

Finite element modelling of stainless steel shear connectors in composite beams

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ABSTRACT

Stainless steel has gained great popularity in recent decades, for its advantages on durability, corrosion resistance and fire resistance. These advantages bring significant benefits for the stainless steel applications in stainless steel-concrete composite structures, which is considered as an innovative and attractive structural form for current civil and building infrastructures. Despite this, an in-depth understanding of the load-slip behaviour of stainless steel shear connectors in stainless steel-concrete composite beams is still required due to the lack of pertinent experimental and analytical research. This paper aims to perform a finite element analysis on investigating the load-slip behaviour of stainless steel bolted and welded studs in the composite beams. A finite element model of pushout test is developed by applying the commercial program ABAQUS. Both austenitic and duplex stainless steels are considered in the model. The effect of pre-tensioning of bolts is taken into account in the finite element simulation by using the expansion option in ABAQUS. One-quarter of the specimen is modelled to save the simulation time and the model is validated against the existing experimental research. Based on the validated FE model, a series of parametric studies are conducted and the key parameters include the type of stainless steels, the type of shear connectors, bolt-to-hole clearance, the pretension forces of bolts, as well as the tensile strengths of bolted studs. The effects of the parameters on the load-slip behaviour of stainless steel shear connectors in the composite beams are evaluated through the numerical model.

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1. INTRODUCTION

The composite steel-concrete structure is considered as one of the most efficient structural systems and gains notable popularity in recent construction. The composite steel-concrete beams significantly improve the bending and shear capacity of structural beams by optimal use of the individual properties of two materials, such as the steel strength and ductility in tension and concrete high stiffness and robustness in compression (Uy and Craine 2004). Recent records show that the performance of composite steel-concrete beam subjected to flexure is greatly dependent on the characteristics of shear connectors. The strength and load-slip behaviour of shear connectors greatly influence the flexural strength of composite beams owing to the shear force transmitted and the slip degree at the interface of steel beam and concrete slab (Mirza and Uy 2009). Among the typical mechanical shear connectors, the welded stud is one of the most conventional methods for its benefits in cost-efficient and easy to maintain. However, the steel bolt is becoming a more attractive form in modern construction. Bolts with nuts are considered as sustainable and environmental-friendly solutions because they can be dismantled and reused after their useful service lives.

Pushout test is a reliable and efficient approach to determine the strength and stiffness of shear connectors in real composite steel-concrete beams. The stress state of the shear connectors is highly complex, for the reason that the shear connectors are under combined shear force and bending moment. An enormous number of research studies have been conducted by using pushout test for investigating the load-slip behaviour of carbon steel bolted and welded studs (Mirza and Uy 2009, 2010, Pavlovic et al. 2013, Ban et al. 2015). More discussions on innovative bolted stud types have been undertaken by taking consideration of the effects of pretension forces on bolted studs (Liu et al. 2014, Pathirana et al. 2016, Yang et al. 2018). Recently, the use of stainless steel in bolted and welded shear connectors increasingly attracts the attention of practical structural engineers.

The interest in the application of stainless steel in modern construction is snowballing in recent decades. Stainless steel raises public awareness as an innovative and attractive alternative to conventional carbon steel, for its benefit in better durability, remarkable corrosion resistance and fire resistance. However, by reviewing the historical literature in the past fifty years, few studies can be found specifically on the load-slip response of stainless steel shear connectors in stainless steel-concrete composite beams. Hence, study on the behaviour of stainless steel shear connectors in the composite beams is carried out in this paper. The primary purpose is to have an investigation on numerical analysis of the load-slip response of the stainless steel bolted and welded studs with two different materials, viz. austenitic 304 and duplex 2205, by using pushout test. Under this goal, a three-dimensional finite element model was developed by applying commercial program ABAQUS. Moreover, a parametric study is also demonstrated in this paper, with the key parameters involving the type of stainless steel, type of shear connectors, bolt-to-hole clearance, the pretension forces of bolts, as well as the tensile strengths of bolted studs.

2. FINITE ELEMENT MODELLING

2.1. Geometry

In this paper, a three-dimensional finite element model simulating the pushout test process (as shown in Figure 1) was established to analyse the load-slip response of stainless steel bolted and welded studs in stainless steel-concrete composite beams. The pushout test specimens were designed by referring to the standard pushout test outlined in Australian Standard AS2327 (2017) and Eurocode 4 (2004). A thickness of 120mm was chosen for concrete slab and the section size of stainless steel beam was designed as same as the dimensions of Australian hot rolled steel universal beam 200UB29.8. Stainless steel bolted and welded shear connectors with same gross cross-section area, as shown in Figure 1(c), were adopted in this study. The diameter of the stainless steel shear connectors was 19mm, and the embedded height in concrete slab was 80mm.

Due to the complicated geometry shapes and multiple contact interactions between different components, the “explicit” method was utilised to avoid the numerical convergence difficulties, which is often encountered in the “implicit” method (Thai et al. 2017). Under the “explicit” step, a “general contact” interaction type was used to define all the contact surfaces, except the welded studs to beam surfaces which were tied together. A friction coefficient of 0.4 was adopted for both concrete to steel and steel to steel contacts. Moreover, to simulate the pretension force on the bolted stud when fastening the nuts at the ends of bolts, the “expansion” function was employed by defining the thermal expansion coefficient. A negative temperature was input in the predefined field, and hence the inner bolts compression force can be accurately simulated.

In order to reduce the computational time, only one-quarter of the specimen was modelled for this study. Besides, mesh convergence studies were conducted and a reasonable mesh was obtained to achieve reliable results with less simulation time. Based on the mesh convergence studies, a finite element mesh was adopted with the smallest element size being 4mm for elements within and around shear studs. The fine mesh was

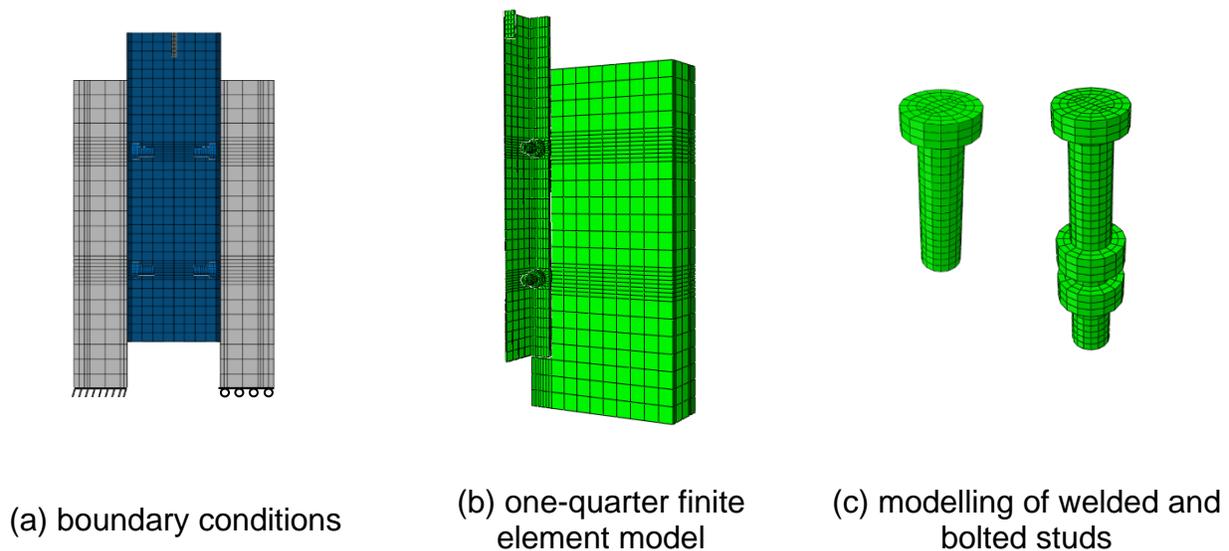


Figure 1 Layout of finite element model

created at the region of the contact surfaces around shear connectors, while the course mesh was adopted for the rest elements, as is presented in Figure 1. A selection of a suitable type of element is also significant for finite element modelling. In this research, the eight-node linear brick element with reduced integration and hourglass control (C3D8R) element type was employed to model all joint components, such as the stainless steel beam, stiffeners and shear connectors, as well as the concrete slab, while the stainless steel reinforcement bars were modelled by the truss elements (T3D2).

2.2. Boundary and loading conditions

The pushout test specimen was modelled with a roller support boundary condition at one concrete slab bottom, while the other support was fixed, which is shown in Figure 1(a). An axial load was applied vertically on the top of stainless steel beam via a displacement control method. The loading rate in the “loading” step was controlled by the smooth step amplitude with the relatively slow speed at the beginning and end of the step. Besides, an extra step of “pretension” was added before the “loading” step when simulating the pretension behaviour of bolted studs. An initial pretension force was created in this step through the axial direction of the bolted studs.

2.3. Material properties

In this paper, plastic formulation with von Mises' yield function, associated plastic flow and isotropic hardening was used to model the stainless steel material. For stainless steel, the material duplex 2205 and austenitic 304 were applied in this numerical investigation for stainless steel beam, shear connectors and reinforcement bars, as they are the most commonly used stainless steel in the current market. Austenitic 304 has remarkable

durability and easy to produce and fabricate, hence, it has a wide range of applications, such as cooking ware, water tanks and civil structures. However, the strength of duplex 2205 is considerable higher than that of austenitic 304, which can reach 800MPa. And due to the high chromium content but lower nickel level, duplex stainless steel performs a higher corrosion resistance but can stay a reasonable price.

To express the material properties of duplex 2205 and austenitic 304, a full-range stress-strain relationship model of stainless steel was adopted in this paper. Considering the accuracy and simplicity, the Ramberg-Osgood expression developed by Rasmussen (2003) was used to define the full range of stress-strain curves of stainless steels. The whole expressions are presented as,

$$\varepsilon = \frac{\sigma}{E} + 0.002 \times \left(\frac{\sigma}{f_y}\right)^n \quad \sigma \leq f_y \quad (1)$$

$$\varepsilon = \varepsilon_{0.2} + \left(\frac{\sigma - f_y}{E_{0.2}}\right) + \varepsilon_u \times \left(\frac{\sigma - f_y}{\sigma_u - f_y}\right)^m \quad \sigma > f_y \quad (2)$$

$$m = 1 + 3.5 \times \left(\frac{f_y}{\sigma_u}\right) \quad (3)$$

where, E denotes the elastic Young's modulus; f_y denotes the 0.2% proof stress; $E_{0.2}$ denotes the tangent modulus at f_y ; and $\varepsilon_{0.2}$ denotes the strain corresponding to f_y . Referred to Eurocode 3 EN 1993-1-4:2006, the value of n for stainless steel austenitic 304 and duplex 2205 were 6 and 5 respectively. The yield strengths for austenitic 304 beams, shear connectors and reinforcement bars were taken as 230, 450 and 500MPa, while the ultimate strengths were taken as 540, 700, 550MPa. The yield and ultimate strengths for duplex 2205 beams, shear connectors and reinforcement bars were taken as 500, 640, 650MPa and 800, 800, 715MPa respectively.

A suitable selection of the concrete model is also vitally significant during the simulation of the pushout test. The behaviour of concrete material was modelled in ABAQUS by applying the option of CDP (concrete damage plasticity) model. A stress-strain compression curve of plain concrete proposed by the Carreira and Chu (1985) is adopted in this study (as shown in Figure 2), which was widely applied by academics, such as Mirza and Uy (2009, 2010), Pathirana et al. (2016) and Uy et al. (2017). In the stress-strain curve, the concrete compressive strength is represented by f'_c , and the concrete stress-strain compression relationship is assumed to be linear elastic up to $0.4f'_c$. Beyond the yielding point, the concrete stress is presented as a function of strain, which is expressed by,

$$\sigma_c = \frac{f'_c \times \gamma \times \left(\frac{\varepsilon_c}{\varepsilon'_c}\right)}{\gamma - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^\gamma} \quad \varepsilon_y \leq \varepsilon_c \leq \varepsilon'_c \quad (4)$$

where, σ_c denotes the concrete compressive stress; ε_c denotes the concrete compressive strain; ε'_c denotes the strain corresponding to compressive strength; and ε_y denotes the strain corresponding to $0.4f'_c$. The expression for parameter γ is given by

$$\gamma = \left| \frac{f'_c}{32.4} \right|^3 + 1.55 \quad (5)$$

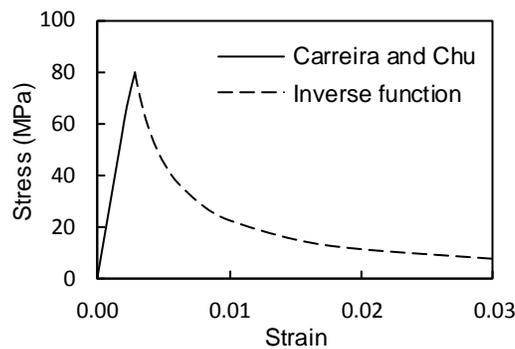


Figure 2 Stress-strain behaviour of concrete in compression

For the descending branch after the peak compression stress, a simple inverse function proposed by Pathirana et al. (2016) was adopted for the compression behaviour of concrete in this study. The simple inverse function is described by

$$\sigma_c = \frac{a}{\varepsilon_c} \quad \varepsilon'_c \leq \varepsilon_c \quad (6)$$

$$a = \sigma_c(\varepsilon'_c) \times \varepsilon'_c \quad (7)$$

For the concrete tensile region, the stress increases linearly until the cracking begins, where the stress f'_t was assumed to be $f'_c/10$, then the stress decreases linearly to zero.

In ABAQUS, the damage parameters need to be defined in the CDP model to derive the damage behaviour of concrete. The compressive and tensile damage for the concrete was presented by damage parameters d_c and d_t respectively. The expressions for d_c and d_t are given respectively by

$$d_c = 1 - \frac{\sigma_c}{f'_c} \quad (8)$$

$$d_t = 1 - \frac{\sigma_t}{f'_t} \quad (9)$$

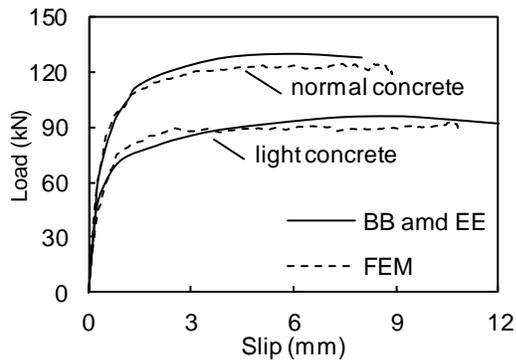
2.4. Model validation

In order to verify the accuracy of the computational model in ABAQUS, five specimens from the research undertaken by Ollgaard et al. (1971), Kwon et al. (2010) and Pathirana et al. (2016) were examined in this section. Since no investigation can be found on the pushout tests regarding the stainless steel shear connectors, only the experimental results of bolted and welded carbon steel shear connectors were used in this study for finite element model validation purpose. Once the model was proved to be capable of accurately simulating the pushout test and obtaining the load-slip behaviour of carbon steel shear connectors, it would be adopted for the simulation of pushout tests with stainless steel bolted and welded shear connectors.

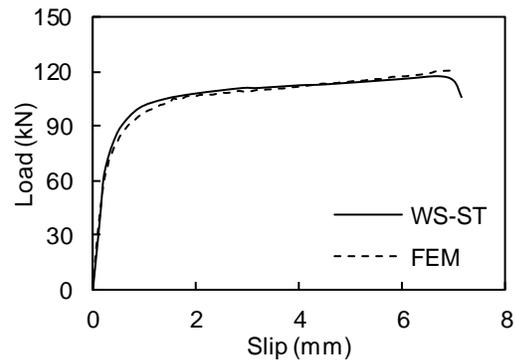
The details of the five specimens are presented in Table 1, which covering both bolted and welded shear connectors with different diameters and tensile strengths. The comparisons of load-slip curves of shear connectors between test results and finite element analysis results are reported in Figure 3 and Figure 4. A great agreement can be observed with the differences of ultimate shear resistances between finite element analysis and experimental results being less than 4%. Moreover, the initial stiffness and the trend of load-slip curves, especially for the critical slip stage of bolted studs, were well captured in the finite element simulation.

Table 1 Details of the specimens used for validation of the finite element model

Specimen	Connector type	Publication	Connector diameter (mm)	f_y (MPa)	f'_c (MPa)	Difference
BB (normal concrete)	welded stud	Ollgaard et al. (1971)	19	500	35	-4%
EE (light concrete)	welded stud	Ollgaard et al. (1971)	19	500	32.5	-3%
WS-ST	welded stud	Pathirana et al. (2016)	19	515	42	2.6%
BB2-RT	bolted stud	Pathirana et al. (2016)	20	795	46	0.5%
DBLNB-05ST	bolted stud	Kwon et al. (2010)	22	860	20.9	0.1%

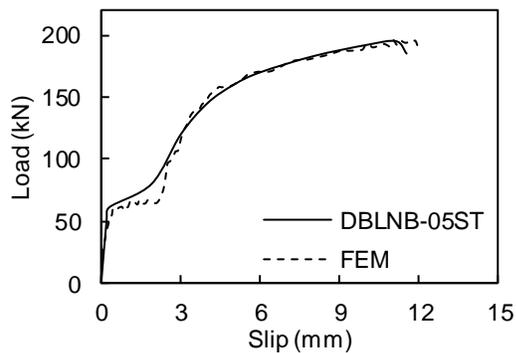


(a) Ollgaard et al. (1971)

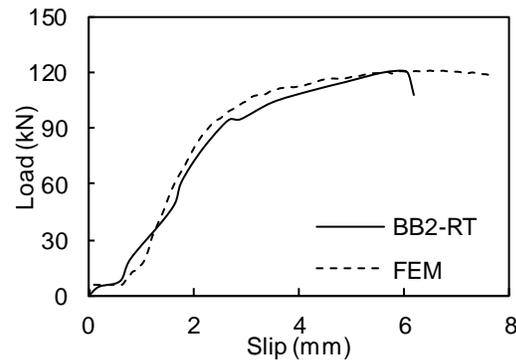


(b) Pathirana et al. (2016)

Figure 3 Comparison of FE results and experimental test results for welded studs



(a) Kwon et al. (2010),



(b) Pathirana et al. (2016)

Figure 4 Comparison of FE results and experimental test results for bolted studs

3. PARAMETRIC STUDIES

Parametric studies have been carried out for investigating the effects of various parameters on the load-slip behaviour of stainless steel shear connectors in stainless steel-concrete composite beams, by using the finite element modelling of pushout tests. A comparison between stainless bolted and welded studs was conducted. The effect of stainless steel types viz. austenitic 304 and duplex 2205 was studied. Besides, key parameters considering the effects of the variations in pretension on bolted studs, bolt-to-hole clearance and tensile strength of bolted studs were investigated to build up a comprehensive understanding of the load-slip behaviour of stainless steel shear connectors. A concrete strength up to 80MPa with the Young's modulus of 39GPa was adopted in this section to allow the shear failure of connectors occurring before concrete crushing.

3.1. Effect of type of stainless steels

Figure 5 and Figure 6 illustrates a comparison between the load-slip behaviour of bolted and welded studs with the stainless steel material of duplex 2205 and austenitic 304 respectively. Higher ultimate shear strength can be achieved by the duplex shear connectors due to the high strength material characteristic of duplex 2205. Moreover, the load-slip curve of shear connectors fabricated by duplex 2205 displays a higher stiffness than that made by austenitic 304. The large stiffness and strength exhibited in duplex shear connectors are mainly caused by the mixture metal components of duplex material, whereas, austenitic stainless steel only consists of one metal phase. However, from the aspect of ductility, austenitic grade reaches the better ductility value than duplex grade does.

3.2. Effect of type of shear connectors

The load-slip curve behaviour shown in Figure 5 and Figure 6 also present significant differences between the bolted and welded shear connectors. Given the same diameter and height above flange, the bolted and welded studs exhibit approximate the same initial stiffness, whereas, the welded stud has slightly better shear resistance than bolted studs. At the early nonlinear stage, bolted shear connectors show less bearing loads than welded shear connectors. This is brought by the reduction of bearing stress of the concrete in front of the embedded nut, due to the pretension force and the confinement effects on the concrete between the nut and bolt head (Pavlovic et al. 2013).

3.3. Effect of pretension on bolted studs

Generally, four distinctive stages are observed on the load-slip curve of bolted studs. At the beginning of the loading, a relatively small load increases linearly to balance the static friction force between the stainless steel beam and concrete slab, followed by the critical slip stage. Once the maximum friction force being reached, the slip increases with the load slowly rises. The reason for occurred large slip is that the bolt needs to overcome the clearance between the prefabricated hole in stainless steel flange and bolted stud. When the bolt shank begins to contact the surface of hole, the concrete slab starts to bear the external force by the pressure from the bolt shank. At this stage, the bolted studs are subjected to a combined action of shear force, tension and bending moment. Eventually, the bolted shear connectors are loaded until the specimens failed.

Figure 7 demonstrates the effect of pretension on the load-slip behaviour of bolted shear connectors through the pushout test. Pretension force was generated when installing the bolt threads and nuts on the stainless steel flanges. Different pretension forces of bolted studs, viz. 10, 50, 100, 150kN, were considered in this group. By increasing the pretension force, the load to overcome the friction force at the interface between stainless steel beam and concrete slab is increased. Hence, an increment of the load at the slip stage can be observed in Figure 7. In addition, a decrease of the maximum shear resistance is recognized in the plot when increasing the pretension force. This is due

to the reduction of bearing stress on concrete around the bolted studs when fastening the bolts to assemble the steel

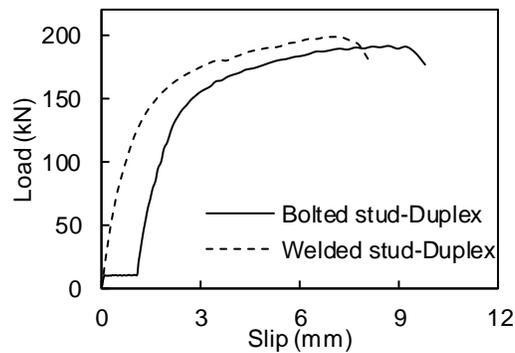


Figure 5 Load-slip behaviour of duplex shear connectors

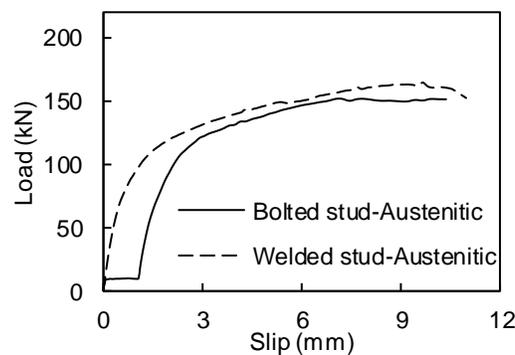


Figure 6 Load-slip behaviour of austenitic shear connectors

beam and concrete slab. However, the pretension force has no significant effect on the stiffness of the stainless steel bolted studs.

3.4. Effect of bolt-to-hole clearance

Figure 8 illustrates the load-slip behaviour of stainless steel bolted studs with various diameters of prefabricated holes. The same 19mm bolted studs were installed on stainless steel beam, while the different diameters of prefabricated holes were applied, viz. 19, 21, 23, 25mm. As demonstrated in Section 3.3, the clearance between the prefabricated holes in the flange and bolted studs has a significant effect on the critical slip stage. The maximum value of slip at this stage was exactly close to the distance between the surface of hole and the bolted studs. However, no changes can be observed on the stiffness and ultimate load capacity of the load-slip curve for stainless steel bolted stud.

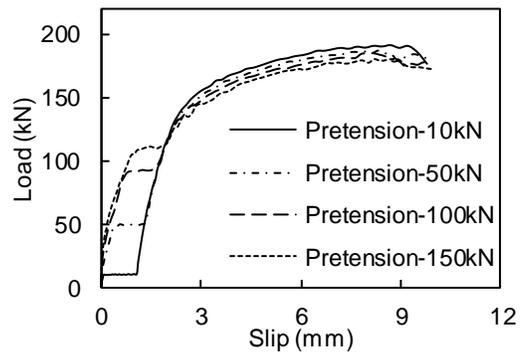


Figure 7 Effect of pretension on bolted studs

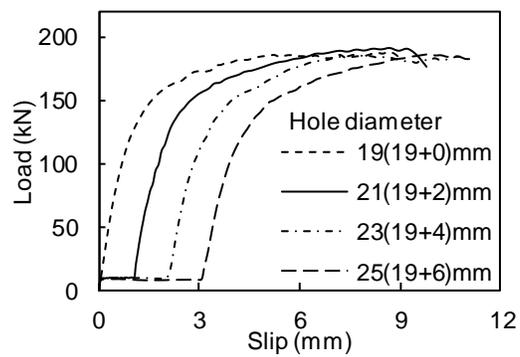


Figure 8 Effect on bolt-to-hole clearance

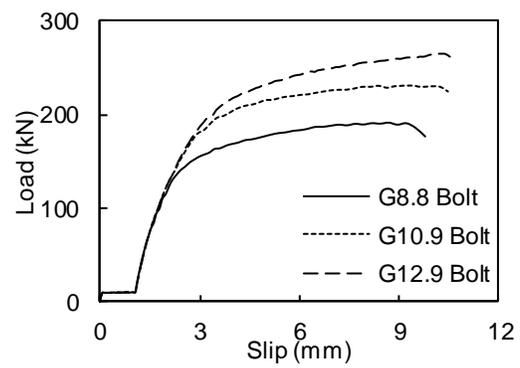


Figure 9 Effect of tensile strength of bolted studs

3.5. Effect of tensile strength of bolted studs

The effect of tensile strength of stainless steel bolted stud on load-slip response is shown in Figure 9. A group of three bolts grade, G8.8, G10.9 and G12.9 were considered with the ultimate tensile strength of 800, 1000 and 1200MPa separately. Although the initial stiffness has no significant differences, the ultimate bearing capacity has a great increment by increasing the tensile strength of bolts. For example, by increasing tensile strength from 800 to 1200MPa, the ultimate capacity increases by 39%.

4. CONCLUSIONS

A finite element model of pushout test with stainless steel shear connectors has been developed in this research. An investigation on the load-slip behaviour for both stainless steel bolted and welded stud in stainless steel-concrete composite beams has been conducted. Different stainless steel material, duplex 2205 and austenitic 304, were introduced and considered in this paper. Moreover, an extensive parametric study was also carried out to analyse the effects of the pretension force, bolt-to-hole clearance and the tensile strength of bolted studs. It can be concluded that, the changes in pretension and bolt-to-hole clearance greatly influenced the load-slip response of bolted studs at the critical slip stage, whereas, no significant effects on the initial stiffness. Besides, by increasing the tensile strength of stainless steel bolts, an increment of the ultimate shear connection resistance was observed.

It is worth noting that stainless steel shear connectors not only have outstanding corrosion resistance but also have remarkable structural characteristics. Stainless steel shear connector can be considered as an innovative and attractive alternative to conventional carbon steel shear connector for its remarkable shear connection resistance and ductility.

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