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Post-fire Behaviour of Innovative Shear Connection for Steel-Concrete Composite Structures

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ABSTRACT

Steel-concrete composite structures are commonly used in buildings and bridges because it takes advantage of tensile strength of steel and compressive strength of concrete. The two components are often secured by shear connectors such as headed studs to prevent slippage and to maintain composite action. In spite of its popularity, very little research was conducted on steel-concrete composites particularly on headed stud shear connectors in regards to its post-fire behaviour. This research investigates the post-fire behaviour of innovative shear connectors for composite steel and concrete. Three types of connectors were investigated. They are conventional headed stud shear connectors, Blind Bolt 1 and Blind Bolt 2 blind bolts. Push-out test experimental studies were conducted to look at the behaviour and failure modes for each connector. Eighteen push tests were conducted according to Eurocode 4. The push test specimens were tested under ambient temperatures and post-fire condition of 200 °C, 400 °C and 600 °C. The results in ambient temperature are used to derive the residual strength of shear connectors after exposing to fire. This research showed that the headed studs performed well compared to Blind Bolts 1 and 2 at ambient and target temperatures. The stress concentrations around the casing of Blind Bolt 1 were found to cause a reduction in strength of the specimens. Findings from this research will provide fundamental background in designing steel-concrete composites where there is danger of fire exposure.

1. Introduction

Steel-concrete composite beam/slab construction is common practice in bridges and multi-storey buildings due to the combination of compressive strength of concrete and tensile strength of steel [12]. The two components are often secured by shear connectors that greatly influence its strength and ductility [15]. Despite its popularity in these types of constructions, composite members are still a subject of continuous development [16]. One of the areas of interest in the development of composite structures is the shear connectors that bond concrete and steel [16]. Interests in these developments are however limited due to the high cost in setting up in a laboratory environment [8]. Even though the costs of these experiments are monumental, researchers still manage to set up experiments with good results such as conducted by Wang et al. [20] and Alderighi and Salvatore [1] in multi-level framed buildings.

A review of literature shows that research on steel-concrete composite structures has focused behaviour of push-out tests at ambient temperature and at elevated temperature. Push-out tests of composite structures at ambient temperature showed that their strength and ductility were often influenced by their material properties [8,10]. Galjaard and Walraven [10] conducted push-out tests for five different shear connectors: headed studs, continuous perfobond strip, oscillating perfobond strip, waveform strip and T-connector. Similarly, Baran and Topkaya [3] conducted an experimental study on another type of shear connector: channel type shear connector or C-channel. The tests aim was to determine the strength of different sizes of C-channel as shear connector in steel-concrete composite structure [3].

Push-out tests on steel-concrete composite structures utilising headed studs were also conducted at elevated temperatures by Zhao [21], Mirza and Uy [15], Anderson [2], Wang [19] and Imagawa et al. [13] among others. Push-out tests on steel-concrete composite structures utilising continuous perfobond strip [16] and T, T-block and T-perfobond [17] have also been conducted at elevated temperatures.

Most of the research on push-out tests of steel-concrete composite structures focusses on the behaviour of specimens at ambient and elevated temperatures. A review of other types of composite structures such as the concrete-filled steel tubular columns shows that their strength after exposure to fire can be predicted through the development of mechanics models [11]. Future research will focus on the use of post-fire mechanical properties of shear connectors and concrete to predict the post-fire behaviour of steel-concrete composite structures.

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This paper focuses on the behaviour of steel-concrete composite structures using innovative shear connectors under post-fire. Post-fire behaviour of steel-concrete composite structures is investigated with a focus on failure in push tests made up of three types of shear connectors; headed studs, Blind Bolt 1 and Blind Bolt 2. Eighteen push-out tests were carried out at ambient temperature and post-fire condition of 200 °C, 400 °C and 600 °C. The results at ambient temperature are used to determine the residual strength of steel-concrete composite structures after exposure to fire.

2. Experimental study

2.1. Experimental set-up and specimen

The test specimens were based on the Eurocode 4 [9] standard and were fabricated in a similar manner as outlined in the standard. However, due to the size limitation of the furnace, all specimens were modified to fit in the furnace. The steel section adopted was a 200PFC and two 200PFC configured as shown in Fig. 1. The width of the slabs for the

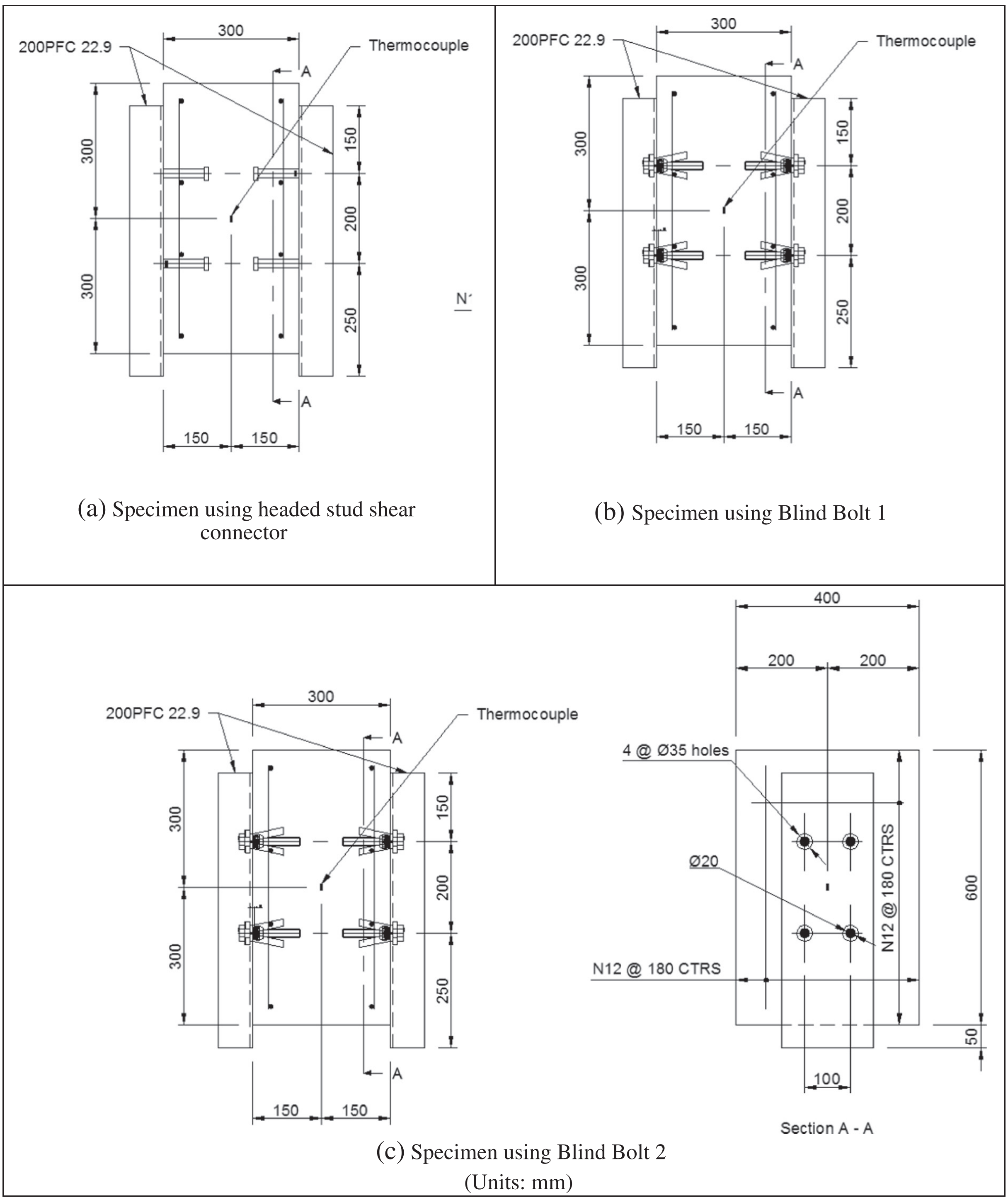

Fig. 1. Push-out test specimens using (a) headed stud shear connectors, (b) Blind Bolt 1 and (c) Blind Bolt 2.

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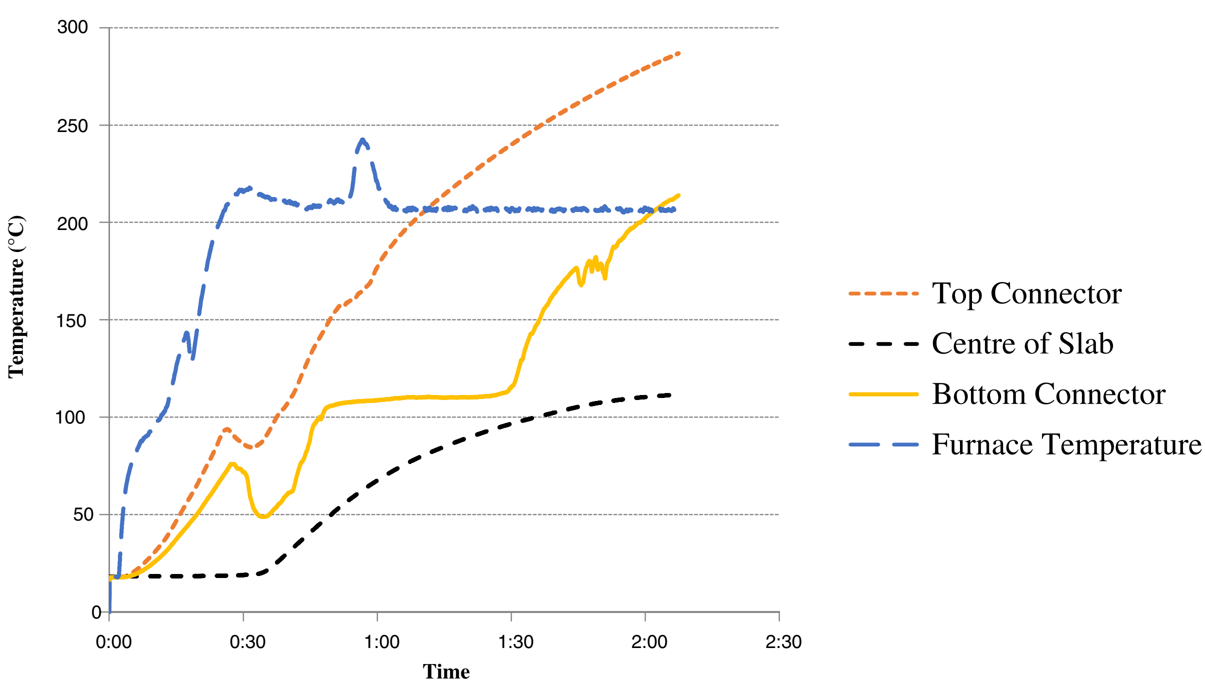
specimens were also been downsized from 600 mm specified by the Eurocode 4 to 400 mm. The only exception is the reinforcing bars where all the bars were upsized to N12 (12 mm diameter) instead of 10 mm diameter specified in Eurocode 4. The spacing and size of the shear connectors were kept the same as provided in Eurocode 4. Specimens using headed studs are shown in Fig. 1(a). Specimens using Blind Bolt 1 and 2 bolts as shear connectors were also used and are shown in Fig. 1(b) and (c) respectively.

Push-out tests of specimens using headed studs, Blind Bolt 1 and Blind Bolt 2 as shear connectors were carried out for specimens at ambient temperature and post-fire condition of 200 °C, 400 °C and 600 °C. The push-out test followed the Eurocode 4 testing protocol although some ambient tests were also tested without the application of 25 cycles for comparison.

Following the Eurocode 4 push-out test protocol, the load was applied in increments up to 40% of the expected failure load and then cycled 25 times between 5% and 40% of the expected failure load. The application of 25 loading cycles between 5% and 40% of the estimated failure load gives a response that is close to elastic but enables the specimen to settle and therefore stabilize for the loading to failure thereafter. Subsequent incremental loads were then applied to prevent the failure of the specimens in <15 min. In order to prevent the specimens from

(a)



(b)

Fig. 2. (a) Time-temperature curve of AJAX bolts at post-fire 200 °C and (b) push-out test set up for ambient and post-fire test specimens.

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failing in <15 min, a loading rate of 0.01 mm/s was used. The loading rate of 0.01 mm/s ensures that the specimen will simulate a static loading condition. Part of the requirement for Eurocode 4 push test is to determine the relative slip between the steel and concrete continuously during loading. In order to achieve this requirement, linear variable displacement transducers (LVDT) were attached to the steel and the concrete (see Fig. 2(a)). Data of slip versus load was recorded and the failure modes noted. The data and failure modes at ambient temperature serve as the baseline for comparison with post-fire test specimens. The collection of data was ceased when the load dropped to 20% of the maximum load.

The preheating of all specimens subjected to post-fire analysis followed the ISO834 standard fire curve in obtaining the desired temperature. Prior to the preheating of the specimens, a 40% preload was applied to all the post-fire specimens to reflect the specimens under service loading. A total of two specimens were heated at each temperature regime (200 °C, 400 °C, and 600 °C) for every type of shear connector. In order to achieve the desired temperature, a temperature controlled furnace was used. The furnace uses three gas burners in heating the specimens with two on one side and one at the other. When the heating reached the desired temperature, heating was continued for 1 h of soaking time before the furnace was switched off. A typical time-temperature curve is shown in Fig. 2(b) which was determined using thermocouples. The temperature at the centre of the slab (Fig. 1) and the connectors are also shown in Fig. 2(b).

The cooling process used in this experiment was the natural air cooling – leaving the specimen overnight to reach ambient temperature. The cooling method has an effect on residual compressive strength of concrete. Compressive strength loss is generally higher for rapid cooling or quenching using water compared to relatively slow cooling in air. Rapid cooling generally causes the development of detrimental micro-cracking as a result of temperature differentials between the outer and inner layers of concrete [5]. The push-out test procedure used to determine the residual strength of post-fire specimens was the same as that for specimens tested at ambient temperature.

2.2. Material and geometric properties

Three types of shear connectors were used in this investigation; the headed studs, Blind Bolt 1 and Blind Bolt 2. The headed studs used have a diameter of 19 mm, length of 100 mm and ultimate tensile strength of 410 MPa, while the Blind Bolt 1 used have a diameter of 20 mm, length of 100 mm and ultimate tensile strength of 390 MPa. On the other hand, the Blind Bolt 2 bolts used have a diameter of 20 mm, length of 100 mm and ultimate tensile strength of 830 MPa.

The 200PFC sections used in this investigation had flange width of 200 mm, flange thickness of 12 mm, web thickness of 6 mm, yield strength of 300 MPa and ultimate tensile strength of 440 MPa. For fire protection, a hypercoating paint was used to provide a 2 h fire protection. Hypercoating paint is a ceramic-based coating which is about 1 mm thick. The hypercoating paint was applied to all exposed steel section of the specimen after the removal of the formwork. In this experimental investigation, the time for the removal of formwork was 21 days after the concrete was cast.

The concrete used in the concrete slab had a 28 day compressive strength of 30 MPa and Young's Modulus of 36,690 MPa. The reinforcing bars used in the concrete slabs had a diameter of 12 mm and yield strength of 500 MPa.

3. Results and discussion

The three types of push-out test specimens using headed studs, Blind Bolt 1 and Blind Bolt 2 were tested at ambient temperature and at post-fire condition of 200 °C, 400 °C and 600 °C. For each type of specimen, the specimens tested at ambient temperature were also tested by applying either 25 cycles as per EC4 testing protocol while others were tested without cyclic loading for comparison.

3.1. Behaviour of headed stud shear connector

Fig. 3 shows the load-slip relationship for the headed stud shear connector specimens tested at ambient temperature under 25 and no cycles. Despite the cycle loading, headed studs that were tested under 25 cycles showed greater slip and loading capacity compared to the specimen that was tested with no cycle loading. The level of load at which cyclic loading is applied in the push tests is based on the Eurocode 4 recommendations of 25 cycles between 5% and 40% of the expected failure load. This procedure is for monotonic tests [7]. This level of cyclic loading is typical of loads designed to cause high cycle fatigue and therefore does not significantly influence static strength [14]. However, both specimens experienced a sudden drop in load capacity due to concrete failure. The weaker compressive strength of concrete leading to concrete failure was the primary factor in the sudden drop of the load as shown in Fig. 3.

Failure modes of headed stud specimens at ambient temperature were mainly dominated by the concrete failure – splitting of the concrete slab as shown in Fig. 4. This type of failure occurred because of the weaker compressive strength of concrete and therefore no yielding of the shear connector was observed. The specimens tested under 25 and no cycles showed similar failure modes (Fig. 4).

The post-fire push-out tests, for headed stud shear connector specimens were also carried out. Fig. 5 shows the load versus slip graphs of the headed stud specimens at post-fire condition of 200 °C, 400 °C and 600 °C. A sudden drop in load is more evident in post-fire conditions of 200 and 400 °C. Despite the low rigidity at the start of testing, the test at 200 °C showed greater ductility and maximum load compared to the tests at 400 °C and 600 °C. The failure mode in the push-out tests show that the specimens failed through a combination shear failure of the concrete due to vertical slip and tensile failure of the concrete due to opening of the concrete cracks. This combined shear and tensile failure of the concrete, see Figs. 4, 8 and 12 has contributed to the reduced ductility of the specimens observed in the load-slip curves.

Headed shear studs post-fire 200, 400, and 600 °C specimens all showed a similar type of failure mode as shown in Fig. 6. All the post-fire headed stud specimens failed through splitting of the concrete slab or concrete failure. The spalling of concrete after exposure to high temperature had a significant impact on the strength of concrete making the slab the weakest part of the steel-concrete composite specimens. These specimens were tested between a month and a month and half after casting of the concrete. Previous research shows to avoid spalling, specimens may be heated at about 18 months after casting when they have low moisture content [6]. After heating, the steel sections did not show any signs of deformation except the minor expansion of the fire protection coating. Minor cracks on the concrete slab were observed

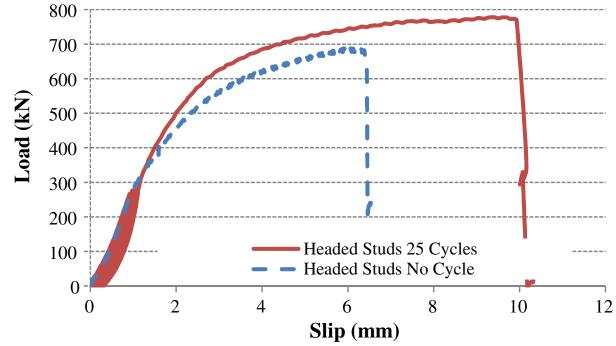

Fig. 3. Load–slip relationship for headed stud shear connector specimens at ambient temperature.

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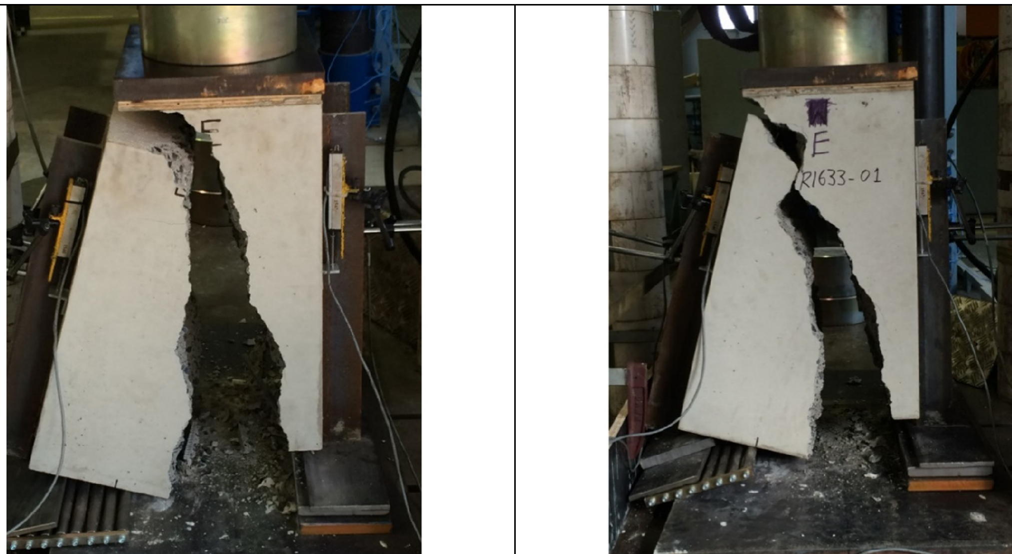

(a) Specimen loaded to 25 Cycles

(b) Specimen with no cycles

Fig. 4. Failure mode of headed stud shear connector specimens at ambient temperature.

on most of the post-fire headed stud specimens as part of the thermal damage caused by the fire. A separation between steel and concrete slab was also observed on some of the specimens prior to the testing.

3.2. Behaviour of Blind Bolt 1

Fig. 7 shows the results of load versus slip for the Blind Bolt 1 specimens tested at ambient temperature under 25 cycles and no cycles respectively. As illustrated in Fig. 7, the difference between two testing conditions was very minimal.

The push-out tests conducted for the Blind Bolt 1 specimens tested at ambient temperature failed through concrete failure as shown in Fig. 8. The Blind Bolt 1 specimens showed a different concrete failure mode to the headed stud and Blind Bolt 2 specimens. Instead of splitting the concrete slab in half, the specimen failed by pulling out a portion of concrete closer to the steel section, see Fig. 8. The possible cause of this type of failure mode may be due to the geometric arrangement at the end of the Blind bolt 1. The sleeve that secures the grip into the steel section of the Blind Bolt 1 forms petals which can create stress concentrations in the surrounding concrete. An illustration of the petal formation that causes stress concentration in Blind Bolt 1 specimens is shown in Fig. 1(b).

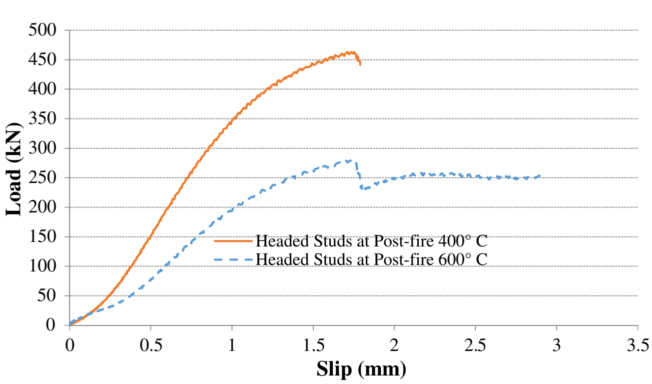

Fig. 5. Load–slip relationship for headed stud shear connector specimens post-fire.

The post-fire push-out tests for Blind Bolt 1 specimens was also carried out. Fig. 9 shows the load versus slip of the Blind Bolt 1 specimen push-out tests at post-fire condition of 200 °C, 400 °C and 600 °C. The Blind Bolt 1 specimens that were tested tend to reach the ultimate capacity followed by a drop in load before another increasing trend in loading before final failure. The ductility shown by all the specimens that were tested, is similar to the strain hardening phenomenon of steel. The post-fire 200 °C and 400 °C specimens showed greater ductility compared to specimen at post-fire condition of 600 °C, see Fig. 9.

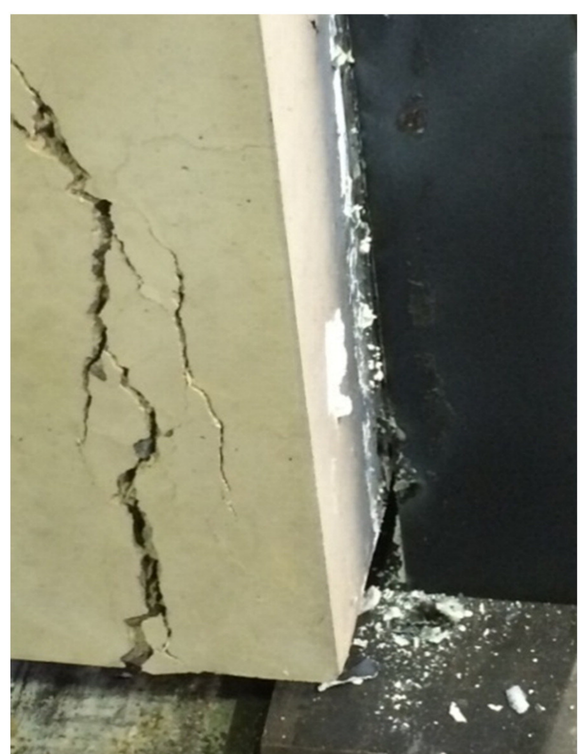

Fig. 6. Failure mode of headed stud shear connector specimens post-fire.

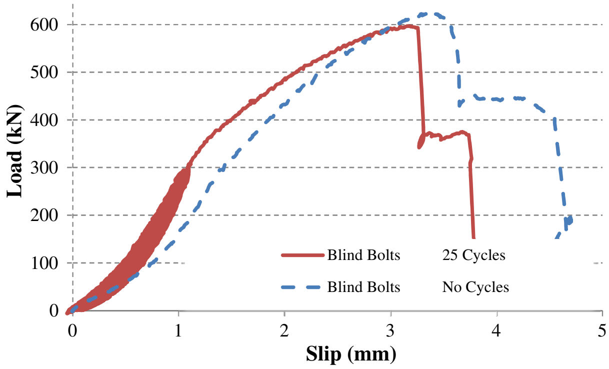

Fig. 7. Load–slip relationship for Blind Bolt 1.

The failure mode of Blind Bolt 1 specimens at post-fire conditions was due to concrete failure. However, all Blind Bolt 1 specimens tested at post-fire conditions of 200, 400, and 600 °C failed due to the splitting of the concrete slab. This was unlike the concrete failure of the Blind Bolt 1 specimens at ambient temperature which tended to be localized at the position of a Blind Bolt 1. In general, the failure modes for the post-fire Blind Bolt 1 specimens were mainly due to concrete failure and separation between the steel and the concrete as shown in Fig. 10.

3.3. Behaviour of Blind Bolt 2

Fig. 11 shows the load-slip relationship for the Blind Bolt 2 specimens tested at ambient temperature under 25 and no cycles. The specimen subjected to 25 cycles showed more stability and achieved a greater load and slip before failure.

Fig. 12 shows the typical failure of the Blind Bolt 2 specimens tested at ambient temperature with 25 and no cycles. As illustrated in Fig. 12 failure modes were mainly dominated by the concrete failure. The Blind Bolt 2 specimen subjected to 25 cycles showed yielding of the reinforcement bars which occurred when the splitting of the slab crossed the bars. This type of failure led to the higher maximum slip compared to the specimen tested without cycling.

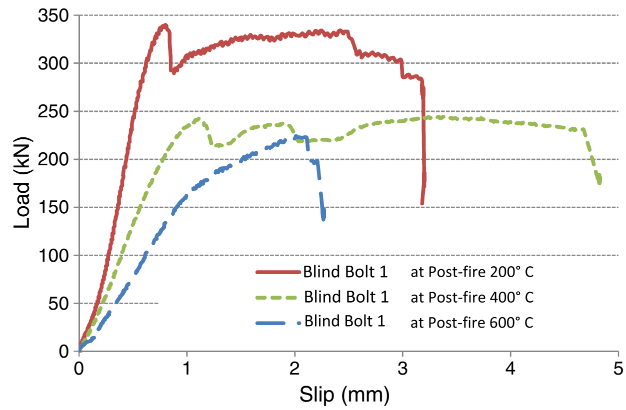

Fig. 9. Load–slip relationship for Blind Bolt 1 specimens post-fire.

The push-out tests for Blind Bolt 2 specimens was also carried out at post-fire conditions of 200oC, 400 °C and 600 °C. Fig. 13 shows the load versus slip of the Blind Bolt 2 specimens tested at post-fire conditions. The Blind Bolt 2 specimens tested showed a drop in load followed by a gradual increase in loading before a sudden drop in load. The loading capacity behaviour was similar to the strain hardening of a steel material in a tensile test. The ductility of the Blind Bolt 2 specimens was more evident at the post-fire condition of 200 °C compared to post-fire conditions of 400 and 600 °C.

The failure modes for all the Blind Bolt 2 specimens tested at post-fire conditions of 200, 400, and 600 °C were all concrete failures, see Fig. 14. Furthermore, minor separation of steel and concrete was observed for post-fire 400° and 600 °C before the test was conducted. The separation between the steel and concrete prior to the test was caused by the thermal expansion of the steel and the concrete which in turn resulted in a reduction in load capacity.

As described earlier, the observed failure in all the specimens was through concrete failure incorporating a combination of shear and tensile failure in concrete. This has resulted in the observed reduction in ductility in the load-slip relationship observed in these tests when compared to the characteristic slip of 6 mm recommended by Eurocode 4 for

(a) Specimen loaded to 25 Cycles

(b) Specimen with no cycles

Fig. 8. Failure mode of Blind Bolt 1 specimens at ambient temperature.

Fig. 10. Failure mode of Blind Bolt 1 connector specimens post-fire.

plastic behaviour. Future research will investigate the improvement in ductility through a combination of concrete strength and specimen detailing to cause shear connector failure.

3.4. Comparison of results at ambient temperature

Standards such as Eurocode 4, AISC [4] and the Australian Standard AS2327.1-2003 can be used to predict strength of the shear connectors. It should be noted that at present there are no design rules for determining the shear strength of Blind Bolt 1 and 2. The use of current standards in estimating the shear strength of Blind Bolt 1 and 2 in this investigation, is an indicator of how current rules for headed stud shear connectors can be used to benchmark the strength of new types of connectors.

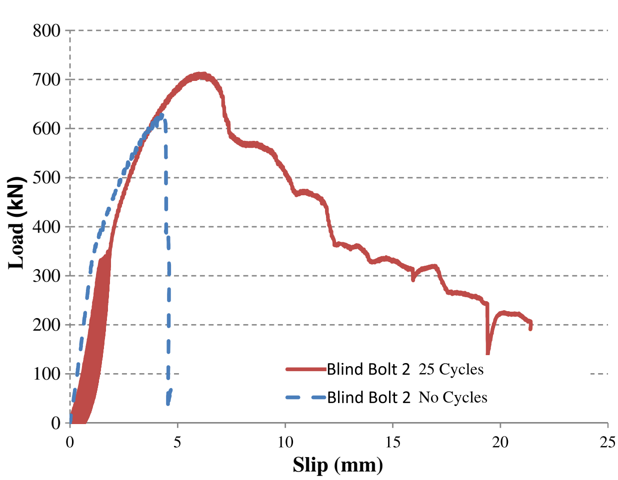

Fig. 11. Load–slip relationship for Blind Bolt 2.

The failure load of a shear connector based on Eurocode 4 can be predicted using the lesser of Eqs. (1) and (2) as follows:

$$F_L = \left(0.29\alpha d^2\sqrt{f_{ck}E_c}\right) \quad (1)$$

$$F_L = \left(0.8 f_u \frac{\pi d^2}{4}\right) \quad (2)$$

where,

α modification factor, 0.2(h / d + 1) < 1.0,
d diameter of shear connector (mm)
h 100 mm
f_{ck} concrete cylinder compressive strength (MPa)
E_c static elastic modulus of concrete (MPa)
f_u ultimate tensile strength of the shear connector (MPa)
F_L failure load (N).

Eqs. (3) and (4) are used by the American Institute of Steel Construction, AISC [4] to estimate the failure load of shear connectors. The lesser value of Eqs. (3) and (4) are used to predict the failure load of shear connector.

$$F_L = A_s f_u \quad (3)$$

$$F_L = 0.5A_s\sqrt{f_{ck}E_c} \quad (4)$$

where,

F_L failure load (N)
A_s shank cross sectional area of the shear connector (mm^2),
f_u ultimate tensile strength of the shear connector (MPa)
f_{ck} compressive strength of concrete (MPa)
E_c elastic modulus of concrete (MPa)

Eqs. (5) and (6) are used by the Australian Standard AS2327.1–2003 [18] to estimate the failure load of the shear connectors. The lesser value of Eqs. (5) and (6) are used to predict the failure load of shear connector.

$$F_L = 0.63d^2 f_u \quad (5)$$

$$F_L = 0.31d^2\sqrt{f_{ck}E_c} \quad (6)$$

where,

F_L failure load (N)
d shank diameter of the shear connector (mm),
f_u ultimate tensile strength of the shear connector (MPa)
f_{ck} compressive strength of concrete (MPa)
E_c elastic modulus of concrete (MPa).

Table 1 shows the experimental failure loads as well as the predicted failure loads based on different standards for the push-out tests at ambient temperature. Table 2 shows the ratios of the average test load to predicted failure loads for push-out test specimens using different shear connectors at ambient temperature.

From Tables 1 and 2, AISC [4] significantly overestimated the failure capacity of all the shear connectors in the push-out test specimens, as shown by the average ratio of tested failure load to predicted failure load in Table 2. Eurocode 4 and the Australian standard were comparatively better in predicting the failure capacity of the different shear connectors.

Based on the materials properties, the American standard, AISC [4], Australian Standard [18] and Eurocode 4 see Table 1, predicted failure

(a) Specimen loaded to 25 Cycles (b) Specimen with no cycles

Fig. 12. Failure mode of Blind Bolt 2 specimens at ambient temperature.

of the headed studs and Blind Bolt 1 to be dominated by the shear connector failure (i.e. Eqs. (2), (3) and (5) had the lesser value). The predicted failure mode for the headed studs and Blind Bolt 1 by the standards contradicts the failure mode observed in the specimens. Most of the specimens tested failed by concrete failure – splitting of the section of concrete around the shear connector and through the specimen.

Based on theoretical analysis of Eurocode 4, AISC [4] and AS2327.1-2003, all three standards correctly predicted the failure mode of Blind Bolt 2 specimens as concrete failure. Despite the correctly predicted failure mode, the standards predicted failure loads are considerably different to the experimental test failure loads.

Based on the analysis of the predictions by the three different standards (Eurocode 4, AISC [4], and AS2327.1-2003), Eurocode 4 followed by the Australian Standard can be considered to be reasonable in predicting the shear capacity of all the specimens tested at ambient temperature (see Table 2). From the result of this analysis Eurocode 4 can be considered to be a more reliable basis for determining the residual strength in post-fire analysis.

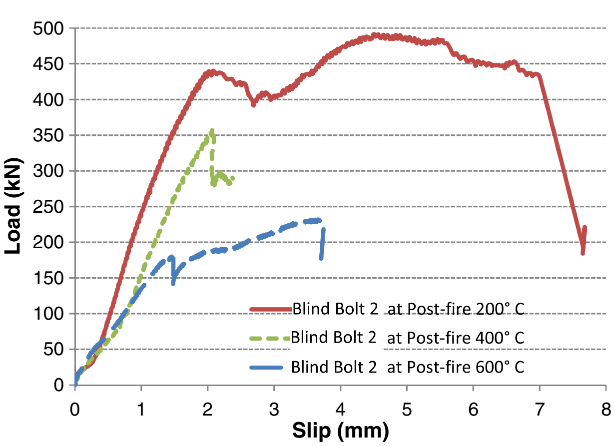

Fig. 13. Load–slip relationship for Blind Bolt 2 specimens post-fire.

3.5. Comparison of results at post-fire

Table 3 shows the summary of test results for headed stud specimens. Table 3 shows the test failure loads and residual strength for the headed studs specimens tested at ambient temperature and post-fire conditions of 200, 400 and 600 °C. The residual strength is defined as the ratio of the failure load for post-fire specimen to the failure load for the ambient temperature specimen. The ambient temperature specimen subjected to 25 cycles was used for comparison as its test follows

Fig. 14. Failure mode of Blind Bolt 2 connector specimens post-fire.

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Table 1
Test and predicted failure loads for push-out test specimens using different shear connectors.

Shear connectors	Test 25 cyc. (kN)	Test no cyc. (kN)	EC4 (kN)	AISC [4] (kN)	SAL [18] (kN)
Headed stud	778	688	744[a]	930[a]	746[a]
Blind Bolt 1	601	626	784[a]	980[a]	786[a]
Blind Bolt 2	712	629	974[b]	1318[b]	1040[b]

[a] Shear connector failure predicted by standard.
[b] Concrete crushing predicted by standard.

Table 2
Ratios of average test to predicted failure loads for push-out test specimens using different shear connectors.

Shear connectors	Average test load/EC4 predicted load	Average test load/AISC predicted load	Average test load/SAL predicted load
Headed stud	0.99	0.79	0.98
Blind Bolt 1	0.78	0.63	0.78
Blind Bolt 2	0.69	0.51	0.64
Mean ratio	0.82	0.64	0.80

Table 3
Comparison of Headed studs test results for ambient and post-fire.

Temperature (°C)	Test failure load (kN)	Residual strength
Ambient 25 cycles	809	1.00
Post-fire 200-01	561	0.69
Post-fire 200-02	–	–
Post-fire 400-01	389	0.48
Post-fire 400-02	463	0.57
Post-fire 600-01	314	0.39
Post-fire 600-02	280	0.34

the Eurocode 4 procedure. The specimen subjected 200 °C had a post-fire strength loss of 31% in load capacity compared to the specimen tested at ambient temperature. The specimens subjected to 400 °C had a post-fire strength loss of 52% and 43% respectively. On the other hand, the specimens subjected to 600 °C had a post-fire strength loss of 61% and 66% respectively.

Table 4 shows the test results for Blind Bolt 2 specimens tested at ambient and post-fire. From Table 4, the specimens subjected 200 °C had a post-fire strength loss of 39% and 36% in load capacity respectively compared to the specimen tested at ambient temperature. The specimens subjected to 400 °C had a post-fire strength loss of 65% and 53% respectively. On the other hand, the specimens subjected to 600 °C had a post-fire strength loss of 61% and 70% respectively.

The summary of the loading capacity of Blind Bolt 1 specimens ambient and at post-fire condition of 200, 400, and 600 °C is shown in Table 5. From Table 5, the ambient temperature loading capacity was the baseline for all post-fire analysis. The specimens subjected 200 °C had a post-fire strength loss of 29% and 43% in load capacity respectively compared to the specimen tested at ambient temperature. The specimens subjected to 400 °C had a post-fire strength loss of 53% and 59% respectively. On the other hand, the specimens subjected to 600 °C had a post-fire strength loss of 68% and 62% respectively.

Table 4
Comparison of Blind Bolt 2 test results for ambient and post-fire.

Temperature (°C)	Test failure load (kN)	Residual strength
Ambient 25 cycles	765	1.00
Post-fire 200-01	464	0.61
Post-fire 200-02	491	0.64
Post-fire 400-01	265	0.35
Post-fire 400-02	357	0.47
Post-fire 600-01	298	0.39
Post-fire 600-02	232	0.30

Table 5
Comparison of Blind Bolt 1 test results for ambient and post-fire.

Temperature (°C)	Test failure load (kN)	Residual strength
Ambient 25 cycles	597	1.00
Post-fire 200-01	474	0.79
Post-fire 200-02	340	0.57
Post-fire 400-01	278	0.47
Post-fire 400-02	244	0.41
Post-fire 600-01	191	0.32
Post-fire 600-02	224	0.38

4. Conclusions

The behaviour of headed studs, Blind Bolt 1 and Blind Bolt 2 as shear connectors at both ambient temperature and post-fire condition were tested using the push-out test specimens. Additionally, the experimentally determined test failure loads were compared to the theoretically predicted failure loads using the Eurocode 4, AISC [4] and AS2327.1-2003 method of analysis. The results of the experimental tests showed that all specimens were dominated by the concrete failure of the slab at both ambient temperature and at post-fire. The following observations were made based on the experimental tests and comparison with predictions from the current standards:

1. The experimental test failure loads of headed studs and Blind Bolt 2 specimens, at ambient temperature, were of the same magnitude. Blind Bolt 1 specimens, however, showed less failure capacity due to the stress concentrations around the casing of the bolts.
2. Headed studs performed well compared to Blind Bolt 1 and 2 at ambient temperature and all post-fire target temperatures. On the other hand, Blind Bolt 2 performed better than Blind Bolt 1 at ambient temperature and all post-fire target temperatures.
3. The residual strength of the headed studs in all post-fire target temperatures was better compared to the Blind Bolt 1 and 2. When compared to the failure loads at ambient temperature, the residual strength of Blind Bolt 1 and Blind Bolt 2 are comparable at all post-fire target temperatures.
4. Following exposure to various degrees of temperatures, all the specimens exhibited minor structural damage, with slight separation of the steel and concrete evident and minor spalling. However, thermal damage to the specimen causes the concrete to become brittle. As a consequence, a sudden drop in load was observed for all specimens at post-fire.
5. For the 30 MPa strength of concrete used for all specimens, the eight shear connectors per specimen had greater shear strength compared to concrete. Therefore, no shear connector yield failure was observed at both ambient temperature and at post-fire.

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