DOI 10.47176/sjfst.4.3.1

Original Article

SRPH

SJFST, 2022; 4(3): 1-8

Finite Element Modelling of Bolted Shear Connectors

Abdolreza Ataei*

Department of Civil Engineering, University of Isfahan, Isfahan, Iran.

***Corresponding Author:**
a.ataei@eng.ui.ac.ir

Received: 15 June, 2022
Accepted: 22 July, 2022
Published: 10 August, 2022

ABSTRACT

A three-dimensional finite element modelling of a composite connection having prefabricated concrete slabs and friction-grip bolted shear connectors are presented in this study. A finite element model of the composite connection considering the non-linearities of the geometry, interfaces between the components, and materials is developed by means of ABAQUS software. Numerical model was verified against experimental results available in literature, and was shown to accurately simulate their observed structural behaviour. The calibrated FE model can be employed for a parametric study in which the effects of different parameters can be investigated.

Keywords: Bolt shear connectors, Composite beam, Deconstructability, Steel-concrete composite connection, Finite element model

Introduction

To investigate the structural performance of various types of bolted shear connectors, several studies have been carried out by some researchers over the past decades. An experimental investigation on composite connections using bolted shear connectors post-tensioned by the turn-of-nut method was carried out by Dallam [1]. It was indicated that high strength bolted shear connectors have a higher shear bearing capacity compared to headed stud shear connectors. Marshall et al. [2] carried out push-out tests on composite connections constructed by bolted shear connectors. This study showed that the failure mode for all composite specimens was fracture of the shear bolts. An experimental study on composite connection employing embedded bolted shear connectors with double-nut were conducted by Sedlacek et al. [3] to determine the maximum shear force capacity and steel-concrete interface slip capacity of this type of composite shear connection. It was observed that bolt fracture was the main failure mode of all composite specimens. Standard push tests on composite specimens using headed stud and high-strength bolts shear connectors were carried out by Dedic and Klaiber [4]. Their study indicated that both headed stud and bolt shear connectors have the same shear behaviour. Hungerford [5] and Schaap [6] investigated the possibility of strengthening of non-composite bridge decks using post-installed shear connector. It was indicated that the common failure mode of all specimens was crushed of concrete. In addition, for developing composite action between the concrete slab and steel beam of non-composite bridge decks, three different post-installed composite connections were recommended. Kayir [7] developed a numerical model to predict the strength of bolted shear connections according to those tests carried out by Hungerford [5] and Schaap [6]. An experimental study on composite connections employing three types of shear connectors including bolted shear connectors, double-nut bolted shear connectors and adhesive anchors, was conducted by Kwon et al. [8-10] in order to study the mechanical behaviour of these types of shear connectors in steel-concrete composite bridge girder. Test results showed that the fatigue strength of fiction-grip bolted shear connectors was significantly higher than that of headed stud shear connectors. Mirza et al. [11] conducted and reported an experimental study on composite connections employing two dissimilar types of blind bolts including AJAX fasteners and Hollo bolts. In this study, concrete crashing was the main failure of all composite specimens. The test results showed that both blind bolts provide almost same shear load capacity. Dai et al. [12] used bolted shear connectors machined from headed stud to construct steel-concrete composite connections. They conducted experimental tests on all composite specimens under static loading,

Publisher: Scientific Research Publishing House (SRPH), Shirvan, Iran
http://srpub.org
Email: sjfst@srpub.org

showing that shear load capacity of bolted shear connectors was about 84% of that of headed stud shear connectors welded to the steel beam at 6 mm slip between the steel beam and concrete slab. Lam et al. [13] investigated the structural behaviour of demountable composite shear connectors under static loading and compared the performance of demountable shear connectors to that of headed stud shear connectors. Based on their test results, Lam et al. [13] concluded that the ductility of demountable shear connectors was much higher than the headed stud shear connectors. Lee and Bradford [14] experimented on post-installed bolted shear connectors under static loading to investigate the load-slip behaviour of the composite beams having prefabricated concrete slabs. Pavlovic et al. [15] carried out a series of static tests on single-nut embedded bolted shear connectors. Test results indicated that the strength capacity and initial stiffness of this type of shear connectors were about 50% and 95% of those of headed stud shear connectors welded to the top flange of steel beam. Ataei et al. [16-28] conducted a series of static tests and numerical modelling on demountable steel-concrete composite beams and joints having prefabricated concrete panels and friction-grip bolted shear connectors. Based on their test results, it was concluded that both demountable steel-concrete composite beams and joints had significant ductility; and slip between the steel beam and prefabricated concrete panels being developed during the static loading. It was also concluded that both composite beams and joints can be deconstructed easily for loading within the service load range. Recently, Zhang et al. [29] carried out eleven push-out tests and developed a finite element model to investigate the shear behaviour of bolted shear connections in a composite beam. Their study indicated that bolt strength, bolt diameter and concrete strength had significant effect on the shear strength capacity of the bolted shear connectors. However, it appears that the researches on the shear behaviour of composite connection using deconstructable bolted shear connectors are limited.

In order to study the structural behaviour of deconstructable friction-grip high strength steel bolted shear connectors when exposed to a monotonic loading, and to study the feasibility of using this type of shear connector in steel-concrete composite beams, a three-dimensional finite element modelling of a composite connection having prefabricated concrete slabs and friction-grip bolted shear connectors are presented in this study. A finite element model of the composite connection considering the non-linearities of the geometry, interfaces between the components, and materials is developed by means of ABAQUS software. Numerical model was verified against experimental results available in literature, and was shown to accurately simulate their observed structural behaviour. The calibrated FE model can be employed for a parametric study in which the effects of different parameters can be investigated.

Finite Element Model

In order to simulate and describe the steel-concrete composite connection tests, the finite element (FE) program ABAQUS was employed in this research. All components comprising the precast concrete slab, bolted shear connectors, steel square washers, steel reinforcing bars and steel beam which influencing the behaviour of the bolted shear connection were properly modelled to capture the accurate results from the model developed in this study. Material and geometric non-linerities were considered in the FE model. The interaction and constraint conditions, constitutive law for the materials used, element types and meshes for all components of the composite connections, boundary conditions and load application are described in detail in the following sections.

Material Constitutive Relationship

Steel components

As mentioned in section 2.3, the material characteristics of all steel components employed in this study and the modulus of elasticity, yield strength, ultimate strain and strength were obtained based on the standard uniaxial tensile tests. An idealised piecewise linear representation of these tensile tests was used in the FE model to simulate the properties of steel materials. The multi-linear stress-strain curves adopted in the FE model are shown in Fig. 1.

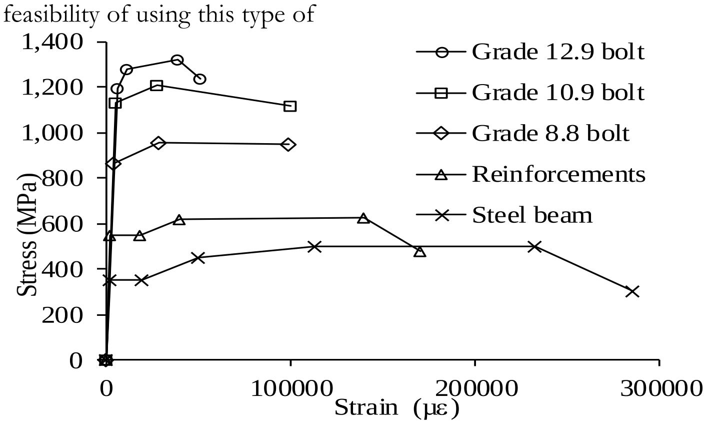


Figure 1. Stress-strain relationship for steel components.

[DOI: 10.47176/sjfst.4.3.1]

Concrete

In this research, a simple model proposed by Carreira and Chu [30] was taken into account to simulate the compression behaviour of the concrete. In this model, two distinctive parts can be identified that include an elastic range and a non-linear parabolic portion. In the first part, the compressive stress increases to 35% of its compressive strength. The second part of the stress-strain curve starts from the proportional limit stress (i.e. 35% of its compressive strength) and

$$\sigma_c = \frac{f_c \gamma \left(\varepsilon / \varepsilon_c \right)}{\gamma - 1 + \left(\varepsilon / \varepsilon_c \right)^{\gamma}}$$

thereafter, in which $\gamma = \left(f_c / 32 \cdot 4 \right)^3 + 1 \cdot 55$, f_c is the mean cylinder compressive strength (in MPa), ε_c = 0·002. It is worth mentioning that the damaged-plasticity model which is available in ABAQUS [31] was employed to simulate concrete in compression and tension. The tensile stress was considered to be increased linearly up to 10% of its compressive strength. Once concrete was cracked, the stress drops to 0.0 at strain of about 10 times of its failure strain.

Loading and Analysis Method

Similar to the test set-up, the analysis of the model consisted of two steps. In the first step, bolts connecting the precast concrete slabs to the steel beam were subjected to the pre-tensioning forces. The pretension load was exerted to the bolts by using the BOLT LOAD feature available in ABAQUS [31]. In the second step, the steel beam was subjected to a displacement-control loading protocol using the modified RIKS method available in ABAQUS, which is based on the arc-length method. The Riks method is able to capture the non-linear and un-stable collapse of the model.

Boundary Conditions

In order to restrain the motion of the model and to accurately simulate the push-out test specimens and obtain a unique solution, after constructing the finite element model, appropriate displacement boundary conditions should be applied to the model. As can be seen in Fig. 2, all nodes of the precast concrete slab (surface 1) were prevented from translating in *X, Y* and *Z* directions. Due to symmetry, all nodes along the middle of the steel beam web (surface 2) were restrained in the *Y* direction and rotating in the *X* and *Z* directions. In addition, all nodes of the precast concrete slab and steel beam (surface 3) were restrained in *X* direction and rotating in the *Y* and *Z* directions.

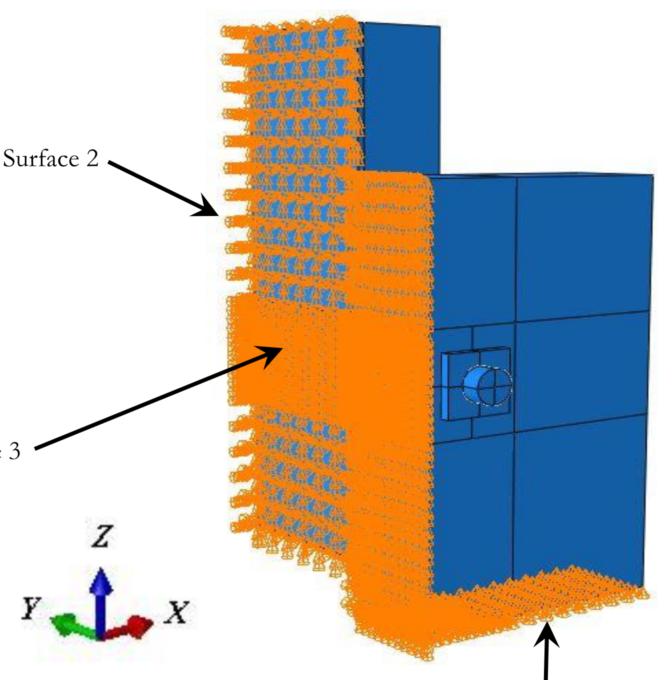


Figure 2. Boundary conditions of model.

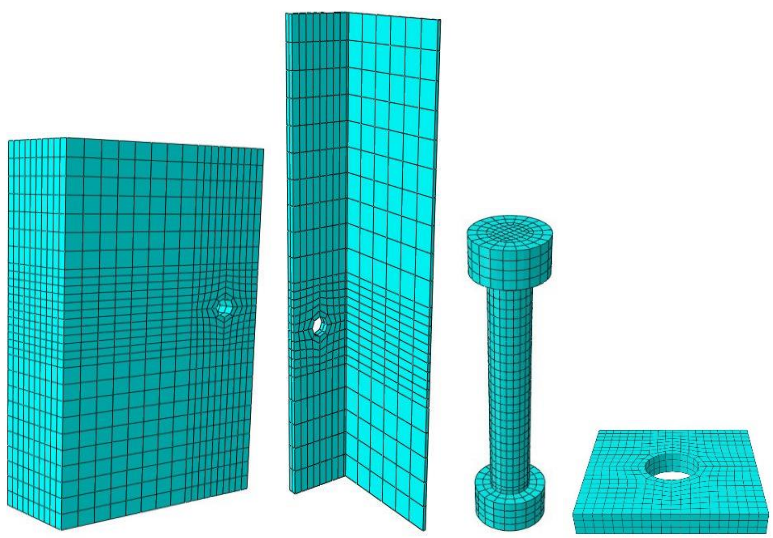
[DOI: 10.47176/sjfst.4.3.1]

Interaction and Modelling of Contact

Since there are a few components in the composite connection including the prefabricated concrete slab, reinforcing bars, bolted shear connectors, steel beam and steel washers which interact with each other, different contacts/interfaces affecting the steel-concrete composite connection modelling were considered in this study. Once all components of the composite connection were assembled together, appropriate interaction were applied between components which interact with each other. The surface-to-surface contact interaction technique available in ABAQUS was taken into account to define the contact between the various components, viz. the bolt head and steel washer, bolt nut and steel beam, steel washer and precast concrete slab, bolt shank and precast concrete slab, steel beam and precast concrete slab. For the tangential behaviour between two surfaces the PENALTY option was used, in which for the interaction between the steel beam and precast concrete slab and between the other interaction 0.45 and 0.25 were considered [14, 32, 33], respectively.

Element Type and Mesh

As the specimens were symmetric with respect to material properties, geometry, boundary conditions and applied load, only one quarter of the steel-concrete composite connection specimen was simulated, which indeed leads to a significant saving in the computational efforts. To model the steel-concrete composite connection, three-dimensional solid elements were taken into account, in which two node linear three dimensional truss elements (T3D2 in *ABAQUS*) and 8-node solid elements with reduced integration (C3D8R in *ABAQUS*) were employed in order to model the steel reinforcement and the other components, respectively. The C3D8R elements not only can prevent the shear locking difficulties compared to other element types but also can provide reasonable accuracy. A sensitivity analysis was also conducted for the FE modelling of the composite connection to ensure that a good compromise between accuracy and computational efficiency can be achieved and the FE models developed can capture global and local response of the structural components. The outline of the FE mesh for all components of composite connections is illustrated in Fig. 3. In order to reduce the computational efforts and time as well as to obtain the reasonable results, a fine mesh was used for the bolted shear connectors, steel washer and the region around the holes as can be seen in Fig. 3.



(a) (b) (c) (d)

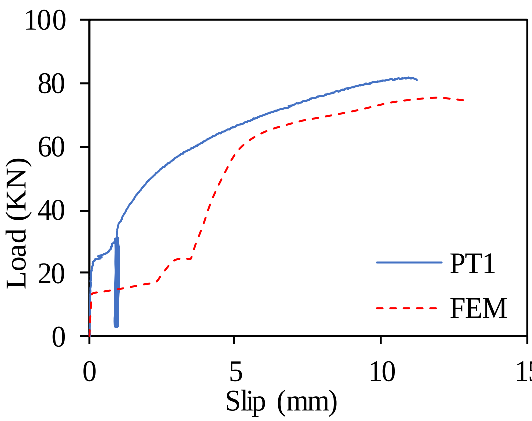
Figure 3. Finite element mesh of FE model: (a) concrete slab, (b) steel beam, (c) shear connector, (d) square washer.

Comparison with Test Results

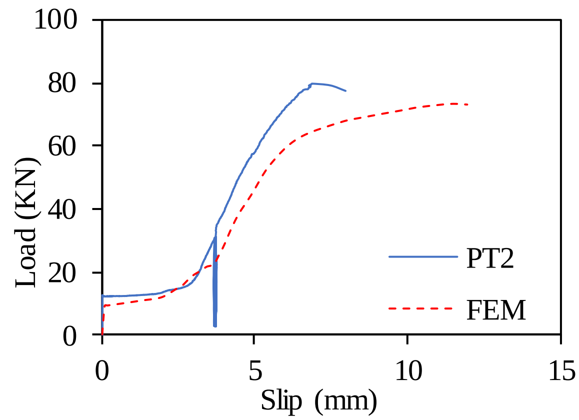
In this section, results obtained from the FE models are illustrated and compared to the test results to validate the FE models developed in this study. As mentioned before, an extensive finite element modelling was carried out to investigate the behaviour of demountable composite connections having prefabricated concrete slabs and steel beams. Force-slip relationships obtained from the FE models were compared with those obtained from the experimental study conducted by [34], as shown in Fig. 4. It is shows that the FE model was generally able to predict the structural behaviour of the composite connections in

[DOI: 10.47176/sjfst.4.3.1]

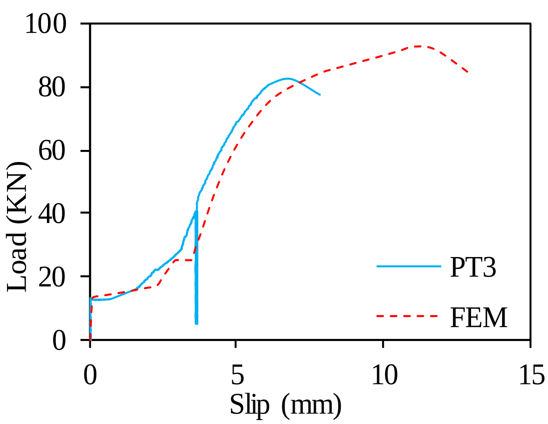
terms of the shear load per bolt for the first bearing, the average major slip at the first bearing, the maximum shear load per bolt, the slip corresponding to the maximum shear load and the maximum average slip between the precast concrete slab and steel beam with sufficient accuracy. In addition, the calibrated FE model can be employed for a parametric study in which the effects of different parameters can be investigated.



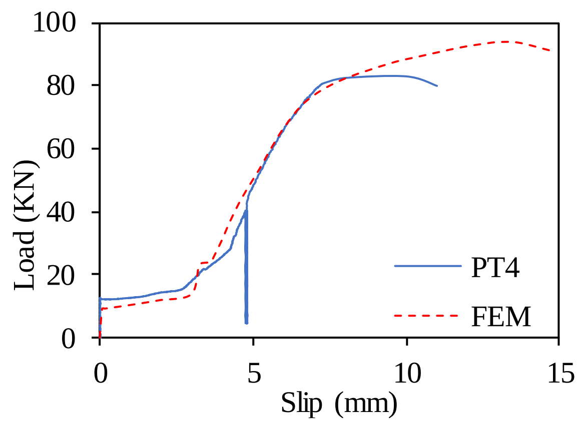
(a)



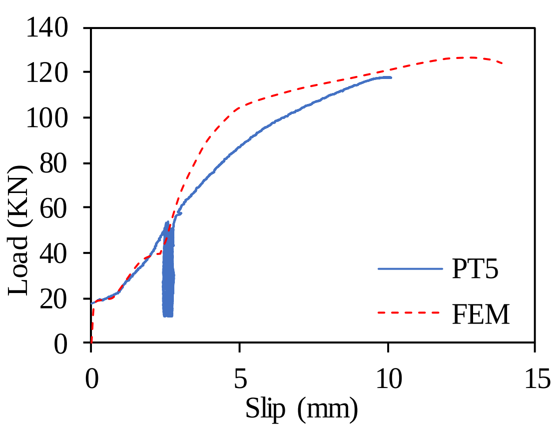
(b)



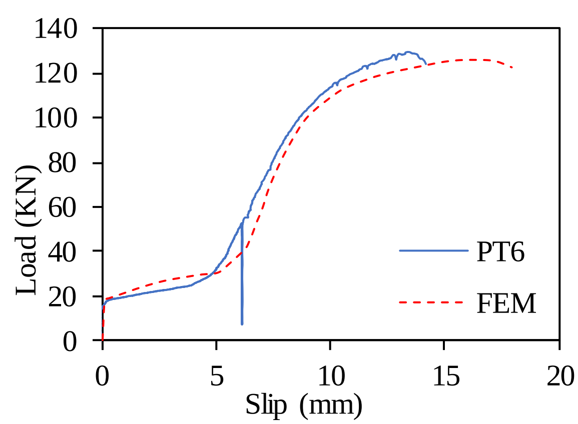
(c)



(d)



(e)



(f)

[DOI: 10.47176/sjfst.4.3.1]

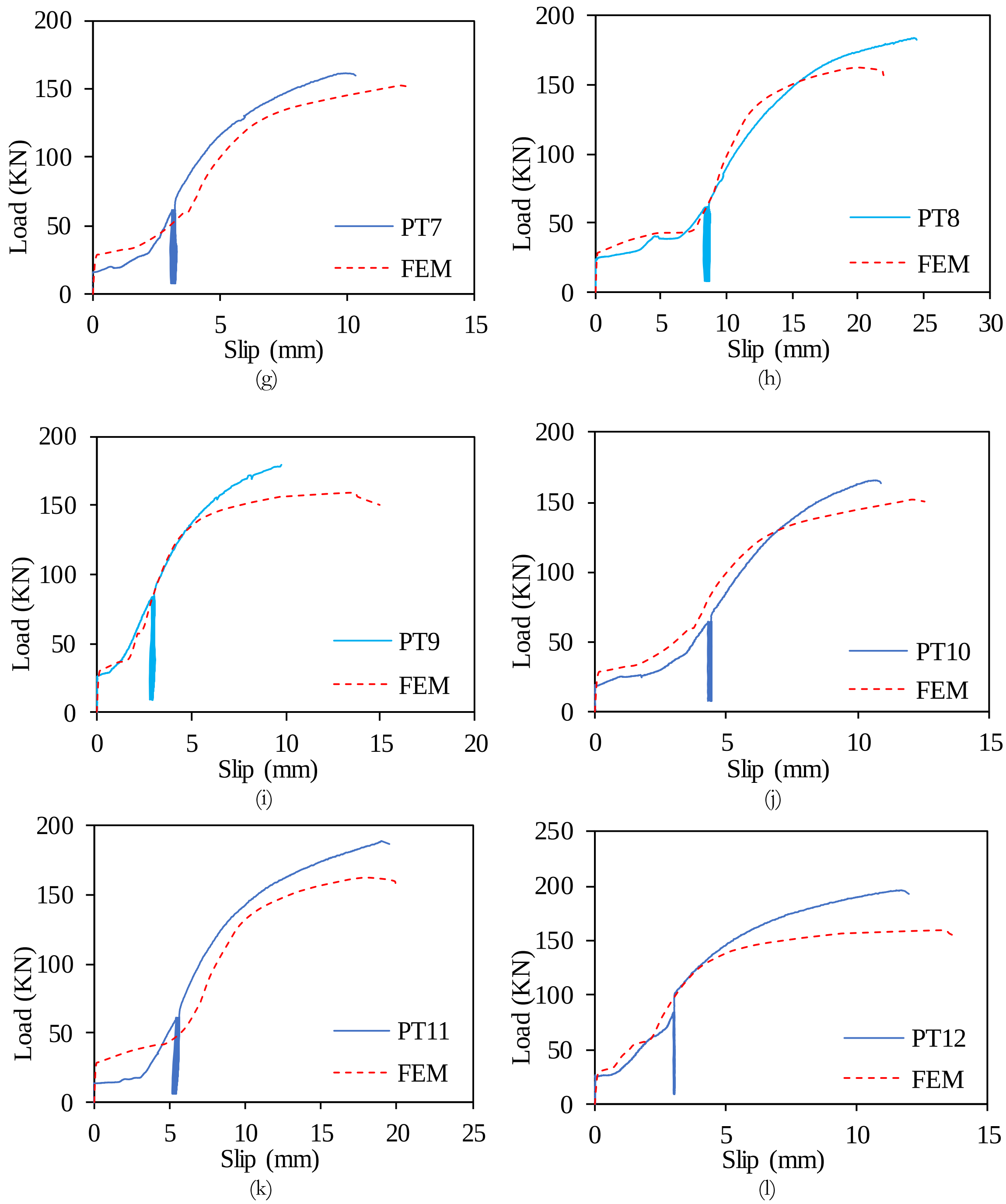


Figure 4. Comparison of the FE predictions with the experimental results

Conclusion

A three-dimensional finite element modelling of a composite connection having prefabricated concrete slabs and friction-grip bolted shear connectors are presented in this study. A finite element model of the composite connection considering the non-linearities of the geometry, interfaces between the components, and materials is developed by means of ABAQUS software. Numerical model was verified against experimental results available in literature, and was shown to accurately simulate their observed structural behaviour. The calibrated FE model can be employed for a parametric study in which the effects of different parameters can be investigated.

References

1. Dallam LN HJ. Composite beam tests with high-strength bolt shear connectors. Report for Missouri

[DOI: 10.47176/sjfst.4.3.1]

State Highway Department, Department of Civil Engineering, University of Missouri-Columbia (MI); 1968.
2. Marshall WT, Nelson HM, Banerjee HK. An experimental study of the use of high-strength friction-grip bolts as shear connectors in composite beams. *Struct Eng.* 1971; 49: 171-178.
3. Sedlacek G, Hoffmeister B, Trumpf H, Kühn B. Composite bridge design for small and medium spans. Final report. European Commission - technical steel research Contract No 7210-PR/0113. Luxembourg. 1971.
4. Dedic DJ, Klaiber WF. High-strength bolts as shear connectors in rehabilitation work. *Concr Int.* 1984; 6(7): 41-46.
5. Hungerford BE. Methods to develop composite action in non-composite bridge floor systems: part II. MS Thesis, Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin. 2004.
6. Schaap BA. Methods to develop composite zction in non-composite bridge floor systems: part I. MS Thesis, Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin. 2004.
7. Kayir H. Methods to develop composite action in non-composite bridge floor systems: fatigue behavior of post-installed shear connectors. MS Thesis, Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin. 2006.
8. Kwon G, Engelhardt MD, Klingner RE. Behavior of post-installed shear connectors under static and fatigue loading. *J Construct Steel Res.* 2010; 66: 532-541.
9. Kwon G, Engelhardt MD, Klingner RE. Experimental behavior of bridge beams retrofitted with postinstalled shear connectors. *J Bridge Eng.* 2011; 16: 536-545.
10. Kwon G. Strengthening existing steel bridge girders by the use of postinstalled shear connectors. PhD thesis. The University of Texas at Austin: 239p.
11. Mirza O, Zhu XQ, Uy B. Retrofitting/strengthening strategy for existing bridges using blind bolts as shear connectors. 4th Australian Small Bridges Conference 201, 10-11th May, 2011.
12. Dai XH, Lam D, Saveri E. Effect of concrete strength and stud collar size to shear capacity of demountable shear connectors. *J Struct Eng.* 2015; 141: 04015025.
13. Lam D, Dai X, Saveri E. Behaviour of demountable shear connectors in steelconcrete composite beams. Proceedings of the 2013 Composite Construction in Steel and Concrete VII. Queensland, Australia. 2013.
14. Lee SSM, Bradford MA. Sustainable composite beams with deconstructable shear connectors. 5th International Conference on Structural Engineering, Mechanics and Computation, Cape Town, South Africa. 2013.
15. Pavlović M, Marković Z, Veljković M, Buđevac D. Bolted shear connectors vs. headed studs behaviour in push-out tests. *J Construct Steel Res.* 2013; 88: 134-149.
16. Ataei A, Bradford MA, Valipour HR, Liu X. Experimental study of sustainable high strength steel flush end plate beam-to-column composite joints with deconstructable bolted shear connectors. *Eng Struct.* 2016; 123: 124-140.
17. Ataei A, Bradford MA, Valipour HR. Experimental study of flush end plate beam-to-CFST column composite joints with deconstructable bolted shear connectors. *Eng Struct.* 2015; 99: 616-630.
18. Ataei A, Bradford MA, Valipour HR. Finite element analysis of HSS semi-rigid composite joints with precast concrete slabs and demountable bolted shear connectors. *Finite Elem Anal Des.* 2016; 122: 16-38.
19. Ataei A, Bradford MA, Valipour HR. Moment-rotation model for blind-bolted flush end-plate connections in composite frame structures. *J Struct Eng.* 2015; 141: 04014211.
20. Ataei A, Bradford MA, Liu X. Experimental study of composite beams having a precast geopolymer concrete slab and deconstructable bolted shear connectors. *Eng Struct.* 2016; 114: 1-13.
21. Ataei A, Bradford MA, Liu X. Experimental study of flush end plate beam-to-column composite joints with precast slabs and deconstructable bolted shear connectors. *Struct.* 2016; 7: 43-58.
22. Ataei A, Bradford MA, Liu X. Computational modelling of the moment-rotation relationship for deconstructable flush end plate beam-to-column composite joints. *J Construct Steel Res.* 2017; 129: 75-92.
23. Ataei A, Bradford MA. Numerical study of deconstructable flush end plate composite joints to concrete-filled steel tubular columns. *Struct.* 2016; 8: 130-143.
24. Ataei A. PhD thesis SoCaEE. A low-carbon deconstructable steel-concrete composite framed system with recyclable beam and slab components 2016.
25. Ataei A, Moradi M, Valipour HR, Bradford MA. Finite element modelling of demountable precast reinforced concrete deck slabs with external confining system. *J Construct Steel Res.* 2018; 151: 204-215.
26. Ataei A, Zeynalian M, Yazdi Y. Cyclic behaviour of bolted shear connectors in steel-concrete composite beams. *Eng Struct.* 2019; 198: 109455.
27. Ataei A, Bradford MA, Valipour H. Sustainable design of deconstructable steel-concrete composite structures. *Proc Eng.* 2016; 145: 1153-1160.
28. Ataei A, Bradford MA. Sustainable and deconstructable semi-rigid flush end plate composite joints. Appl Mech Mater. 2014; 553: 557-563.
29. Zhang Y, Chen B, Liu A, Pi Y-l, Zhang J, Wang Y, et al. Experimental study on shear behavior of high

[DOI: 10.47176/sjfst.4.3.1]

strength bolt connection in prefabricated steel-concrete composite beam. *Compos B Eng*. 2019; 159: 481-489.
30. Carreira DJ CKS-srfpcicASJ, 82(6): 797-804.
31. ABAQUS 6.141 [Computer software]. Providence R, Dassault Systemès Simulia.
32. Liu X, Bradford MA, Lee MSS. Behavior of high-strength friction-grip bolted shear connectors in sustainable composite beams. *J Struct Eng*. 2015; 141: 04014149.
33. Liu X, Bradford MA, Ataei A. Flexural performance of innovative sustainable composite steel-concrete beams. *Eng Struct*. 2017; 130: 282-296.
34. Ataei A, Zeynalian M. A study on structural performance of deconstructable bolted shear connectors in composite beams. *Struct*. 2021; 29: 519-533.

[DOI: 10.47176/sjfst.4.3.1]

SJFST

Citation: Ataei A. Finite Element Modelling of Bolted Shear Connectors. SJFST, 2022; 4(3): 1-8.

https://doi.org/10.47176/sjfst.4.3.1