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SHEAR STRENGTH OF CONCRETE AT ELEVATED TEMPERATURE

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INTRODUCTION

Performance based methods for designing concrete structures in fire have focused to date upon the flexural performance of beam and slab elements and large displacement mechanisms for sustained load capacity at high temperature. Shear failure has received little attention, but there is a growing awareness that shear can govern the failure of concrete structures in fire, for example in punching shear (Bamonte *et al.*, 2009) or as a consequence of restrained thermal expansion (Faria *et al.*, 2010).

Shear is carried in reinforced concrete through the interaction of (Regan, 1993)

- compressive force paths within the concrete;
- tensile crack bridging by the reinforcing steel (relying upon concrete-steel bond);
- dowel action in the reinforcing steel; and
- friction across cracked surfaces due to aggregate interlock.

Modelling the complex interplay of these shear-carrying mechanisms is notoriously difficult, even at ambient temperatures. Accurate finite element modelling requires a very detailed representation of the load carrying phenomena and their constitutive responses (Kotsovos & Pavlović, 1995). Whilst we have understanding of how (for example) the compressive strength of concrete and the tensile strength of steel are affected by elevated temperature (e.g. Khoury, 2000; Zhang *et al.*, 2000), there is currently insufficient elevated temperature understanding of the shear mechanisms and their interaction to allow reliable finite element modelling of concrete in shear in fire.

This paper describes an investigation of the effect of elevated temperature upon the shear performance of concrete. It is a first step in determining detailed constitutive information that can be used in modelling and design.

1 EXPERIMENTAL PROGRAMME

A series of shear blocks were constructed and tested, which are shown in Fig. 1. These were similar in concept to the shear blocks tested by Mattock (Mattock & Hawkins, 1972), but a modified geometry was adopted, based upon that used by Ali *et al.* (2008).

Shear blocks are designed to load a reinforced concrete section in pure shear, and hence fail along by cracking along the central shear plane (Fig. 1). The behaviour of this crack is characterised by aggregate interlock action and reinforcement bridging, and is particularly relevant to the shear failure of columns where aggregate interlock is mobilised due to the confinement provided by the axial force in the column.

The shear blocks were heated so as to expose the concrete to temperatures that are known to affect the properties of concrete. Residual strength tests were conducted on the specimens after cooling. (The second phase of these tests will involve strength tests whilst at elevated temperature).

1.1 Specimen Construction and Conditioning

Sixteen shear block specimens were cast. The specimens had dimensions 100×160×320mm, which was governed by the physical size and the thermal mass that could be effectively heated. The specimens were reinforced with 6 mm diameter smooth steel bars with an ambient yield strength of 415 MPa (Fig. 2). Four pieces of reinforcement crossed the shear failure plane, with additional reinforcement to provide anchorage and to prevent failure of the concrete away from the shear plane.

The concrete was provided by a local readymix supplier, with a maximum aggregate size of 10mm, an ambient compressive strength of f_c = 29 MPa (based upon cube tests), and an ambient tensile strength of f_t = 1.8 MPa (based upon split-cylinder tests).

After removal from the moulds, the specimens were cured in a water tank for one week, followed by seven weeks in a low humidity environment, controlled by a dehumidifier. To reduce the moisture content of the specimens and hence minimise the likelihood of spalling, the specimens were pre-dried at 90°C for seven days. Two standard 100mm cylinders specimens were cast for each shear block, and these were conditioned in the same way.

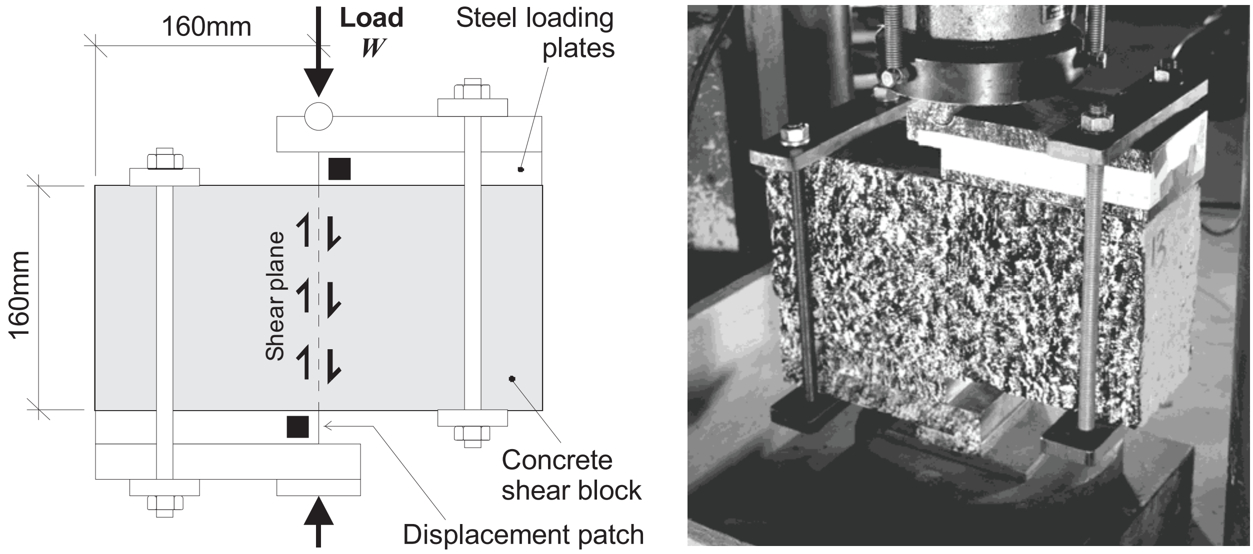

Fig.1 Overview of the shear block test arrangement

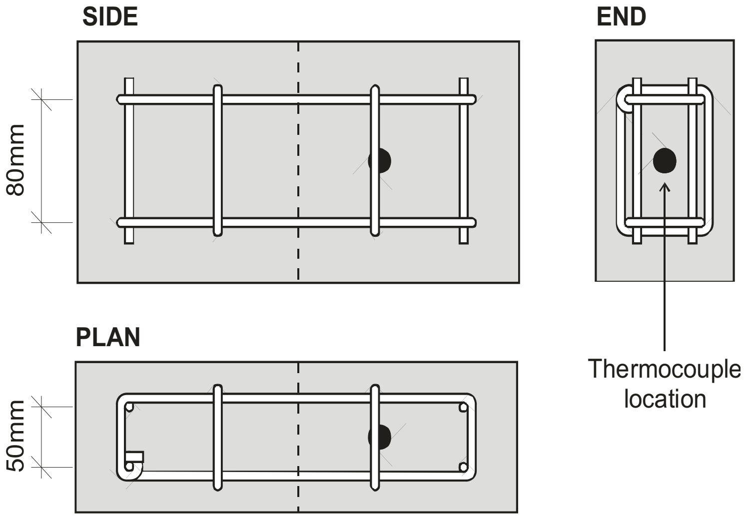

Fig.2 Details of the shear block reinforcement

1.2 Heating regime

The specimens were heated in an electric furnace, which could accommodate one shear block and two cylinders at a time. They were heated to temperatures of 112°C, 188°C, 390°C, 475°C and 622°C, as shown in Tab. 1. Another set of specimens was unheated (17°C).

Tab. 1 Specimen Test Programme and Key Results

Specimen ID	Heating duration [mins]	Target internal temperature [°C]	Achieved peak internal temperature [°C]	Compressive concrete strength [N/mm^2]	Tensile concrete strength [N/mm^2]	Shear failure load [kN]	Shear failure stress [N/mm^2]	Frictional shear stress [N/mm^2]
17-1	-	17	17.2	25.1	4.1	100.5	6.3	-
17-2			17.0			93.7	5.9	-
17-3			17.1			110.5	6.9	3.5
17-4			17.5			119.2	7.5	2.6
112-1	120	112	102.7	26.9	3.7	103.5	6.5	2.9
112-2			109.2			97.5	6.1	3.9
112-3			122.6			102.0	6.4	2.7
188-1	120	188	178.1	27.8	3.9	93.0	5.8	2.4
188-2			191.2			88.5	5.5	3.6
188-3			196.1			106.3	6.6	3.3
390-1	120	390	379.9	19.3	2.5	91.0	5.7	1.9
390-2			399.8			95.0	5.9	3.3
475-1	120	475	464.1	17.5	2.2	79.8	5.0	-
475-2			486.5			81.8	5.1	1.5
622-1	165	622	619.9	12.6	1.8	71.8	4.5	1.8
622-2			624.4			67.9	4.2	1.8

A thermocouple was placed at the centre of the shear block (Fig. 2) to record the internal temperature, and a second thermocouple was used to record the furnace temperature. The furnace was used to heat the specimens as quickly as possible, with an oven temperature increase rate in the range 5 and 15ºC/min. After the initial heating, the furnace was controlled manually to achieve the required temperature inside the concrete. All specimens were heated for 2 hours, except for those at the highest temperature, for which it was necessary to increase the heating duration to 2 ¾ hours.

After heating, the specimens were left in the furnace to cool, and then each specimen was left for seven days before its strength was determined.

1.3 Strength tests

Steel loading plates were added to the shear block to force shear failure, as shown in Fig. 1. The specimens were loaded using a hydraulic universal test machine at an initial rate of 20 kN/min, with the applied load recorded using a load cell.

Digital image correlation was used to obtain the specimen displacements from a sequence of 21 megapixel photographs taken at a frequency of 0.2 Hz. The specimens were painted with a high-contrast speckle pattern prior to testing, and a bespoke image-processing algorithm was used to track the motion of selected patches of the speckle pattern from image to image (Bisby & Take, 2009). Digital image correlation was chosen rather than a traditional displacement measurement technique because it allows the positions at which displacements are measured to be selected after the test; allows relative displacements to be measured within the concrete (hence avoiding the effects of local crushing at the supports); allows both the shear displacement and crack opening displacement to be measured across the cracked surface; and allows any variations in displacement along the crack surface to be observed. The resolution of digital image correlation for this application was in the order of 0.006 mm

A cylinder compression and split-cylinder tension test (conducted to EN 12390) accompanied each shear block test.

2 EXPERIMENTAL RESULTS

Tab.1 provides a summary of the key experimental results.

2.1 Heating regime

Fig. 3 shows the temperatures recorded within the concrete shear blocks and the corresponding temperatures in the furnace. The peak temperatures within each specimen are given in Tab. 1.

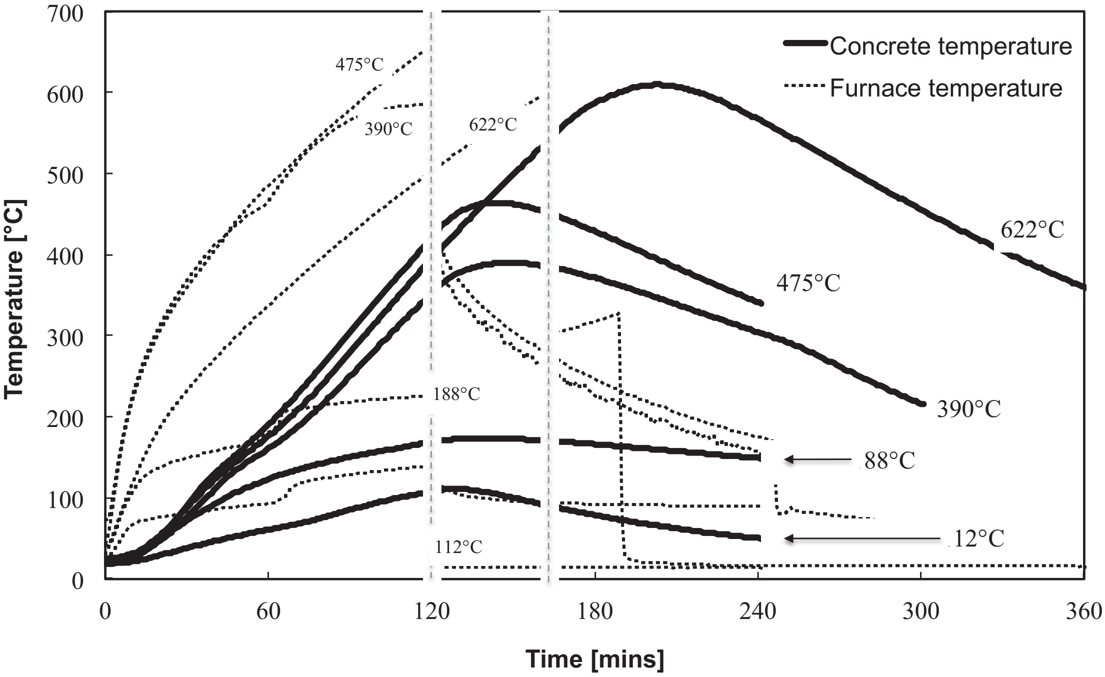

Fig. 3 Recorded temperatures in the furnace and within the concrete blocks

2.2 Strength variation with temperature

Fig. 4 plots the variation in compressive and tensile strengths of the concrete that were obtained from the cylinders that were heated at the same time as the shear blocks. For clarity, these have been normalised by the ambient temperature strength of the concrete, and the average strength variation with temperature is shown. The reduction in concrete strength with temperature is as expected, but it should be noted that some of the specimens suffered from poor compaction.

Fig. 4 also plots the variation in the shear strength of the shear blocks with temperature. The shear strength follows a similar trend to the concrete strength variation. However, the reduction in shear strength is less pronounced at high temperatures, because it is dependent upon the strengths of both the concrete and steel.

2.3 Load-displacement and crack opening width responses

Fig. 5 shows the load versus shear displacement measured across the crack. For clarity, one load-displacement response has been plotted for each temperature; these were chosen to be a good representation of the full set of results; other responses were similar.

The load-deflection response of the shear blocks has an initial peak load, at which point the shear crack fully forms and the shear capacity drops to a frictional value that is governed by aggregate interlock, confinement by the reinforcement, and reinforcement dowel action. The initial stiffness and the peak strength of the specimen reduced with temperature, whereas the displacement corresponding to the peak strength increased with temperature.

The post-peak frictional shear strength was also affected by temperature, with two clear groups apparent: the lowest three temperatures carried a frictional shear of 50 kN; the highest three temperatures carried a frictional shear of 25 kN. At the three lower temperatures, diagonal tension cracks initially formed at an angle to shear plane, which coalesced into a single shear crack. The reinforcement sheared across the crack, and caused some separation of the cover concrete.

At the three higher temperatures, the straight shear crack formed immediately. Cover concrete bursting was far more extensive, and this allowed the reinforcement to debond and reduced confinement of the shear crack. The aggregate could also be heard to "snap" during the higher temperature residual tests. Consequently, the performance of the shear blocks was governed by a combination of the residual strength of the concrete, the residual strength of the reinforcement and the complex interaction between the two.

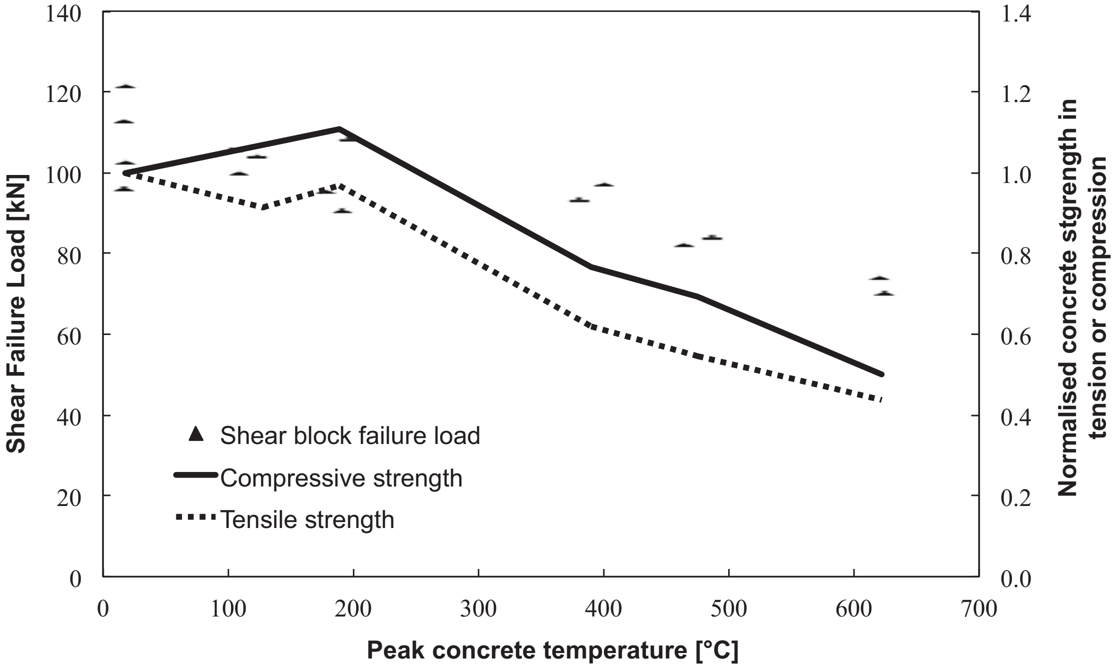

Fig. 4 The effect of temperature upon the residual strength of the shear block, and upon the residual compressive and tensile strengths of the concrete.

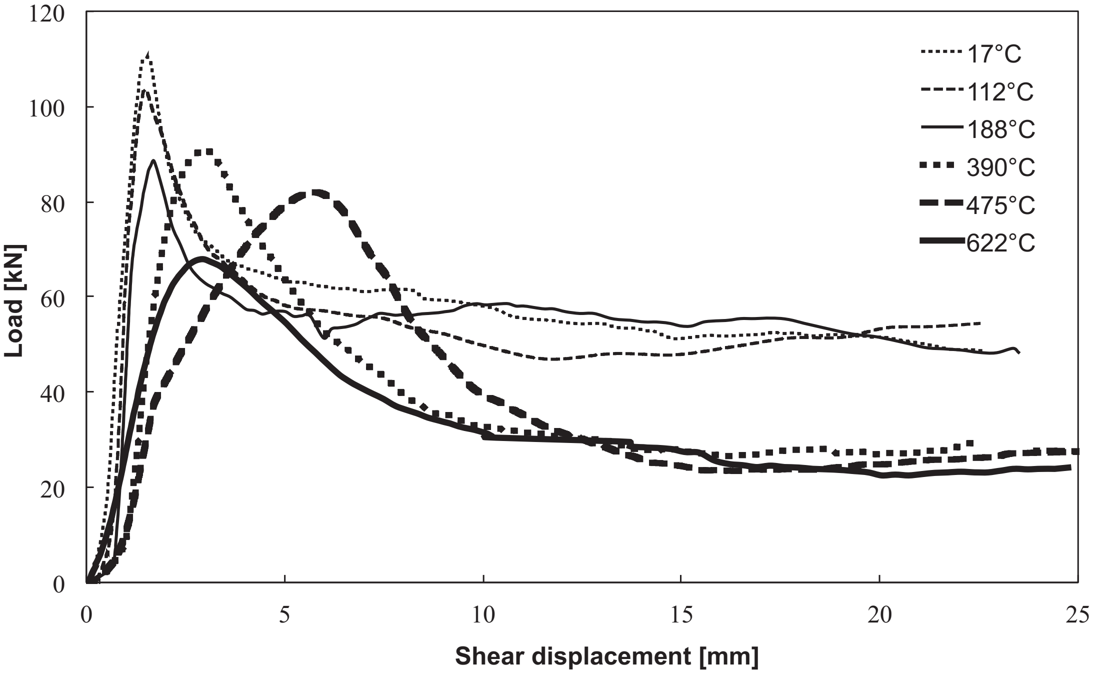

Fig. 5 The effect of temperature on the residual load-displacement response of the shear blocks

Digital image correlation was used to determine the crack opening widths that developed as the load was applied, and these are plotted in Fig. 6. Again, the response is split into two groups, with the three higher temperatures characterised by larger crack opening displacements, even prior to the peak load being reached.

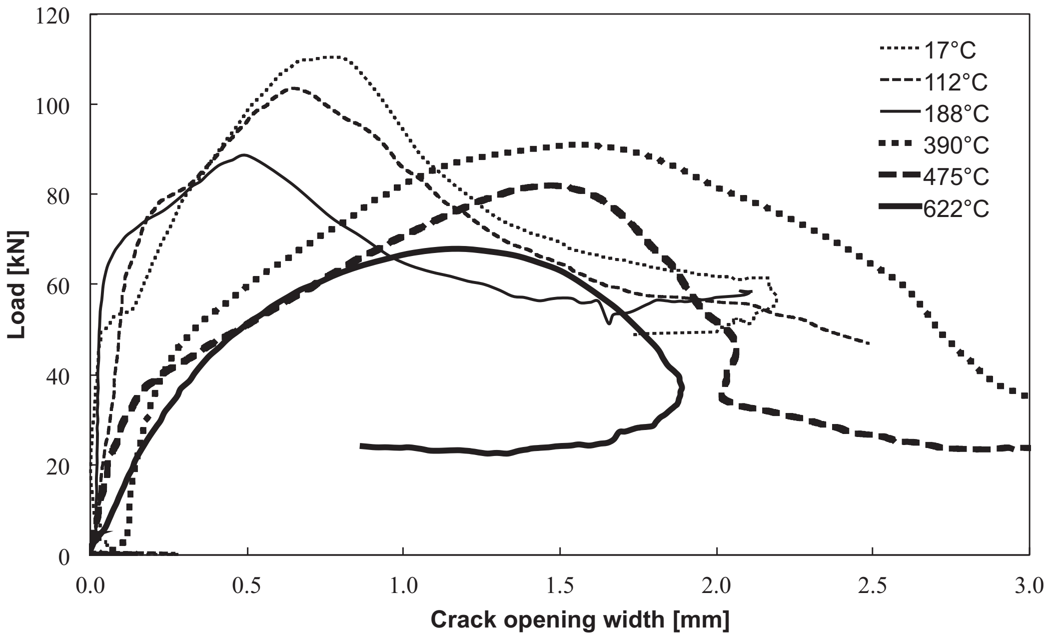

Fig. 6 The effect of temperature on crack opening width development.

3 SUMMARY

The results presented in this paper demonstrate that the residual shear strength of reinforced concrete is affected by the temperature to which is has been exposed. The reduction in shear performance depends upon the interaction of the concrete and the reinforcing steel. For example, the tests have shown that concrete exposed to high temperatures suffers from increased cover separation (due to the reduced tensile strength), which allows greater reinforcement debonding and hence less confinement, which in turn mobilise less aggregate interlock shear.

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