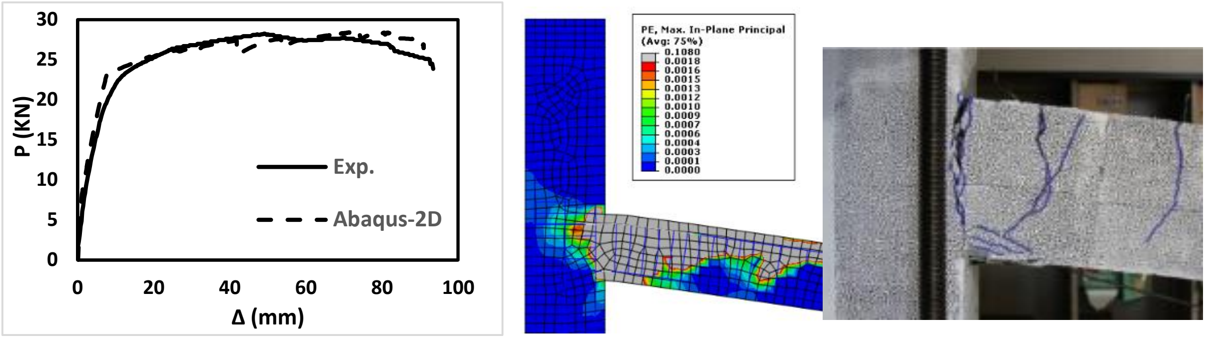


Fig. 4. The geometry and details of the test specimen[20].



(a) **(b)** **(c)**

Fig. 5. Comparison between FE Model results and experimental results: a) Load-deflection curve;

b) Numerical plastic strain distribution at peak load; c) Experimental failure condition.

The numerical results confirmed the weak-beam–strong-column condition adopted in the experimental work. The flexural cracks were developed and widened in the plastic-hinge regions of beams, while the column and joint core remained intact. The failure was also accompanied by concrete crushing in compression. The yield displacement of the tensile reinforcements of experimental and numerical is 6.5 mm and 7.5 mm respectively. In addition, the maximum load was recorded at 28 kN experimentally and 28.3 numerically. Fig.5 shows the finite element analysis results of force displacement curve which are compared with the monotonic curve of the test and plastic strain distribution at peak load.

4. PARAMETRIC STUDY

To study the behavior of seismically BCJs under varying column axial load and proposed an interaction diagram, two specimens designed according to Eurocodes [6,21] were studied under varies column axial load levels from the tensile capacity to the compression capacity of column using verified FE Model.

4.1. Design of Specimens According to Eurocode

Two specimens had the same material properties, the yield stress of longitudinal reinforcement, the yield stress of transverse reinforcement and the elastic modulus (E_s) were 400 MPa, 280 MPa and 200 GPa respectively, in addition, the concrete compressive strength (fc'), the concrete tensile strength (f_t) and the concrete elastic modulus (E_c) were 30 MPa ,2.9 MPa and 33 GPa respectively. The two specimens have stirrups ratio able to prevent the shear failure in beam and column sections according to Eurocode-2 [21]. First specimen (C1) designed at column compression level (V_d = 0.2), while specimen (C2) designed under column tension level (V_d = -0.15). The two specimens satisfy the following Eurocode-8 [6] recommendations.

$$\frac{\sum M_{R_C}}{\sum M_{R_b}} \geq \mathbf{1.3} \qquad \text{Equation (1)}$$

$$\boldsymbol{A_{sh}} \geq \frac{1.2 * A_{sb} * F_{yb}}{F_{y_{wd}}}(\mathbf{1} - \mathbf{0.8} * \boldsymbol{V_d}) \qquad \text{Equation (2)}$$

$$\boldsymbol{A_{sv.i}} \geq \frac{2}{3} * \boldsymbol{A_{sh}} * \frac{h_{jc}}{h_{jb}} \qquad \text{Equation (3)}$$

Where:

$\sum M_{R_C}$: The sum of the design values of the minimum moments of resistance of the columns within the range of column axial forces produced by the seismic design situation.

$\sum M_{R_b}$:The sum of the design values of the moments of resistance of the beams framing the joint.

A_{sh}: The total area of horizontal hoops to be provided within the joint.

A_{sb} : The area of the beam longitudinal tensile reinforcement.

F_{yb} : Yield stress of beam reinforcement bars.

F_{ywd} : Yield stress of joint stirrups bars.
v_d: The normalized design axial force of the column (v_d = N / Ac × fc').
$A_{sv.i}$: The total area of intermediate bars placed in the relevant column faces.
h_{jb} : Depth of beam section.
h_{jc} : Depth of column section in the relevant column faces.

Table 3 shows geometric characteristics of the two specimens, and Fig.6 shows details of specimen C1. The two specimens C1 and C2 are calibrated by the FE Model that verified before using software Abaqus/standard [11], Fig.7 displays concrete plastic strain and reinforcement S11 stresses output at each column load level related to specimen C1 only to shortcut.
Through the peak load and mode of failure corresponding to each column load level, Abaqus used to construct ID as shown in Fig.8 and Fig.9, where symbols B, C and J refer to beam, column and joint failure respectively.

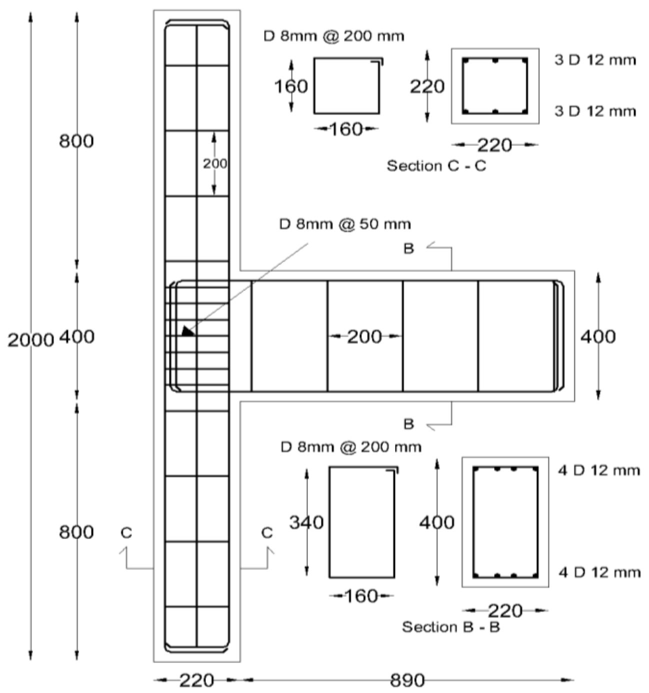


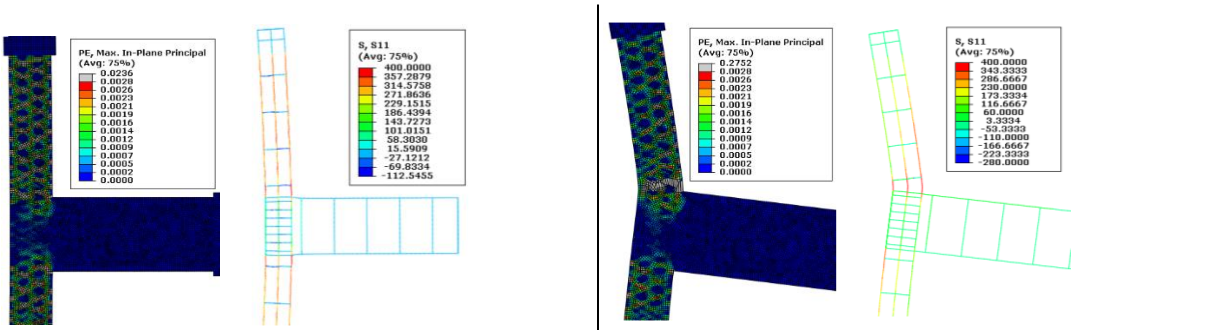
Fig. 6 Geometric characteristics of specimen C1.

Table 3: Geometric Characteristics of Specimens.

Specimen	Beam			Column				Moment capacity			Joint	
	b_b (mm)	h_b (mm)	As =As' (mm²)	b_c (mm)	h_c (mm)	Main bars (mm²)	Column level (V_d)	M_c kN.m	M_b kN.m	$\frac{\sum M_c}{\sum M_b}$	Intermediate bars (mm²)	Stirrups (mm²)
C1	220	400	4D12 = 452	220	220	6D12 = 678	0.2 Comp.	42.3	64.0	1.32	2D12 = 226	7D8 = 351.75
C2	300	400	4D12 = 452	300	300	16D12 = 1808	-0.15 Tens.	42.0	64.6	1.3	6D12 = 678	7D8 = 351.75

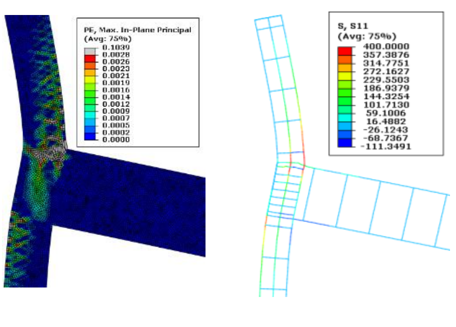
4.2. Results and Discussion

Abaqus-ID of specimen C1 that designed on compression axial load level (v_d=0.2) show that the column collapse mode occurred when the compression level of the column over 70% (v_d=0.7) or when the column is exposed to tension axial load level over 5% (v_d=-0.05). As well, the failure transfers directly to the joint if the column subject to compression axial load level less than design level (v_d=0.2).
Abaqus-ID of specimen C2 that designed on a tension axial load level(v_d=-0.15), the range of beam failure widen from the design column level (v_d= -0.15) to high compression level (v_d= 0.9). Also, joint failure occurred in column load level range from v_d= -0.15 to v_d= -0.2.
Comparing Abaqus results with Eurocode shows some variations in capacities and mode of failures at some column levels. For specimen C1 from column load level v_d= -0.186 to v_d= -0.05 mode of failure difference between Eurocode and Abaqus. Two different failures mode are observed; joint and column failure for Eurocode and Abaqus respectively. It is mean that Eurocode was under estimation comparing with Abaqus results. Also from v_d= -0.05 to v_d= 0.1 the difference is still in mode of failure between two IDs as observed, the column failed according to Eurocode while the joint failed according to abaqus. Compatibility between both Eurocode and Abaqus was observed in the remaining period of v_d= 0.2 to full compression capacity.
Comparing Abaqus results with Eurocode for specimen C2 show that from v_d= -0.29 to v_d= -0.2 the failure was at joint according to Eurocode while there are varying in mode of failure in abaqus results. At range from v_d= -0.2 to v_d= -0.15 both Eurocode and Abaqus agrees to the failure mode is at the joint. The deactivation of Eurocode for joint capacity at some tensile column load levels makes it greatly under estimated. From v_d= -0.15 to v_d= -0.05 modes of failure were joint and beam for both of Eurocode and abaqus respectively. There are no significant differences between the results of Eurocode and Abaqus in the remain column load levels.
Authors work on more study to these variations by design more specimens and analysis them using FE Model. Also work on getting more compatibility between Eurocode and abaqus by develop Eurocode joint shear strength equations.



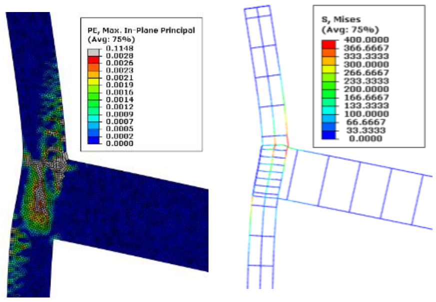
(a)	(b)	(a)	(b)
v_d=-0.2		v_d =-0.15	

Fig.8 Eurocode-ID and Abaqus-ID for specimen C1.



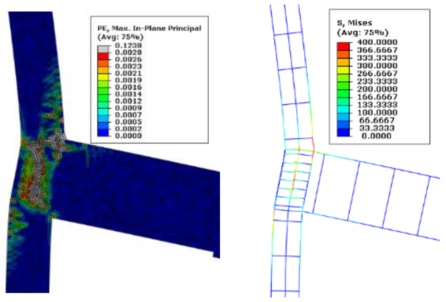
(a)	(b)

v_d =-0.10



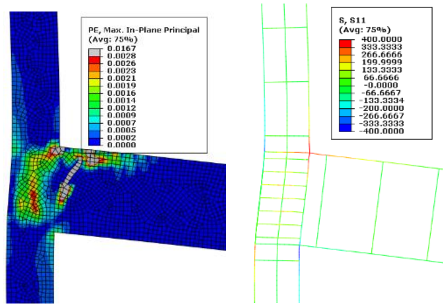
(a)	(b)

v_d =-0.05



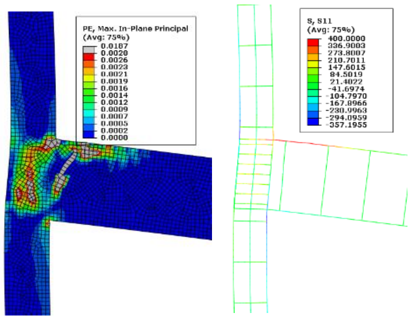
(a)	(b)

v_d =0.0



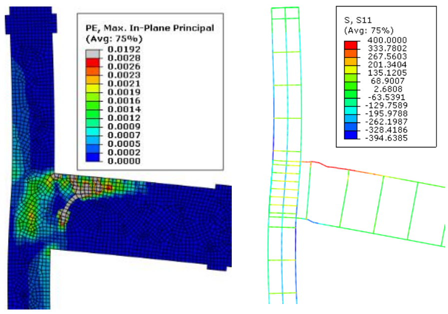
(a)	(b)

v_d =+0.1



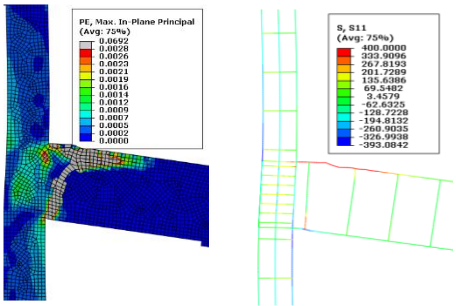
(a)	(b)

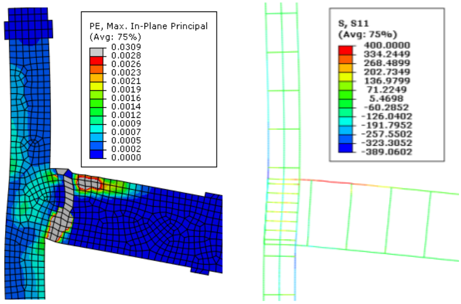
v_d =+0.2

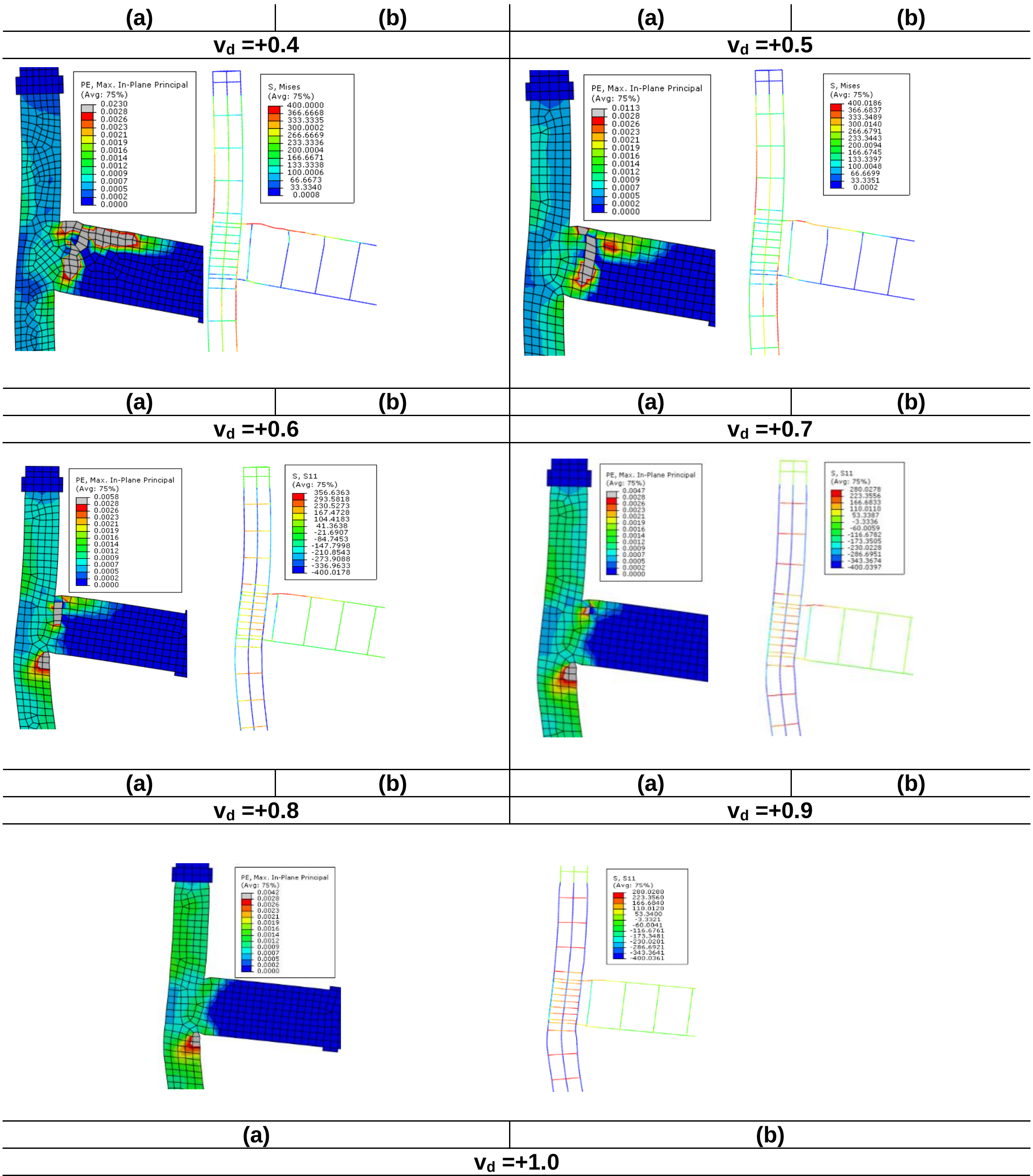


(a)	(b)

v_d =+0.3







a) Concrete plastic strain b) Reinforcement S11 Stresses
Fig. 7: Numerical Results for Exterior RC-BCJ Specimen C1.

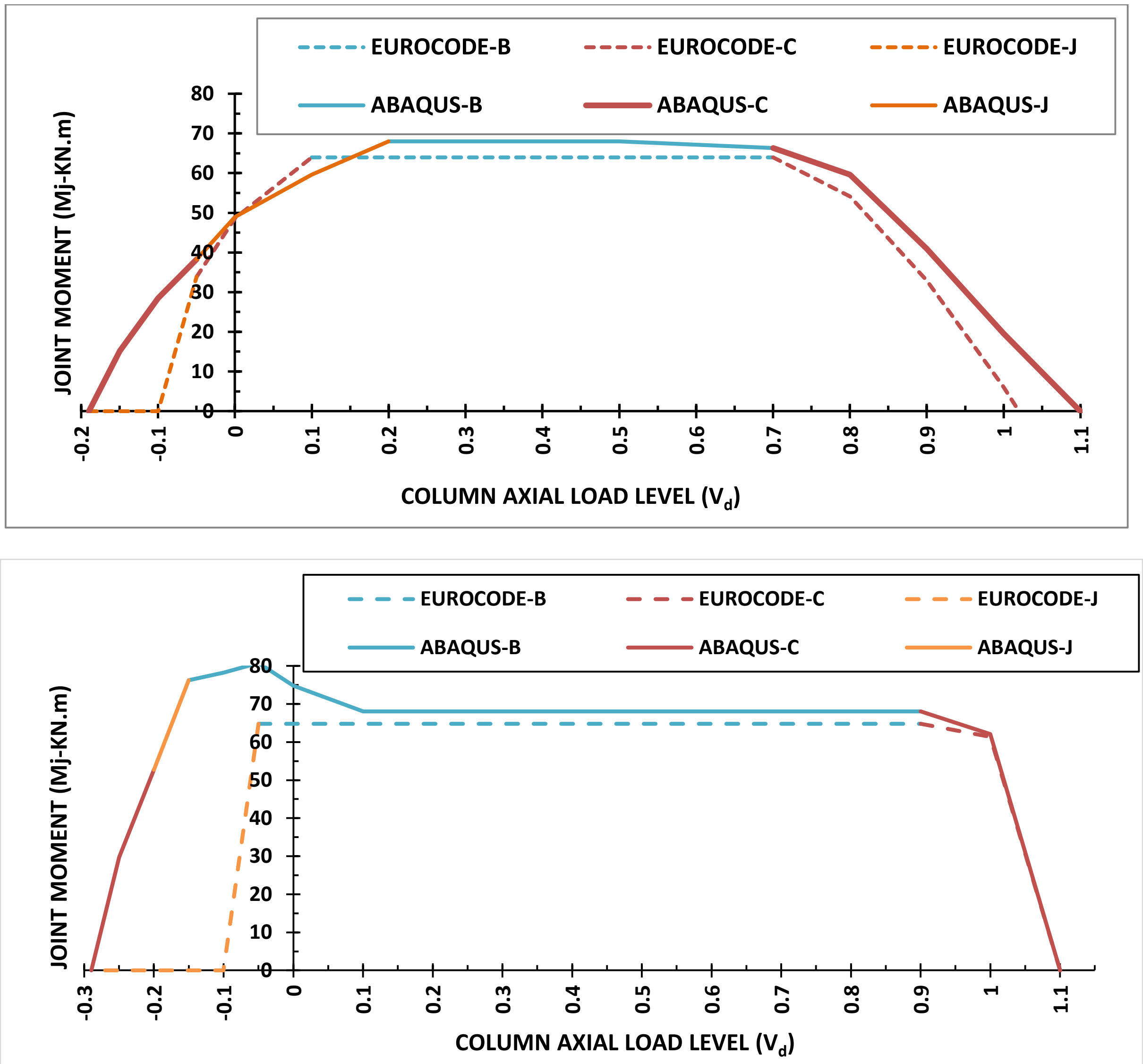


Fig.9 Eurocode-ID and Abaqus-ID for specimen C2.

5. CONCLUSIONS

The purpose of the investigation described herein was to evaluate the effects of column axial load on the response of beam-column joints. The range of column axial load level was from tension column capacity to compression column capacity.
The following remarks can be drawn:

- The 2D FE Model takes material non linearity into consideration presented in this research is able to accurately estimate the ultimate load and the behavior of RC beam-column joints under varying column axial load levels. Verified the proposed FE Model accuracy by comparing it with experimental results available in literature.
- Varying column load level has a direct and definite effect on the change mode of collapse by increase or decrease joint shear strength capacity.
- BCJ-IDs which proposed using Eurocode equations and FE Model results proofed that the Eurocode with some column load levels is under estimate the failure load and the mode of failure.

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