

Mechanical behavior of RC exterior wide beam-column joints under lateral loading: a parametric computational study

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Abstract—A computational investigation was conducted using finite element model to evaluate the influence of geometric parameters on the behavior of exterior wide beam-column connections for reinforced concrete (RC) members under 5% lateral drift. After accurately verifying this model against existing experimentally recorded data, the force–displacement curves were determined for various dimensions of wide beam-column joints. The influence of dimension variation for wide beam on ductility, strength and energy dissipation of the exterior joint was quantitatively evaluated. The results demonstrated that the amount and configuration of steel reinforcement has significant influence on behavior of wide beam-column connections. For widths ranging from 600 to 1000 mm, an increase in width can result in up to 36% reduction in ductility, 36% strength enhancement and 33% increase in energy dissipation. In addition to this, the effect of axial load on strength of structures was studied and the results showed that for the axial load increase from 150 to 350 kN resulted in a 30% reduction in strength.

Keywords: Reinforced concrete, wide beam, beam-column connection, finite element model.

I. INTRODUCTION

One of the most useful structures in civil engineering for resisting against lateral loading is moment frame system. It is clear that beam-column connections are the most critical parts in the moment frame systems, as they tolerate maximum loads and moments, under lateral loading. Wide beam-column joints are one of several types of reinforced concrete (RC) connections that are being used in these frame systems and it has many advantages such as decreasing the time and cost of construction processes. These merits have led to the development of several studies to evaluate the behavior of this connection [1]. Despite its advantages, there are some performance limitations such as low capacity to absorb energy which restricts the application of this connection type in locations with seismic activity [2, 3]. However, some researchers have suggested that improving the details of these connections can enable the use of them in seismic regions without limitation [4, 5]. Previous research into wide beam-column connections includes experimental tests that were carried out to understand and improve lateral sway behavior. Russell Gentry and Wight conducted an experimental test by using 850 mm wide beam-column joints in high seismic areas and concluded that the transfer of plastic hinge bending moment to the column should be taken into account to prevent transverse beam damage by cracking due to torsional moments [6]. Li and Kulkarni investigated 800 mm wide beams experimentally and numerically, where it was found that reinforcement ratio in the column-to-beam connection has significant effect on behavior of these connections [2, 9]. LaFave and Wight evaluated three exterior reinforced concrete wide beam-column joints according to the American Concrete Institute provisions under lateral quasi static loading and concluded that the strength of these joints when resisting against torsional moment is similar to conventional joints [7, 8]. Elsouiri and Harajli conducted an experimental test on four interior wide beam-column connections, with 800 mm wide beams and 200 by 650 mm columns, to assess the behavior of RC wide beam-narrow column under seismic loading. The results revealed that by improving reinforcement detailing, behavior of joints dramatically improved [11]. Elsouiri et al. investigated seismic behavior of exterior wide beam-column joints by using two full scale gravity-load designed specimens under quasi static cyclic loading and two more joints considered “earthquake resistant”. They concluded that the detail of reinforcements can significantly increase seismic resistance by delaying shear failure in joints [10]. A study was carried out by Dominguez et al. on one slab with wide beam-column joints under the 2011 Lorca earthquake loading of magnitude 5.1 in Spain. They concluded that buildings designed without any seismic provisions did not survive Lorca earthquake loading, even in low seismicity areas. While, other buildings that had met seismic requirements, survived under higher seismic loadings [12]. An experimental study was carried out by Fernando et al. to investigate European code provisions about behavior of wide beam-column connections. It was revealed that by applying these provisions the behavior of wide beam joints was similar to conventional joints under the same lateral loading [13]. Another

investigation was conducted by Mirzabagheri et al. on two conventional joints and two joints with wide beam. The results demonstrated that the shear strength of the wide beam-column joints was sufficient while it was not sufficient for conventional beam-column connections. Additionally the energy dissipation was the same for all specimens [14].

Some analytical research has also been conducted to evaluate the behavior of connections especially in wide beam-column joints areas. An analytical study was carried out by Rodriguez et al. in beam-column connections to investigate the effect of bond deterioration between bars and concrete [15]. To estimate the displacements of several types of beams, especially wide beams, a method that is called the indirect displacement estimation using acceleration and strain (IDEAS) was developed by Cho et al. [16]. A study conducted by Unal and Burak produced models for predicting the influence of a variety of parameters such as eccentricity and transverse beams on the seismic behavior of the beam-column joint [17].

Using finite element (FE) model is one of the most convenient and practical analytical methods to evaluate the behavior of structures. Limitations of experimental tests, such as the high financial costs for full scale tests and the time constrains for preparation of complex geometry and load applications, can be solved by using finite element simulations [18- 21]. Moreover, a key parameter which can influence the behavior of connections under lateral loading, is the axial load being applied to the column. A number of research studies have been performed to investigate the effect of this parameter on the column-to-beam joint behavior. An investigation performed by Kitayama et al. [22] cited that an axial load smaller than $0.5 f_c A_g$, where f_c is compressive strength of concrete and A_g is gross area of RC column section, does not have significant effect on shear strength of connection. Bing Li and Kukarni [2] studied the effect of axial load on shear strength by investigating axial loads in the range of $0.1 f_c A_g$ to $0.4 f_c A_g$. They conclude that when the axial load increased to $0.2 f_c A_g$ and $0.25 f_c A_g$, shear strength of models enhanced, whereas for loads above $0.25 f_c A_g$ the shear strength decreased. However no study to date has examined the influence of beam width variations and amount of axial loads smaller than $0.1 f_c A_g$, on behavior of exterior wide beam-column connections under lateral displacement.

To investigate the influence of dimension variation and load application on the behavior of RC wide beam-column connections, this study selected a numerical investigation to evaluate the behavior of exterior wide beam-column connection specimen (EWBCC) under lateral loading. This model was verified by experimental results reported from test carried out by Fadwa et al. [3]. The influence of the geometric parameters on ductility and strength of the exterior joint was quantitatively evaluated. In addition to this, dissipated energy and the impact of axial load on the wide beam-column connections were investigated.

II. METHODOLOGY

A parametric study was performed to quantitatively investigate the influence of beam width variation on the behavior of the exterior wide beam-column joint. ABAQUS/CAE software was used to model a EWBCC specimen with the same details as those experimentally tested in Fadwa et al. [3]. According to the experimental test, an exterior wide beam with cross-section of 900 by 300 mm and column with cross section of 400 by 450 mm, were used. Figure 1 shows the details and the locations of the reinforcements of this joint which are identical to Fadwa et al.'s specimens. As is shown in Figure 1, 4 of the 7 longitudinal reinforcing bars in the beam are located outside the column core. Additionally, 4 and 6 bars with diameters of 16 mm were used at the top and bottom of the column core respectively, to represent the transverse beams reinforcing bars. The transverse bars help to confine and improve the joint's behavior. In the numerical setup, the beam ends had vertical constraints and the bottom of the column was pinned, to match the test setup of Fadwa et al.'s experimental research.

Table 1 shows the geometric characteristics of different specimens where the column and beam reinforcement details have been reported in this study, the models have been labelled by the letters BW which relate to the beam width. For instance BW600 is a wide beam-column connection where the width of beam is 600 mm. In this study the beam width is the key parameter and it varies from 600 to 1000 mm. As is presented in Table 1, longitudinal reinforcement bars are also a key parameter and their amount is either 2 or 4 and 5 or 7 for bottom and top of the beam respectively, with wide beams receiving more reinforcing bars. The dimensions for the column cross section are 400 by 450 mm and the height of the beam is 300 mm for all models.

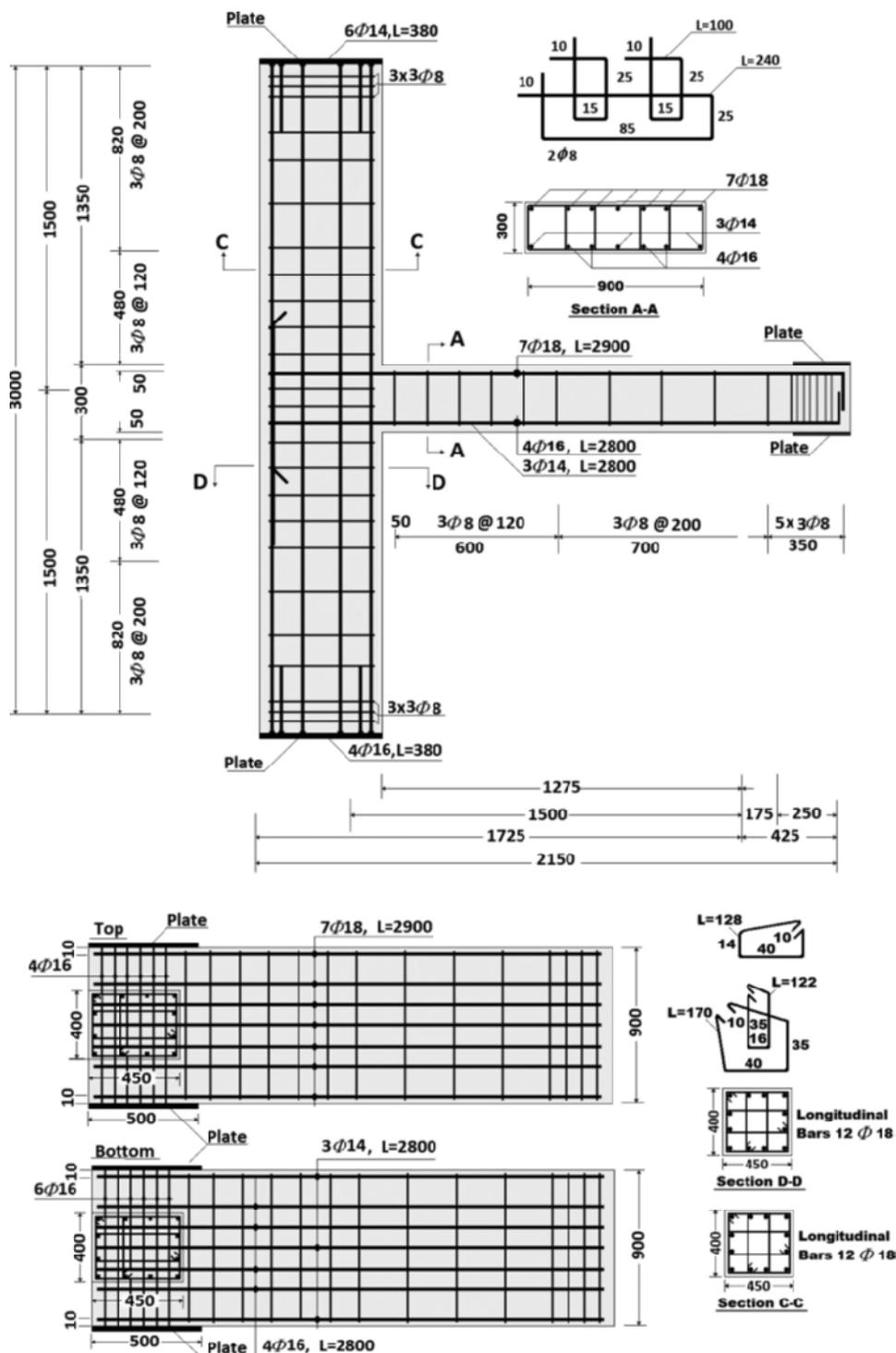


Fig.1. Reinforcement and dimension details of experimental test [3]

TABLE I. Reinforcing Bar Detailing

Row	Specimen name	Column reinforcement	Beam reinforcement	
			Down	Up
1	BW600	12Ø20	3Ø14+2Ø16	5Ø18
2	BW700	12Ø20	3Ø14+2Ø16	5Ø18
3	BW900	12Ø20	3Ø14+4Ø16	7Ø18
4	BW1000	12Ø20	3Ø14+4Ø16	7Ø18

A. FE model

ABAQUS 6.13 software was used for analyzing the specimens by using finite element method. Having symmetric specimens, half models were simulated to decrease computational time. Loading and boundary conditions of the specimens are exactly similar to the experimental tests [3]. A lateral displacement of 150 mm, which corresponds to a 5% drift for the 3 m columns, and an axial load of 230 kN were applied on the top surface of the column. In accordance with the experimental study, both ends of the beam were restricted to move only through the beam axis as shown in Figure 2, and as such were vertically constrained. Elastic-linear plastic model was used to define mechanical properties of the steel reinforcement. The value of the elastic modulus and yield stress of the reinforcement as reported in experimental study was in the range of 195.7 - 224.5 GPa and 345 - 497 MPa, respectively. Ultimate stress of the reinforcement was 730 MPa and ultimate strain was 0.51. For the concrete, the elastic modulus, tensile strength and compressive strength were reported as 20.2 GPa, 2.68 MPa and 28.73 MPa, respectively. Concrete Damage Plasticity model was used to model concrete behavior subjected to lateral displacement. A 3 dimensional solid shape model using 3D Stress Hexahedral element type (C3D8R) was implemented to simulate concrete behavior. Wire shape model, in which truss elements (T3D2) were implemented, was used to simulate steel reinforcement behavior. The size of elements was refined several times in order to obtain a converged solution. Accordingly, 26433 C3D8R elements and 14300 T3D2 elements were defined as the most optimized number of elements for this FE model as shown in Figure 3.

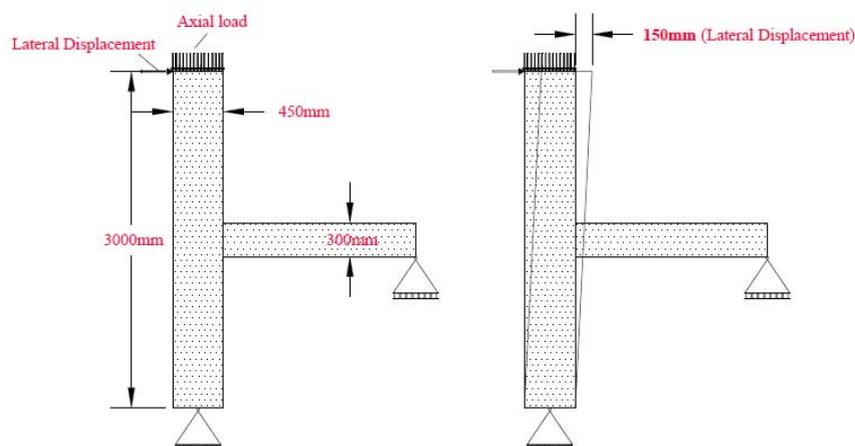


Fig. 2. Schematic view of the loading and constraints applied to FE model

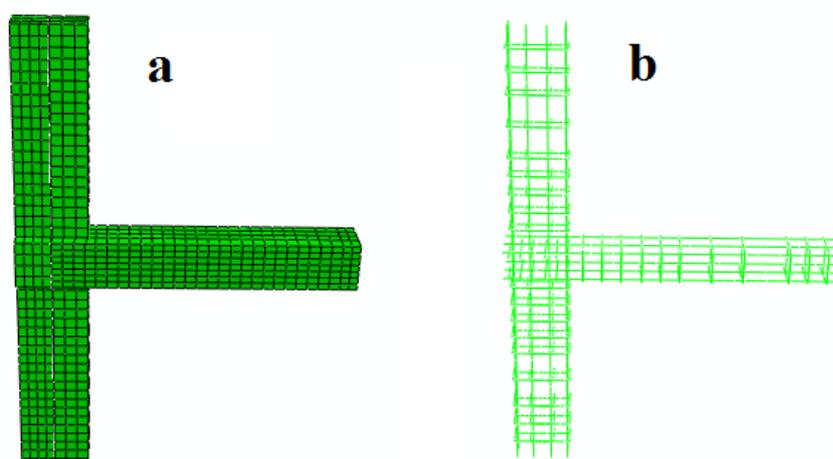


Fig. 3. Elements structure; (a) concrete (b) reinforcements

B. Model Verification

Figure 4 shows the graph of lateral load-horizontal drift of EWBC specimen for experimental test conducted by Fadwa et al. [3]. The trace of the envelope behavior of EWBC structure is compared with the force-displacement graph from the numerical model simulated by ABAQUS software and shown in Figure 5.

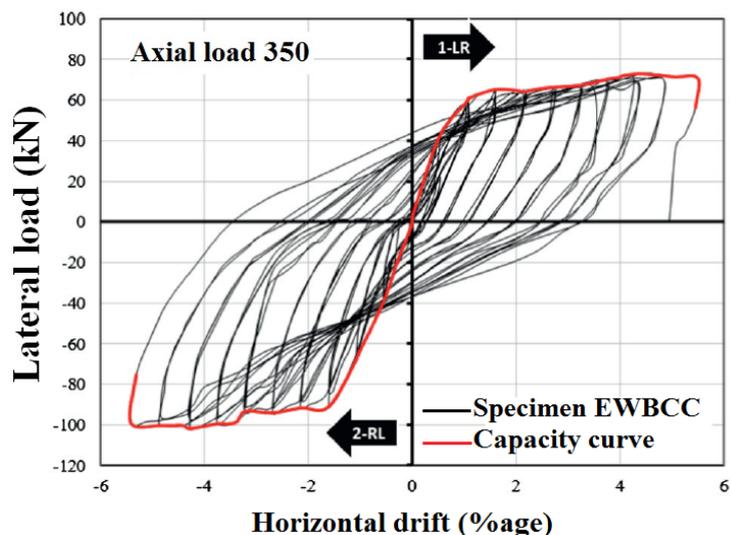


Fig.4. Lateral load versus drift ratio of experimental test

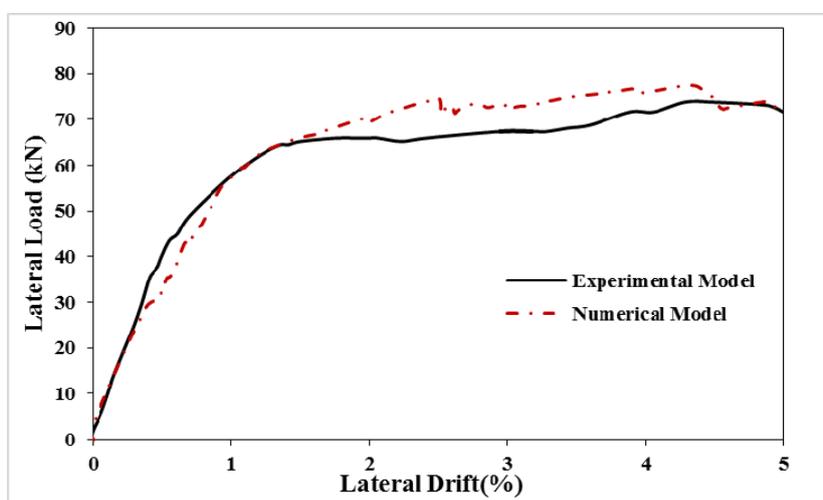


Fig.5. Verification of finite element model of BW900 results with experimental results

As can be seen in Figure 5, there is a close correlation between the force-displacement graphs of the FE simulation and experimental test which verifies the accuracy of the numerical model. The elastic phase of the FE model, which corresponds to a lateral load up to approximately 25 kN shown in the Figure 5, shows very close agreement with the experimental model. Furthermore, the plastic phase shows good agreement with a maximum difference between experimental and numerical curves occurring at approximately 2.25 percent drift with only 11 % difference. It is worth noting that the ultimate lateral drift experienced during the experimental testing is slightly above 5%, as shown in Figure 4. The FE modeling simulated a lateral displacement of 150 mm, which corresponds to a drift value of exactly 5%, as shown in Figure 5.

III. RESULTS AND DISCUSSION

C. Mechanical properties

To determine the influence of varying beam width on mechanical parameters, including ductility and stress distribution, four models with various sizes of beam width (BW600, BW700, BW900 and BW1000) were simulated. The results of this simulation have been presented and investigated in the following sections.

Figures 6 and 7 demonstrate von Mises stress distribution of concrete and steel reinforcement respectively, for all four beam width configurations (i.e., BW600, BW700, BW900 and BW1000). The stress distributions are presented for an application of 150 mm of lateral displacement.

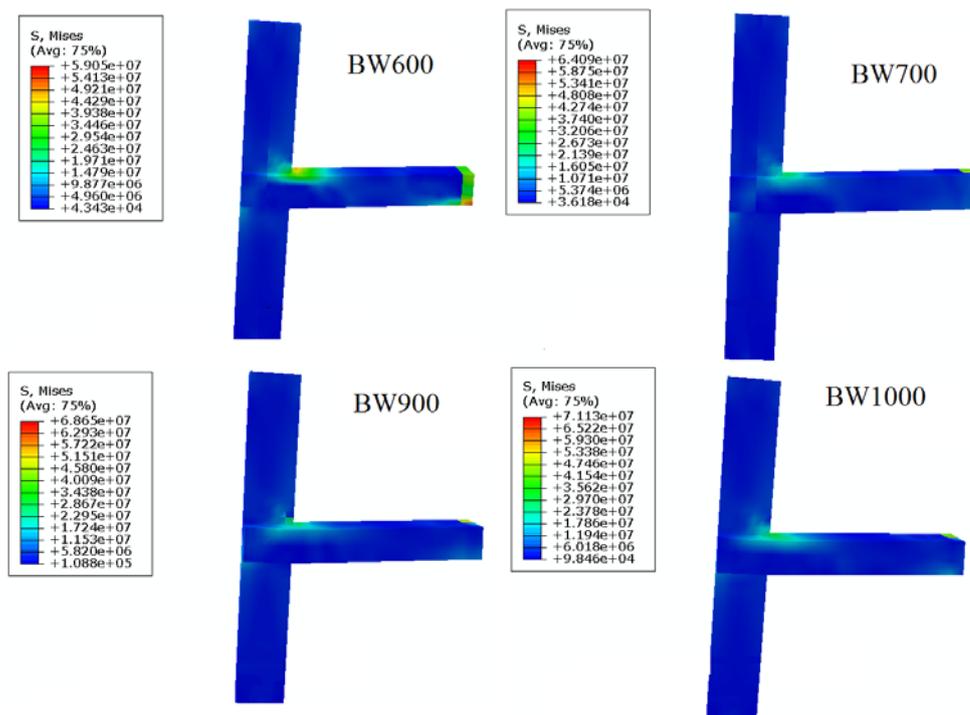


Fig. 6. Distribution of concrete stress in all beam width configuration

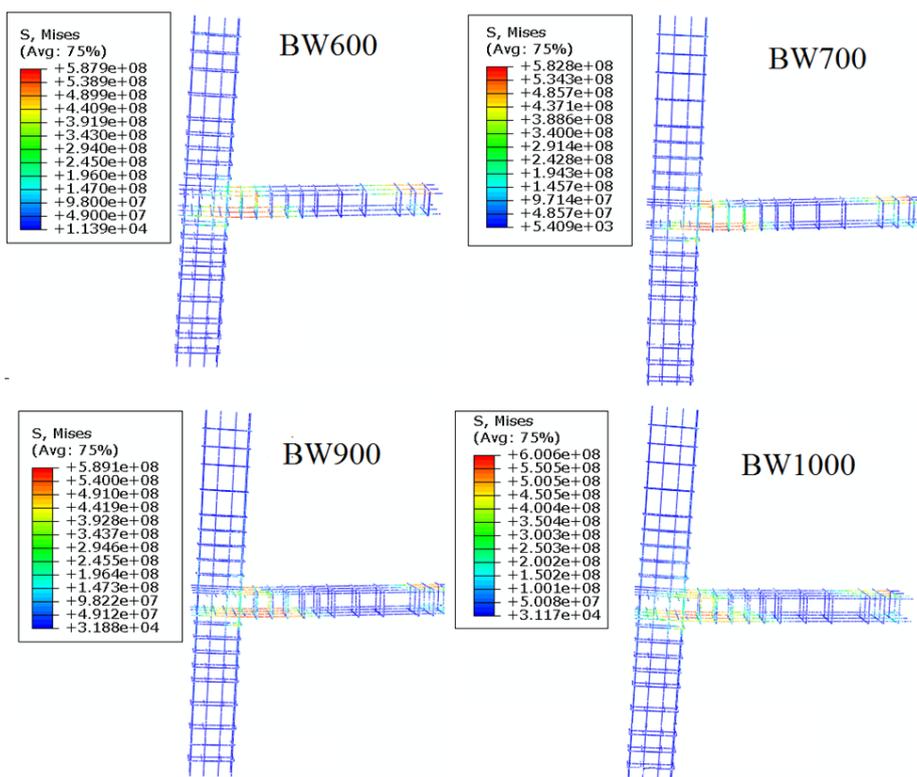


Fig. 7. Distribution of steel reinforcement stress in all beam width configurations

As expected, it can be seen in Figures 6 and 7 that the critical area of maximum stresses is located close to the beam-to-column connection. From Figure 6, it can be seen that the reported von Mises stresses for the concrete are 59, 64, 68 and 71 MPa corresponding to BW600, BW700, BW900 and BW1000 specimens, respectively. Therefore, it can be concluded that by increasing the width of the beam, the von Mises stress will increase under the applied lateral displacement. This outcome indicates that increasing the beam's width can result in the local damages in EWBC. It should be noted, Figure 6 demonstrates the stress distribution in concrete which is based

on the Concrete Damage Plasticity model. In this figure, higher stress, in a specific area, shows a local damage in each structure, while the strength of the whole structure may be higher in comparison with other specimens. Moreover, it should be noted that the loading process is by displacement-control and higher forces are required in specimens with wider beams to achieve the 150 mm displacement which can lead to higher concrete stresses in connection areas.

Figure 7 shows that, as expected, the stresses developed in the steel reinforcement are much higher than those in the concrete. Maximum stress developed in the reinforcement for all specimens is approximately 600 MPa, which indicates yielding of the reinforcement bar occurred for all 4 specimens.

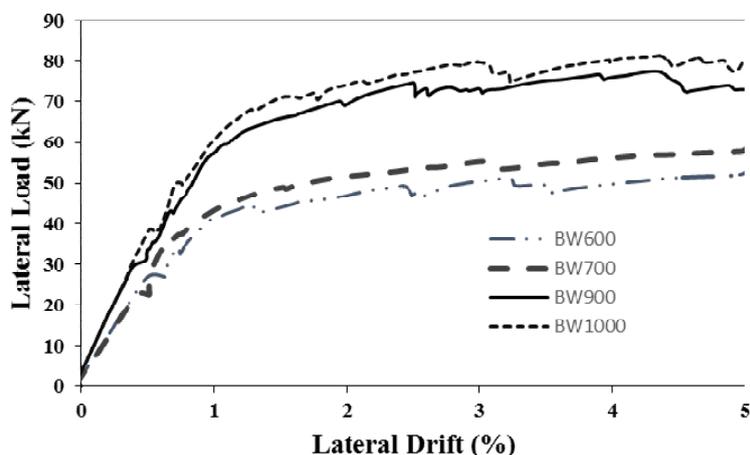


Fig.8. Force-displacement curves of all specimens

Figure 8 presents the force-displacement curves obtained from the FE simulation for all specimens of EWBC. As can be seen in Figure 8, the value of the lateral loads is almost the same when comparing beams with similar reinforcement (i.e., comparing BW600 to BW700 and BW900 to BW1000) until 0.7% drift which can be considered as the corresponding point in which plastic phase is initiated. Maximum tolerated lateral load of the BW600, BW700, BW900 and BW1000 specimens are 60, 62, 76 and 81 kN, respectively. Therefore, it can be understood that in plastic phase the beams with widths of 900 and 1000 mm resist approximately 60% higher loads when compared to beams with widths of 600 and 700 mm. It shows that the BW900 and BW1000 specimens can tolerate significantly more lateral force than others. This increase in lateral load can be attributed to the increase in steel reinforcement from 5Ø18 to 7Ø18 in top and 2Ø16 to 4Ø16 in bottom of beam as well as the increase in beam width.

According to the Fadwa's research [3], the yield strength was estimated as 0.75% of the ultimate strength, which was obtained from the force-displacement curves of the specimens and the displacement corresponded to the point of intersection of initial tangent stiffness with horizontal line at 0.75Vu. Displacement ductility ($\mu\Delta$) is defined by ultimate displacement divided by displacement corresponding to yield stress. Using this definition of yield strength the calculated yield strength for BW600, BW700, BW900 and BW1000 specimens are 45, 47, 57 and 61 kN, respectively. It can be understood that the yield strength of the models with the beam's width of 900 and 1000 mm is much higher compared with the models with the beam's width of 600 and 700 mm. The value of the displacement ductility for BW600, BW700, BW900 and BW1000 specimens are 3, 2.8, 2.1 and 1.9, respectively. Therefore, it can be concluded that by increasing the width of the beam, the value of the yield displacement will be increased which has led to the decrease of ductility. Table 2 shows the comparison of mechanical properties between all specimens, where the performance of BW600 is used as a reference point. The beam height for all specimens was kept constant at 300 mm and the percentages strength increase and ductility decrease are summarized in Table 2.

TABLE II. Comparison between Mechanical Properties of BW600 and Other Specimens

Properties	BW700	BW900	BW1000
Increase in ultimate strength (%)	3.3%	25.8%	35.6%
Increase in yield strength (%)	3.3%	25.8%	35.7%
Decrease in ductility (%)	4.6%	28%	36.2%

D. Energy Dissipation

One of the most important parameters for structures designed to resist against earthquake loading is the capacity for energy dissipation. When structures are subjected to seismic loading, after passing elastic phase, they start to dissipate energy. Therefore, more dissipation of energy results in a decrease in damages experienced during an earthquake. Due to the importance of this parameter, researchers conducted several investigations into the ways to increase energy dissipation. In this study, the energy dissipation capabilities of the four specimens are compared. After analyzing the models by using finite element method, the curves of plastic energy dissipation were obtained from ABAQUS output data. Figure 9 (a) shows the graph of the plastic dissipated energy versus lateral drift for finite element models. It can be understood that by increasing beam width the amount of the energy dissipation increases. From this figure it can be easily understood that BW600 and BW700 have similar behavior throughout the curve, including the plastic zone. Moreover, at the lateral drift of 5% the dissipation energy for BW1000 is 33% more than that of in BW600. The value of the dissipation energy of BW900 is slightly smaller, but still comparable with BW1000. It is evident that the amount and configuration of steel reinforcement significantly influences the value of the dissipation energy. Figure 9 (b) demonstrates plastic dissipated energy versus applied force. It shows for the similarly reinforced BW600 and BW700, the amount of dissipation energy is similar, with this trend also evident when comparing the results for BW900 to BW1000. Furthermore, it can be understood from Figure 9 (b) that dissipation energy for all models is initiated at approximately 25 kN during the aforementioned transition from elastic to plastic phase, however it can be seen that rapid development of dissipation energy occurs at approximately 40 kN for all specimens.

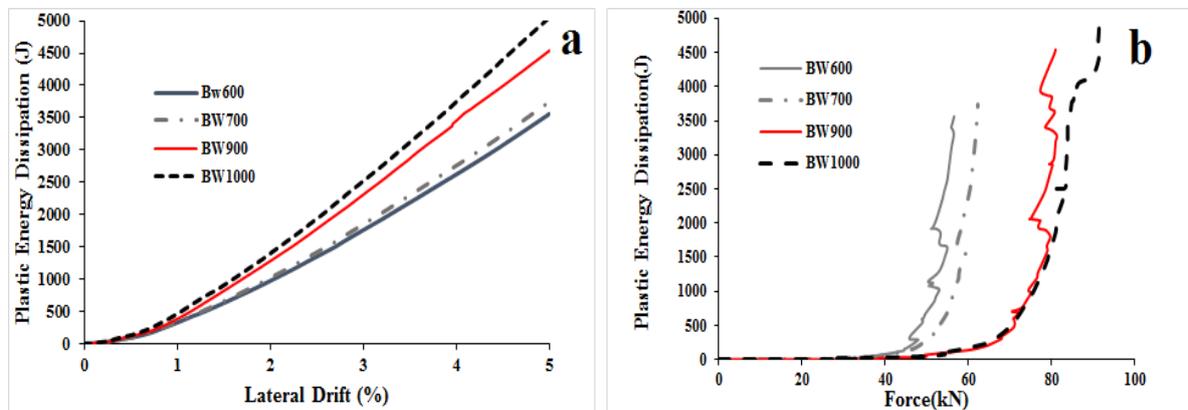


Fig. 9. Development of plastic energy dissipation (a) applied lateral drift (b) applied force

E. The influence of axial load

In this study, the influence of the column axial load on the behavior of exterior wide beam under lateral loading was investigated. As explained previously, analyses of axial loads smaller than $0.1 f_c A_g$ were considered. For this aim one of the exterior wide beam specimens (BW700) was subjected to axial loads of $0.029 f_c A_g$, $0.04 f_c A_g$ and $0.068 f_c A_g$ which corresponds to axial loads of 150, 230 and 350 kN. These values were chosen based on experimentally recorded data [3]. Figure 10 shows the effect of the axial load on the force-displacement graph for the BW700 specimen.

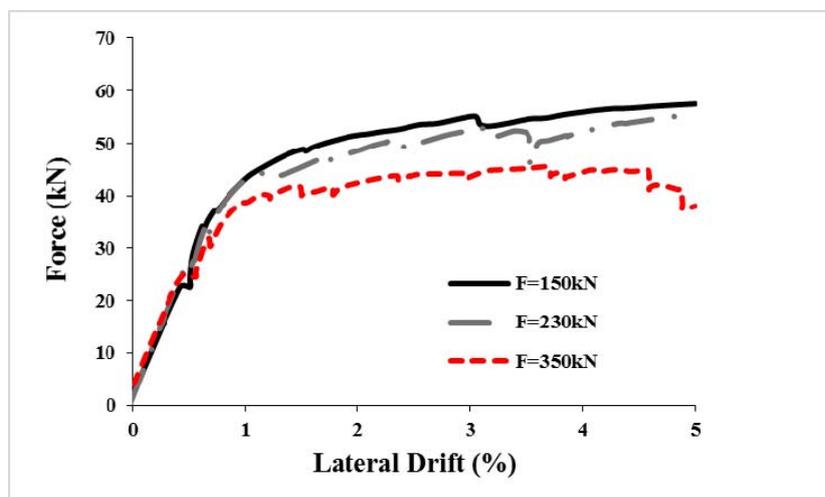


Fig. 10. Influence of axial load on behavior of BW700 model

Figure 10 reveals that, in the elastic phase, column axial loading does not have a significant influence on the lateral behavior of the structure. However, in the plastic zone, increasing the column axial load can cause a reduction in strength. For example, at the drift of 5% the strength of the structure with $0.68 f_c A_g$ axial load is 30% lower than the strength of the structure with $0.029 f_c A_g$ axial load.

IV. CONCLUSION

This study has presented a computational investigation using finite element method to quantitatively evaluate the effect of beam width on the behavior of wide beam-column connections under lateral loading. Four configurations with beam widths of 600, 700, 900 and 1000 mm were simulated. These models were exterior wide beam- column connections and the dimension and reinforcement details for columns in each model remained constant. The influence of varying the beam width on ductility, strength and plastic energy dissipation of the joints was studied. In addition to this, the effect of the amount of axial load applied on the column was evaluated.

- An increase in beam width results in a significant reduction in ductility of the beam-column joint against lateral loading. This outcome was observed for beam widths varying from 600 to 1000 mm which led to a maximum reduction in ductility of the structure by 36.2%.
- Amount and configuration of reinforcement bars played an important role on strength of the specimens. So that, an increase in amount of reinforcement from $5\phi 18$ to $7\phi 18$ in top and $2\phi 16$ to $4\phi 16$ in bottom of beam has led to increase of 35.6% in strength.
- For wide beam specimens, an increase in width of beam will result in enhancement of energy dissipation. So that, a beam width increase from 600 to 1000 mm led to 33% increase in plastic energy dissipation.
- For axial loads smaller than $0.1 f_c A_g$ and creating an elastic force-displacement response, there was no significant influence caused by increasing the axial load. Whereas, in the plastic phase, an increase in the axial load results in a significant decrease in strength of the structure.

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