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PERFORMANCE OF SHEAR STUDS IN FIRE

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Introduction

❑Technology surrounding fire safety design for composite structures has been advanced due to introduction of new insulation materials, the development of computational modelling technology and advanced design methodologies obtained through extensive full scale experiments in fire.

❑ The structural fire safety calculations have been traditionally based upon prescriptive method according to hourly ratings, on code requirements with respect to standard fires, such as ASTM E119, BS 476 Part 20 or ISO 834. Now both domestic (UK) and international regulations permit design for structural fire safety to be carried out according to performance based concepts.

❑A wide-ranging investigation for the in-fire performance of such composite structures has highlighted various local instabilities that are deemed to likely govern the overall flexural performance of the structures.

Context of Research

❑Analogous to the ULS, the capacity of shear connectors in fire is also required to maintain the function without the premature brittle failure. However, it would be ideal to tolerate against an occurrence of local buckling and a mechanism transition.

❑The capacity of stud shear connector embedded in a solid slab was first evaluated by Ollgaard, Slutter and fisher. By the empirical method, an assessment formula of the strength is proposed with an upper limit equal to the tensile strength of the stud, as a function of the stud area and concrete properties.

$$Q_u = 0.5A_{sc}\sqrt{f_{ck}E_c} \le A_{sc}f_u \qquad (1)$$

where A_{sc} is the cross-sectional area of the stud shear connector

f_{ck} is the cylinder compressive strength of the concrete ($= 4730\sqrt{f_{ck}}$)

E_c is the modulus of elasticity of concrete

f_u is the ultimate tensile strength of the stud material

❑Eq. 1 is included in AISC and CSA codes for a fundamental formula to assess the stud strength. In Eurocode 4 Part1.1, the strength of headed studs in solid slabs is based on the simplified model that a stud fails either in the concrete alone (height / diameter of stud > 4) or in the steel alone as follows.

$$Q_u = 0.37A_{sc}\sqrt{f_{ck}E_c} \le 0.8A_{sc}f_u \qquad (2)$$

❑Stark et al determined the coefficient of 0.37 used in Eq. 2 by means of a statistical study, and the upper limit is taken as 80% of the tensile strength of the stud.

❑Zhao and Kruppa conducted experiments to determine the shear capacity of headed studs and angled connectors, subject to the standard ISO fire, in conjunction with solid and composite slabs with profiled sheets. The strength of headed stud at elevated temperatures must be assessed using an absolute 20% strength reduction and that the strength retention of steel in relation to the ultimate tensile strength is:

$$Q_{u\theta} = 0.8(0.8A_{sc}f_u)SRF_{u\theta} \qquad (3)$$

where SRF_{u}❑ is the strength retention at ❑ °C with respect to the ultimate tensile strength

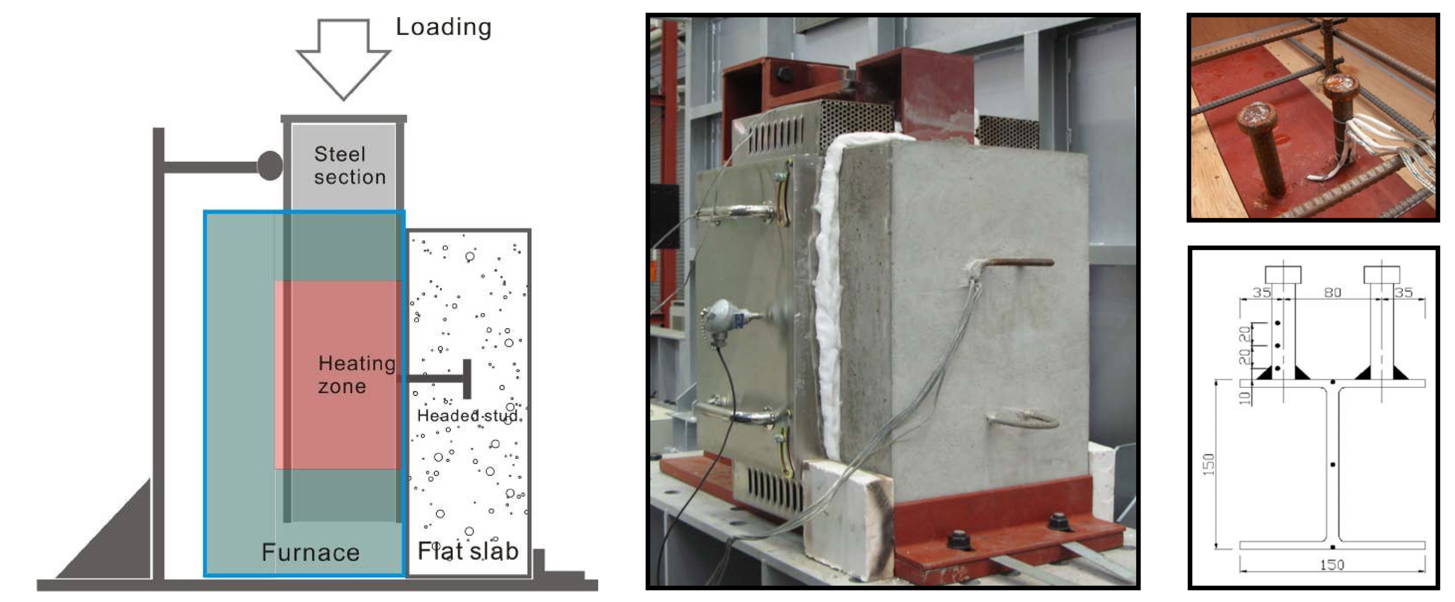
❑Eq. 3 is adapted in Eurocode 4 Part 1.2 as verification of the shear resistance of stud in fire and, whilst concrete crushing failure at elevated temperatures is also considered in the code.

Experimental Programs

❑One side of the solid concrete block in the standard push-out specimen was replaced by an electric furnace to provide a 3-sided fire exposure to the steel member. (Figs. 1a & 1b)

❑A vertical loading was applied downward from the top of the steel section and the relative displacements were measured from the top of the steel section to the top of concrete slab.

❑Lateral movements of the slab base and top of the steel section were restrained. Under the boundary condition, the development of uplift forces in the connectors may be limited.

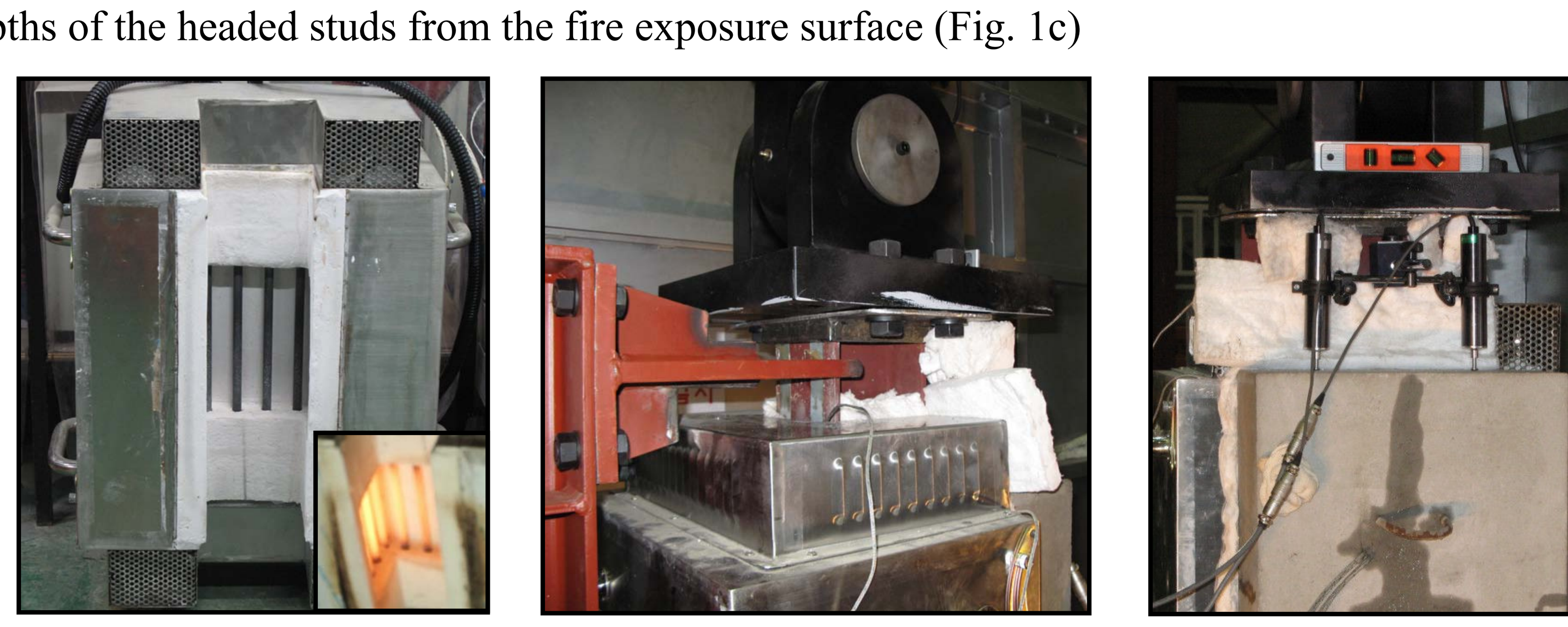


(a) Schematic drawing of the modified push-out test (b) Instrumentation arrangements (c) Locations of thermocouples (•)

Fig. 1. Modified push-out tests in fire and specimen

❑The specimen consists of a 650 mm length of S355 steel section (150×150×30 UC) connected to a C30 flat concrete slab (400 mm width × 150 mm depth × 500 mm height), using two headed studs of 19 mm diameter × 100 mm depth. (greasing the steel flanges before casting the slab)

❑K-type thermocouples location : flanges and web in the steel section and 10 mm, 30mm and 50 mm depths of the headed studs from the fire exposure surface (Fig. 1c)



(a) Electric furnace for the test (b) Upper part of full installation (c) LVDT for slip measuring

Fig. 2. Heating, loading and measuring facilities for the fire tests

Fire Tests and Results

❑Characteristic properties of the materials are shown in Table 1.

❑Loading was imposed until collapse, at room temperatures (20❑), 30 and 60 minutes after the standard ISO fire.

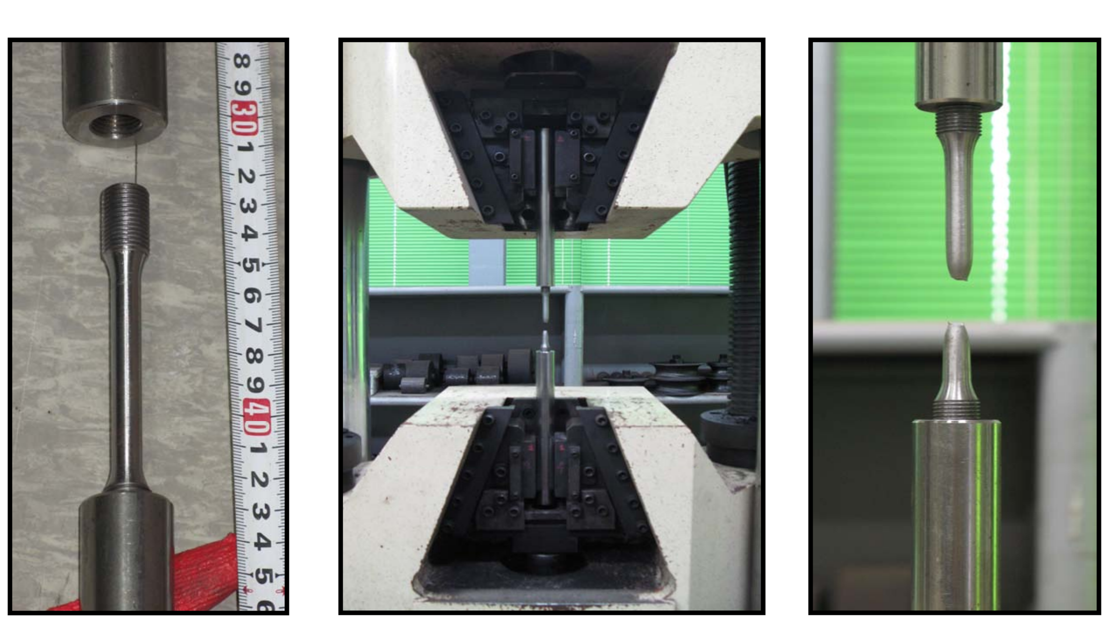


Fig. 3. Material test for headed stud

Table 1. Properties of Steel and Concrete

	Yield Strength	Tensile Strength	Elongation
Shear Stud (Ø19)	349 MPa	427 MPa	25 %
H-beam	322 MPa	452 MPa	33 %

Slump	W/C	S/a	Unit Weight	Design Strength
18cm	34 %	41 %	2415 kg/m^3	28 MPa

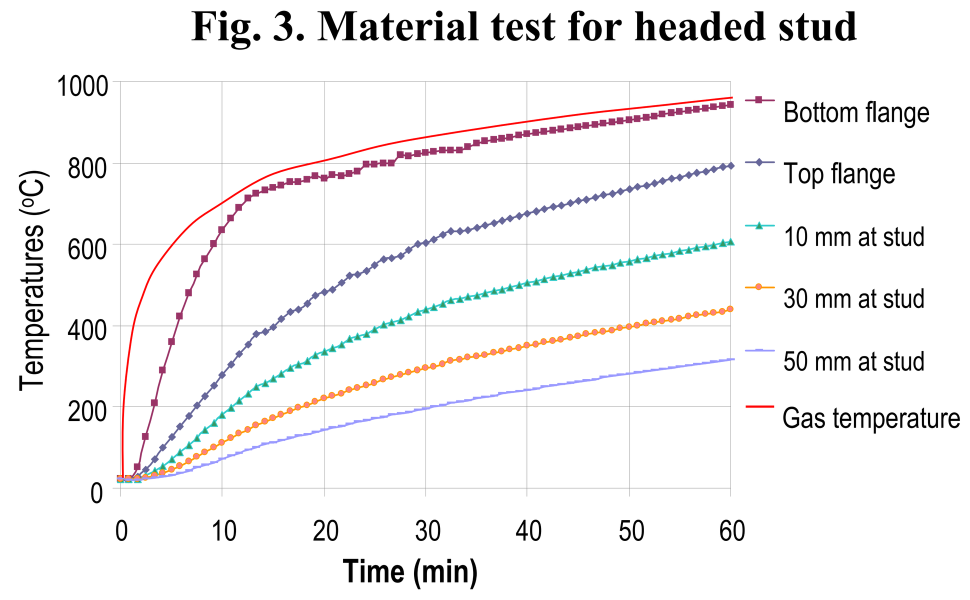


Fig. 4. Temperature-time curves in steel and stud connector for standard fire

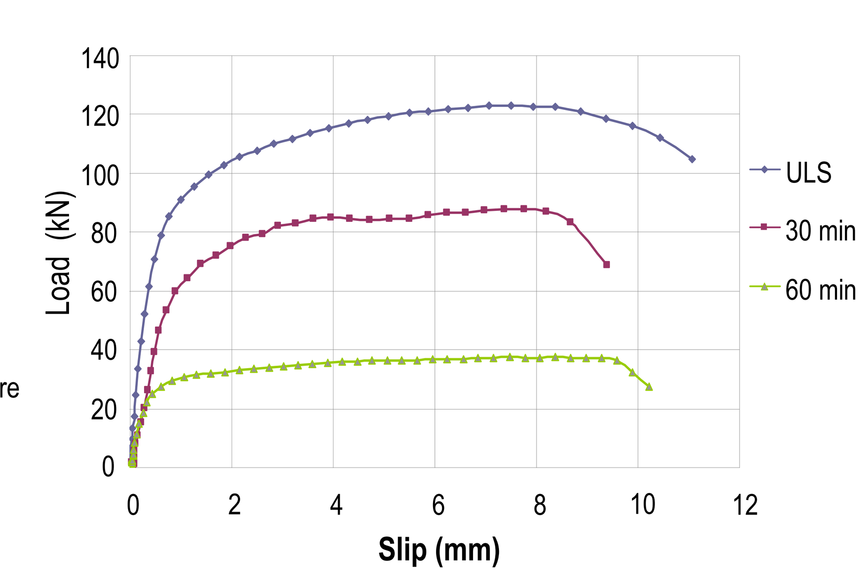


Fig. 5. Load-slip curves for stud connectors at elevated temperatures

❑In order to establish the shear capacity of the headed stud subjected to the standard ISO fire, the temperature developments of the specimen were obtained for the duration of the tests. (Figure 4)

❑The temperature difference between the 10 mm and mid-depth (50 mm) reference points was in excess of 200 °C within 30 minutes of the standard fire and approximately 300 °C at 60 minutes.

❑As the temperature rise at 10 mm was over 400 °C at 30 minutes, a corresponding and significant reduction of strength was seen in this area. The collar area of the shank will experience the highest levels of the strength reduction due to the temperature increase.

❑The load-slip relationship for stud shear connectors was monitored at ultimate limit state, 30 and 60 minutes of the standard ISO fire; the relationship per stud is plotted in Figure 5. At a slip of 5 mm, the ultimate capacity of the stud was measured to be 120 kN at 0 minutes, 85.0 kN at 30 minutes and 38.0 kN at 60 minutes respectively.

Analysis of Results

❑By modifying Eq. 1 an equation can be proposed to evaluate the stud strength at high temperatures.

$$Q_{u\theta} = A_{sc}f_u SRF_{u\theta} \qquad (4)$$

❑The strength of the stud at ULS (121 kN by Eq. 1) shows very good agreement with the test result (120 kN) at ULS. Using Eq. 4, the residual strength of the studs at 30 and 60 minutes in fire is calculated as 88.7 kN and 45.0 kN respectively, which also demonstrates excellent agreement with the experimental results of 85.0 kN and 38.0 kN, respectively.

❑Failure mechanism of the stud, for crushing of the concrete surrounding the connector and connectors shearing off at the base are similar, interaction of the failure modes occurred at ultimate limit state.

❑ At elevated temperatures, shear failure was consistently occurred at the weld-collar/shank interface. (Figure 6)

❑At the weld-collar/shank interface : (1) a concentration of high stress occurs in the push-out tests and (2) a higher temperature rise develops in the area due to the heat flux through the top flange of steel.

❑ In comparison with the research of Zhao and Kruppa, the observed failure mode of the headed studs in fire is generally alike, but higher strength was recorded due to the lateral restrain at the bottom of the slab.

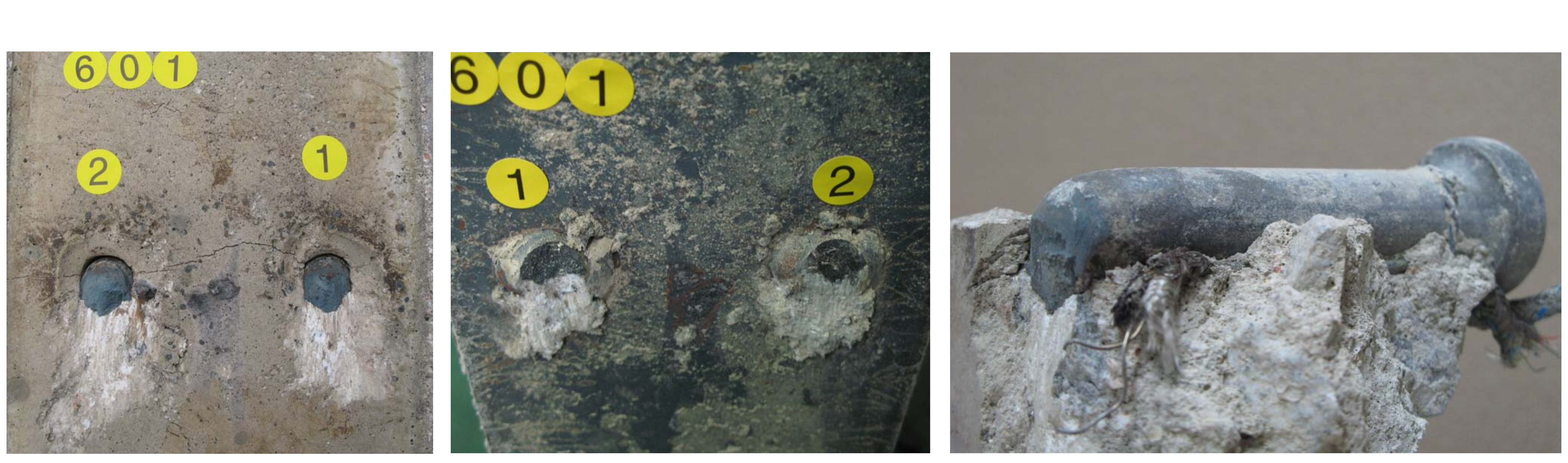


Fig. 6. Failure of stud shear connector after push-out test at 60 minutes of the standard fire

Conclusions

❑This pilot project was designed to investigate the capacity of headed shear stud at elevated temperatures through the use of a modified push-out test with a solid concrete slab. An electric furnace attached to the test assembly provided three-sided fire exposure to the specimen.

❑At room temperature, 30 and 60 minutes of the standard ISO fire, tests were conducted to identify the strength retention properties of the studs. Temperature developments were measured across the steel section and along the stud shank.

❑The headed studs failed at elevated temperatures due to shear of the weld-collar/shank interface. An equation was proposed to allow assessment of the residual strength of the stud in fire and this demonstrated a very good agreement with the test results.