The effect of load induced thermal strain on flat slab behaviour at elevated temperatures

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1. Abstract

Several recent sets of experimental results on the punching shear behaviour of flat slabs in fire have produced apparently anomalous deflections results, where the slab deflections on heating are in the opposite direction to that expected if arising from free thermal expansion. Using numerical analysis, this paper shows that the results are explained by load induced thermal strains (LITS). Using two independent modelling approaches, the profound effect of LITS on deflection behaviour is demonstrated. The findings have implications for the design of flat-slab structures to resist fire because ignoring LITS may result in non-conservative design predictions.

2. Introduction

Flat plate concrete structures are an economical type of building commonly used for offices and similar structures. They are easy to construct, offer flexible column arrangements and are relatively cheap to build. However, they are susceptible to a type of failure known as “punching shear” (Figure 1), where columns pierce floor slabs, leading to collapse. This is a particularly dangerous type of failure as it is brittle and occurs suddenly. Punching shear occurring at high temperatures, such as in fire, is a concern [1]. This condition has been studied experimentally, but to date, there has been a little numerical investigation of the topic. This paper presents a numerical study of the mechanics of punching shear failure at elevated temperatures, with a focus on the role of load induced thermal strain (LITS), which is shown to explain some apparently anomalous experimental results.

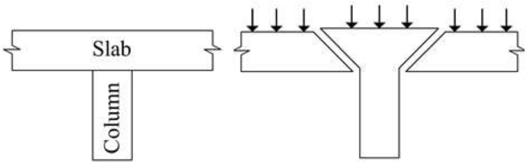


Figure 1 Schematic diagram of a flat plate structure and the punching shear failure mechanism.

After the car park collapse in Gretzenbach, Switzerland in 2004 due to fire [1], various experimental studies investigated punching shear in heated slabs. These included Salem et al. [2], Liao et al. [3] and Smith et al. [4–7]. All these studies took a similar approach of testing a portion of the slab with a column stub attached, as indicated conceptually in Figure 2. Sometimes the slab portions were simply-supported at their edges while in other tests in-plane restraint was applied to simulate the rest of a larger structure. The gravity loading typical in real structures was simulated by imposed displacements applied to the column stubs, which caused line-load type reactions at the slab edges. After mechanical loading, heating from gas radiant panels or similar systems was applied.

In all the above tests, and most clearly documented by Smith *et al.* [4–7], the deflections of the slabs when heated was in the opposite direction to that expected by the experimentalists (Figure

2). A simple thermo-mechanical analysis suggests that when heated as described, deflections of Smith's slabs due to thermal expansion would be towards the heating source. The large thermal gradient set up in the slab leading to thermal expansion on the lower surface would be expected to result in a convex deflected shape as indicated Figure 2a. However, the observed experimental deflections were in the opposite direction, resulting in a concave shape as shown in Figure 2b.

This finding could not be explained directly by the experimental results but was in line with the work of Liao et al. [3] who observed the same effect. Kordina [8,9] also highlighted the combined effects of load and thermally induced deflections in earlier tests. It is this previously unexplained behaviour that the present study focuses on and explains using a numerical approach. It is found that a strain component seen in heated concrete called load-induced thermal strains (LITS) explains the behaviour. However, LITS is a complex and not fully understood the phenomenon that presents difficulties for numerical models. Hence, the remainder of this paper is structured as follows:

- An overview of the phenomenon of LITS;
- A presentation of the techniques used to model the experimental results of Smith with a demonstration of the importance of LITS for explaining the observed behaviour;
- A parametric study exploring the behaviour of different types of slab and heating conditions;
- Conclusion drawn from the results highlighting potential future work and design implications.

Expected deflection Experimental deflection

Figure 2 Conceptual arrangement for testing heated flat plate beam-column connections.
(a) Expected deflection response under heating and (b) Deflection response observed in Smith's tests [4–6].

3. Load Induced Thermal Strain (LITS) and Transient Thermal Strain

A key aspect of the behaviour of heated concrete is LITS, a component of total strain. LITS is a compressive strain that develops under combinations of temperature and compressive stress. The precise definition of LITS is somewhat confused in the literature [10,11]. Here we adopt the definitions used by Torelli *et al.* [11], who give the total strain, ε_{tot}, in concrete subject to both stress and heating as

$$\varepsilon_{tot} = \varepsilon_{ela,0} + \varepsilon_{th} + \varepsilon_{lits}$$

Where $\varepsilon_{ela,0}$ the elastic strain at ambient temperature, $\varepsilon_{\mathrm{th}}$ is the free thermal strain, and ε_{lits} is the LITS. LITS itself consists of several components

$$\varepsilon_{lits} = \Delta\varepsilon_{ela} + \varepsilon_{ts} + \varepsilon_{cr}$$

where $\Delta\varepsilon_{ela}$ is the change in elastic strain due to loss of elastic modulus on heating, ε_{ts} is the transient thermal strain and ε_{cr} the basic creep strain that develops during heating. Here we will not consider ε_{cr} further as it is normally a small component of LITS [12]. Transient thermal strain, the dominant portion of LITS, is largely irrecoverable (plastic) and only develops on first heating of concrete.

LITS increases with both increasing compressive stress and increasing temperature [11]. Thus, under suitable thermal and mechanical conditions, compressive LITS strains may be larger than the expansive free-thermal strain and result in an apparent thermal contraction on first heating of concrete (Figure 3), behaviour at odds with that of most materials and intuitive expectations.

Several analytical models have been proposed to represent LITS [13]. In this study, the model proposed by Anderberg and Thelandersson [14] is adopted, in which the transient thermal strain component of LITS in compression is given by:

$$\varepsilon_{ts} = -k_{tr}\frac{\sigma}{\sigma_{u0}}\varepsilon_{th} \qquad \text{for } T \leq 550\ °C$$

$$\frac{\partial \varepsilon_{ts}}{\partial T} = -0.0001\left(\frac{\sigma}{\sigma_{u0}}\right) \qquad \text{for } T > 550\ °C$$

where σ_{u0} is the compressive strength of concrete at ambient temperature and k_{tr} is a material parameter. While this model has been criticised for not fully capturing all experimental results, particularly at higher temperatures, it has the advantages of capturing general trends in behaviour and avoiding many non-physically meaningful coefficients that alternative models contain.

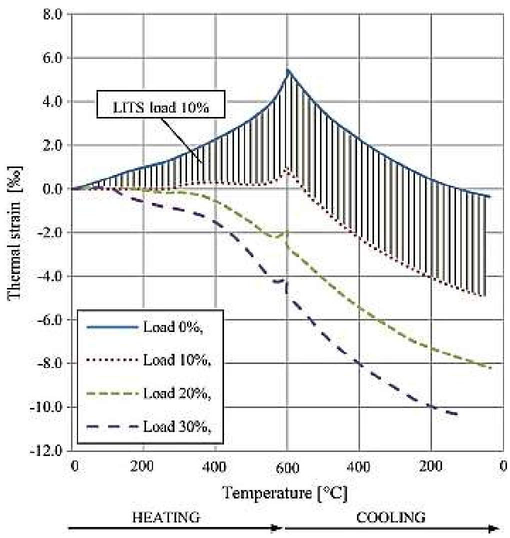


Figure 3 Typical LITS behaviour expressed as a function of temperature for different load levels. (Adapted from http://dx.doi.org/10.1016/j.engstruct.2016.08.021 under Creative Commons License).

4. Modelling Approach and Validation

The finite element package Abaqus was used in the majority of this study. To obtain a reliable modelling approach for a single column and associated area of concrete floor slab in punching shear (Figure 2), models were first developed and validated against ambient temperature experimental results provided by Salman *et al.* [15–17] for punching shear, before high-temperature effects were introduced.

Salman performed tests of a similar scale and nature to those of Smith, but with a focus on ambient temperature behaviour and these provided a comprehensive data set for model development. For validation purposes, Salman's test 1 (Figure 4 and Figure 5) was used. In this test, a concrete slab with an associated column stub was loaded to failure with the load-deflection behaviour recorded (Figure 7).

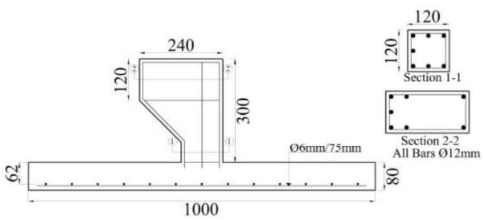


Figure 4 Dimensions and reinforcement details for Salman's test.

Figure 5 Salman’s [15] experimental setup.

This experimental setup was simulated using the finite element package Abaqus [30]. The simulations used 8-noded hexahedral solid elements with reduced integration for all concrete parts of the test specimens, together with truss (axial forces only) elements to represent the reinforcement. Full mechanical bond between the two materials was assumed [18]. Concrete was represented using the damaged plasticity model provided with Abaqus with the uniaxial compressive stress-strain relationship taken from Eurocode 2 [19]. The main parameters used for the damage plasticity model were taken from the literature [19] [20] [21] [22] and are shown in Table 1. Steel behaviour was taken from measured behaviour in coupon tests and modelled using a von Mises yield criterion.

Table 1 Concrete damge placicity parameters [19] [20] [21] [22]

Dilation Angle	**Eccentricity**	σ_{b0}/σ_{c0}	K	**Viscosity Parameter**
40°	0.1	1.16	2/3	0

The results from this modelling approach are shown in Figure 7 for two cases, firstly when a Riks solution procedure that can track softening behaviour was used and secondly when a general quasi-static solver was used. Both show an excellent comparison with the physical behaviour thus validating the modelling approach. For the high-temperature modelling work (below) the quasi-static solver was used as it can model temperature loading effectively.

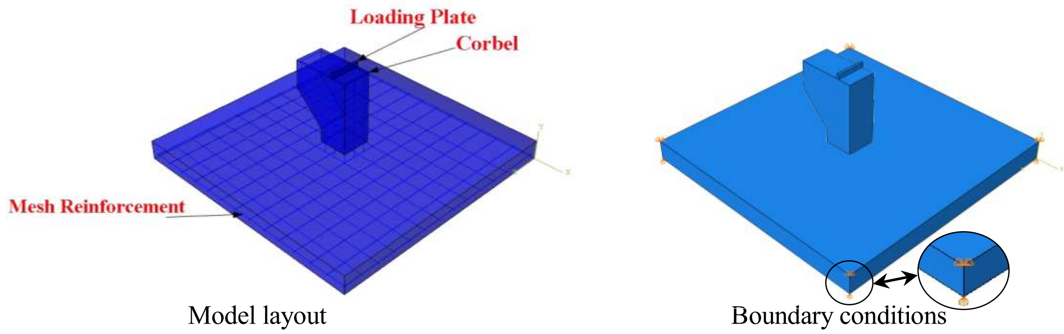


Figure 6 Finite element modelling approach used to represent Salman’s slabs.

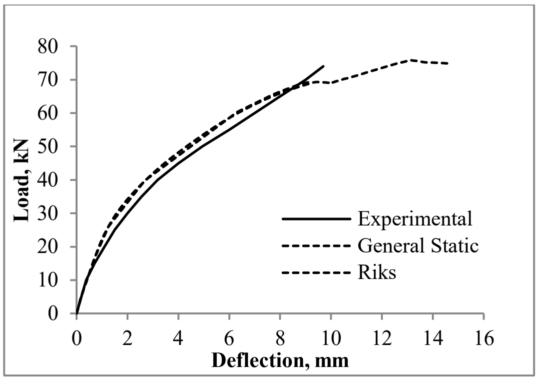


Figure 7 Load-deflection behaviour of Salman's experimental results [23] and that predicted by numerical simulations.

5. Elevated temperature modelling

The same modelling approach was then adopted to represent the high-temperature behaviour of Smith's slabs by introducing temperatures to the model in addition to the mechanical loading. This was done in two steps. First, a thermal heat transfer model was developed to generate the thermal profile for the slab. Next, this thermal profile was imported into the concrete part of the mechanical model The reinforcement was assumed unheated in the mechanical model. However this will have little effect on the results because reinforcement temperatures remain sufficiently low for neither stiffness nor strength to be significantly affected.

Concrete behaviour at high temperature depends on various quantities. In this study, the variation of Young's modulus, compressive strength, tensile strength and thermal expansion of heated concrete were all taken from Eurocode 2 ENV [24]. [25]. This (superseded) design code was used because it contains a concrete stress-strain-temperature description where no attempt to include the effects of transient thermal strain is included, which is what was required for this study (solid lines in Figure 9). The code provides a range of strains for a given normalised stresses with the lower bound of the range, not including the effects of transient thermal strain. [26,27] The current version of the code does include the effects of LITS in a crude form, so it was not used. The variation of plasticity parameters included in the concrete damage plasticity model was assumed not to vary with temperature.

For an initial study, a slab that had simple supports at all edges (no vertical movement but free to rotate) with a thickness of 75 mm was chosen (S75). Only tension reinforcement was present. Heating was provided in Smith's experiments by radiant panel heaters, with a peak surface temperature of around 380^{0}C being reached. The surface temperature in this slab was measured by Smith (

Figure 8) using thermal couples [7]. This data was used as an input to the numerical thermal analysis that then predicted temperatures at all depths within the slab through time. This thermal field was in turn introduced to the stress analysis model.

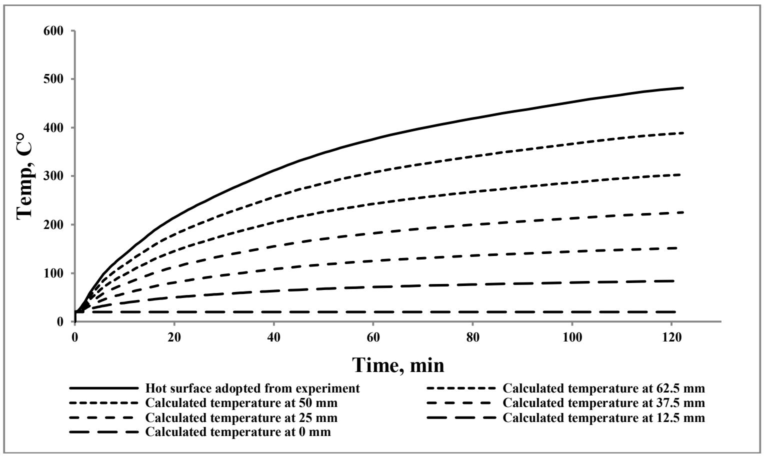


Figure 8 Temperature-time data for the heated surface adapted from Smith [7].

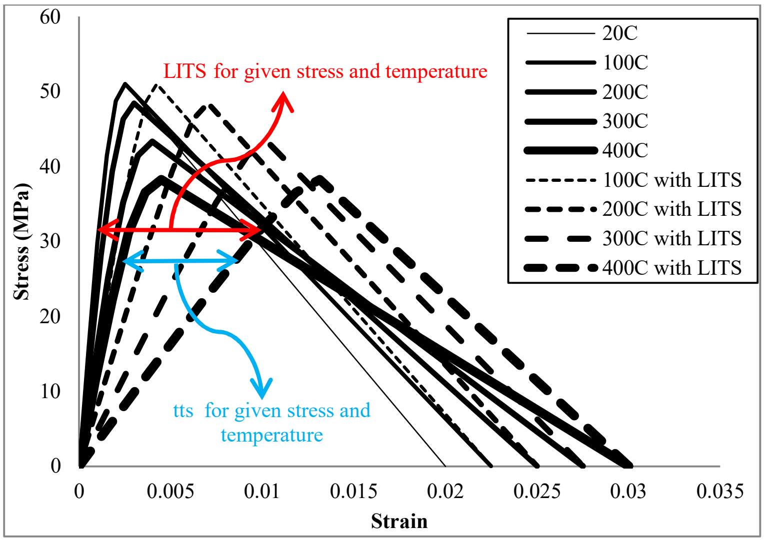


Figure 9 Stress-strain behaviour of concrete at various temperatures according to ENV (solid lines) and ENV plus transient thermal strain (tts) (dashed lines).

It was found that simply introducing elevated temperatures together with the above material properties to the ambient temperature model was not sufficient to reproduce Smith's [4–6] experimental results (Figure 10). Instead, a response as might be expected from a simple consideration of thermal expansion was seen, as in Figure 2.

Next, an additional strain component was introduced so that LITS according to Anderberg and Thelandersson [14] was captured numerically. This was done by adding transient thermal strain components to the concrete stress-strain-temperature description (dashed lines Figure 9). With this in place, the predicted deflections corresponded well with the experimental result for most of the heating period (Figure 10), highlighting clearly the important effects of LITS on the deflection response of this structure.

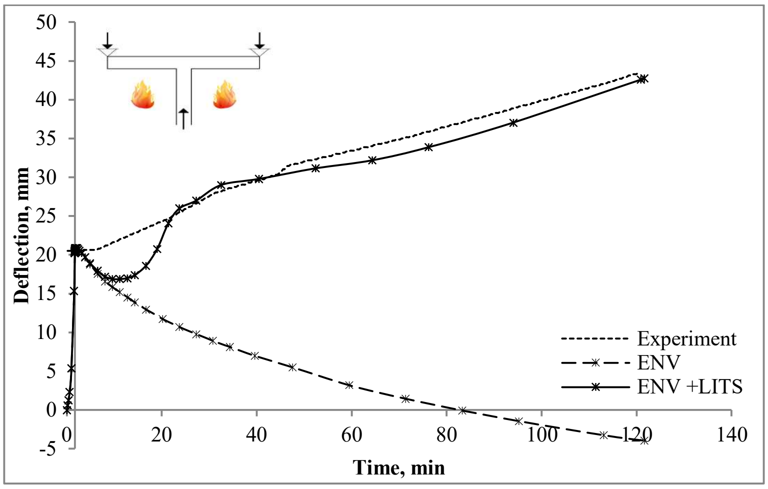


Figure 10 Deflection-time response of Smith's slab (S75), together with predicted numerical predictions for concrete models without LITS (ENV) and with LITS (ENV+LITS).

To confirm these results were not a consequence of either a particular numerical code or an anomalous experiment, another of Smith's experiments was modelled with the finite element package Code Aster. This experiment had no steel reinforcement and a 100 mm slab thickness (S100). A similar material behaviour law incorporating elasticity, thermal expansion as well as Anderberg and Thelandersson's [14] LITS model was implemented and used to evaluate the deflection of the slab when heated. As in the Abaqus model, significantly better deflection predictions result when LITS is included (Figure 11). Together with the results in Figure 10, these give a high level of confidence that the previously inexplicable experimental results are due to LITS dominating deflections at high temperatures.

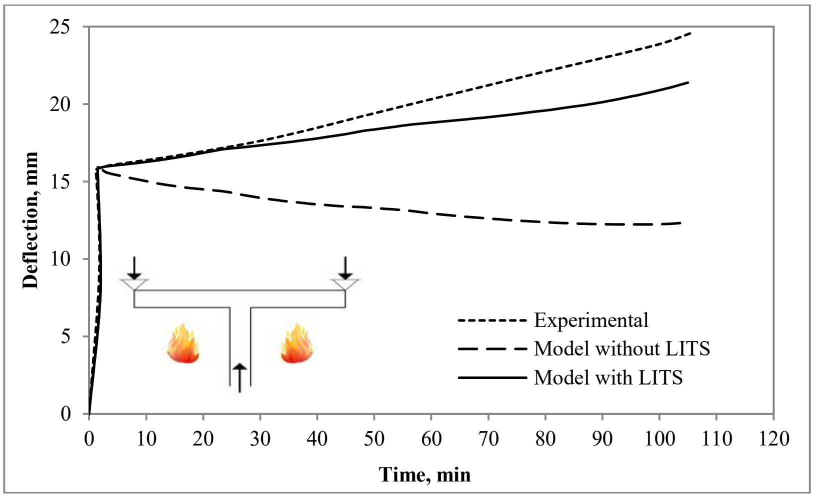


Figure 11 Deflection-time response for the Code Aster model (S100).

6. Effect of higher temperatures and failure

The experimental work of Smith and others highlighted above-obtained results for lower surface slab temperatures up to about 480 C°. The peak temperatures were limited by the heating equipment available and are substantially below the temperatures that might occur in a real fire or those that might cause slab failure. Therefore the behaviour of slabs subjected to higher temperatures was studied numerically assuming two heating scenarios - "slow" and "fast" fires.

6.1. Slow fire

First, a "slow" fire was modelled. Here the initial temperature-time field measured by Smith was included (as before) but extended by assuming a linear increase in temperature from the point at which experimental measurements ceased (Figure 12).

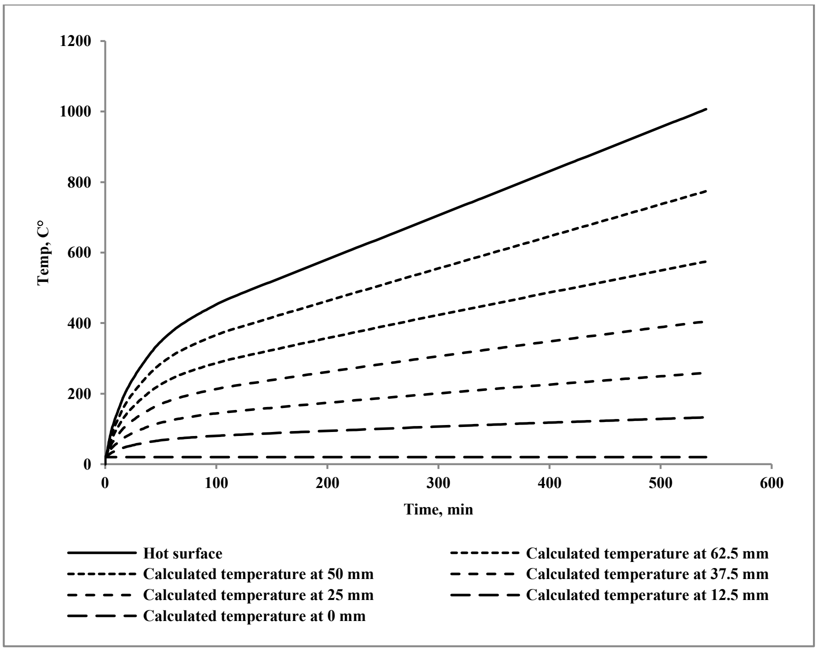
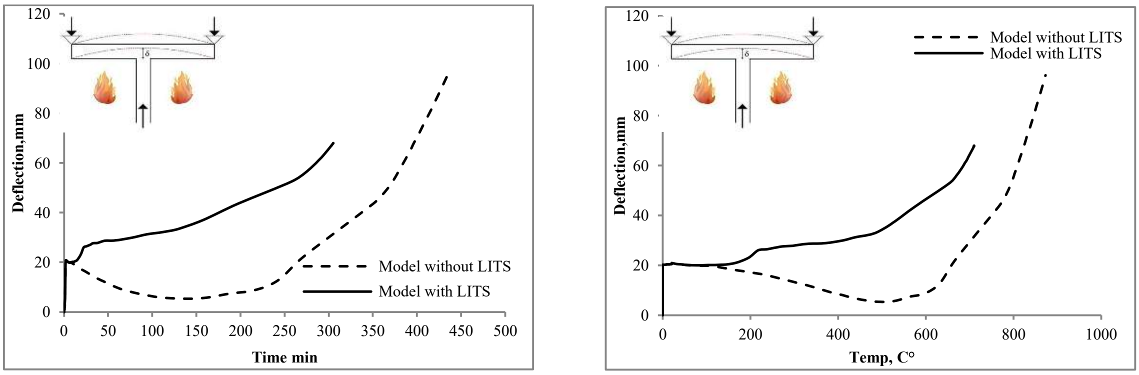


Figure 12 Temperature-time data are assuming linear increases in temperature beyond the measured results of Smith.

The predicted deflection behaviour for this case is shown in Figure 13 plotted against both time and lower surface slab temperature. In a qualitative sense (see lower for a quantitive discussion) it is clear from these plots that failure, indicated by rapidly increasing deflections, occurs earlier when LITS is included in the models than when it is ignored. Taking a somewhat arbitrary failure deflection of span/20 (=50mm), ignoring LITS gives a lower surface failure temperature over 100C higher than when LITS is included, which is highly unconservative.



a. b.

Figure 13 Deflection response against a) time and b) temperature for a “slow” fire.

6.1. Fast fire

Second, a “fast” fire, here modelled by the ISO834 “Standard Fire” curve, was adopted to identify the slab behaviour in a more realistic case for a compartment fire, and when higher thermal gradients were present (and hence less concrete in compression and subject to LITS). The slab temperatures are shown in Figure 14. The structural response here is similar regarding trends to that produced by a slow fire (Figure 15). However, the predicted failure temperatures are less different when LITS is included and ignored, as a result of the smaller proportion of the slab acting in compression.

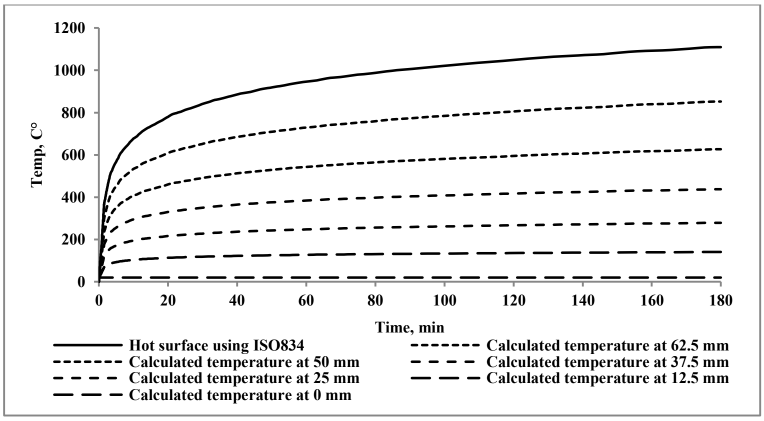
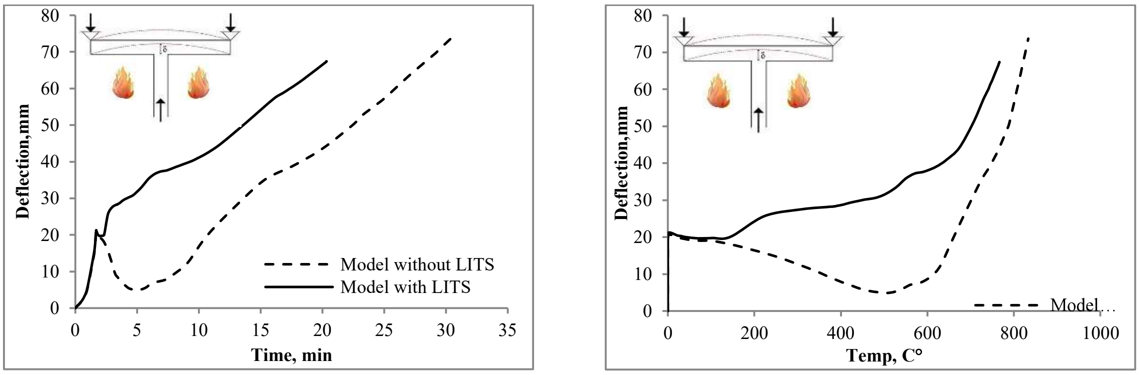


Figure 14 Temperature-time data for the heated surface for Standard Fire heating.



a. b.

Figure 15 Deflection response against a. Time b. Temperature Standard Fire curve heating.

7. The Mechanics of High-Temperature Punching Shear

Punching shear is a complex phenomenon involving three-dimensional stress states and interaction between concrete, rebar, cracks and other factors. Capturing and identifying the mechanics involved with a numerical model is not straightforward. A simple way of identifying when punching shear is likely to initiate is to examine the maximum principal stresses in a slab along an assumed crack line (Figure 17). When these stresses reach the ultimate tensile stress of the concrete, a crack can be assumed to have formed at this point. This approach does not capture the effects of reinforcement or interlock and is thus approximate. However, it does offer a simple way to identify how LITS affects the internal mechanics of heated slabs, and to explain the experimental results and numerical predictions given above and is in line with earlier work ambient temperature studies of punching shear [28]. Figure 16 shows a contour plot of the principal stresses in the slab at the end of heating to show the effectiveness of this approach –the classic cone shape failure shape of a punching failure is clearly visible.

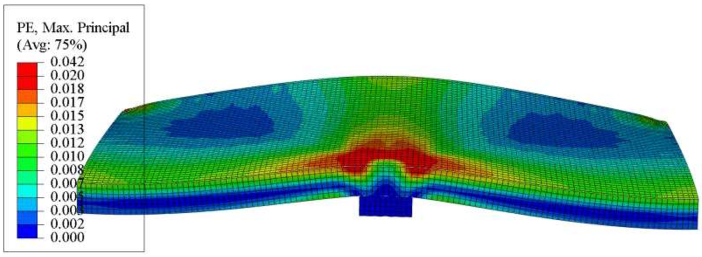


Figure 16 cracking pattern for the slab.

Figure 18 shows the maximum principal stresses through the thickness of the slab for the slow-fire scenario considered along a line at 45 degrees to the horizontal as shown in Figure 16. This line approximates the (varying and non-linear) precise location of the maximum stresses, in line with theories predicting crack formation, such as Mutoni's Critical Shear Crack Theory [29]. Accordingly, the maximum principal stresses are also approximately normal to this line. Stresses at two states are plotted: at a lower surface slab temperature of 500 °C, and at incipient failure as defined above. "Failure envelopes'', which show the maximum tensile stress that the concrete can sustain at each location, taking account of the temperature profiles and how concrete material properties vary with temperature are also plotted. Figure 18a shows clearly the difference in stresses that result from inclusion of LITS in the analysis, which in turn explain the differences in deflections observed. By contrast Figure 18 b, indicates that at incipient failure, the stresses in the slabs are very similar. This implies that LITS does not affect the failure mechanism of heated slabs but that it does affect both stresses state before failure and the time (or temperature profiles) at which failure occurs.

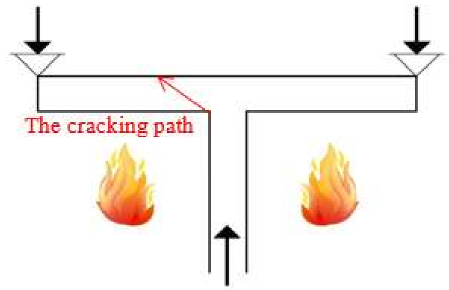
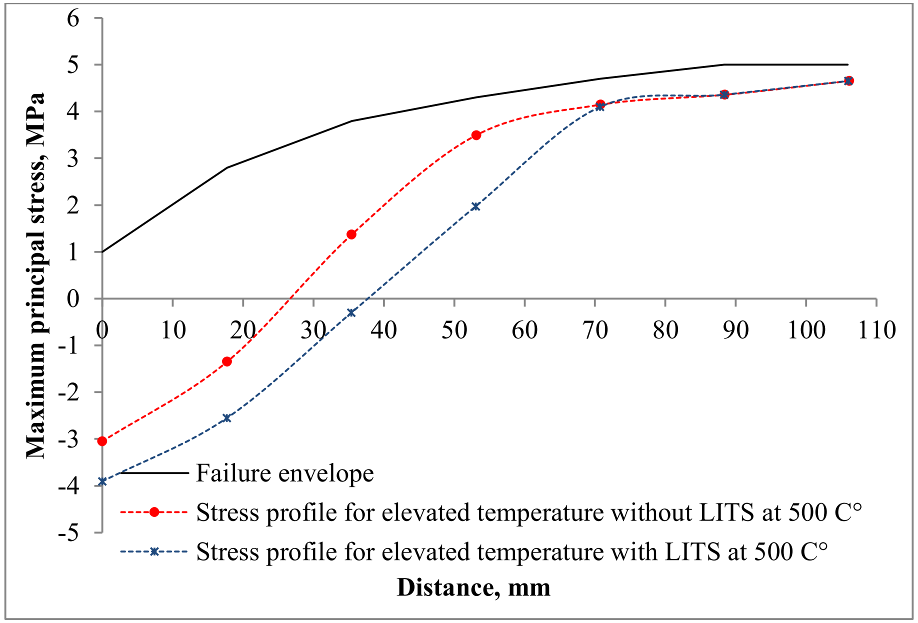
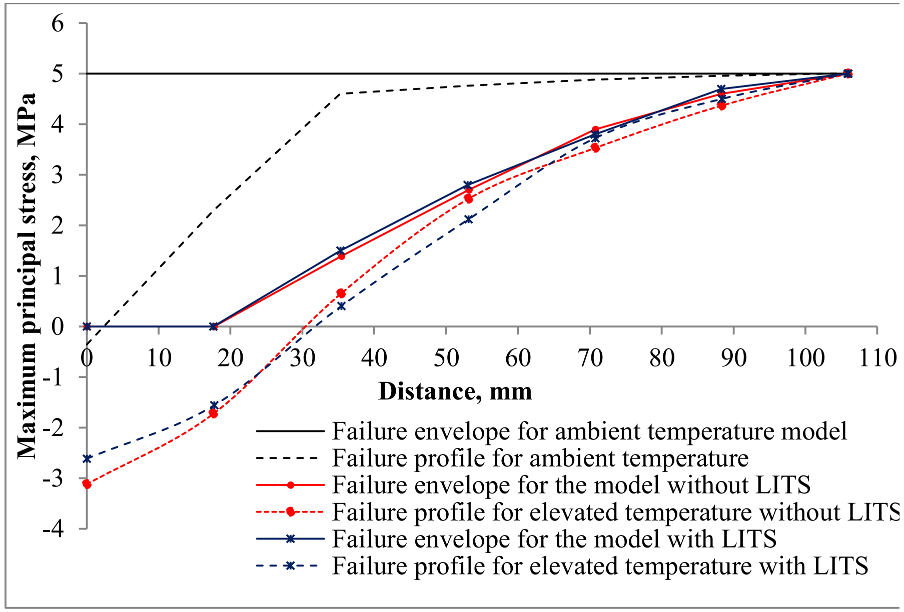


Figure 17 The assumed cracking path at failure.



(a)



(b)

Figure 18 Stress state for the slab (a) when the bottom surface reaches 500 C° (b) at failure.

8. Conclusions

Numerical studies have been presented that identify the role of LITS in the response of flat-slab structures to fire. The results clearly show that LITS accounts for the apparently anomalous experimental deflection results seen in punching shear experiments in the fire. While LITS has been known of for a long time, in building structures its effects have often been assumed to be small, and often ignored or included crudely in analyses. The results of this paper show that in cases where compressive regions (herein slab soffits close to columns) govern structural behaviour, this assumption is not valid. If LITS is not included in analyses, this will not only result in incorrect deflection predictions but may also lead to non-conservative estimates of fire resistance times.

The consequences of these findings for the design of slabs in punching shear in a fire should be determined. In particular, the implications of the predictions for the recently developed and widely adopted critical shear crack theory for flat slab design [29] should be identified. This approach to calculating punching shear strength relies on estimates of the rotation of slabs to predict initiation of cracking. The larger deflections (and hence rotations) seen experimentally in fire conditions and now explained numerically, may mean the method needs additional calibration for fire loading. For example, the currently available method of applying critical shear crack theory in fire as developed by Bamonte [30], where the thermal displacement is added to the total rotation of the slab, will likely need adjustment in order to account for LITS_induced rotations.

Further experimental and numerical studies should be undertaken to identify the likely effects of LITS on stresses when in-plane restraint is present, as is likely in real floor plates. Compressive in-plane stresses serve to increase punching shear capacity, and a simple analysis would suggest restrained thermal expansion produces highly compressive in-plane stresses. However, if, as appears likely, LITS results in lower compressive (or even tensile) in-plane stresses in fire, this would result in punching shear capacity below that anticipated by current design approaches.

9. ACKNOWLEDGEMENTS

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