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Research Paper

Numerical Analysis of Steel-Concrete Composite Beam with Blind Bolt under Simultaneous Flexural and Torsional Loading

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ABSTRACT: This paper investigates the composite beam with bolt shear connectors. Composite beams are usually used as secondary beam in buildings. It is clear that studying the torsion in side beams in buildings such as balconies is of great importance. The composite beam was loaded under three different loading conditions including a pure flexural loading, and simultaneous flexural loading with two alternative torsional loading modes. The obtained results from the analysis were compared with each other by three-dimensional non-linear finite element model using ABAQUS. The obtained results, including the mid span deflection, the rotation and slip of composite beams under different loading conditions were investigated. The effect of the type and number of shear connectors on slip of composite beam was studied, too. The results indicated that the slip between the steel beam and the concrete slab along the composite beam increased due to flexure loading, but the torsional loading had a slight effect on the slip.

Keywords: Bolt Shear Connectors, Composite Beam, Flexural And Torsional Loading, Slip Effects.

INTRODUCTION

Composite beam is constructed by placing a concrete slab on a steel beam using shear connectors, which is commonly used in high buildings, bridges, stadiums and so on. One of the main factors affecting the properties and function of infrastructures under the current and future loading is age. Recent studies indicate that improvement of old infrastructures leads to extension of their service life and resistance under future loads (Engineers Australia, 2010). Regarding that the composite beam is made of two different materials (steel beam and concrete slab), it is the task of mechanical shear connectors to resist the shear stress and transfer it to the structure that must withstand the slip. Thus,

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shear connectors are used in such beams. Common shear connectors include channel, angle, stud and bolt.

In the past years, the use of stud shear connectors has been common due to their easy use in buildings, and many papers investigated this type of connectors (Oehlers and Coughlan, 1986; Shariati et al., 2013; Zabihi-samani et al., 2019). Fanaie et al. (2015) studied channel connection and the comparison between face to face and back to back position in this connection using ABAQUS. The results showed that in both positions, composite beam stiffness were of the same amount although in face to face channel position better function was observed.

Khorramian et al. (2017) analyzed the tilted angle in composite beam. They investigated different degrees tilted angle using nonlinear finite element modeling and compared these results with the one's from push-out test. Ding et al. (2017) examined stud behavior under loading of earthquake. In laboratory, mechanical behavior of stud such as failure and stiffness were studied. The results obtained were similar to the results from ABAQUS. By employing experimentally obtained data, they found hysteretic curve to display load-displacement relation.

Bonilla Rocha et al. (2018) tested the behavior of stud connection in concrete slab and composite beam in lab and compared obtained results with results from six different codes. These results indicated that estimation of stud strength was not completely accurate. Xu et al. (2017) studied function of fatigue and static behavior of stud in steel fiber reinforced concrete using push-out tests. They concluded that improvement of stud function was obtained in steel fiber reinforced concrete, while compressive strength of concrete was low.

Tan and Uy (2011) analyzed straight and curved composite beams with stud shear connectors under the influence of flexure and torsion by finite element model. Their results indicated that the composite beam with stud shear connectors has greater maximum ultimate strength compared to steel beam and concrete slabs The use of bolt shear connectors instead of stud in composite beam has several important features. Bolts have the ability of attachment and detachment on one side of the structure in rehabilitation of the building which is not possible for stud. The installation process of bolt using powerful tool is much faster than of the welding the stud, but welding the shank of stud connectors to the steel beam is a time consuming and difficult process. It is not necessary to install heavy equipment along the beam. Therefore, with non-destructive methods, efficient evaluation of the bolt connection's quality can be reached. Whereupon, the quality evaluation of the bolts is much more reliable than the welded stud shear connectors (Pathirana et al., 2016; Raji et al., 2019).

Lam and Saveri (2012) compared the behavior of bolt shear connectors with stud shear connectors using a push-test in laboratory. The results of the test indicated that the capacity and behavior of the bolt shear connectors are similar to those of the stud shear connectors. Using ABAQUS, Shayanfar et al. (2018) analyzed the Finite Element model of reinforced concrete beam-column connection for two different models with steel and GRFP rebars. The results indicates that GRFP rebars reduce the connection plasticity.

Bahrami and Madhkhan (2019) applied welded connections as a type of precast reinforcement connection that welded on the corbel by plate. They investigated the pattern of crack and also precast joint. Lacki et al. (2019) examined the steel composite beam including top-hat profile connectors. They concluded that increasing the sheet length leads to increase in load-bearing capacity.

Bezerra et al. (2018) tested and analyzed composite beam with V-shaped connectors by ABAQUS. There was a good consistency between the Finite Element modeling and modeling in the lab. Milosavljevic et al. (2018) studied behavior of static bolt shear connections with mechanical coupler embedded in concrete. They studied different modes of failed specimens using tests and Finite Element method. They also analyzed tensile strength of bolts, bolts diameter and distance of them from edge slab concrete.

Pavlovic et al. (2013) compared the local behavior stud shear connectors and bolt shear connectors. They investigated shear strength, ductility, stiffness and failure modes. They also used Finite Element modeling to examine the shear strength factors of the bolt shear connectors. Both reviews were constrained to the study of the specific slip behavior of the stud and bolt connectors.

Vakili et al. (2019) studied lightweight concrete beam with glass fiber reinforced polymer bars. The results of their tests show that the fiber affects the lightweight aggregate concrete. Moynihan and Allwood (2014) tested three composite beams with lengths of 2, 5 and 10 meters with M20 bolt shear connectors. The beams were loaded and unloaded. After that the steel beam and concrete slabs were separated before failure, and the connectors were examined. They used various standard nuts with this bolt and found that the use of this type of bolt was quite confident.

For the first time, Mirza et al. (2010a) examined the slip behavior of blind bolt connectors by conducting a set of push tests. The blind bolt connectors were of M20- grade 8.8 type. The results indicated that this type of blind bolt connectors have a comparable behavior and capacity against the stud connectors. Further researchers studied four beams under flexural loading. These beams included two composite beams with blind bolt-M20-grade 8.8 shear connectors, a composite beam with stud shear connectors and a beam without shear connectors between the steel beam and concrete slab. They compared the ultimate strength, mid span deflection and the slip between the steel beam and the concrete slab of these four beams in the laboratory (Pathirana et al., 2016; Zabihi-Samani, 2019). They also validated the obtained results of the laboratory using the Finite Element method and ABAQUS, which had similar results. In their study, the beam without shear connectors had the least strength and the most slip.

In this paper the Finite Elements of composite beams with bolt shear connectors were studied under the influence of simultaneous flexural loading with different torsional loading modes by ABAQUS software.

DETAILS OF COMPOSITE BEAM

Based on paper (Pathirana et al. 2016), the composite beam design that was investigated earlier, was used in this paper. The steel beam is designed according to the AS4100 and the concrete slab is designed based on the AS3600. Composite design is based on AS2327.1 and AS1170.1 is used for loading. Figure 1 represents the used bolt type in the composite beam.

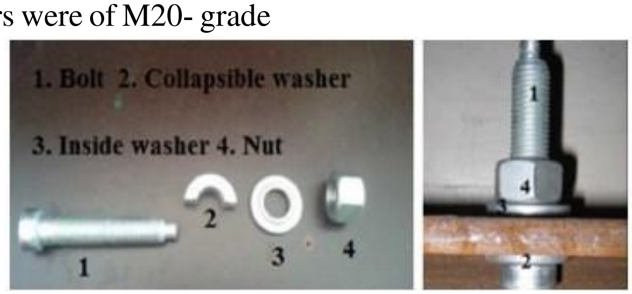


Fig. 1. Blind Bolt M20-grade 8.8

The number of bolt shear connectors used in composite beam was 27 connectors. The details of the composite beam are in Table 1.

Table 1. Design details of composite beam

Span length	6200 mm
Steel section	460UB74.6
Concrete slab width	1 m
Concrete slab thickness	150 mm
Slab cover	50 mm
Main bars in top and bottom	N12@240 mm c/c
Transverse bars	N12@240 mm c/c
Number of bolt shear connection	27
Distance between bolt	230 mm c/c

Figure 2 illustrates the cross section details of the composite beam, the placement of the bolt and the placement of connectors in the plan.

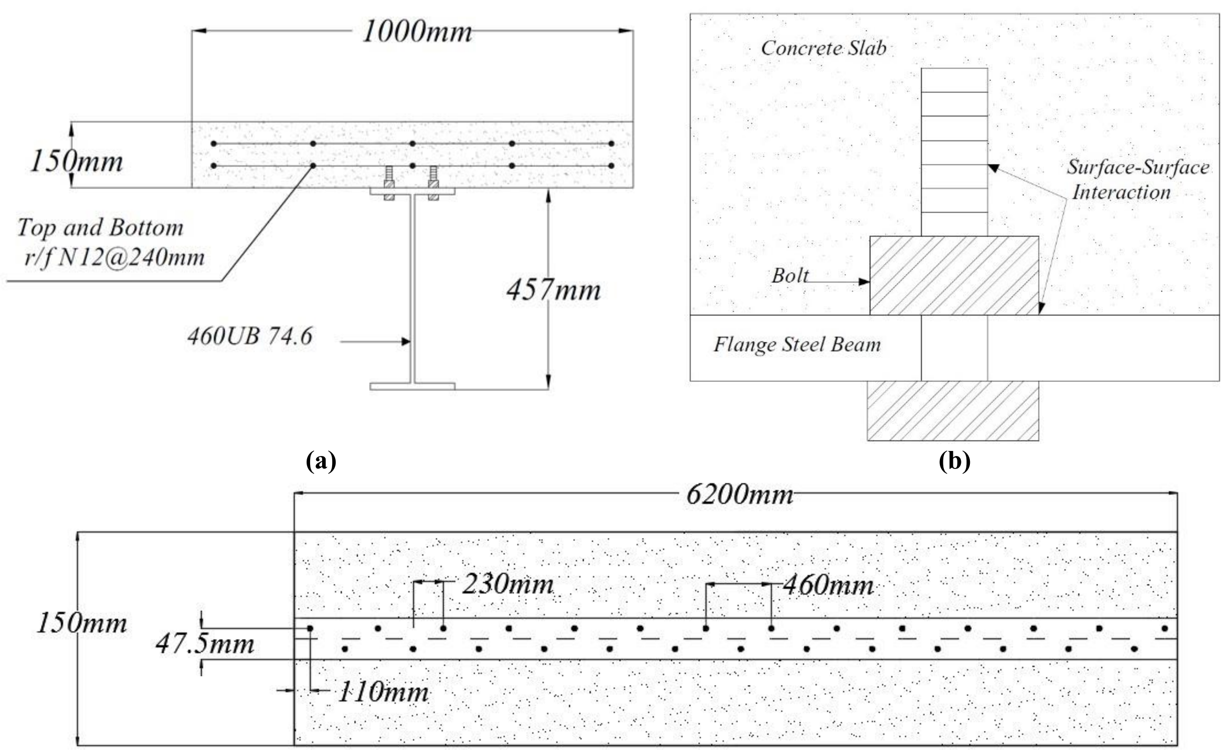
FINITE ELEMENT MODELING

In this paper, the composite beam modeling was conducted as a three dimensional Finite Element using ABAQUS. All main components of the composite beam including the steel beam, concrete slab, bolt shear connectors and rebars were defined non-linear for the software. In the sub-section of this section, the details of modeling are addressed.

Properties of Concrete Material

The properties of the linear and non-linear behavior of the concrete for compressive and tensile strength were defined based on the Carreira and Chu (1985), which is calculated by Eq. (1).

$$\sigma_C = \frac{f'_C \gamma \left(\frac{\varepsilon_C}{\varepsilon'_C}\right)}{\left(\gamma - 1 + \left(\frac{\varepsilon_C}{\varepsilon'_C}\right)^{\gamma}\right)} \quad (1)$$



(c)

Fig. 2. Details of the composite beam: a) Cross-section; b) Placement of the bolt; c) Placement of connectors in the plan

where $\gamma = \left(\frac{f'_c}{32.4}\right) + 1.55$ and f'_c, the maximum compressive strength of concrete are 34 MPa and the elasticity module is considered 30000 Mpa. Using the Concrete Damage Plasticity option, the non-linear section was defined for the concrete in the software. The compressive and tensile strength of the concrete were defined using the compressive behavior and tensile behavior option for the software respectively. The stress-strain relationship in tensile is assumed to be linear. The tensile stress is increased linearly to the point in which the concrete starts to crack in tensile region, and after that point it starts to decrease linearly till reaching zero. According to the Liang et al. (2004), the ratio of uniaxial tensile stress to uniaxial compressive stress in the failure is 0.1.

Properties of Steel Materials

For a correct modeling, stress-strain relationship of steel materials should also be introduced linearly and non-linearly to ABAQUS. Table 2 shows the properties of steel materials used in the composite beam, which are used for linear and nonlinear modes. The relationships of non-linear stress-strain curve of steel materials used for steel beam, bolt shear connectors and rebars in Pathirana et al. (2016) were extracted numerically and these results were defined to ABAQUS according to the Table 2.

Interaction Properties and Boundary Conditions

In reality, the objects are in contact with each other, or connected to each other or overlapped. Therefore, the collision of objects must be defined in ABAQUS that in this research it includes the steel beam, concrete slab, rebars and shear connectors. The Tie constrain option was used in the interaction between steel beams and bolt shear connectors because with this option the shear connectors do not separate from the steel beam. The surface to surface option was used for collision and slip between the steel beam and the concrete slab. The shank of bolts in the concrete slab were also defined as surface to surface.

For the normal behavior, the “Hard” option and for the tangential behavior, the “Penalty” option is used in ABAQUS. In most articles, the friction coefficient is between 0.3-0.4, which is selected according to the type of problem. In this research, it is considered 0.4. The rebars in the concrete slabs are also defined as embedded regions. This is an appropriate method to prevent the movement of rebars in the concrete slab, the rebars are buried in the concrete slab just as it is in reality.

Loading

Two simple supports are at each end of the considered composite beam. One pin supported and the other roller supported. Loading in ABAQUS is defined as Static general. Three loading modes are considered for the beam: mode A is the case when the composite beam is loaded only 435 KN. This amount of loading is applied evenly to the beam at a distance of 500 mm from the center of the beam. In this mode, the beam is only under flexural moment and undergoes pure flexure. Figure 3 represents the mode A. This mode usually occurs in the beams of buildings.

Mode B is the case when the beam is loaded under the first mode, and a sum of 15 kN load is applied on and below the concrete slab surface, causing the torsional moment as observed in Figure 4.

Mode C is the case when the beam is under the first mode of loading and also a distributed 100.44 N/mm load is applied to one side of the concrete slab. In this case, the beam is under combined flexural and torsional moment simultaneously as indicated in Figure 5. This mode of loading is used when the surrounding beam loads the intended beam.

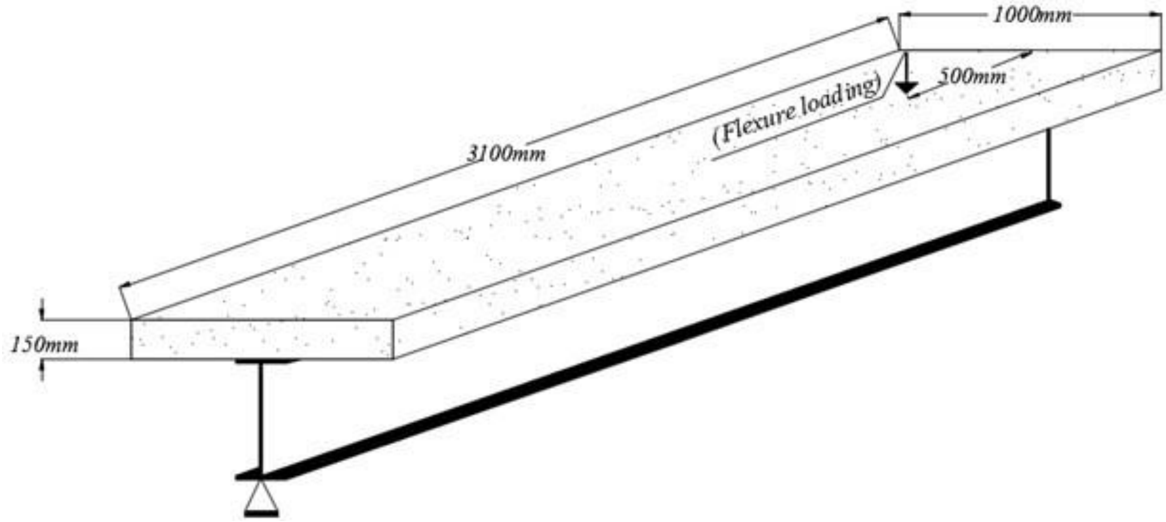


Fig. 3. Half of the composite beam span under the A-mode loading

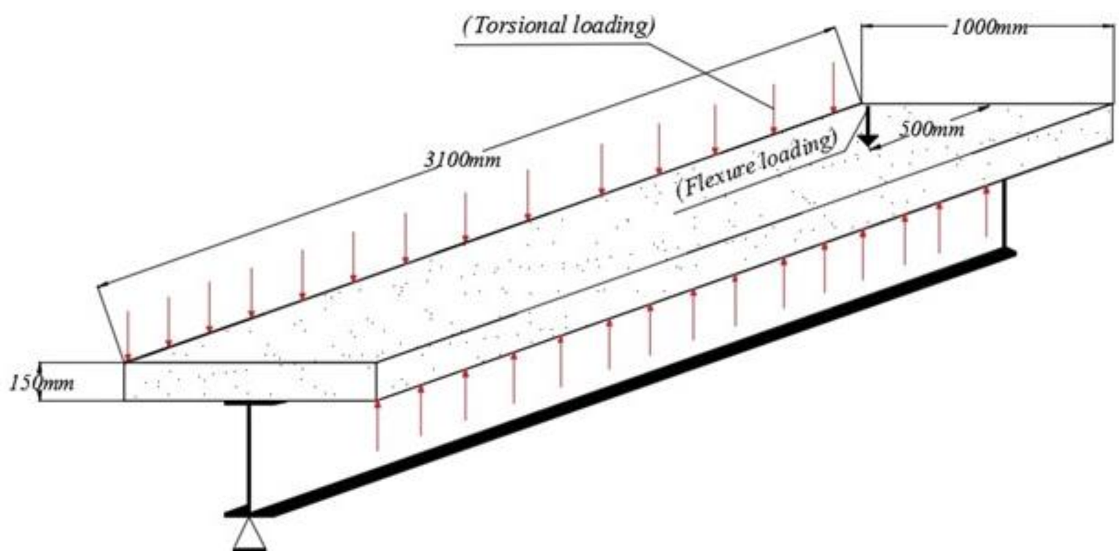


Fig. 4. Half of the composite beam span under the B-mode loading

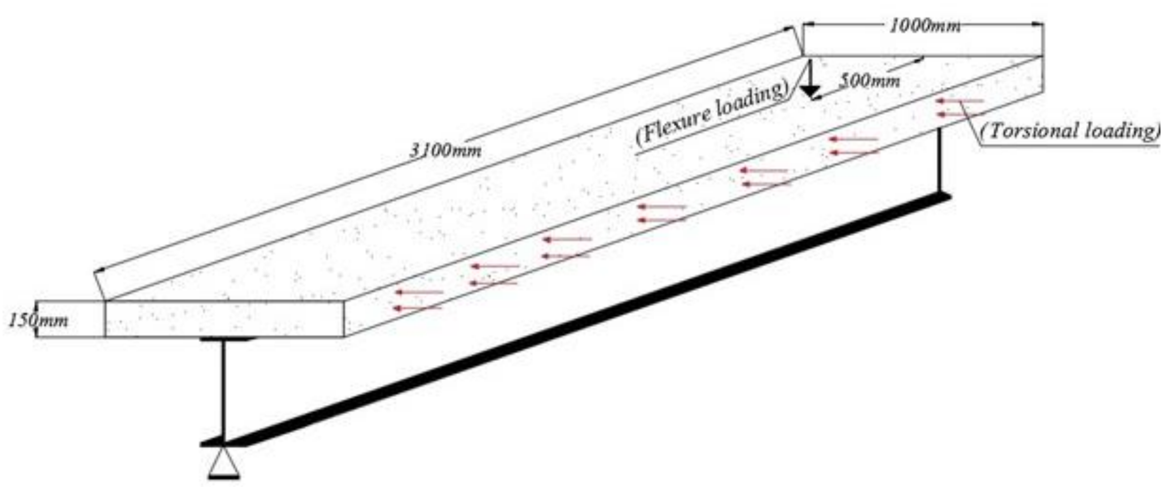


Fig. 5. Half of the composite beam span under the C-mode loading

Table 2. Steel properties used for steel materials

Material type (Mpa)	Elastic modules (Mpa)	Ultimate strength (Mpa)	Yield stress (Mpa)	Plastic strain
Steel beam	200000	555	392.065 398.2319 544.9151	0 0.0156059 0.0534859
Blind bolt	187000	900	746.3082061 833.2942585	0 0.019760915
Steel reinforcing	194000	650	548.2854 609.64328	0 0.1059919

In modes B and C of loading, the beam undergoes combined flexural and torsional moment simultaneously. The amount of torsional moment is the same in modes B and C, but the loading mode is different for the beam to undergo torsional moment.

Element Type and Meshing

The steel beam, concrete slab and bolt shear connectors are defined as eight-node linear-hexahedral solid element with reduced integration and hourglass control (C3D8R) and three transitional degrees of freedom. In addition, the rebars are defined as two-node linear three- dimensional truss elements (T3D2) in the software. The meshing method is indicated in Figure 6.

The optimal number of meshing these elements was considered. As shown in figure 6, the nuts and bolts are meshed individually so the mesh is more accurate.

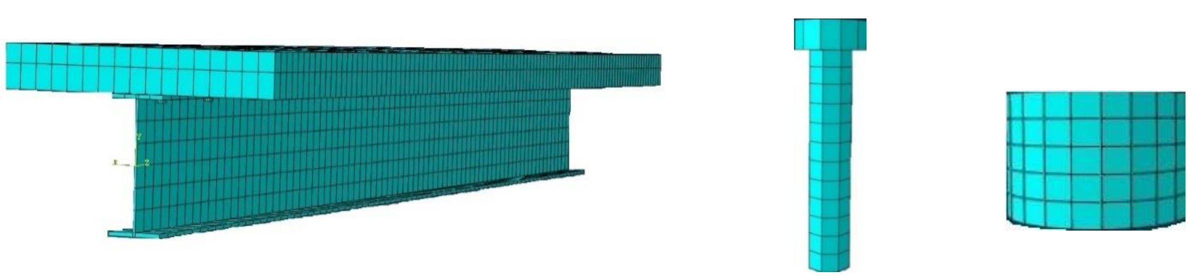
Validation

Regarding the type and shape of the bolt, the behavior of steel and concrete according to Tables 2 and 3, as well as the interaction of elements of the composite beam, the modeled composite beam was loaded under A mode and the obtained mid span deflection was compared with the paper Pathirana et al. (2016), as shown in Figure 7.

RESULTS AND DISCUSSION

Mid Span Deflection

The value of mid span deflection is very important, so it was investigated. The deflection of composite beams under loading modes (A, B and C) were compared and the results are presented in Figure 8. This figure illustrates that the maximum deflection is related to mode A, which is about 81.5 mm. The deflection of B and C modes are about 80 and 80.5 mm respectively. In validation modeling, as in Pathirana et al. (2016), the interaction of the bolts with the flange of steel beam was surface to surface method and the holes larger than the bolt diameter were placed on the flange of steel beam, but in this paper, the interaction between the steel beam and bolts were defined by the Tie constrain method in the software, and the diameter of the bolts and the diameter of holes on the steel were assumed to be the same, and therefore the value of deflections obtained in diagram of Figure 8 are less than that of Figure 7.



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

Fig. 6. Meshing the elements: a) composite beam; b) shank of bolt; c) bolt nut

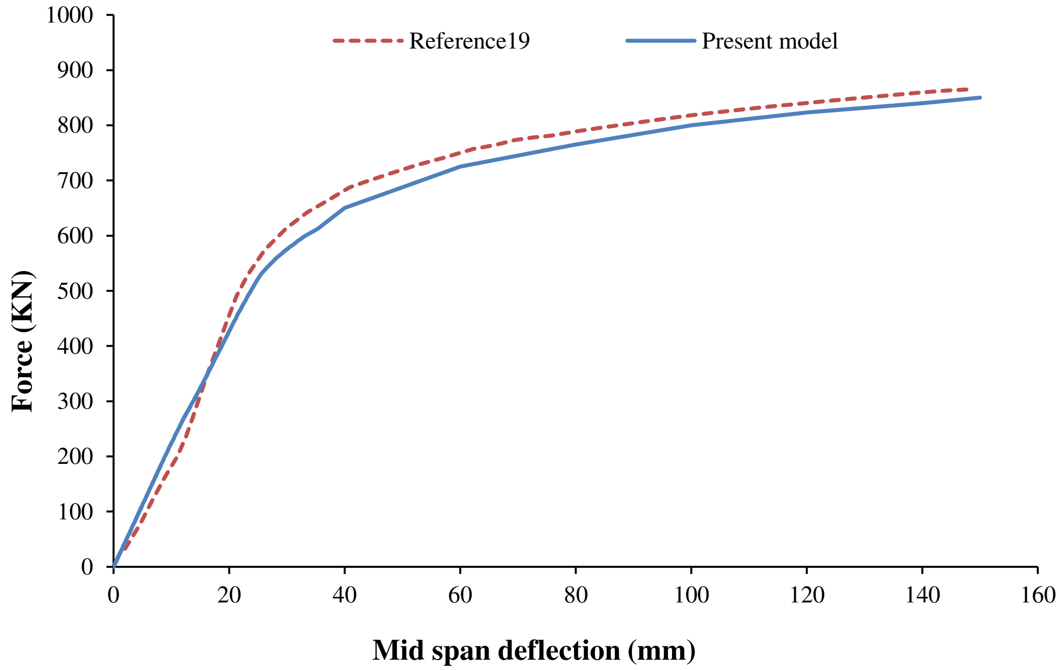


Fig. 7. Validation curve

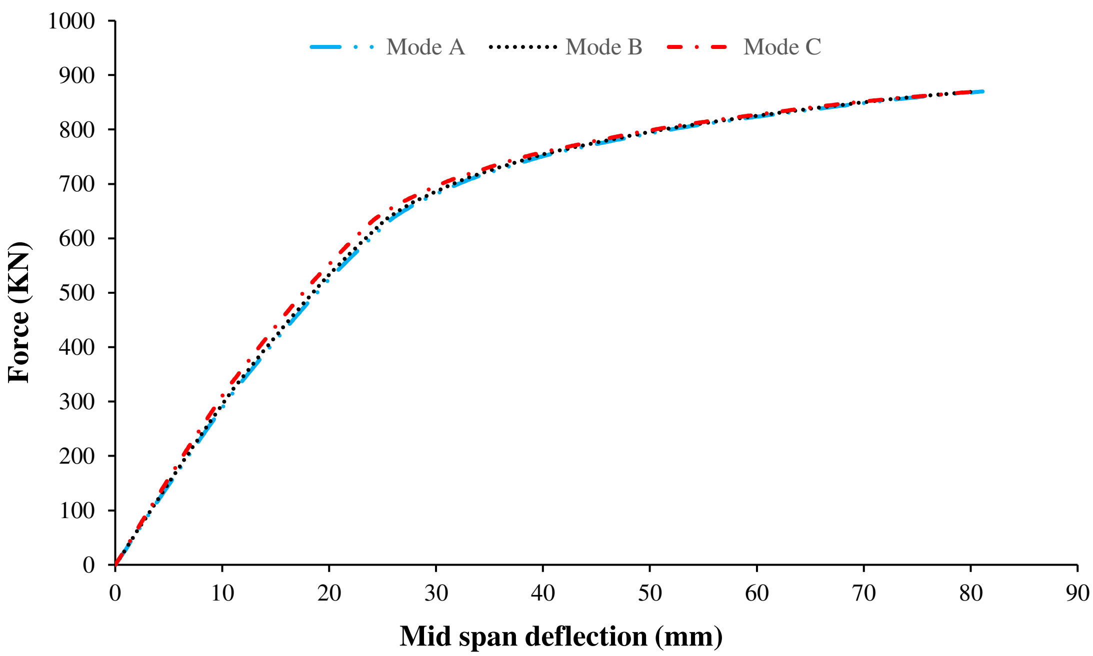


Fig. 8. Mid span deflection curves in different loading modes

In B and C modes, the shear forces that cause torsion in the beam bring the composite beam slightly upwards, which is why the mid span deflection of beam under flexural loading is more than the other two modes. Moreover, the results of the diagram shows that the shear forces that cause the torsion of beam do not have a significant effect on the mid span deflection. The total shear forces applied to the beam that cause the torsion in the beam is 15 kN, resulting in a moment of 2466.98 KN.mm. The results from analysis carried out shows that the shear forces more than 15 kN resulted in more torsional moment in the beam leading to bolt condensation.

The Rotation of Composite Beam

Regarding the importance of torsion in the building, the rotation of composite beam was investigated under three loading modes. The diagram in Figure 9 indicates the rotation value of the beam until the end of the loading duration.

It is observed in Figure 9 that the highest amount of rotation was related to mode C, which is about 40 degrees, and the lowest value was for mode A and about 0.9 degrees. Considering that the analysis was non-linear, it is clear that beam had 0.9 degrees rotation under pure flexural loading. The amount of rotation in the mode B was less than that of mode C, which in this mode; the concrete slab was loaded from the side, causing the intended beam to rotate in two directions, except the y direction. However, in mode B, the loading was in the direction of y and rotated very little in the other two directions, and thus the amount of rotation in mode B was much less than that of mode C. The rotation amount was almost the same throughout the composite beam. The highest amount of failure in the concrete slab of composite beam is observable under modes A and C of loading in Figures 10 and 11.

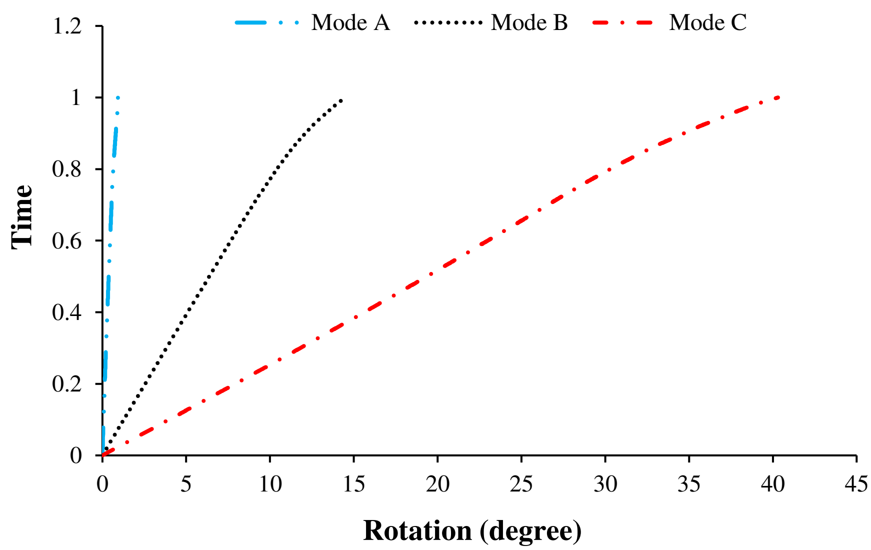


Fig. 9. Composite beam rotation curves in different loading modes

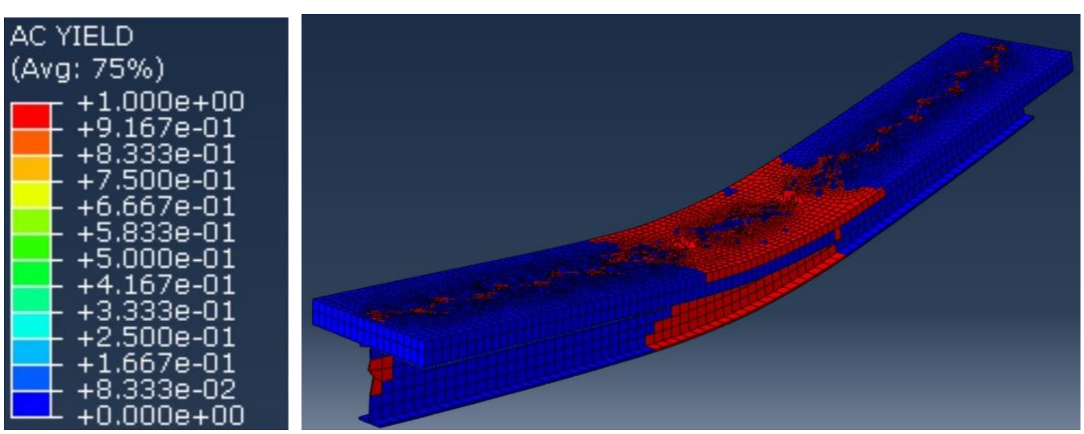


Fig. 10. Composite beam under mode A

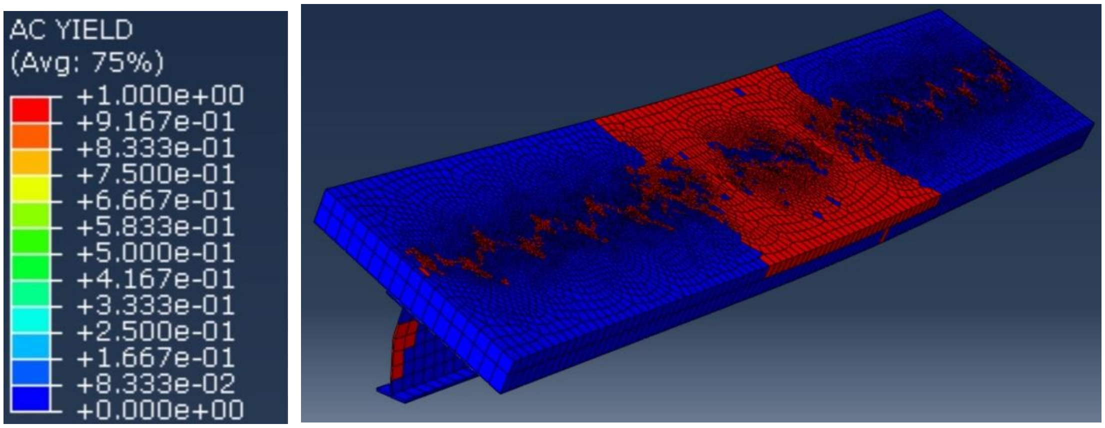
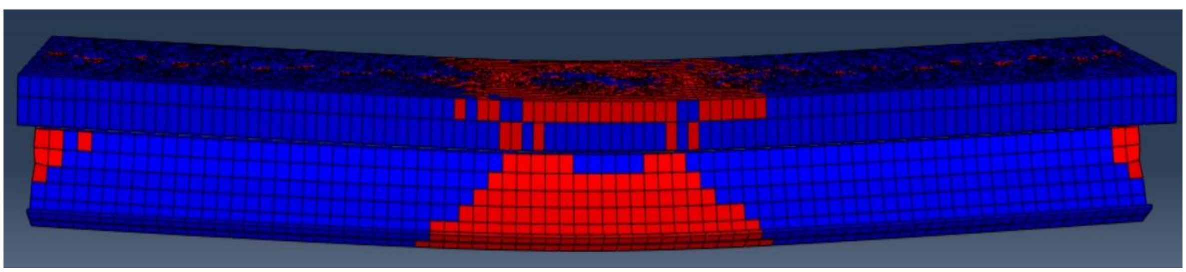


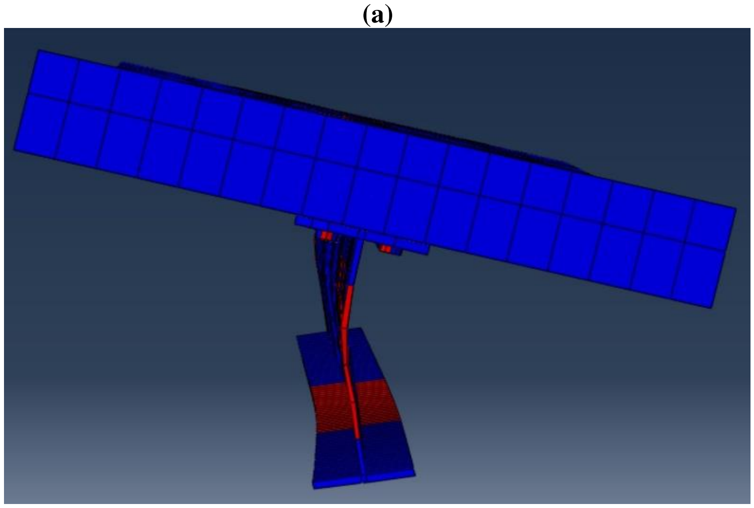
Fig. 11. Composite beam under mode C loading

In Figures 10 and 11, the highest amount of failure was in the middle of the concrete slab. In both modes, shear forces which caused flexure in composite beam were in this region. Moreover, shear forces that lead to torsion in the beam had much less effect on concrete slab failure. Figures 12a and 12b represent the highest amount of steel beam failure and the torsion of steel beam under the B and C loading modes, respectively. The stress contour was the same amount in all three modes.

The torsion of steel beam under two different loading conditions is observable in Figures 12a and 12b. As the concrete slab, in the section where the flexural load was applied to the steel beam, the greatest amount of failure of the steel beam.



(a)



(b)

Fig. 12. Composite beam under different modes of torsional loading: a) The amount of steel beam failure under mode B; b) The torsion of steel beam under mode C

The Slip between the Steel Beam and the Concrete Slab

One way to find the slip between two things is displacement between nodes. In this study, according to the paper (Mirza and Uy, 2010b), a node on the top of steel flange and a corresponding node of the selected node in the bottom surface of concrete slab are chosen. These two nodes should have the least distance. The displacement between these two nodes is equal to the slip between the steel beam and the concrete slab. The slip between the steel beam and the concrete slab was investigated in three different loading conditions and their results are presented in Figure 13.

Figure 13 shows the load-slip diagram of the three loading modes that the highest amount of slip relates to mode C loading, followed by the mode A loading and the lowest amount of slip is related to mode B loading, and their values are about 3.77 mm, 3.74 mm and 3.71 mm, respectively. The results indicate that the slip is caused by the flexural load and the torsional load does not cause a significant slip between the steel and concrete slab. These slip values are created along the length of the beam span, and slip value in two other directions are negligible and can be ignored.

The Effect of Concrete Slab Strength

Due to the fact that concrete is one of the main components of the composite beam, the effect of concrete strength is discussed. Regarding that the most rotation was related to the mode C, the compressive strength of different concretes is investigated in this loading condition. The elasticity module was considered according to the ACI code, and the stress-strain relationship for concrete was defined for the software according to the mentioned references in the previous sections. Table 3 indicates the amount of rotation and the maximum mid span deflection with different concrete strengths.

Table 3. Effect of concrete slab strength on mid span deflection and the rotation of the composite beam

Concrete strength (Mpa)	Rotation (degree)	Deflection (mm)
25	41.55	105
32	40.62	88
36	40.179	78
40	39.84	71

The results in Table 3 illustrate that by increasing the strength of concrete slab, there was not any significant effect on the amount of rotation, but decreased the mid span deflection. By the increase of the concrete slab strength, the stiffness of the concrete slab has increased, and because in the structures the force is distributed proportionate to the stiffness, thus the concrete slab force bearing capacity is more than the steel beam, which is why the mid span deflection is decreased.

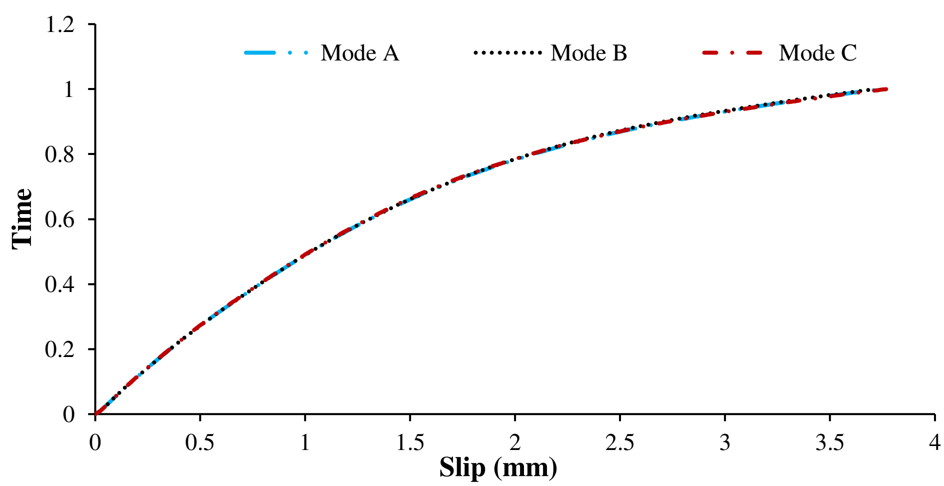


Fig. 13. Composite beam slip curves in different loading modes

The Effect of Changing the Bolt Diameter

In order to investigate bolt diameter effect, M20, M24 and M30- grade 8.8 bolts were used. Three composite beams were modeled for each of these bolts. In all three cases, the bolts cross section (AS) and the loading conditions were the same for all three composite beams with different bolts diameter. Considering that the slip in C mode was more than two other loading modes, this loading mode was investigated. The number and spacing between each bolt is given in Table 4.

Table 4. Number and spacing of different bolts diameter in composite beam

Bolt model	Number of bolt	Spacing of bolt (mm)
M20	27	230
M24	18	345
M30	12	530

The results of slip between the steel flange and the bottom surface of concrete slab during the loading are represented in the diagram of Figure 14.

Regarding the diagram of Figure 14, due to the increase of bolts diameter, the number of bolts are decreased. With reduction in number of bolts, the number of bolt shanks in concrete slab which are in interaction with the concrete slab and cause the composite beam to resist more decreases. As a result, more shear forces are introduced to the beam and the slip between the steel and the concrete slab is increased. As bolts with larger diameter has more cross-sectional area, the nut that is needed to be around the bolt should be larger. Thus, more steel is consumed resulting in more expenses for projects. So, the most suitable bolt is the M20.

The Effect of Changing the Bolt Diameter

The slip of composite beams was compared using three bolts M20, M24 and M30 with two different grades of 8.8 and 10.9. The results are observable in Figures 15a-15c. The stress-strain curve of bolt grade 10.9 was defined for software according to the DIN EN ISO 4762.

As it can be observed in Figures 15a-15c , in each 6 composite beams, 3 composite beams with bolt grade 10.9 has less slip compared to bolt grade 8.8 between the steel beam and concrete slab in the mentioned sizes. The stress tolerance of bolt grade 10.9 is greater than bolt grade 8.8, therefore the slip value is decreased. It can also be concluded that the lower the number of bolts, with the increase of grade bolt, the slip in the composite beam is decreased.

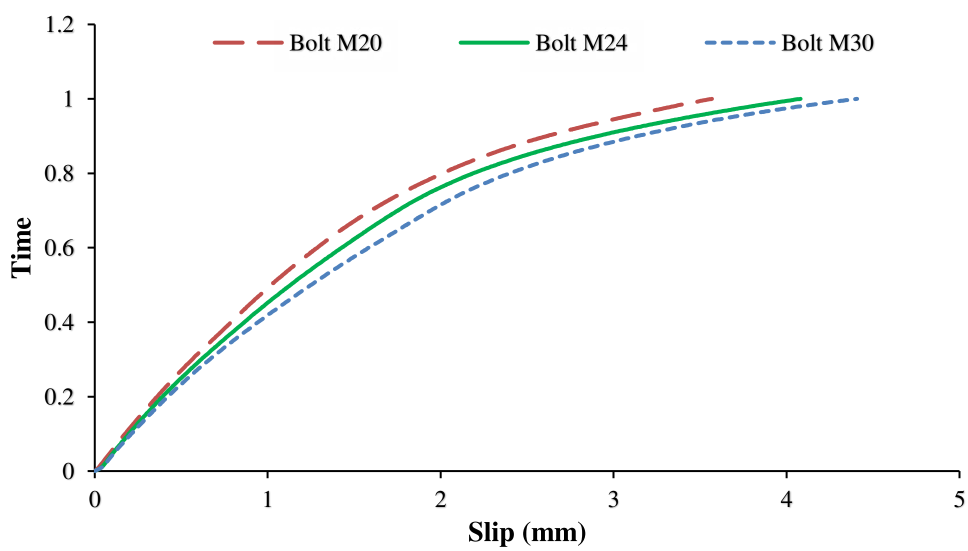
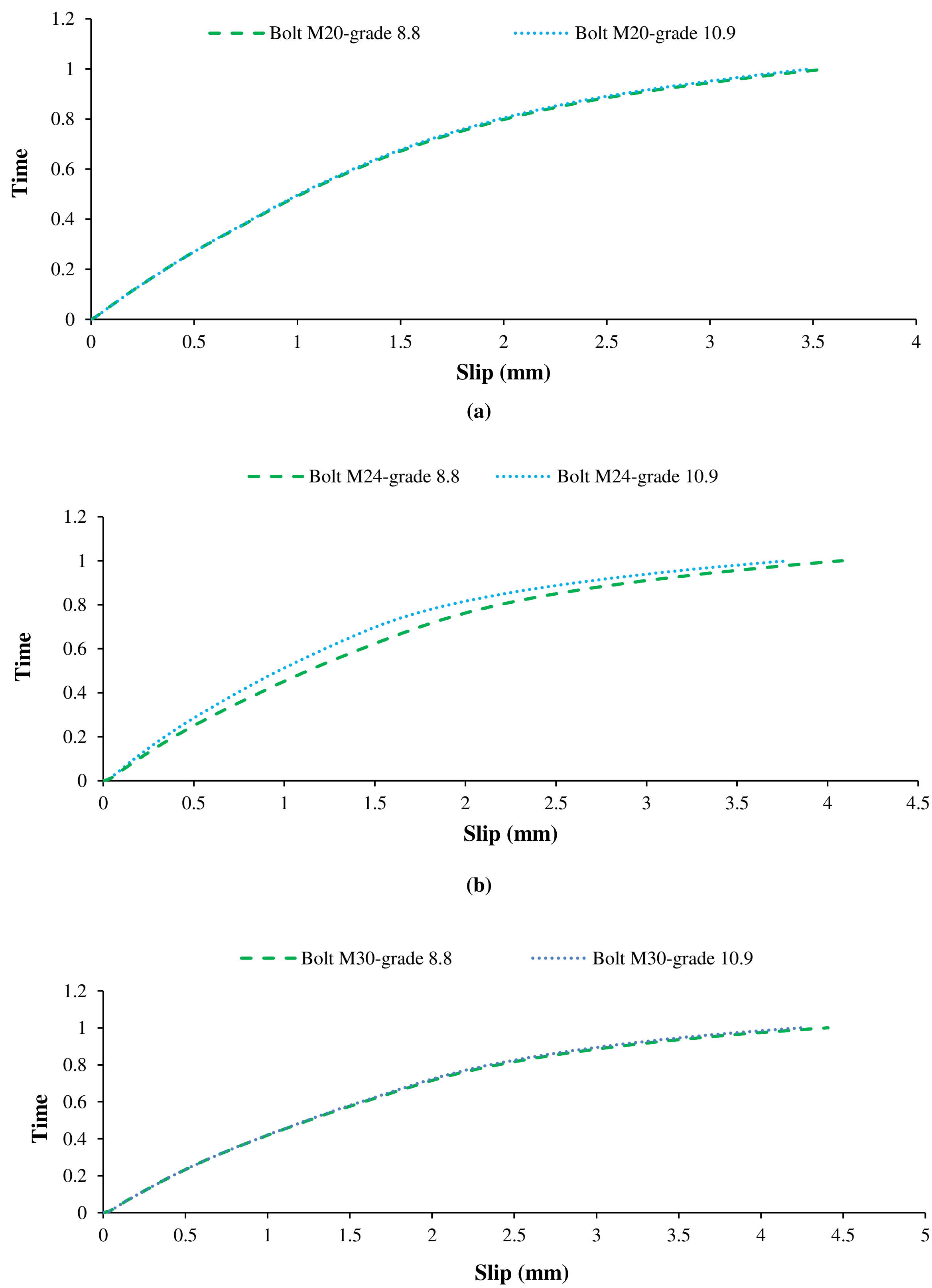


Fig. 14. Slip curves for composite beam with different bolts in mode C



(a)

(b)

(c)

Fig. 15. Slip curves for: a) M20 bolt with grade 8.8 and grade 10.9; b) M24 bolt with grade 8.8 and grade 10.9; c) M30 bolt with grade 8.8 and grade 10.9

CONCLUSIONS

This study investigated composite beam with bolt shear connectors under three different loading conditions including pure flexural loading, simultaneous flexural loading with two alternative torsional loading modes considering the slip effects. Based on the conducted analysis, the following results were obtained:

- The mid span deflection of the composite beam under the pure flexural loading mode and the simultaneous flexural and torsional loading mode was not significantly different. Shear forces that leaded to flexure in the beam increased mid span deflection while the shear forces that caused the torsion in the beam did not affect the deflection.
- The maximum rotation of composite beam was related to the C mode loading that the composite beam rotated in length. In the modes B and C which the composite beam is under simultaneous flexural and torsional loading, rotation of composite beam in the mode B was nearly 38% more than in the mode C.
- The slip between the steel beam and the concrete slab increased due to flexural loading, and the torsional loading had a slight effect on the slip of the beam length. This result shows that the flexural loading did not affect bolt shear connectors.
- By increasing the concrete slab strength, the mid span deflection decreased, but the amount of rotation in the composite beam changed very slightly. The deflection of composite beam with concrete strength of 40 Mpa was approximately 33% lower than the composite beam with concrete strength of 25 Mpa.
- By reducing the number of bolts, the slip between the steel beam and the concrete slab increased. Although the bolts cross sections (AS) were the same for all three composite beams with different bolts diameter, an increase in number of bolts leads the shear surfaces to reduce. Moreover, by the increase of grade bolt, this amount of slip decreased because the stress tolerance of bolt grade 10.9 was higher than bolt grade 8.8.

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