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Behaviour of Shear Connectors for Sustainable Construction under Static Loading

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Abstract

The purpose of this study is to identify structurally efficient and practical post-installed shear connectors for composite structures designed with a focus on sustainability. According to the Australian 2010 Infrastructure Report Card, a large number of Australian infrastructures are reaching the end of their design life. Therefore, there is a need for repair and strengthening of deteriorated, damaged and substandard infrastructures. The use of post-installed shear connectors to develop composite action in lieu of conventional headed shear studs and in strengthening and retrofitting of existing composite structures can be a structurally efficient and cost-effective approach. While composite beams that are retrofitted with post-installed shear connectors are potentially sustainable and recyclable elements, research contributions on these types of beams are very limited. In this paper a three-dimensional finite element model is developed to investigate the structural performance of a steel–concrete composite beam with post installed shear connectors and the factors that influence static strength of these types of connectors. The accuracy of the 3-D finite element model proposed in this work is validated by comparison with available experimental results.

Keywords: Composite beam, Post-installed shear connector, Finite element model

1. INTRODUCTION

Sustainability has become increasingly interested in civil engineering. Retrofitting existing structures has become a growing interest because of finite resources and expensive construction costs. The shear connection between the concrete slab and the steel section is an essential component of a composite beam. The use of post-installed shear connectors to develop composite action in lieu of conventional headed shear studs and in strengthening and retrofitting of existing composite structures can be structurally efficient and cost-effective approach. For strengthening an existing bridge, both the structural behaviour of shear connector and the installation problems are significant factors to select a post-installed shear connector. While composite beams that are retrofitted with post-installed shear connectors are potentially sustainable and recyclable elements, research contributions on these types of beams are very limited (Kwon, 2008).

More recently, Kwon (2008) continued the research conducted by Schaap (2004), Hungerford (2004) and Kayir (2006). They focused on the post-installed capacity for retrofitting existing structures. One recent research project on sustainability was conducted by Mirza and Uy (2010) using blind bolts as shear connectors. The objective of using blind bolts in the composite steel beams is to develop recyclable and sustainable structures. Consequently portable and sustainable structures can be developed since these bolts have the capability of being unbolted and bolted from one side only. The installation procedure of blind bolts is less complex and more rapid than that of conventional systems (Pathirana et al., 2016). In Figure.1, two blind bolt types referred to as Blind Bolt Type 1 (BB1) and Blind Bolt Type 2(BB2) are shown. The flexural performance of composite beams with two blind bolt types and headed stud connectors were experimentally evaluated by Pathirana et al. (2016) using full-scale beam specimens. Based on the experimental results, Pathirana et al. (2016) pointed out that these blind bolts have similar load capacity and behaviour to the welded stud.

(a) Blind Bolt 1 (BB1) (b) Blind Bolt 2(BB2)

Figure 1. Different Types of Blind Bolts (Pathirana et al., 2016).

The study of shear connector behaviour in composite beams using push-out tests is much more convenient than the use of beam tests; but in many cases these can be expensive and time-consuming. Therefore, numerical studies were undertaken to provide an effective alternative to the experimental procedures to investigate the structural behaviour of shear connectors. The performance of blind bolts under static loading condition still remains unknown; hence this study will focus on characterizing the static performance of the welded stud and the blind bolt connectors (BB2). The main purpose of the authors is to develop a three-dimensional finite element model using ABAQUS software to simulate the mechanical behaviour of different connector types. Subsequently, the simulation results are analysed and compared with results of selected push-off tests.

2. FINITE ELEMENT MODELING

2.1. General

The push-out test is the most common way used to investigate shear connector strength and behaviour. Concrete blocks, steel plates, reinforced bars and shear connectors are the four main parts in push-out tests. A series of push-out tests similar to the standard push-out test specimen in accordance with EC4 was conducted by Lam and El-Lobody (2005).The test setup of the push-out specimens is shown in Figure.2a. The test set up, instrumentation, test material and tests result were explicitly described in (Lam and El-Lobody, 2005). Experimental investigations undertaken by Lam and El-Lobody (2005) were used and compared with the finite element analysis to evaluate the mechanical behaviour of shear connectors in this study. Therefore, finite element modelling of the push-out tests was carried out to determine the load-slip behaviour of the shear connectors. Since the specimen is symmetric, only one half of the model was built using the Abaqus software, as shown in Figure.2b. Appropriate symmetrical constraints were applied to the models to simulate the real structure. Material nonlinearity is associated with the inelastic behaviour that was considered in the model. Abaqus/Standard analysis was used to analyse the three dimensional model for the push-out test. It is essential to model all details of the experimental test specimen to obtain accurate results and derive reliable conclusions (Wang et al., 2012). Therefore both the geometrical and material nonlinearities, including softening and yielding of material, were considered in the model. The concrete slab, steel beam and shear connectors were modelled using 8-node element with reduced integration (C3D8R) and each model has three translational degrees of freedom (DOF).The steel reinforcement was meshed with 2-node linear 3D truss elements (T3D2), which have three degrees of freedom. The whole model used coarse mesh and mesh sizes for critical zones such as shear connector and concrete slab around shear connector are carefully controlled to get accurate calculated results by using fine mesh.

Figure 2. (a) Push-out Specimen (Lam & El-Lobody, 2005.); (b) 1/2 FE model with ABAQUS

The actual connector geometries were modelled for this analysis; it should be noted that the collar and the nut of the bolted connector were not considered as separate parts. Figure 3. demonstrates the typical geometries and element types used to simulate the push out test specimens and different connector types.

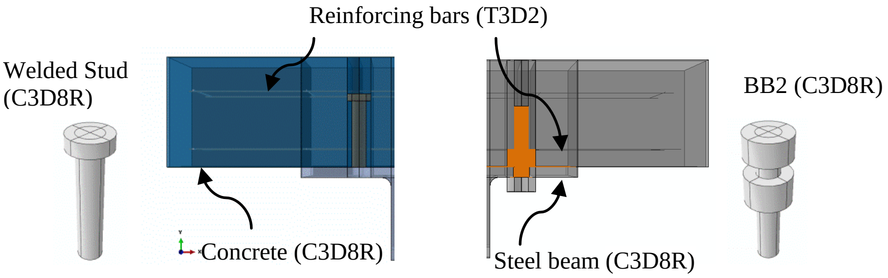


Figure 3. (a) Finite Element Model of Stud; (b) Finite Element Model of BB2

2.2. Material Models

The material properties used for finite element simulations are shown in Table 1.

Table 1. Steel properties for various steel components.

Material type	Material property		
	E-modulus (N/mm^2)	Yield strength (N/mm^2)	Ultimate strength (N/mm^2)
Reinforcing Steel	190,000	510	650
Steel beam	200,000	275	350
Welded Stud (19 mm dia.)	200,000	470	600
BB2 (M20,grade 8.8)	187,000	780	930

2.2.1. Material model of concrete

The concrete material behaves elastically up to the yield stress and will exhibit plasticity after yield point (See Figure 4.).

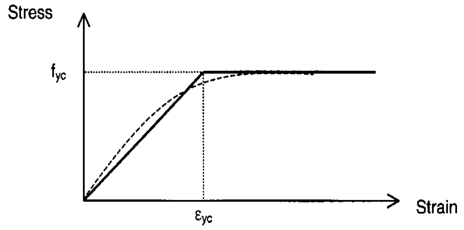


Figure 4. Stress–Strain Diagram for Concrete.

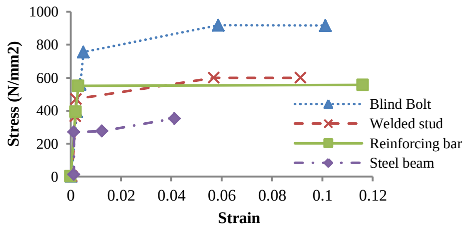


Figure 5. Stress–Strain Diagram for different Steel Materials.

The following relationships can be used to calculate average values of yield strain, yield stress and the Young's modulus of concrete in accordance to BS 8110 (BSI 1997) ((Lam & El-Lobody, 2005.)):

$$\varepsilon_{yc} = 0.00024\sqrt{f_{cu}} \quad (1)$$

$$f_{yc} = 0.8 f_{cu} \quad (2)$$

$$E_C = f_{yc}/\varepsilon_{yc} \quad (3)$$

The used FE-model considers a nonlinear material behaviour for the concrete. The plastic region of the stress–strain curve for the concrete was defined using the concrete damaged plasticity model in ABAQUS. The tensile behaviour of concrete has been modelled by fracture energy to make the model in FEM less dependent on the element size. The compressive strength of the concrete used for the finite element models was 35 MPa.

2.2.2. Steel properties

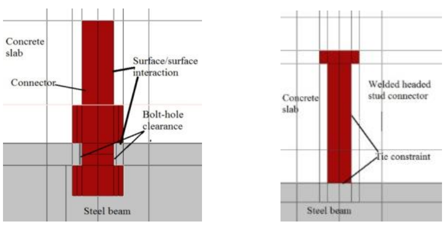
In the finite element modelling, the stress–strain diagram of various steel materials was determined using material property test data. Prior to the yield point the steel material will deform elastically and this elastic range of behaviour is followed by further yielding and then by failure. In this study, the stress strain behaviours of these materials were transformed into piecewise linear curves. The stress–strain diagrams of the steel materials utilized to the push out test model; reinforcing bar, welded shear studs and the blind bolt connector respectively are shown in Figure 5.

2.3. Contact Properties, Loads and Boundary Conditions

The contact interaction and constraint methods available in ABAQUS were used to model the interactions between components of the push out test. The surface-to-surface contact algorithm was applied to the contact surface between the concrete slab, steel beam and connector to achieve practical structural design procedures for connections as listed in Table 2. In addition, Figure 6. describes the details and contact interaction between various parts of finite element model of the push-out test and each connector type. Penalty contact method was utilized to simulate the normal and tangential contact behaviour by using a tangential friction coefficient of 0.6.

Table 2. Contact interaction between various parts finite element model of the push-out test.

Part instance		Contact type	
1	**2**	**Welded Stud**	**BB2**
Concrete slab	Steel beam	Interaction	Interaction
Concrete slab	Reinforcing bars	Embedded	Embedded
Concrete slab	Connectors	Tie	Interaction
Steel beam	Connectors	Tie	Interaction



(a) (b)

Figure 6. Details of The Interaction Between (a) The Bolted Connectors & (b)The Welded Stud Connectors and other Components of Finite Element Modelling .

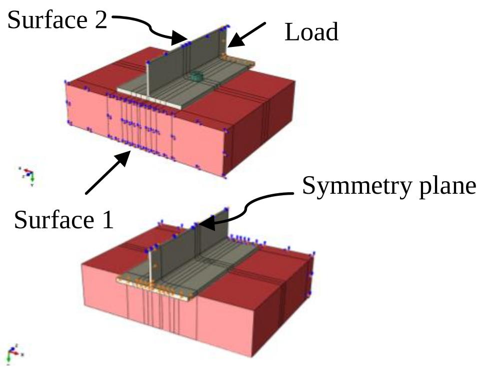


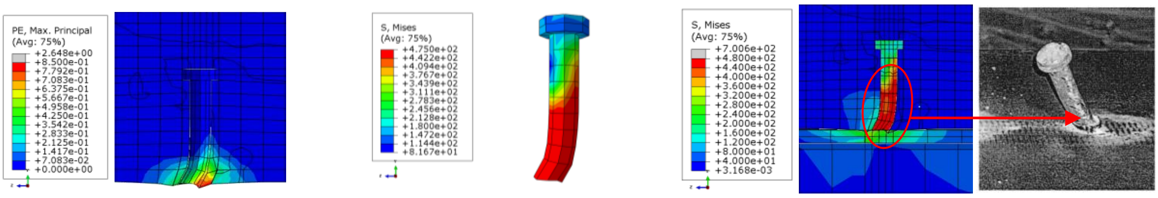
Figure 7.Boundary and Loading conditions.

The reinforcing steel model was embedded inside a concrete element using the embedded element method. The top surface of the beam is subjected to uniformly distributed load as shown in Figure 7. The bottom surface of concrete block in the opposite direction of loading (surface 1 in Figure 7.) was fixed in all directions. As 1/2 of the specimen was modeled, all nodes at the middle of the steel beam web (surface 2) are restricted to move in the X-direction because of symmetry as shown in Figure 7.

3. RESULTS AND DISCUSSION

3.1. Analysis Results

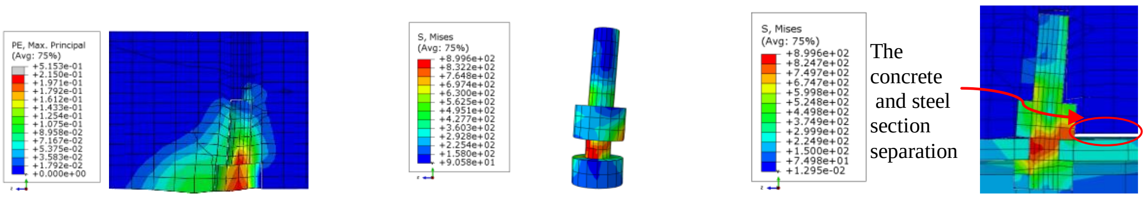
Figure 8 and 9 illustrate the stress and strain distribution of connectors and concrete. Under the action of a uniformly distributed load along the top of the beam, the connectors have obvious shear deformation. The concrete around the stud root has plastic strain as shown in Figure 8 (a); Figure 8 (b) and (c) demonstrate the static failure appearances at stud roots and stud shank embedded in concrete when the structure cannot take any more load. Furthermore, Figure 8 (c) also shows there is a good agreement between the observed failure mode of the stud and the FE model results. The experimental failure load recorded was 102.0 kN on each stud at a slip of 6.1 mm compared to 99.5 kN at a slip of 6.1mm evaluated by the finite element analysis with similar strength properties of concrete. These results also reveal that the model is able to capture the actual performance of the experimental push-out tests during loading. Consequently this model was used to study the load–slip behaviour of the demountable connectors.



(a) Maximum Principle Plastic strain of concrete (b) Mises stress of stud (c) Failure elements on stud

Figure 8. Stress and strain distribution for Welded studs.

Figure 9(a) describes the region of plastic strain of concrete around the shank and nut of the blind bolt. The static failure appearances at the bolt shank embedded in the concrete slab and the steel beam is demonstrated in Figure 9 (b) and (c). In addition, at 6.1 mm slip, the maximum load was 146.8 KN for each blind bolt connector based on the finite element results. As shown Figure 10(b) these connectors have a slip of up to 14 mm before failure. Figure 9 (c) also shows the separation between the concrete and steel section at high loading stages, therefore, the current design of the blind bolt connector still needs improvement .



(a) Maximum Principle Plastic strain of concrete (b) Mises stress of BB2 (c) Failure elements on BB2

Figure 9. Stress and strain distribution for Blind bolts.

3.2 Verification of Finite Element Models with the Experimental Results

The load-slip curve of each connector type obtained from finite element modelling was compared to the push-out test data, as shown in Figure 10. These load-slip curves have a clear elastic-plastic region. In the elastic portion, the load-slip curves show approximately linear behaviour for all connectors. It can be seen there is good match between the calculated load-slip curves of the welded stud and the experimental results.

In addition, the numerical simulation results indicated that with similar strength of concrete and failure mode, the blind bolt connector exhibits more ductility when compared with the welded headed stud. However, the conventional shear connectors demonstrated relatively large initial stiffness and the slip capacity than the blind bolt connectors. The blind bolt stiffness in practice may drop due to the bolt-hole clearance. Following the friction between the bolted connector and the steel beam is overcome, the connector slip may occur within the oversized holes. According to the numerical curve, the demountable connectors exhibited higher ultimate load capacity under static load when compared with the the headed shear stud connectors. Hence the reliability of the load–slip performance of the innovative blind bolts allows composite beams to be made demountable.

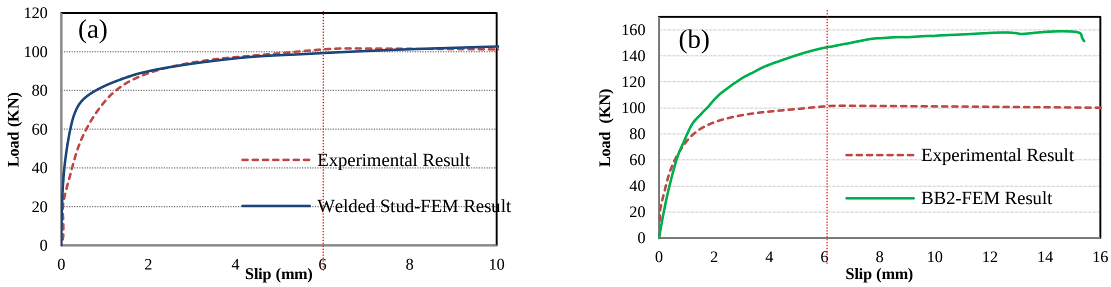


Figure 10. Comparison of FEM Calculated Results with Experimental Results.

4. CONCLUSIONS

The paper illustrates the development of a detailed finite element model that is capable of predicting load-slip behaviour and failure modes of different type of shear connectors in composite beam and could confidently replace some expensive experimental testing. Nonlinear, three-dimensional finite-element models were built in this study to evaluate the mechanical behaviour of different types of shear connectors utilising in composite steel–concrete beams. Abaqus software is used to investigate the load-slip behaviour of the blind bolt and welded shear connectors. The failure modes, stiffness and ductility have been compared in detail. Based on the finite element analysis the following conclusions can be made:

- The composite beam with the blind bolt connectors showed significantly higher strength and ductility.
- The results obtained from the finite element model suggest that the behaviour of the demountable connectors is comparable with that of the headed stud shear connectors to achieve composite action between the slab and the beam.
- A further investigation of the model results also reveals that these blind bolt connectors can be used as innovative shear connectors to develop recyclable and sustainable structures.

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