Shear transfer capacity of reinforced concrete exposed to fire

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Abstract. Shear transfer capacity of reinforced concrete elements is a function of concrete compressive strength and reinforcement yield strength. Exposure of concrete and steel to elevated temperature reduces their mechanical properties resulting in reduced shear transfer capacity of RC elements. The objective of present study is to find the effect of elevated temperature on shear transfer capacity of reinforced concrete. For this purpose pushoff specimens were casted using normal strength concrete. After curing, specimens were heated to 250°C and 500°C in an electric furnace. Cooled specimens were tested for shear transfer capacity in a universal testing machine. It was found that shear transfer capacity and stiffness (slope of load-slip curve) were reduced when the specimens were heated to 250°C and 500°C. Load level for the initiation of crack slip was found to be decreased as the temperature was increased. A simple analytical approach is also proposed to predict the shear transfer capacity of reinforced concrete after elevated temperature.

1. Introduction
Shear can be transferred across an interface between two members that can slip relative to one another by the mechanism of “shear friction” also known as “shear transfer capacity” [1]. Since 1960, numerous studies [1-9] have been done to investigate the shear transfer behaviour of concrete at room temperature. All these studies have shown that aggregate interlock is the primary source of shear transfer capacity. The aggregate interlock mainly depends upon the concrete compressive strength and crack width. Increase in crack width and decrease in compressive strength reduces aggregate interlock [10].

When concrete is exposed to elevated temperature, cement paste shrinks and aggregate expands which results in the weakening of bond between aggregate and cement paste resulting in reduction of concrete compressive strength [11]. Also, concrete is a poor conductor of heat due to which thermal gradient is developed, causing concrete to crack [12]. Therefore, exposure of concrete to elevated temperature will result in decrease of aggregate interlock hence, decreasing shear transfer capacity. The data available in literature about the effect of elevated temperature on shear transfer capacity of reinforced concrete is very limited [13] and no attempt has been made to predict it through analytical solutions. In this study, effect of elevated temperature on shear transfer capacity of reinforced concrete is investigated. Also a simple analytical approach is proposed to predict the shear transfer capacity of reinforced concrete after elevated temperature.
2. Experimental programme

2.1 Materials
Portland cement, 43 grade confirming to IS: 8112-1989 [14] was used. River sand with a fineness modulus 2.7 was used as fine aggregate. Calcareous aggregate with a maximum size of 12.5 mm was used. Mix proportions of the NSC are given in table 1.

|          | Cement (kg/m³) | Sand (kg/m³) | Coarse aggregate (kg/m³) | Water (kg/m³) | Superplasticizer (%) |
|----------|---------------|--------------|--------------------------|---------------|----------------------|
|          | 400           | 800          | 1004                     | 168           | 0.8                  |

2.2 Specimen preparation
Pushoff specimen size was 150 x 300 x 450 mm³ as shown in figure 1. Area of shear plane was 31,500 mm² (210 mm x 150 mm). Three closed stirrups of 8 mm diameter yielding a reinforcement ratio \( \rho_v \) of 0.96% were used. Yield strength of the stirrups was 500 MPa at room temperature \( \rho_v f_y = 4.57 \) MPa. Six bars of 12 mm diameter were used parallel to shear plane as longitudinal reinforcement. A k-type thermocouple was installed at the mid-depth of each specimen to record the temperature. Cylinders were also casted with each specimen to determine the compressive strength of concrete. After 24 hrs specimens were demoulded and transferred to curing tank. After 28 d curing specimens were removed from curing tanks and were dried at room temperature.

2.3 Heating of specimens
Dried specimens were heated in an electric furnace at a rate of 5°C/min. Once the target temperature (250°C and 500°C) of furnace is reached, the temperature was kept constant until the temperature of furnace and the three thermocouples becomes equal. Then the specimens were allowed to cool naturally upto room temperature by opening the door of the furnace.

2.4 Pushoff test
Pushoff tests were conducted in a universal testing machine of 1000 kN capacity. Specimens were placed on a knife edge and a roller to facilitate horizontal movement. Linear variable displacement transducer (LVDT) was used to measure the crack slip. Load was applied in a displacement control mode at the rate of 0.1 mm/min. After each second the data was recorded in a computerized data acquisition system.
3. Results and discussion

3.1 Thermal response

As described earlier, a thermocouple measured temperature at the mid-depth of the specimen. Temperature development in the specimens is shown in figure 2.

Thermal convection and thermal radiation are directly proportional to the difference in the temperature of furnace wall and the specimen surface [15]. In the beginning this difference in temperature of furnace wall and the specimen surface is small; therefore, temperature increased slowly up to 110 min of heating. After 110 min, temperature increased rapidly because the difference between the temperature of furnace wall and specimen surface increased and the corresponding thermal convection and thermal radiation increased. At about 85°C specimens released water vapour which was seen through the vent hole provided in the door of furnace. No surface spalling was observed in
the specimens, but cracks were detected on the specimen surface. After elevated temperature test, colour of the specimens was bleached.

3.2 Load-crack slip response
Ultimate shear load ($P_u$), ultimate shear transfer capacity ($v_u$), residual shear transfer capacity ($v_r$) and crack slip ($s_u$) at ultimate shear load are given in Table 2. Load-slip responses of the different specimens are shown in Fig.3. Initial cracks were detected at loads about 50 to 75% of the ultimate shear transfer capacity. The cracks were about 2.5 to 5 cm long, oriented diagonally about 15 to 45 degrees to the shear plane. The initial joint failure initiated from a vertical crack joining the diagonal cracks near the shear plane. Post initial joint fracture, the load decreased to a nearly constant residual capacity.

Table 2. Test results of push-off specimens

| Specimen | Temperature (°C) | $f_c'$ (MPa) | $\rho f_y$ (MPa) | $P_u$ (kN) | $v_u$ (MPa) | $v_r$ (MPa) | $s_u$ (mm) |
|----------|------------------|-------------|----------------|----------|-----------|-----------|----------|
| P-25     | 25               | 39.5        | 4.57           | 315.20   | 10        | 5.96      | 0.75     |
| P-250    | 250              | 39.5        | 4.57           | 300.30   | 9.52      | 5.74      | 0.80     |
| P-500    | 500              | 39.5        | 4.57           | 230.70   | 7.32      | 5.58      | 0.89     |

Increase in temperature reduced the ultimate shear transfer capacity of the specimens. Exposure of pushoff specimens to 250°C and 500°C reduced their shear transfer capacity by 4.72% and 26.80%, respectively. Elevated temperature did not affect the residual shear transfer capacity of the pushoff specimens. Slope of ascending branch of the load-crack slip curve reduces after exposure to elevated temperature, which is an indication of the reduction of stiffness. The initiation of crack slip started at the lower load levels after exposure to elevated temperature. For unheated specimen crack slip started at 92 kN. After exposing the specimens to 250°C and 500°C, crack slip started at 74 kN and 44 kN respectively.

Figure 3. Load-crack slip of pushoff specimens
### 3.3 Analytical approach to predict shear transfer capacity of reinforced concrete after elevated temperature

Several equations are proposed in the literature to calculate the shear transfer capacity of reinforced concrete [3-8]. General form of these equations is

\[ v_u = c + \mu \rho f_y \]  

where, \( v_u \) is the ultimate shear transfer strength, \( c \) is cohesion, \( \rho f_y \) is reinforcement index and \( \mu \) is the coefficient of friction between crack faces. Based on statistical evaluations, researchers proposed different values for ‘c’ and ‘\( \mu \)’. Equation proposed by Kahn and Mitchell (2002) [6] gives simple, accurate and conservative prediction of shear transfer capacity for a wide range of concrete strength. The equation includes a value of 1.4 for frictional component (\( \mu = 1.4 \)) and 0.05\( f_c' \) for the component of bond and asperity shear.

\[ v_u = 0.05f_c' + 1.4 \rho f_y \]  

For predicting the shear transfer capacity of reinforced concrete after elevated temperature, compressive strength of concrete at ambient temperature (\( f_c' \)) is replaced by its residual compressive strength (\( f_{cr}' \)) after elevated temperature in Eqn. 2. Residual concrete compressive strength is calculated by the equation proposed by Chang et al. (2006) [16].

\[ \frac{f_{cr}'}{f_c'} = 1.01 - 0.00055T, \quad 20^\circ C < T < 200^\circ C \]  
\[ \frac{f_{cr}'}{f_c'} = 1.15 - 0.00125T, \quad 200^\circ C \leq T \leq 800^\circ C \]

Shear transfer capacity predicted using the equations of Kahn and Mitchell (2002) and Chang et al. (2006) for different temperatures are shown in figure 4. Predicted results are in good agreement with the experimental results. Error in prediction of shear transfer capacity of reinforced concrete specimens after 250°C and 500°C are only 12% and 2%, respectively.

**Figure 4.** Experimental and predicted shear transfer capacity after elevated temperature
4. Conclusions

- Stiffness of load-crack slip response and ultimate shear transfer capacity of reinforced concrete reduced after exposure to elevated temperature.
- Exposure of reinforced concrete to elevated temperature up to 500°C did not affect its residual shear transfer capacity.
- Load required for the initiation of crack slip decreased as the exposure temperature was increased.
- Available equations for shear transfer capacity at ambient temperature along with the equation for residual compressive strength of concrete can predict the shear transfer capacity of reinforced concrete after elevated temperature.

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