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Behavior of reinforced concrete interior wide beam-column connections under lateral loading: A finite element study

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***Abstract*—A Finite Element model was developed to quantitatively investigate the effect of the geometric parameters on the behavior of the RC wide beam-column connection. This model, with a high accuracy, was verified by the experimental test conducted by previous researcher. Force-displacement curves were produced for wide beam-column connections with different geometric parameters. The impact of the geometry of the wide beam on the mechanical properties, types and patterns of the cracks, length of the Plastic hinge through the steel reinforcements and plastic dissipation energy of the joint was investigated. Length of the plastic hinge was computed for all samples and it was understood that increasing the width and height of the beam caused the plastic hinge length to be reduced. For instance by 67 percent increase of the width of the beam, the plastic hinge length was decreased by 6.5 percent. Stress analysis of the FE model showed that tensile stress through the beam axis, compressive stress through the column axis and shear stresses are responsible for initiation of flexural cracks through the beams, narrow flexural cracks though the column and Inclined cracks, respectively. Increasing of the beam width had different influences on resistance of the structure against different types of the cracks. Changing the dimension of the beam, in wide beam-column connections, had a significant impact on the plastic dissipation energy capacity of the structure. For a determined value of the lateral force, structures with the shorter beam width had higher values of the plastic dissipation energy.**

Keyword - Reinforced concrete, wide beam, beam-column connection, finite element model, crack patterns, dissipation energy, and plastic deformation.

I. INTRODUCTION

Moment frames are one of the most important structures being used to resist against seismic loadings. It is apparent that the beam- column connections play an important role in behavior of the frames, especially against the lateral displacement of the civil structures. Over the few past years, there has been a growing body of opinion in favor of using the wide beam-column connections rather than conventional connections. Several advantages of the beam-column joints in which the width of the beam is larger than the column width, such as reducing the necessity of the casting and simplification of repetition (which can considerably decrease the time and expenditure of constructing processes), have caused researchers to develop several studies to investigate different aspects of behavior of such structures [1]. However, the capacity of dissipation energy, as one of the most important indicators of structure resistance against seismic loading, should be taken in to account, while using such components in civil structures [2, 3, 4 and 5]. Over the past few years, some well-known institute have decreased their constraints on using wide beam-column connections. For instance, in 1991 using of this type of connection was completely prohibited by American Concrete Institute (ACI-352) [6]. In 2011, this institute determined a condition in which using of this type of connection was permitted [7]:

$$b_b \leq \min\left(b_c + 1.5h_c; 3b_c\right) \tag{1}$$

Where b_b is the beam width, b_c is the column width and h_c is the column depth.

Many experimental studies have been developed to investigate different aspects of this connection so as to improve its properties. Russell Gentry and Wight experimentally evaluated the performance of the wide beam-column connection in high seismic zones [8]. Their study revealed that to design such a connection, the possibility of the transferring the plastic hinge bending moments to the column should be carefully computed. Otherwise, transverse beam can be damaged by cracking caused by torsional moments [8]. LaFave and Wight [9] investigated the wide beam-column connections in which exterior RC were connected to transverse beam under lateral quasi static loading. Their design was align with requirements defined by American Concrete Institute [10]:

$$b_b \leq \min(b_c + 1.5h_b) \tag{2}$$

Thy concluded that with such a design, the resistance of the wide beam-column connection against the torsional moment is as acceptable as the conventional connection. Two experimental and numerical studies were developed by Li and Kulkarni [2, 11] to evaluate the behavior of the interior and exterior wide beam-column connection in several loading and design conditions. It was understood from their results that column axial load, transverse beam, and beam bar anchorage ratio play important roles in behavior of this connection [2, 11]. The experimental investigation conducted by Elsouri et al. revealed that a detailed design of the reinforcements of exterior wide beam-column connection can effectively increase the earthquake-resistant [12]. Furthermore, another study was carried out on four full-scale interior joints with wide beams, demonstrated that improvement of reinforcements details, can lead to increase the seismic performance by postponing of connection's shear failure [13]. Dominguez et al. evaluated performance of the buildings which were one slab with wide beams under Lorca earth quick. They concluded the buildings that were designed without any seismic provisions did not survive Lorca record, even in low seismicity areas, while other buildings that had met seismic requirements, survived under higher seismic loadings [14]. An investigation conducted by Fernando et al. [15] compared wide beam –column joints with conventional beam –column joints to evaluate provisions of European codes about the behavior factor of joints with wide beam. Results showed that both wide and conventional beam joints had, generally, similar seismic capacities. An experimental test was conducted to compare the behavior of the two conventional and wide beam-column roof joint [16]. They concluded that the shear strength of the wide beam-column connection was sufficient unlike the conventional one. Furthermore energy dissipation was equal for both samples [16].

Several analytical studies have been also developed to investigate the behavior of the beam-column connection, particularly for wide beam-column cases. An analytical model was presented in which the bond deterioration between concrete and reinforcing steel was considered to play an important role in the behavior of the beam-column connection [17]. This model was proven to accurately predict the behavior of the beam-column connection, particularly in wide beam column cases. Unal and Burak based on a wide variety of experimental data reported by previous researchers and using statistical correlation between them, presented an equation which is able to evaluate the effect of the several parameters on the seismic behavior of the beam-column connection [18].

Due to the high expenditures and limitations of specimens' fabrication, developing experimental tests for reinforced concrete structures are impossible or requires spending considerable amount of money and time. Moreover, complex geometry and loading structures, and complicated contact behavior between bars and concrete, makes it very hard to present an accurate and general analytical model for reinforced concrete structures. Hence, finite element model has been known as one of the most reliable and convenient solutions to investigate different types of mechanical and civil structures, especially reinforced concrete structures [19, 20, 21, 22, 23].

Although, to date, valuable studies have been developed to investigate the influence of different parameters such as details of the reinforcement designs and loading structure on the behavior of the wide beam-column connections, there is a lack of comprehensive investigation about the impact of the geometric parameters on the behavior of such structures.

This study aims to investigate the behavior of the interior wide beam–column connection specimen subjected to the lateral displacement. To this aim, a parametric study based on the finite element method is developed to evaluate the effect of the wide beam dimensions on the behavior of the connection, subjected to the lateral displacement of the column. The accuracy of the model was verified by experimental tests conducted by Fadwa et al [3]. The effect of the wide beam's geometry on strength were qualitatively and quantitatively investigated. Sensitivity of the plastic hinge to the beams dimensions in wide beam-column connections is precisely evaluated. The pattern of the crack initiation in such a structure was investigated to define types, positions and correspondent stress of each type of the cracks. Moreover, the influence of the beam width on severity of the cracks was evaluated. The influence of the beam dimensions on the plastic dissipation energy was investigated to reveal the resistance of the wide beam-column connections against earthquake.

II. METHODOLOGY

As mentioned above, this parametric study aims to comprehensively evaluate the impacts of the dimension variation of the beam on the behaviour of the wide beam-column connection.

A. Dimensions and loading design

The design of the structure which have been used to verify the FE model was exactly similar to the interior wide beam column connection (IWBCC) design used in Fadwa et al. [3] experimental test (Figure 1). Furthermore, other models of beam-column structures with different dimensions have been simulated in which width and height of the beam are changed as the variables of this study. To make it easier to report and discus the results, a naming system is implemented to specify geometric characteristics of each model (Table 1). In this system b, w and h represent beam, width and height, respectively. For instance bh300 bw900 represents specimen in which beam has height and width of 300 mm and 900 mm, respectively. For all specimens the height of the column is 450 mm and the width of the column is 400 mm. Table 2 demonstrates the number and design of the reinforcements for each specimen with respect to the reinforcement design was used in experimental tests conducted by Fadwa et al [3](Figure 1).

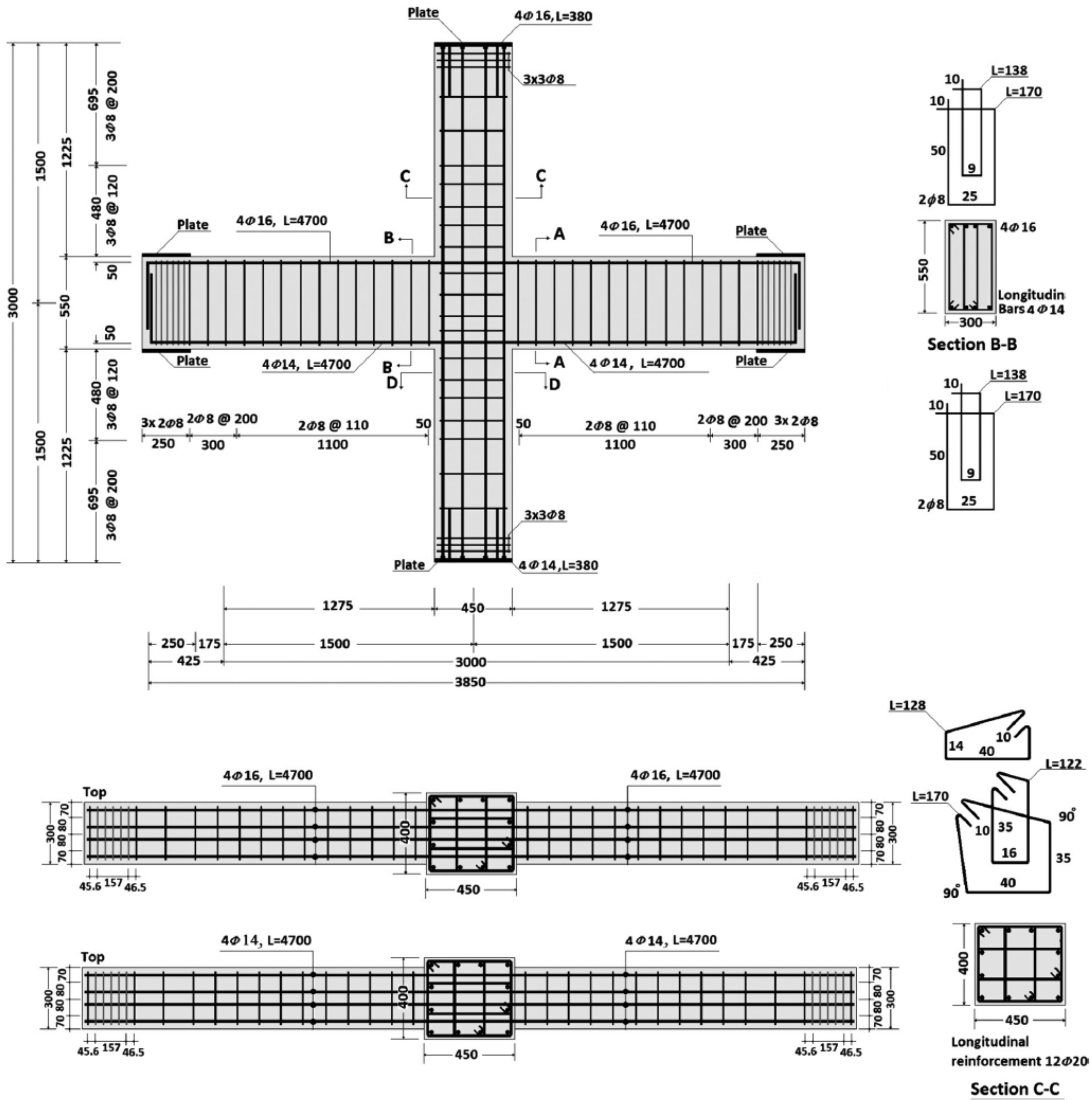

Fig. 1 Dimension details of IWBCC structure used for experimental test [3].

TABLE 1. Geometric Characteristics of Different Samples

Row	Name of the model	column		Beam	
		Width (mm)	Height (mm)	Width (mm)	Height (mm)
		C_w	C_h	B_w	B_h
1	bh300 bw900	400	450	900	300
2	bh400 bw900	400	450	900	400
3	bh300 bw1000	400	450	1000	300
4	bh400 bw1000	400	450	1000	400
5	bh300 bw700	400	450	700	300
6	bh400 bw700	400	450	700	400
7	bh300 bw600	400	450	600	300
8	bh400 bw600	400	450	600	400

TABLE 2. Reinforcements Used in Each Sample

Row	Name of the model	Column reinforcements	Beam reinforcements	
			Down	Up
1	bh300 bw900	12Ø20	3Ø14+4Ø16	7Ø18
2	bh400 bw900	12Ø20	3Ø14+4Ø16	7Ø18
3	bh300 bw1000	12Ø20	3Ø14+4Ø16	7Ø18
4	bh400 bw1000	12Ø20	3Ø14+4Ø16	7Ø18
5	bh300 bw700	12Ø20	3Ø14+2Ø16	5Ø18
6	bh400 bw700	12Ø20	3Ø14+2Ø16	5Ø18
7	bh300 bw600	12Ø20	3Ø14+2Ø16	5Ø18
8	bh400 bw600	12Ø20	3Ø14+2Ø16	5Ø18

B. FE model

Half of the full model was used for the FE analysis since the geometry and loading conditions of the model were completely symmetric with respect to the symmetry plane showed in Figure 2. The boundary conditions, loading and displacement which are used within the FE model are the same as the experimental test. As is shown in Figure 2, the axial load of 350 kN is applied to the column. In the FE model this load was applied in form of pressure to the top surface of the column. Both ends of the beam cannot move up and down and are just limited to move through the beam axis direction. Bottom surface of the column is connected to a pin supported part to exactly apply the properties of the constraints used in the experimental test. Lateral displacement of 150 mm is applied to the top surface of the column for all the models. Elastic-linear plastic model was used to define material properties of longitudinal and transversal reinforcements. Similar to the experimental approach, different elasticity module and yield stress, based on the cross section of the reinforcements, was defined for the steel bars. In accordance with the values presented in Fadwa et al. [3] test, the range of the elasticity modulus and yield stress were defined between 195.7 GPa - 224.5 GPa and 345 MPa- 497 MPa. Ultimate stress and ultimate strain were 730 MPa and 0.51, respectively. Elastic properties of the concrete used in the FE model is based on the values reported in Fadwa et al [3].

Where the tension strength, compression strength and module of elasticity were reported 2.86 MPa, 28.5 MPa and 19.9 GPa respectively. Concrete Damage Plasticity model in ABAQUS 6.13 was used to model plastic behavior of the concrete. A 3 Dimensional solid shape model using 3D Stress Hexahedral element type (C3D8R) implemented to simulate concrete behavior. Wire shape model with truss elements (T3D2) was used to simulate reinforcements behavior. The size of elements was refined several times in order to obtain converged solution. Accordingly, 26433 C3D8R elements and 14300 T3D2 elements were defined as the optimized number of elements for this FE model (Figure 3).

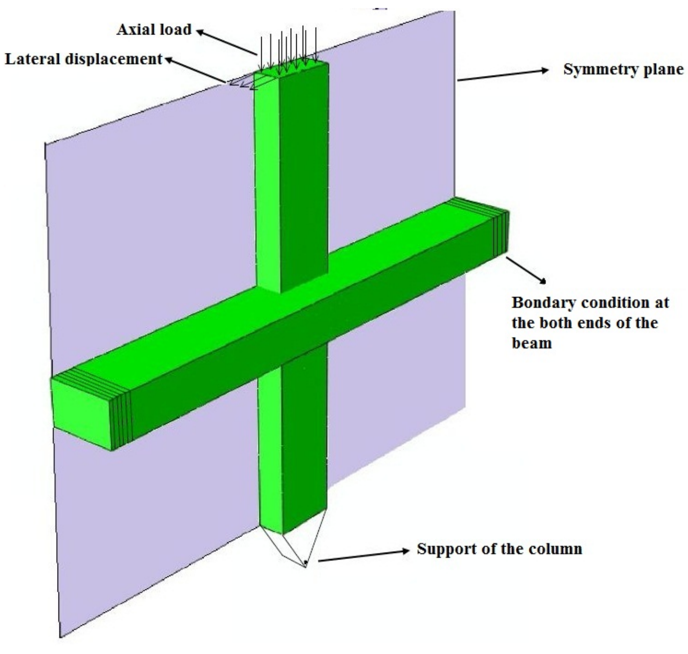

Fig. 2 Schematic view of the loading and constraints used in the FE model

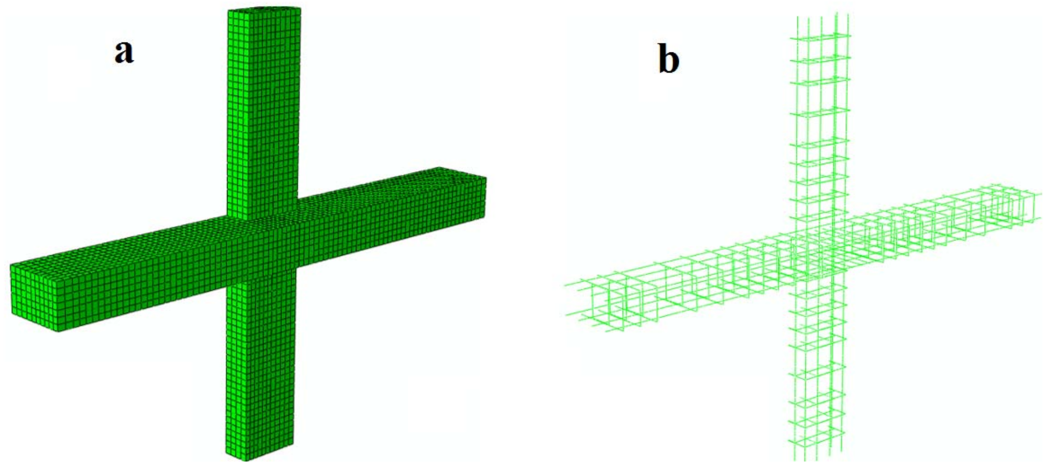

Fig. 3 Elements structure; (a) concrete (b) reinforcements

To verify the FE model, the force-displacement graph obtained from the FE simulation is compared with the trace of the envelop behavior of the structure under cyclic loading reported by Fadwa et al [3]. Figure 4 (a) demonstrates the hysteresis curve presented by Fadwa et al [3] and Figure 4 (b) shows the comparison between FE and experimental results. Generally, there is a good agreement between experimental and numerical results which verifies the accuracy of the FE model. It can be understood from the Figure 4 (a) that FE model prediction in elastic domain is a little higher than what was reported in the experimental test, where in displacement of 0.02 m, lateral load of the FE model is higher than experimental model by 3%. In plastic phase, the FE model accuracy is even more precise. For lateral displacement of 0.12 m, there is a difference of 1.7% between lateral load values of FE model and experimental results.

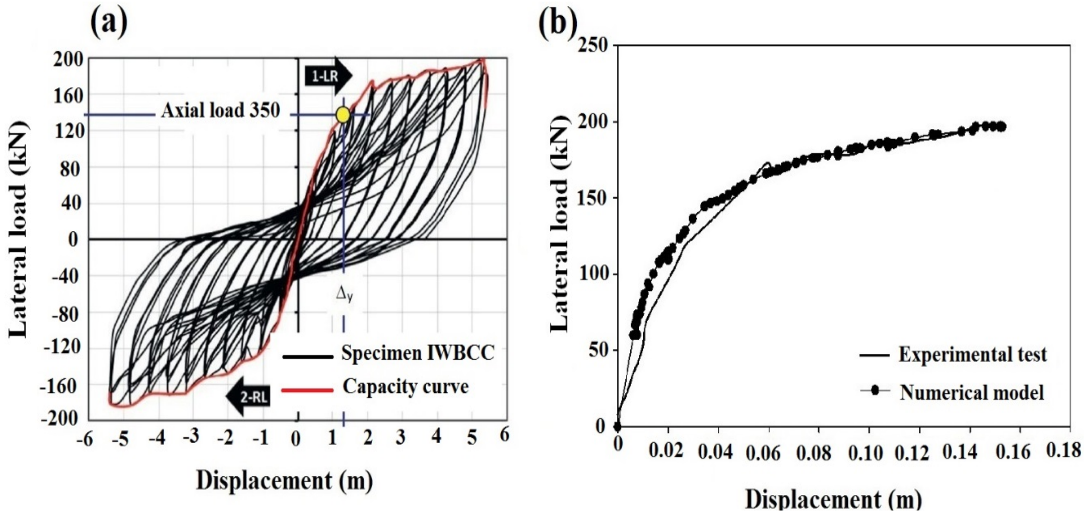

Fig. 4 Force-displacement curve; (a) experimental cyclic loading [3] (b) Comparison between experimental and numerical results

C. Results and discussion

1) Mechanical properties of the structure:

Figure 5 shows the Von misses stress contour of Finite element model for bh400 bw600 and bh400 bw1000 samples after 150 mm displacement of the column' top surface. From the stress contour, it can be easily understood that red part of the longitudinal reinforcements are in plastic phase according to the determined yield stresses. As it is shown in Figure 4, in concrete components, beam tolerates the maximum stress and it happens in region which is close to the column. In experimental tests, initiation of the cracks, as was mentioned in the Fadwa et al [3] study, starts from the same region. The general behavior of the other samples is similar to these two samples, in aspects of the critical regions.

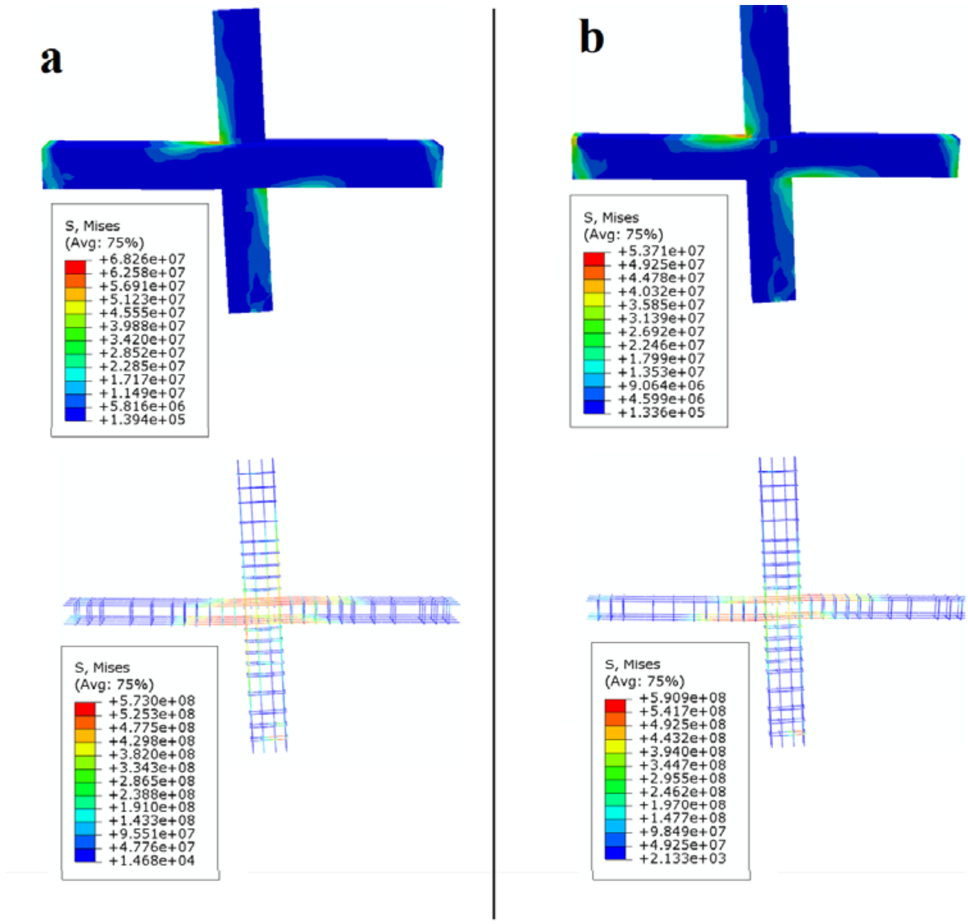

Fig. 5 stress contour of Finite element model; (a) Sample Ch450 cw400-bh400 bw600 (b) Sample Ch450 cw400-bh400 bw1000

Figure 6 shows the force displacement graphs of the samples with the height of 300 mm and 400 mm subjected to 150 mm lateral displacement. It is apparent that the samples with larger height need larger forces to reach a determined lateral displacement. For instance, to reach the displacement of 0.10 meter, the sample with 1000 mm width and 300 mm height needs force of 180 kN, whereas the sample with same width and the height of 400 mm requires force of 250 kN to meet such a displacement. Moreover, among the samples with the same height, those with 900 mm and 1000 mm need larger forces to meet the same displacements compared samples with 600 mm and 700 mm width.

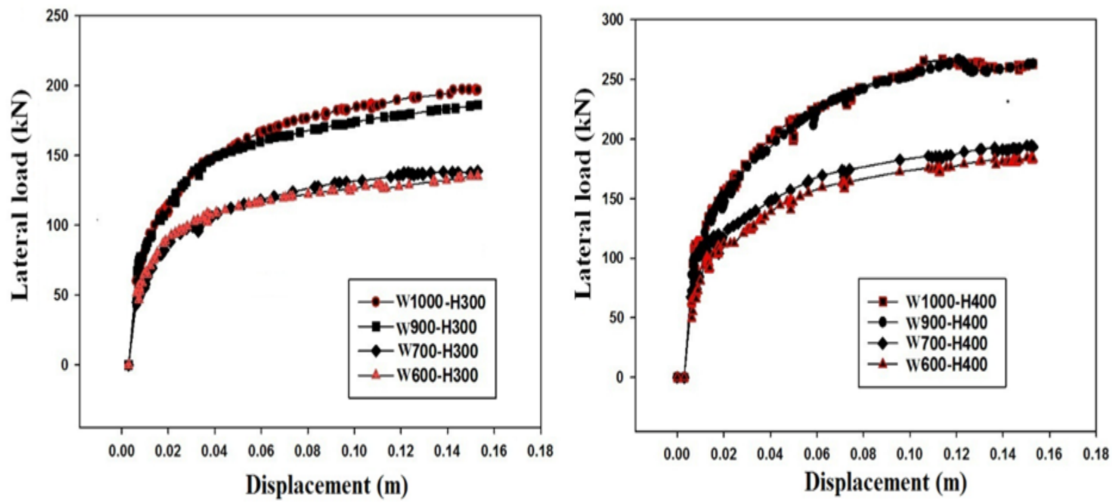

Fig. 6 Force- displacement curves; (a) Samples with the height of 300 (b) Samples with the height of 400

The specimens were investigated and compared in aspect of the plastic hinge caused by applying lateral displacement. Plastic hinge happens when the tensile reinforcement passes the elastic limit in a RC structure. Figure 7 shows a schematic image of a RC member under lateral loading. It is apparent that the curvature is increasing from free end to the supported end. This increasing has a gradual raising trend till the yield moment, but it will dramatically increase when come close to the support.

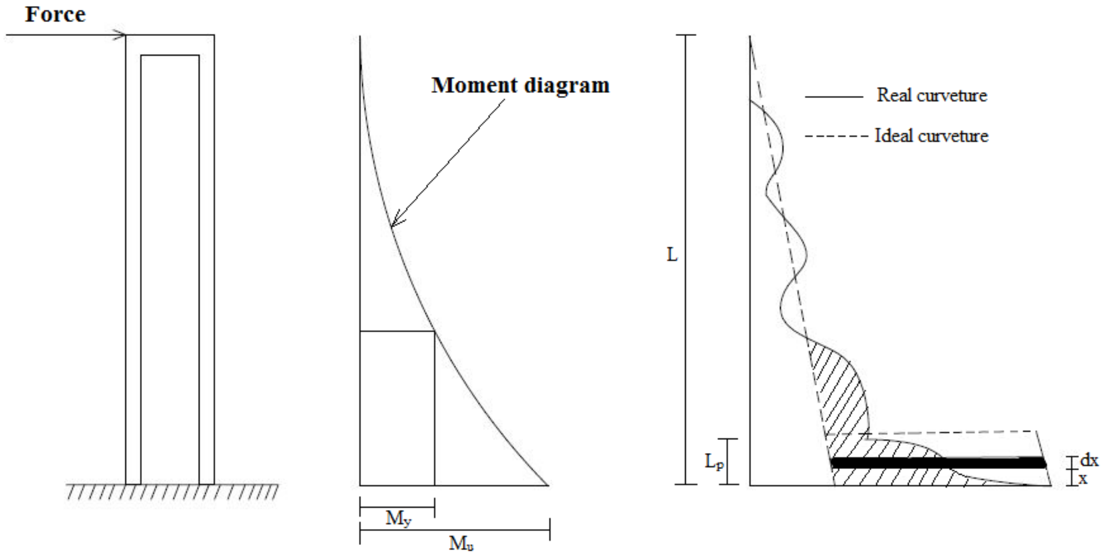

Fig. 7 schematic image of a RC member under loading

Plastic rotation can be computed by Eq. (5) [24, 25].

$$\theta_p = \int_0^{l_y} \left[\varphi(x) - \varphi_y\right] dx \qquad (5)$$

Where φ(x) is the value of the curvature in x position, φy is the yield curvature and Ly is the distance between curvature of the yield moment and curvature of the ultimate moment. Plastic rotation can also be obtained from:

$$\theta_p = (\varphi_u - \varphi_y).l_p \qquad (6)$$

In which L_p is the length of the plastic hinge that can be obtained from:

$$l_p = \frac{1}{(\varphi_u - \varphi_y)} \int_0^{l_y} \left[\varphi(x) - \varphi_y\right] dx \qquad (7)$$

From Eqs. (5) and (6), Eq. (8) can be derived:

$$l_p = \frac{\theta_p}{(\varphi_u - \varphi_y)} \qquad (8)$$

In which φu is the ultimate curvature.

To find the plastic hinge length, the graph of the beam curvature versus distance from the column was drawn for each sample and in accordance with the Eq. (5), the plastic hinge length was computed. Figure 8 shows the curvature versus distance from the column for three specimens. Table 4 shows the length of the plastic hinge for all samples.

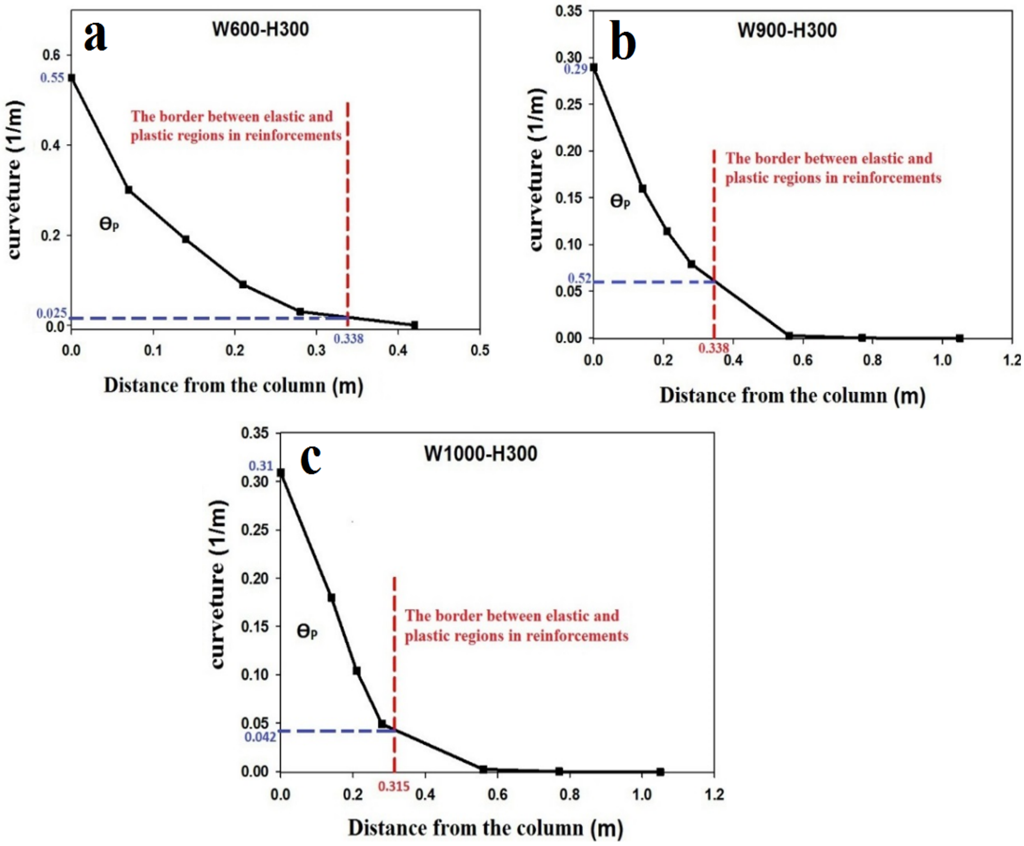

Fig. 8 Curvature versus distance from the column; (a) Sample Ch450 cw400-bh300 bw600 (b) Sample Ch450 cw400-bh300 bw900

TABLE 4. Length of the Plastic Hinge

Row	Name of the model	Lp (m)
1	bh300 bw900	0.159
2	bh400 bw900	0.144
3	bh300 bw1000	0.158
4	bh400 bw1000	0.142
5	bh300 bw700	0.166
6	bh400 bw700	0.151
7	bh300 bw600	0.169
8	bh400 bw600	0.153

From Table 4 it can be concluded that by increasing the height of the beam, the length of the plastic hinge re duces. Moreover, it can be understood that increasing the width of the beam have caused the plastic hinge length to be decreased. Table 5 shows how the increase of the width and height of the beam changes the different prop erties of the structure. First section of the Table 5 shows the changes of different properties in beams with the co nstant height of 300 mm, when the width of the beam increases. The second section of this table is similar to the first part, but it is dedicated to samples with the height of 400 mm. in the third part of this table the influence of the height increasing on the behavior of different samples is evaluated.

TABLE 5. Effect of the Dimension of Beam Width and Height on Changing the Structure Parameters

Row	Two compared models	Increasing the ultimate strength (%)	Decreasing the plastic hinge length (%)
Comparing samples with beam-height of 300 mm and different beam-width			
1	bh300 bw600 to bh300 bw700	3.7	1.8
2	bh300 bw600 to bh300 bw900	45.2	5.9
3	bh300 bw600 to bh300 bw1000	46.6	6.5

Comparing samples with beam-height of 400 mm and different beam-width			
1	bh400 bw600 to bh400 bw700	5.5	1.3
2	bh400 bw600 to bh400 bw900	43.2	5.9
3	bh400 bw600 to bh400 bw1000	43.7	7.2
Comparing samples with the constant beam-width and different beam-height			
1	bh300 bw600 to bh400 bw600	35.5	10.4
2	bh300 bw700 to bh400 bw700	37.8	10
3	bh300 bw900 to bh400 bw900	33.7	12
3	bh300 bw1000 to bh400 bw1000	32.8	10

2) Types and position of the cracks:

Crack initiation and propagation is an important parameter that should be carefully investigated while concrete structures are being studied. Different types of cracks are known as the main reasons of damages of RC wide beam-column connections (figure 9) [3]. Crack Type A: which are distributed on the top and bottom surface through the length of the beam. Crack Type B: initiated from the corner of the column with the approximate angle of 45º. Crack Type C: developed on the outer part of wide beams adjacent to column sides. Crack Type D: Narrow flexural cracks propagated at the face of the column. This types of cracks were seen through experimental tests.

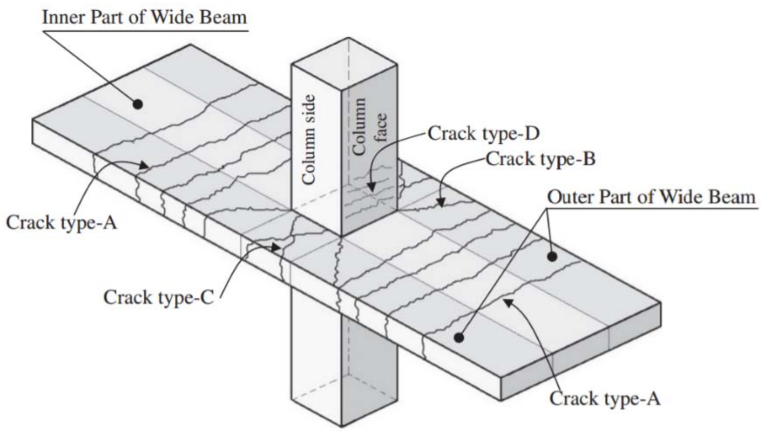

Fig. 9 schematic pattern of positions and types of the cracks initiated in wide beam-column connection subjected to lateral loading [3]

By means of the FE model the correspondent components of stress that can cause to different types of concrete cracks were identified (Figure 10). Moreover, comparing two bh300 bw600 and bh300 bw1000 specimens helps to understand the influence of the width dimension of the beam on damages caused by crack initiation and propagation. Figure 10 shows contours of different stress components for bh300 bw600 and bh300 bw1000 specimens. Figures 10 a and b show the positions of the crack type A for the mentioned specimens. Contour of S11 represents the principle stress through X axis for which negative values represent compressive stress and positive values represent tensile stress. These two figures show that the tensile stress is the main responsible for the initiation of crack type A. it is obvious that in locations defined as the positions of the cracks type A, the tensile stress is larger than the tension strength of the concrete (2.86 MPa). It is apparent that S11, due to its direction, can just be used to analyze tensile and compressive stress through the beam axis. To investigate tensile and compressive stresses through the column axis, the contour of S33 (principle stress through Z axis) is demonstrated in figures 10 c and d. the compressive stress at the face of the column is the main cause of the crack initiation through the column face (crack type D). According to these contours, the compressive values (Positive values) of S33 are very close to the compressive strength of the concrete (28.5 MPa). Figures 10 e and f show the shear stress in X-Y plane. It is obvious that S12 shear stress is responsible for initiation of the crack type B at the corner of the beam and column connection. Figures 10 g and h demonstrate

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the contour of the S13 (shear stress in X-Z plane). This stress can cause to initiation of the crack type C. Comparing the values of the stresses, specimen bh300 bw600 is more vulnerable against the initiation of the crack type A compared with the specimen bh300 bw1000, while specimen bh300 bw1000 can be more damaged by crack types C and B. Both specimens have almost the same stress behavior against S33 stress component that can lead to crack type D. Hence, it can be understood that increasing the width of the beam can improve beam resistance against crack type A (caused by tensile stress). However, such an increase can adversely reduce the resistance of the structure against crack types B and C (caused by shear stress).

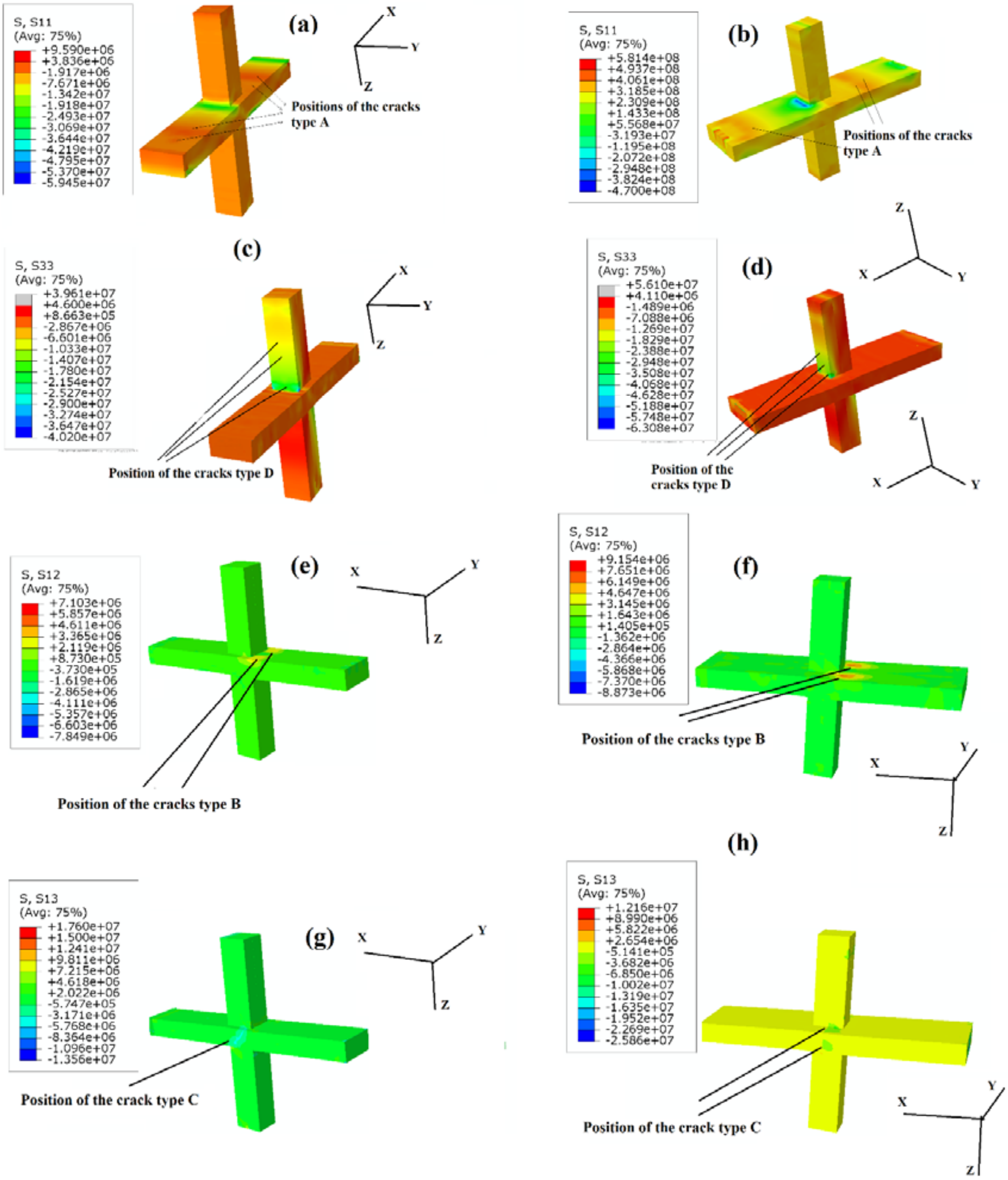

Fig. 10 Stress contours of specimens bh300 bw1000 and bh300 bw600; (a) S11 for bh300 bw600 (b) S11 for bh300 bw1000 (c) S33 for bh300 bw600 (d) S33 for bh300 bw1000 (e) S12 for bh300 bw600 (f) S12 for bh300 bw1000 (g) S13 for bh300 bw600 (h) S13 for bh300 bw1000

3) Plastic dissipation energy:

Plastic dissipation energy of a civil component is an important indicator of its resistance against earthquake loading. Figures 11 and 12 show plastic dissipation energy of the specimens bh300 bw600, bh400 bw600, bh300 bw1000 and bh400 bw1000 versus lateral load and lateral displacement, respectively. It can be found from these figures that plastic dissipation energy is highly depended on the geometric parameters of the beam. It is apparent from the force-displacement graphs (figure. 6), for a determined value of lateral displacement, structures with the larger width and height of the beam have higher values of dissipation energy.

However, as is shown in figure. 11, in equal lateral forces, structures with the larger width of the beam have significantly lower plastic dissipation energy compared with those that have smaller width. Similarly, increase of the height of the beam, decreases the capacity of the plastic dissipation energy.

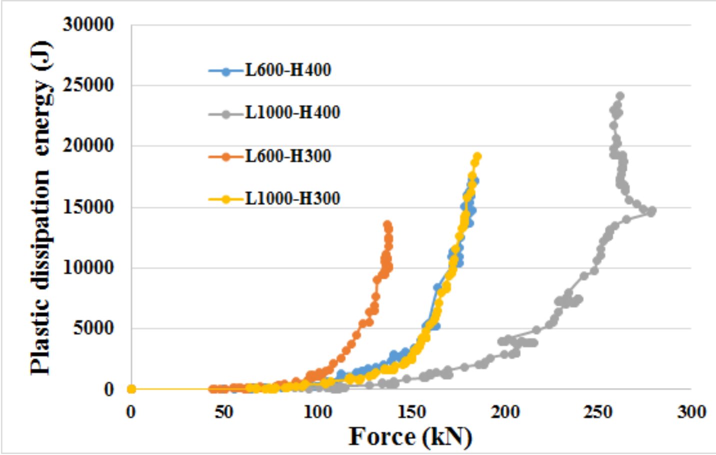

Fig. 11 Plastic dissipation energy versus lateral load

III. CONCLUSION

In this study**,** finite element method was used to quantitatively investigate the influence of the geometry of the wide beam on the mechanical properties, length of the Plastic hinge, crack patterns and dissipation energy of the structure.

- Regarding to figure 6, samples with larger height of the beam experienced more lateral load for the same value of lateral displacement. Where, for the 33 percent increase of the height of the beam, the strength of samples has increased by 39 percent.
- The strengths of the samples with the width of 900 mm and 1000 mm was significantly higher than the samples with the width of 600 mm and 700 mm against the lateral displacement. For example, in figure 6a, for sample with the width of 900 mm and the height of 300 mm, the strength (after 0.04 meter displacement) is 50 percent higher than that of in sample with 700 mm width and 300 mm height. The main reason of such a difference was concluded to be the higher number of longitudinal reinforcements used in the samples with the beam width of 900 mm and 1000 mm beam width.
- Stress analysis of the FE model revealed that tensile stress through the beam axis, compressive stress through the column axis, S12 shear stress and S13 shear stress (figure 10) are responsible for initiation of crack types A, D, B and C, respectively.
- It can be concluded that increasing the width of the beam can improve the beam resistance against crack type A (caused by tensile stress). However, such an increase can adversely reduce the resistance of the structure against crack types B and C (caused by shear stress).
- Changing the dimension of the beam, in wide beam-column connections, can significantly impact on the plastic dissipation energy capacity of the structure. Graph of the plastic dissipation energy versus lateral load revealed that for a determined value of the lateral force, structures with the shorter beam width have higher values of the plastic dissipation energy.

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