Case study

# Finite element modeling of exterior beam-column joints strengthened by ferrocement under cyclic loading

Ibrahim G. Shaaban[a,*], Mohamed Said[b]

[a] University of Liverpool (On Sabbatical, Benha University, Egypt), United Kingdom
[b] Faculty of Engineering, Shoubra, Benha University, Egypt

ABSTRACT

This paper aims to study the seismic performance of exterior beam-column joints in building frames strengthened by ferrocement using nonlinear finite element analysis. Firstly, the proposed model was used to predict experimental results successfully. Secondly, a parametric study was carried out to assess the behavior of such joints with different additional variables. The studied variables were the level of axial loading on the column, compressive strength of specimens, percentage of longitudinal reinforcement in the beam, and orientation of expanded wire mesh in ferrocement layer, for specimens strengthened by different number of ferrocement layers. It was found that strengthening specimens by ferrocement reduced the effect of axial loading level and longitudinal steel ratio in the beam on the ultimate load of studied specimens. In addition, changing the orientation angle of expanded wire mesh from 60° per ferrocement layer to 45° has a minor effect on the ultimate load but it has a significant effect on the ductility of studied specimens. The effect of orientation angle became less significant on the ductility with increasing the number of ferrocement layers used for strengthening. These findings would be helpful to the engineers to develop suitable, feasible and efficient upgrading technique for poorly designed building frame structural joints in seismic zones.

## 1. Introduction

Understanding the response of beam-column joints in reinforced concrete building frames during loading is crucial to the development of an overall efficient and safe structure. Many existing RC structures all over the world (Egypt, Turkey, Iran, etc…) have concrete with low strength and were built before the development of current seismic codes, or without complying with current seismic codes [1]. Such existing buildings have to be rehabilitated for safety of life and maintaining these buildings in good conditions. Among the techniques used for rehabilitation of beam-column joints, the strengthening by ferrocement jackets gains attraction from researchers since it is economical and easily applicable [2]. Extensive experimental based testing has been widely used to study interior and exterior joints before and after rehabilitation [3–9]. Lima et al. [10,11] collected and reported a comprehensive database of experimental results. Experimental work is time consuming, and the use of different materials in studying variables can be quite costly. Therefore, the use of finite element technique to study the behaviour of such elements is an interesting tool [12–14]. The use of computer software to model these elements is much faster, and extremely cost-effective [12,15].

Sasmal et al. [16] studied the seismic performance of exterior beam-column connections experimentally and analytically. They used a strut-and-tie model for evaluating the shear strength of the joint region and they found that most of the energy was dissipated

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through the development of damage in the joint region, which is neither desirable nor safe for the stability of whole structure. Venkatesana et al. [13] carried out experimental tests and numerical simulations using ANSYS 10.0 [17] for the seismic performance of exterior beam-column joints before and after strengthening with ferrocement jackets. They found that the analytical shear strength predictions were in line with the test results and the strengthened specimens exhibited better structural performance than the un-strengthened ones. In a more recent research, Sasmal and Nath [14] introduced a steel bracing technique to strengthen poorly designed beam-column joints. Their finite element modeling of the specimens using ATENA package [18] demonstrated the advantage of the strengthening system for improvement of crack patterns, ultimate load, energy dissipation, and ductility of the studied specimens. Lima et al. [19] proposed a numerical model for representing the cyclic response of RC exterior joints using nonlinear rotational spring elements with strength and stiffness degradations and limited ductility under cyclic loading. Their results confirmed that neglecting the effects of joints damage might potentially lead to non-conservative seismic assessment of existing RC framed structures. Very recently, Subramani et al. [20] carried out an analytical study using ANSYS for traditional T-shaped concrete frame building joints with strong beam-weak columns. They found that both axial forces and beam to column linear stiffness ratio had impacts on joint capacity and ductility behaviour of the specimens.

This paper is part of a larger research devoted for the study of exterior beam-column joints [21,22]. The non-linear finite element analysis was carried out using a computer package "ANSYS 10.0" [17] to model exterior beam-to-column joints in building frames and the ferrocement layers used for wrapping the joints. The envelope of lateral load deflection curve is considered the key aspect in studying the behaviour of beam-column joint. Therefore, a correlative study based on the envelope of lateral load deflection hysteresis of test specimens, was conducted to verify the analytical model with the experimental results for exterior beam-to-column joints strengthened by ferrocement and was reported elsewhere [22]. In addition, a parametric study was carried out to assess the behaviour of beam-column joints with non-ductile reinforcement detailing before and after strengthening with ferrocement layers. The studied variables in the parametric study were the level of axial loading on the column, percentage of longitudinal reinforcement in the beam, orientation of expanded wire mesh in ferrocement layer, number of ferrocement layers and compressive strength for studied elements.

## 2. Research significance

After publishing the recent experimental work for the behaviour of strengthening beam-column joints in building frames using ferrocement by the first author [22], it was decided to further study such joints using finite element modeling by including more variables than those tested in the experimental work. The studied variables were different levels of axial loads on the columns, different compressive strengths of original specimens, different longitudinal reinforcement ratios in beams, number of ferrocement layers and mesh reinforcement orientation per layer. The aim of this study is to help the engineers to develop suitable, feasible and efficient upgrading technique for structural joints in existing building frames, designed poorly in accordance with the old design codes, in seismic zones.

## 3. Non linear finite element analysis (NLFEA) using ANSYS

### 3.1. Idealization of test specimen and material modeling

The test beam-to-column joint specimens were typically discretized using 3-D isoperimetric 8-node solid elements; Solid65. The element "Solid65" was adopted to model the concrete and ferrocement layers as it is capable of simulating cracking in tension and crushing in compression. The element can represent one solid material (concrete or mortar), and up to three different types of reinforcement with different material properties (i.e. reinforcing bars, wire square mesh and expanded metal mesh, etc…). Both linear and non-linear behaviours of the concrete or mortar were considered. The concrete or mortar were assumed to be isotropic materials up to cracking stage and then to undergo plasticity. Cracking may take place in three orthogonal directions at each integration point. The reinforcement of columns, beams and expanded wire mesh embedded in mortar layers were idealized in the discrete model using a 2-node bar (linear) elements or beam elements; Link8, that are connected to concrete mesh nodes. Therefore, the concrete and the reinforcement mesh share the same nodes and concrete occupies the same regions occupied by the reinforcement. The software package "ANSYS 10.0" [17] allows flexural reinforcement to be defined using the smeared reinforcement approach, in which the amount of reinforcement is defined by specifying a volumetric ratio and orientation angles of the mesh.

The assigned concrete material model is characterized by its capability to simulate brittle failure modes. Both cracking and crushing failure modes were accounted for. Additional concrete material data, such as the shear transfer coefficients were taken as 0.30 for open crack and 0.70 for closed crack. A value of 0.6 for stress relaxation after cracking was considered in the analysis. These values revealed accepted behavior for the tested specimens according to the correlative study conducted. For ferrocement layers of one, two, and three layers, shear transfer coefficients were taken as 0.30, 0.325 or 0.35 for open cracks and 0.80, 0.85 or 0.90 for closed cracks, respectively. The input data for material properties of steel reinforcement bars used in ANSYS computer package are Elastic modulus, $E_s$ = 203.9 GPa, Yield stress, $f_y$ = 520 MPa and Poisson's ratio, $v$ = 0.3. The expanded steel wire mesh is defined by specifying a volumetric ratio in x and y directions to simulate the angles used in the published experimental work of similar specimens (see Fig. 1). Input data for ferrocement material properties were ultimate uniaxial compressive strength of the mortar, $f_c$, was taken based on experimental results (17 MPa); elastic modulus of wire mesh, $E_s$ = 148.0 GPa; yield stress of wire mesh, $f_y$ = 385 MPa; and Poisson's ratio of wire mesh, $v$ = 0.3. All the above values and other properties of ferrocement (mortar and expanded wire mesh) were defined in detail by Shaaban and Seoud [22].
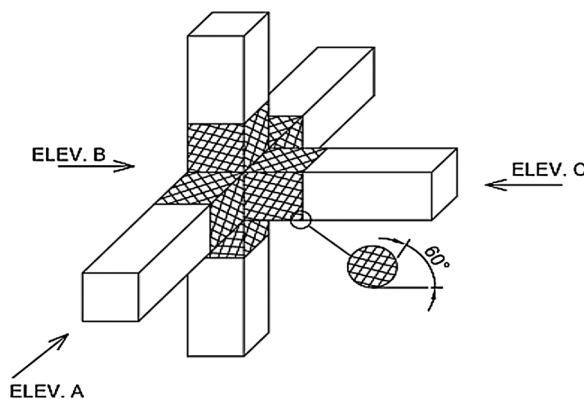
**Fig. 1.** Orientation angle of expanded metal mesh [22].

## 3.2. NLFEA predictions

Experimental behaviour of beam-column joints in building frames strengthened by ferrocement under cyclic loading, previously tested [22], was numerically predicted in this research using the finite element package ANSYS 10.0 [17]. The description of the tested specimens, which are predicted in this research, is shown in Table 1 and the test setup for a typical specimen is shown in Fig. 2(a). The retrofitted specimens were wrapped by a layer or more of wire mesh (with overlap of 100 mm) and each mesh layer was fixed to the embedded shear connectors. The strengthened specimens were plastered with a thin layer of rich cement mortar. Ferrocement layers were considered in the analysis fully bonded to the concrete elements. Boundary conditions, positions of the applied loads and the measurement set-up are described in the recent paper published by the first author [22]. Typical idealization of test beam-to-column joint is shown in Fig. 2(b). The specimens were analyzed under quasi-static displacement control technique. The lateral loading procedure used for all tests is shown in Fig. 3 and it is a load displacement to simulate the one applied to the experimental work [22]. The imposed displacement was applied at the tip of the beam and it is related to the yield of the joint in order to simulate the experimental tests [22]. A correlative study, based on the ultimate capacities and envelope of load displacement hysteresis, was conducted to verify the numerical model with the experimental results. It is worth mentioning that positive and negative envelopes were almost similar and therefore positive envelopes were only considered in the comparison.

Table 2 and Fig. 4 show the comparison between experimental and numerical results. The analysis indicated formation of flexural cracks in the test specimens at low levels of displacements ranging between 1.6 mm and 3.0 mm. Symmetrical crack patterns occurred for both positive and negative loading directions. Table 2 presents a comparison of the predicted ultimate loads and predicted ultimate displacements with the corresponding test results. The ratio of the predicted to experimental ultimate strength for the beam-column joints ranged between 1.01 and 1.04, with a mean value of 1.03 and a standard deviation of 1%. The ratio of the analytical ultimate displacement to experimental one for the beam-column joints ranged between 0.88 and 1.02, with a mean value of 0.93 and a standard deviation of 6%. Implicitly, the analysis reflected the significance of test parameters investigated on the load-carrying capacity. Furthermore, the analysis adequately reflected the enhancement in the ultimate load recorded for specimens provided with ferrocement layers. Fig. 4 shows the analytical results compared with the envelopes for experimentally tested specimens. The analytical results of most of the specimens were in good agreement with the experimental envelopes. Generally, the envelopes of load displacement hysteresis loops for all specimens exhibited similar features. For the initial cycles, the response was almost elastic and just minor residual displacement was obtained.

**Table 1**
Description of the experimentally tested specimens [22].

| Joints | Reference specimens, non retrofitted | | |
| --- | --- | --- | --- |
| REJ1 | Detailed according to local practice in traditional buildings. | | |
| REJ2 | Detailed according to ACI 318 and its subsequent editions requirements [23] | | |

| Retrofitted specimens | | | |
| --- | --- | --- | --- |
| Joints | Main Reinforcement according to: | No. of ferrocement layers | Orientation angle of expanded wire mesh |
| EJ1 | Detailed according to local practice in traditional buildings | One layer | 60° |
| EJ2 | | Two layers | |
| EJ3 | | Three layers | |
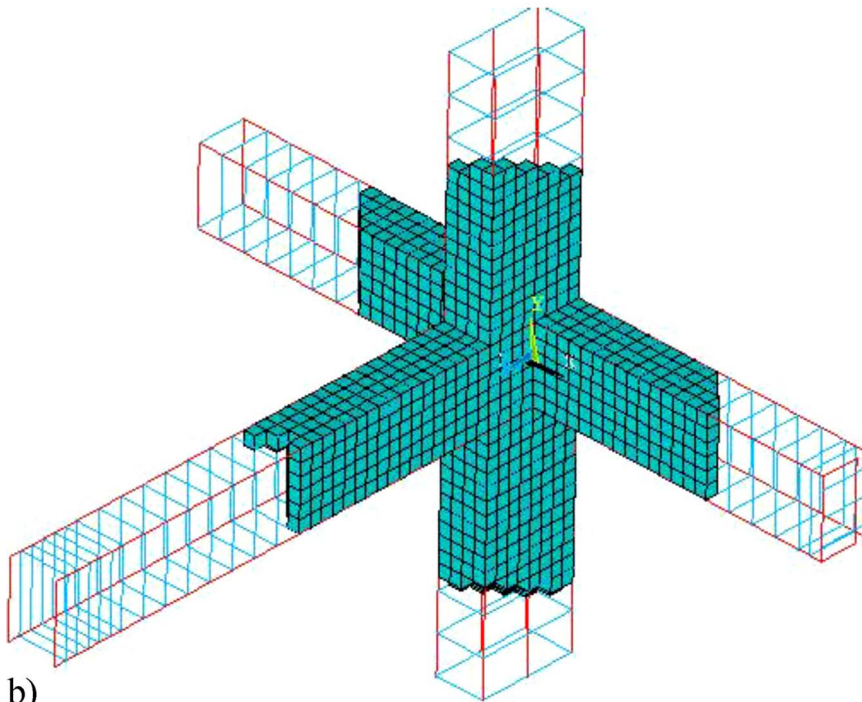
**Fig. 2.** Experimental setup and numerical modeling of exterior beam-column joints.
a) Test setup of experimentally tested exterior beam-column joint [22]. b) Typical idealization of test beam - column joint: concrete element; Solid65 and reinforcing bar element; Link8.

## 4. Parametric study

### 4.1. Variables used in the analysis

After validating the numerical model by comparing its results with the experimental results of Shaaban and Seoud [22], NLFEA was used to evaluate the effect of different parameters used in this study. Number of ferrocement layers used for strengthening, three levels of axial loading to the column, two amounts of longitudinal steel reinforcement in the loaded beam, two concrete compressive strength values for original specimens and two orientation angles of expanded wire mesh. Three different levels of axial loading, P/Po, recorded in Table 3, were applied in this parametric study [23]. Table 3 presents a description for the numerically studied sixteen
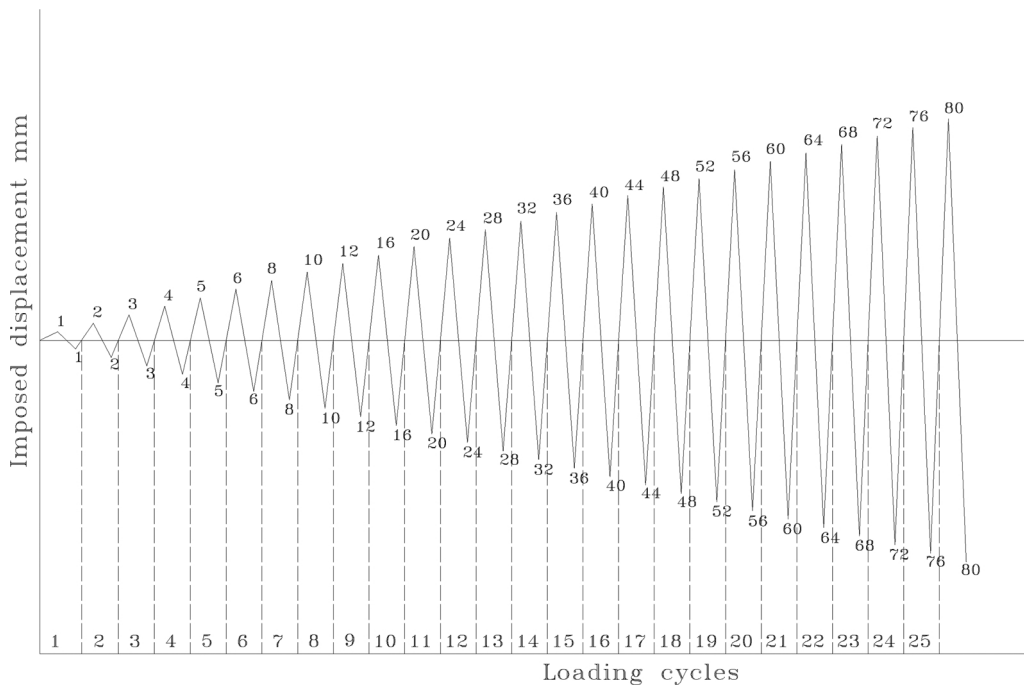
**Fig. 3.** Cyclic load history [22].

**Table 2**
Comparison of test results with NLFEA results.

| Specimens I.D | Experimental Results [22] | | NLFEA Results | | Analytical Results/Experimental Results | |
| --- | --- | --- | --- | --- | --- | --- |
| | Ultimate Displacement mm ($\Delta_{u\text{-}exp}$) | Ultimate Load kN ($P_{u\text{-}exp}$) | Ultimate Displacement mm ($\Delta_{u\text{-}an}$) | Ultimate Load kN ($P_{u\text{-}an}$) | ($\Delta_{u\text{-}an}$)/($\Delta_{u\text{-}exp}$) | ($P_{u\text{-}an}$)/($P_{u\text{-}exp}$) |
| REJ1 | 37.6 | 80.2 | 35.0 | 80.9 | 0.93 | 1.01 |
| REJ2 | 43.0 | 85.7 | 44.0 | 87.8 | 1.02 | 1.02 |
| EJ1 | 45.5 | 80.3 | 42.0 | 83.0 | 0.92 | 1.03 |
| EJ2 | 57.0 | 84.0 | 50.0 | 87.0 | 0.88 | 1.04 |
| EJ3 | 58.0 | 89.0 | 52.0 | 92.3 | 0.90 | 1.04 |
| Mean | | | | | 0.93 | 1.03 |
| Standard Deviation | | | | | 0.06 | 0.01 |

specimens. Among the sixteen studied specimens, there were four specimens before strengthening and twelve ones strengthened by one or two layers of ferrocement with two different orientation angles of expanded wire mesh, under three levels of column axial loading and two different longitudinal beams reinforcement ratio. The joint dimensions were altered in the numerical model compared to the experimentally tested joints [22] in order to assess the sensitivity of the model to changes in the relative dimensions of column-to-beam in the joint. The cross section of the column was 400 × 250 mm and the cross sections of loaded and confining beams were 250 × 300 mm as shown in Fig. 5. Details of reinforcement, anchoring rebar, in the joint as well as the thickness of ferrocement layers are similar to those reported in the experimental work [22]. Ultimate loads, ultimate displacements, initial stiffness and strength degradation rates, $KD_{cr}$, $KD_u$, for the numerically studied specimens are recorded in Table 4. It is worth mentioning that the degradation of the stiffness, both at cracking and ultimate load levels was evaluated using the stiffness degradation rates, [24], as follows:

$$KD_{cr} = \frac{(K_o - K_{cr})}{K_o} x100 \tag{1}$$

$$KD_u = \frac{(K_o - K_u)}{K_o} x100 \tag{2}$$

Where:

   $KD_{cr}$ is the ratio of the lost stiffness at cracking load to initial stiffness.
   $KD_u$, is the ratio of the lost stiffness at ultimate load to initial stiffness.

Beam-column joints strengthened by ferrocement with different numbers of layers



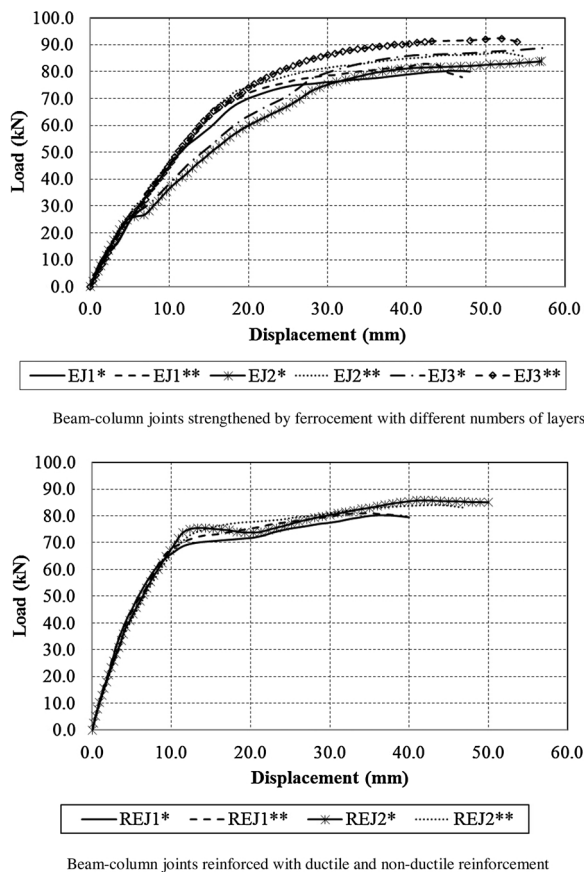Beam-column joints reinforced with ductile and non-ductile reinforcement

**Fig. 4.** Prediction of load-displacement hysteresis envelopes for experimentally tested specimens (*, experimental work [22] and ** predicted by ANSYS [17]).

**Table 3**
Parametric study (Beam-Column joints considered in numerical study).

| Specimen I.D | Axial load level of Column (P/Po) | Longitudinal Steel Ratio of loaded Beam (µ %) | No. of Ferrocement layers | $f_{cu}$ MPa |
|---|---|---|---|---|
| BCJ1 | 0.15 | 0.95 | No layers | 30 |
| BCJ2 | 0.15 | 0.95 | One layer (θ = 60°) | |
| BCJ3 | 0.15 | 0.95 | Two layers (θ = 60°) | |
| BCJ4 | 0.25 | 0.95 | No layers | |
| BCJ5 | 0.25 | 0.95 | One layer (θ = 60°) | |
| BCJ6 | 0.25 | 0.95 | Two layers (θ = 60°) | |
| BCJ7 | 0.55 | 0.95 | No layers | |
| BCJ8 | 0.55 | 0.95 | One layer (θ = 60°) | |
| BCJ9 | 0.55 | 0.95 | Two layers (θ = 60°) | |
| BCJ10 | 0.15 | 0.35 | No layers | |
| BCJ11 | 0.15 | 0.35 | One layer (θ = 60°) | |
| BCJ12 | 0.15 | 0.35 | Two layers (θ = 60°) | |
| BCJ13 | 0.25 | 0.95 | One layer (θ = 60°) | 40 |
| BCJ14 | 0.25 | 0.95 | Two layers (θ = 60°) | 40 |
| BCJ15 | 0.25 | 0.95 | One layer (θ = 45°) | 30 |
| BCJ16 | 0.25 | 0.95 | Two layers, (θ = 45°) | 30 |

$K_o$, is the initial stiffness of the specimen
$K_{cr}$, is the stiffness of the specimen at cracking load
$Ku$, is the stiffness of the specimen at ultimate load

### 4.2. Crack patterns and load-displacement hysteresis loops

Fig. 6(a) shows the simulation of crack propagations of a typical theoretically studied specimen, namely, BCJ9 of longitudinal reinforcement ratio (0.95%), strengthened with two layers of ferrocement and axial applied loading level to the column of the
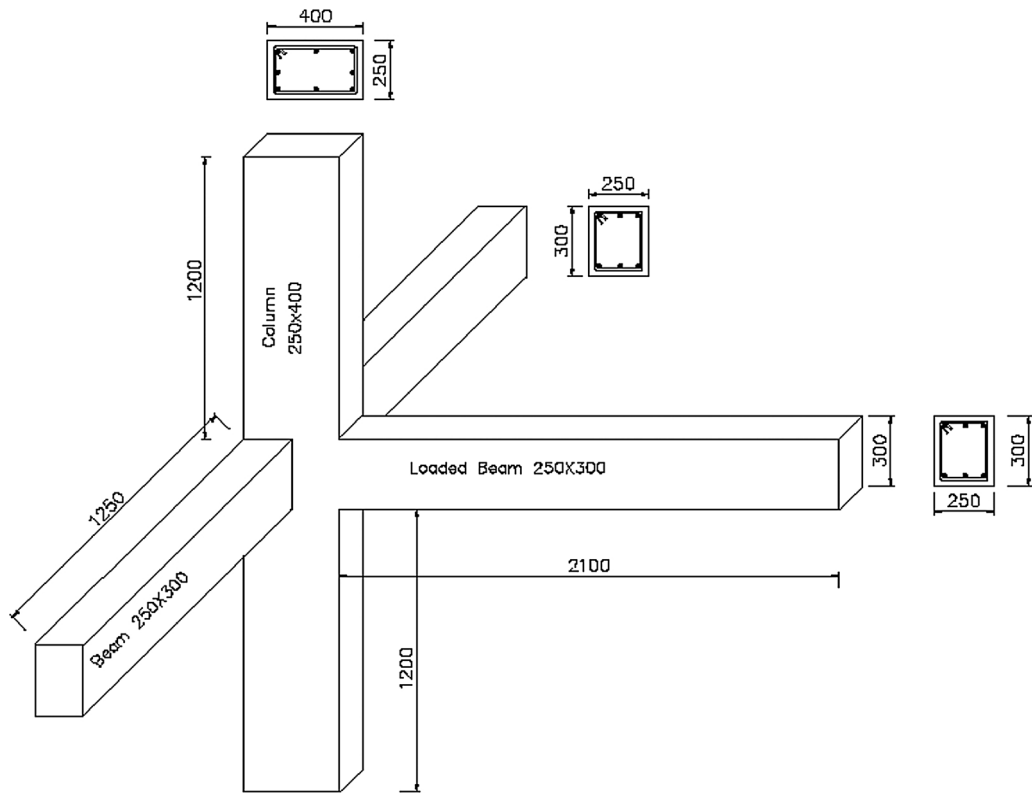
**Fig. 5.** Typical concrete dimensions.

**Table 4**
Ultimate level and stiffness degradation.

| Specimen | Ultimate | | Initial stiffness, $K_o$ (kN/mm) | Stiffness degradation rate% | |
|---|---|---|---|---|---|
| | Displacement (mm) | Load, kN | | $KD_{cr}$ | $KD_u$ |
| BCJ1 | 43.58 | 46.25 | 5.16 | 49.80 | 78.30 |
| BCJ2 | 25.20 | 63.54 | 9.66 | 45.80 | 73.80 |
| BCJ3 | 25.20 | 67.90 | 10.07 | 38.00 | 73.60 |
| BCJ4 | 15.58 | 34.65 | 4.10 | 39.10 | 46.00 |
| BCJ5 | 21.23 | 58.51 | 8.55 | 42.36 | 68.00 |
| BCJ6 | 19.00 | 60.80 | 9.30 | 35.30 | 63.10 |
| BCJ7 | 20.00 | 43.40 | 3.00 | 33.30 | 77.70 |
| BCJ8 | 24.00 | 64.90 | 7.40 | 35.50 | 63.80 |
| BCJ9 | 20.00 | 66.11 | 8.20 | 27.50 | 55.40 |
| BCJ10 | 25.20 | 21.30 | 2.83 | 42.00 | 70.15 |
| BCJ11 | 25.20 | 31.63 | 8.72 | 55.76 | 85.60 |
| BCJ12 | 29.40 | 33.60 | 9.80 | 58.45 | 87.20 |
| BCJ13 | 19.50 | 64.38 | 8.63 | 20.55 | 50.40 |
| BCJ14 | 17.60 | 71.00 | 9.63 | 14.66 | 53.33 |
| BCJ15 | 35.88 | 58.60 | 6.10 | 23.00 | 72.58 |
| BCJ16 | 21.65 | 60.00 | 7.70 | 9.80 | 64.00 |

specimen (55%). Typically, flexural cracks initially appeared at the extreme fibers of the tension zone of the specimen near the column stub and then spread laterally. By increasing the displacement, symmetrical cracks pattern occurred for both positive and negative loading directions. For specimens before strengthening, flexural cracks spread along the beam to a distance of approximately 450 mm measured from the column. As far as the specimens strengthened by ferrocement, the cracks initiated at higher loads. The cracks spread along the beam to a distance of approximately 1000 mm measured from the column. In addition, Fig. 6(b) shows load-displacement hysteretic loops for the same specimen, BCJ9. Test specimen has shown excellent loop symmetry as observed by the first author in the experimental work reported earlier [22]. Comparing specimens in Table 4, which strengthened with the same number of ferrocement layers but subjected to different axial loading level, BCJ3 and BCJ9 showed that the major part of the initial stiffness was resulted from the strengthening layers. Moreover, increasing the axial applied load level from 15% for BCJ3 to 55% for BCJ9
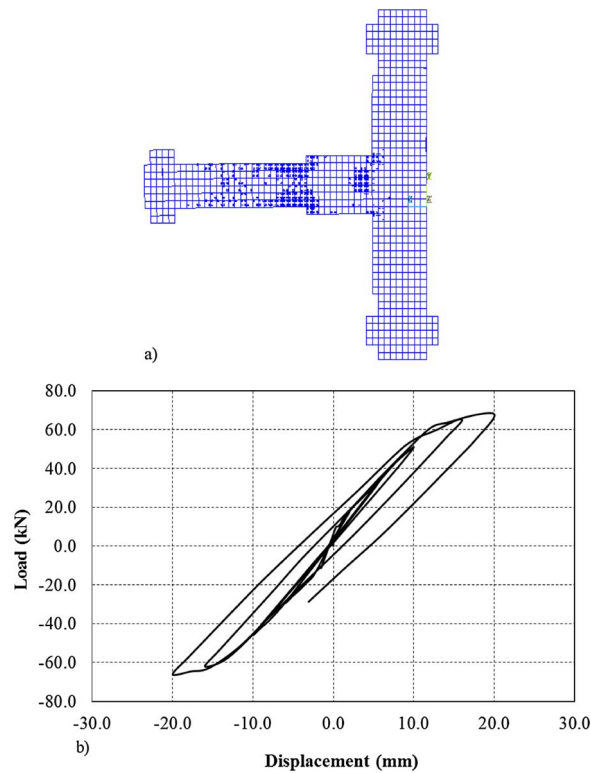
a)

b)

**Fig. 6.** Crack propagation and load-displacement hysteresis loops for a typically studied specimen.
(a) Cracks propagation for Specimen BCJ9 at ultimate load. (b) Load displacement hysteresis loops for Specimen BCJ9.

resulted in a reduction of ultimate displacement by 20%, reduction of initial stiffness by 23%, improvement of ultimate stiffness degradation by 25% while the ultimate load was reduced by 3% only. This may be attributed to the improvement in ductility of such strengthened specimen by two layers of ferrocement with minor effect on its ultimate load in resisting the increase of axial loading level from 15% to 55%.

### 4.3. Effect of axial load level

Three groups were analyzed to study the effect of the axial load level on the behaviour of beam-column joint. The specimens were provided with nil, one or two layers of ferrocement, as indicated in Table 3. The load-displacement hysteresis envelopes of specimens are shown in Fig. 7 and the results of ultimate load, displacement, initial stiffness, stiffness degradation at cracking loads and ultimate loads are reported in Table 4. It can be seen from Table 4 and Fig. 7(a) that for axial loading level, 15%, BCJ2 had higher ultimate capacity and lower ultimate displacement than that of BCJ1 by 37%, and 42%, while BCJ3 had higher ultimate capacity and lower ultimate displacement by 47% and 42%, respectively. Specimens BCJ2 and BCJ3 had a higher initial stiffness than that of BCJ1 by 87% and 95%, respectively. Fig. 7(b) shows the load-displacement hysteresis envelop for specimens BCJ4, BCJ5 and BCJ6 after increasing the axial loading level to 25%. The ultimate load of BCJ5 and BCJ6 were higher than that of BCJ4 by 69% and 75%, respectively. Further increase in axial loading level to 55%, Fig. 7(c) shows that the specimens strengthened by one and two layers of ferrocement BCJ8 and BCJ9 had higher ultimate load than that of BCJ7 by 50% and 52%, respectively. Table 4 shows that the initial stiffness of BCJ8 and BCJ9 are higher than that of BCJ7 by 147% and 173%, respectively. Stiffness degradation rates for BCJ8 and BCJ9 were higher than that of BCJ7 by 130% and 100%, respectively. Li [15], in his study, found also that the applied axial compression stress to the column has a significant effect on the seismic performance of reinforced concrete beam-column joints strengthened by ferrocement jackets.

Fig. 8 shows the stress distribution output images obtained by ANSYS [17] for typical specimens at different levels of axial loading, namely, BCJ1, BCJ3, BCJ6 and BCJ9. It can be seen from the figure and the results reported in Table 4 that the specimens strengthened by two layers of ferrocement, BCJ3, BCJ6 and BCJ9 under axial loading levels, 15%, 25% and 55% had better performance than that of the non-strengthened specimen, BCJ1, under axial loading level of 15%, to different degrees. The reported values in Table 4 shows that BCJ3, BCJ6 and BCJ9 had ultimate capacities higher than those of BCJ1 by 47%, 31% and 43% and their ultimate displacements were lower than that of BCJ1 by 42%, 56% and 54%, respectively. The stiffness degradation of BCJ3, BCJ6 and BCJ9 were lower than that of BCJ1, at first cracking loads, by 24%, 69% and 45%, respectively. At ultimate loads, the stiffness degradation of specimens BCJ3, BCJ6 and BCJ9 were lower than that of BCJ1 by 6%, 19% and 29%, respectively. This is in agreement with the findings of Tran and Hadi [25] who also reported the significance of the effect of axial compression stress applied to the
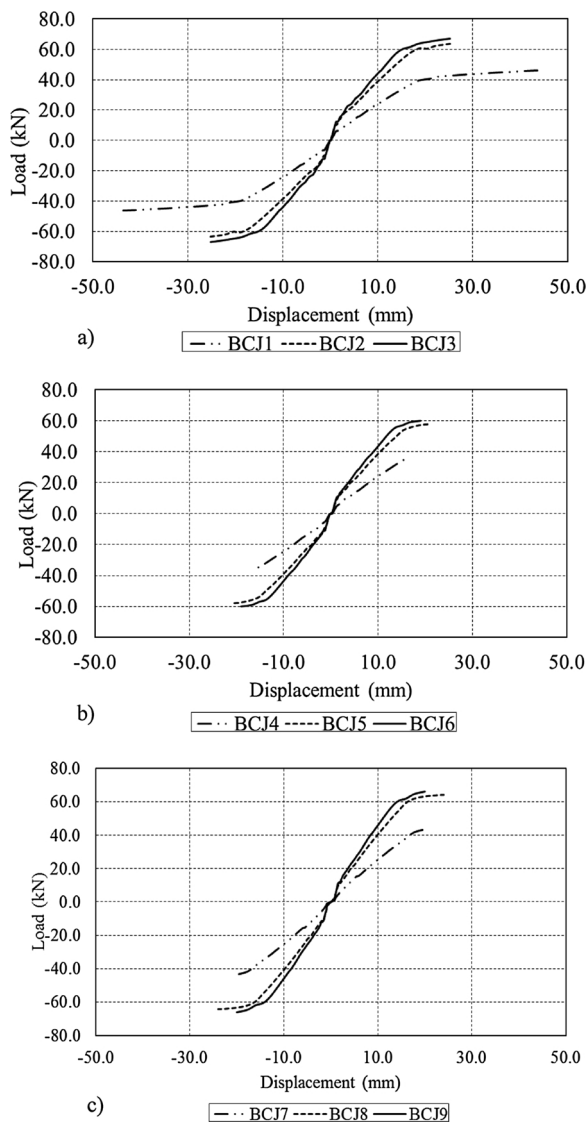
**Fig. 7.** Effect of axial load levels on beam-column joints strengthened by different number of ferrocement layers.

column in their theoretical shear strength model of reinforced-concrete exterior joint under cyclic loading.

### 4.4. Effect of longitudinal steel reinforcement

Analytical results of six specimens were investigated to demonstrate the effect of longitudinal reinforcement amount in the loaded beam on the beam-column joints performance. The specimens had longitudinal steel ratio of 0.35% or 0.95% and strengthened with nil (BCJ1, BCJ10; one (BCJ2, BCJ11) or two layers of ferrocement (BCJ3, BCJ12) (see Table 3). For the specimens before strengthening, BCJ1 and BCJ10, the load displacement relationship enhances significantly with increasing the longitudinal steel ratio as shown in Fig. 9 and Table 4. For example, the ultimate load and ultimate displacement of BCJ1 were higher than that of BCJ10 by 117% and 73%, respectively. For specimens strengthened by ferrocement, the longitudinal reinforcement ratio had a less effect than that for non-strengthened specimens. For example, BCJ2 had a higher ultimate load, higher initial stiffness and better stiffness degradation at initial cracking loads and ultimate load than that of BCJ11 by 100%, 11%, 18% and 14%, respectively. Specimen BCJ3 strengthened by two layers of ferrocement had a higher load carrying capacity, lower ultimate displacement, better stiffness degradation rate, at initial cracking loads and ultimate loads, than that of BCJ12 by 102%, 14%, 35% and 15%, respectively. Fig. 10 shows that strengthening specimens using ferrocement layers had a significant effect on dissipated energy for studied specimens of longitudinal steel ratio of 0.35%. It can be seen from Fig. 10 that as the displacement increased, the energy dissipated per cycle increased. In addition, the cumulative dissipative energy increases with increasing the number of ferrocement layers. For example, the figure shows that at 25 mm displacement, the dissipated energy values of BCJ11 and BC12 were higher than that of BCJ10 by
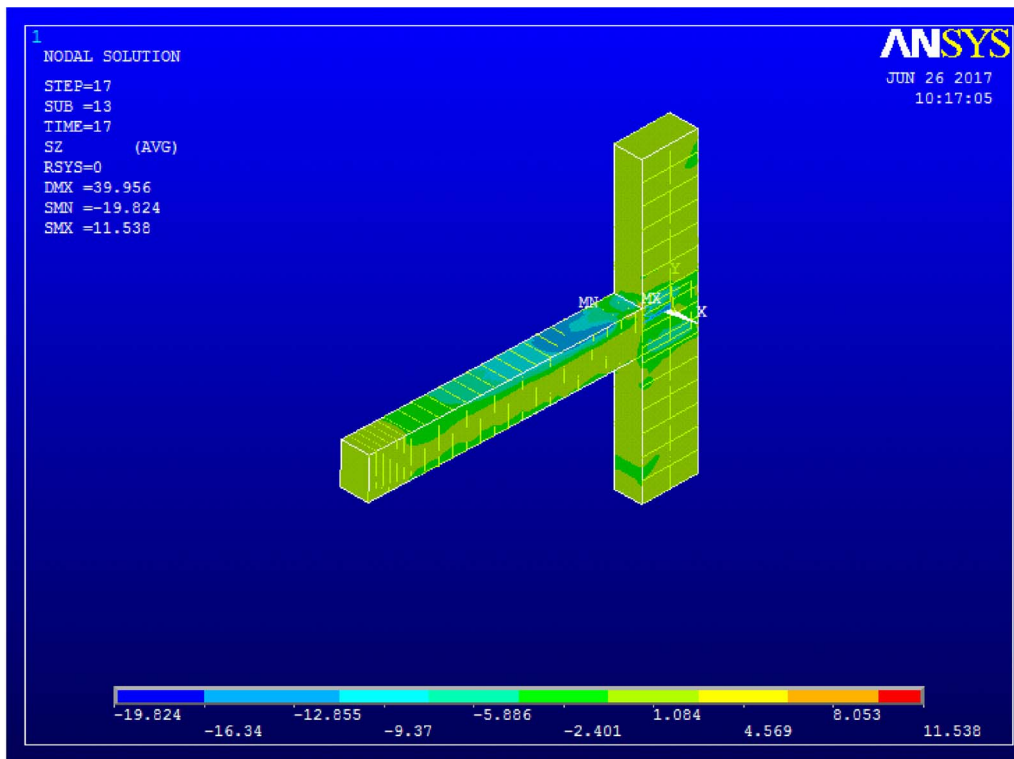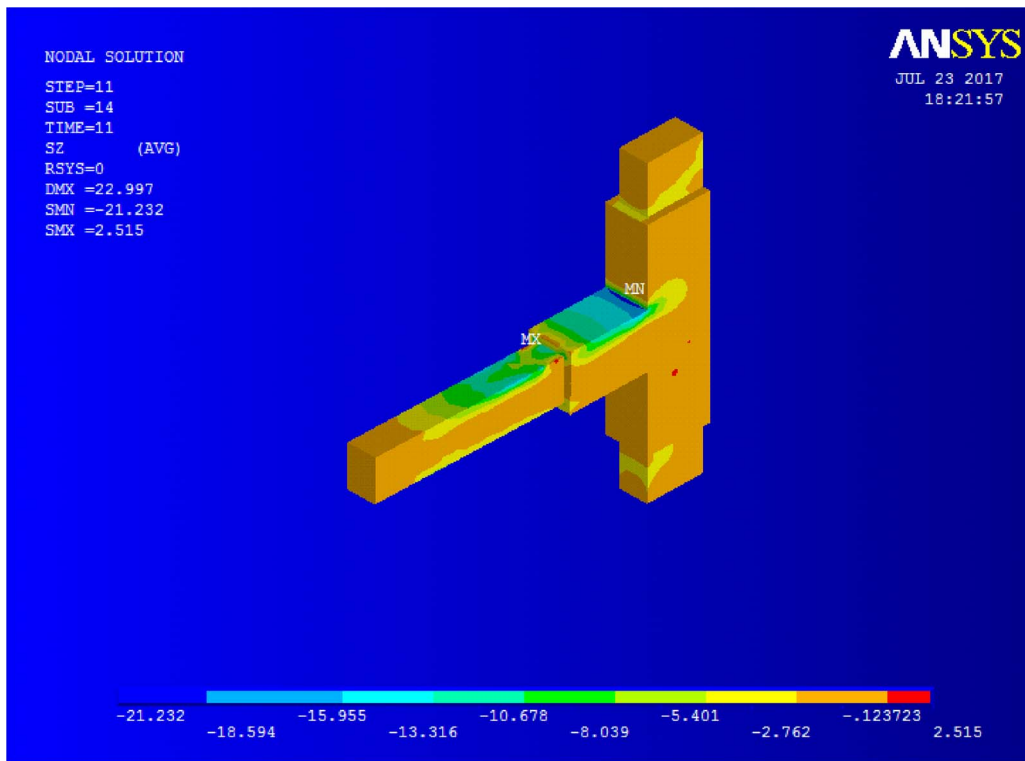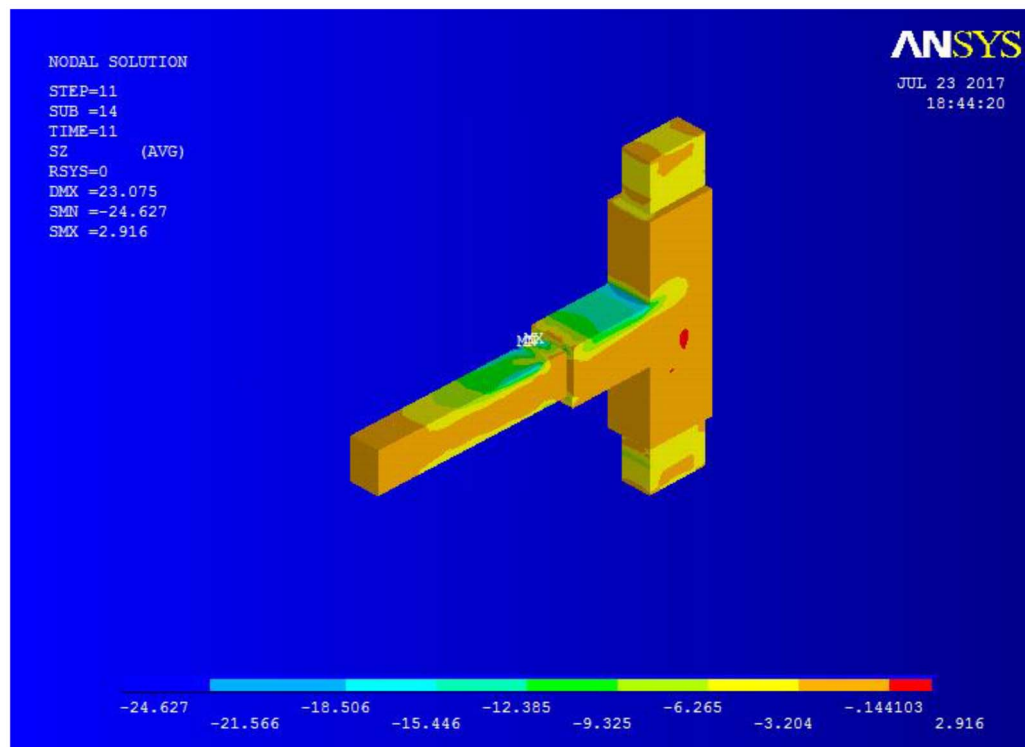
BCJ1
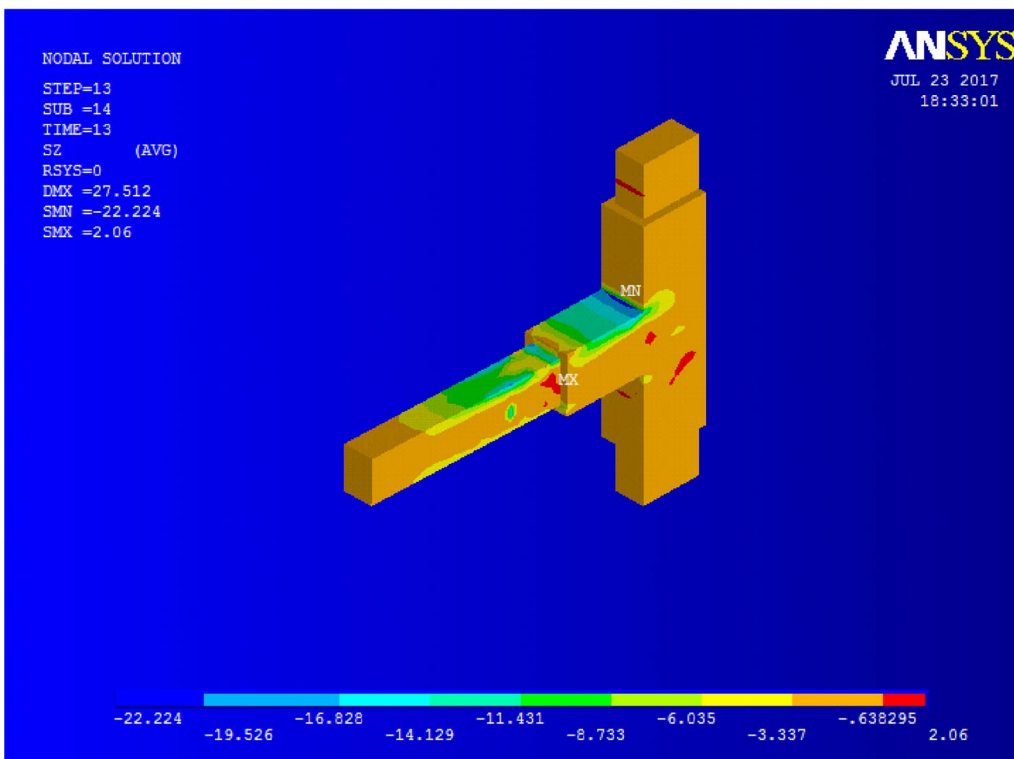


BCJ3

**Fig. 8.** Stress distribution for specimens under different axial loading levels at ultimate load.
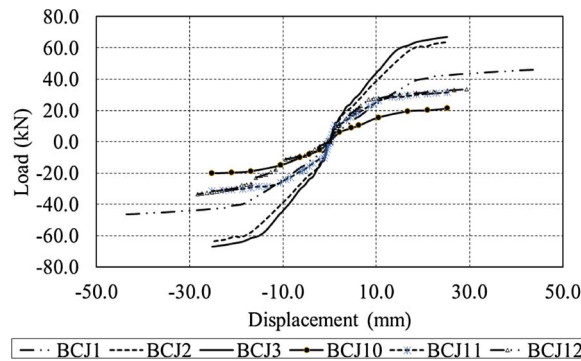
BCJ6



BCJ9

Fig. 8. (*continued*)

**Fig. 9.** Effect of loaded beam longitudinal steel ratio on the ultimate load.
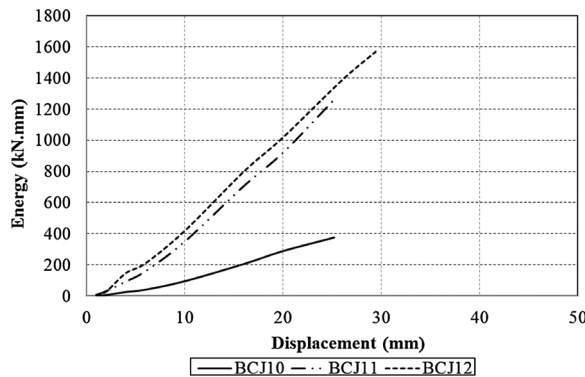


**Fig. 10.** Energy dissipated for test specimens.

200% and 225%, respectively. This is in agreement with the findings of Choi et al. [26] in their experimental work that the structural performances of the beam–column connections (e.g. failure mode, load–drift ratio relationship, shear deformation and energy dissipation of the connections) are mainly affected by the amount of longitudinal reinforcing bars in beams.

### 4.5. Effect of concrete compressive strength

Analytical results on four specimens were investigated to demonstrate the effect of concrete compressive strength on the strengthened beam-column joints performance. Concrete compressive strengths of 30 MPa and 40 MPa were considered in the parametric study. The specimens were studied under 0.25 axial load level. Table 3 shows the design parameters of specimens in detail (BCJ5, BCJ6, BCJ13 and BCJ14). The results were grouped for the specimens with identical number of ferrocement layers. The analytical lateral load displacement responses are illustrated in Fig. 11 and the values of ultimate capacities, displacements, initial stiffness and stiffness degradation are reported in Table 4. It can be seen from the figure and the table that increasing the compressive strength from 30 MPa for specimens BCJ5 and BCJ6 to 40 MPa for BCJ13 and BCJ14 resulted in higher ultimate capacities of the strengthened specimens by 10% and 17%, respectively. On the other hand, the ultimate displacements of specimens BCJ13 and
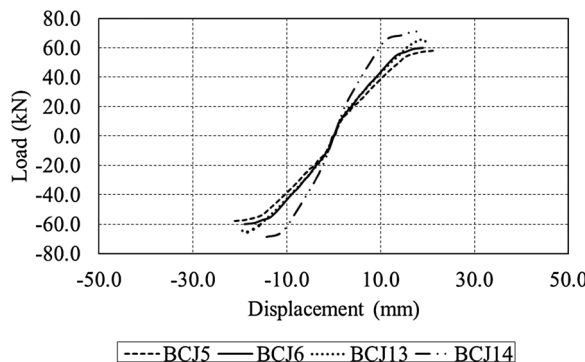


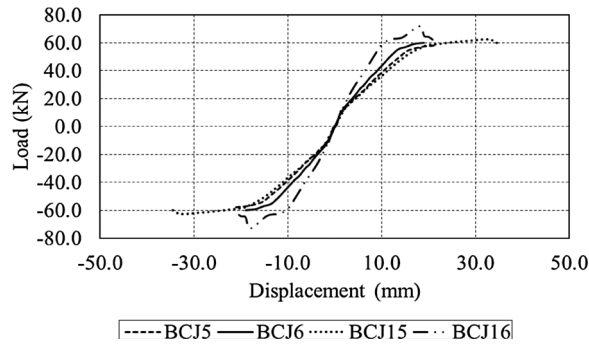**Fig. 11.** Effect of concrete compressive strength on the ultimate load.

**Fig. 12.** Effect of orientation angle of expanded wire mesh on the ultimate load.

BCJ14 were less than that of specimens BCJ5 and BCJ6 by 8% and 7%, respectively. Stiffness degradations for BCJ13 and BCJ14, of higher compressive strength, were less than that of BCJ5 and BCJ6 by 51% and 4% at initial crack loads and by 26% and 0% at ultimate loads. This shows that specimens of higher compressive strength had higher ultimate load, lower ultimate displacement and better stiffness degradation after strengthening by ferrocement layers. Increasing the number of ferrocement layers for strengthening reduced the effect of compressive strength of original specimens. Bedirhanoglu et al. [5] found similar observations in his pilot study for applying precast fiber reinforced cementitious composites for seismic retrofit of deficient RC joints.

### 4.6. Effect of orientation angle of expanded wire mesh

The effect of orientation angle of expanded wire mesh on the load carrying capacity of the strengthened joints using ferrocement layers was plotted versus the displacement in Fig. 12 and the values of ultimate load, displacement, initial stiffness and stiffness degradation were reported in Table 4. It can be seen from the figure and the table that for BCJ5 and BCJ6 strengthened by one and two ferrocement layers and orientation angle of expanded wire mesh, 60°, had almost the same ultimate load as for BCJ15 and BCJ16 strengthened by the same number of layers and orientation angle of expanded wire mesh, 45°. On the other hand, the ultimate displacement increased by 69% for BC15 compared to that of BC5 and increased by 14% for BCJ16 compared to that of BCJ6. Initial stiffness of BCJ15 was less than that of BCJ5 by 29% while the initial stiffness of BCJ16 was less than that of BCJ6 by 17% only. Percentages of stiffness degradation for BCJ15 and BCJ16 were less than those of BCJ5 and BCJ6 by 46% and 36% at initial crack loads while the trend was opposite at ultimate loads but to less degrees, 7% and 1%, respectively. This shows that, for studied specimens, changing the orientation angle of expanded wire mesh from 60° per ferrocement layer to 45° has a minor effect on the ultimate load but it has a significant effect on the ductility of studied specimens. In addition, increasing the number of layers reduced the effect of orientation angle on the ductility. This is in agreement with Bansal et al. [27] who studied the effect of wire mesh orientation of ferrocement jackets in strengthening concrete beams. They found that with an orientation at 45°, the energy absorption was the highest, indicating the significance of the effects of wire mesh orientation.

## 5. Summary and conclusions

The numerical results obtained by ANSYS model were verified using experimental results obtained by the first author [22]. A parametric study was carried out using this model to investigate the effect of additional variables on the behaviour of exterior beam-column joints in building frames strengthened by ferrocement layers. The main conclusions can be drawn from this study as follows:

1. The application of non-linear finite elements model presented in this study yielded satisfactory prediction of load-carrying capacity and load-deflection response for experimentally tested specimens strengthened by ferrocement layers. Crack patterns, load-displacement hysteresis loops, and stress distribution results for theoretically studied specimens were simulated accurately using ANSYS package.
2. The level of applied axial load to the column, longitudinal steel ratio in the beam and compressive strength of the studied specimens had a significant effect on their ultimate load, ultimate displacement and stiffness degradation before strengthening, to different degrees. Applying the strengthening scheme reduced the effect of these parameters. Increasing the number of ferrocement layers in such strengthening scheme led to a further improvement in resisting higher levels of axial loads applied to the column, in the beam-column joints.
3. For the studied specimens, changing the orientation angle of expanded wire mesh from 60° per ferrocement layer to 45° had a minor effect on the ultimate load but it had a significant effect on the ductility of studied specimens. By increasing the number of ferrocement layers, the effect of orientation angle became less significant on the ductility.
4. The results of this research indicates that accurate simulation of beam-column joints before and after strengthening using ferrocement can help engineers to successful upgrading of the joints in existing buildings, saving time, money and lives in seismic zones.

## Conflict of interest

None.

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