Fire Safety Journal 97 (2018) 12–18

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

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

Rwayda Kh S. Al Hamd [a,*], Martin Gillie [b], Holly Warren [c], Giacomo Torelli [d], Tim Stratford [e], Yong Wang [a]

[a] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK
[b] The School of Engineering, The University of Warwick, Coventry, CV4 7AL, UK
[c] AECOM, One Trinity Gardens, First Floor, Quayside, Newcastle-upon-Tyne, NE1 2HF, UK
[d] University of Cambridge, Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK
[e] School of Engineering, The University of Edinburgh, Sanderson Building, Robert Stevenson Road, The King's Buildings, Edinburgh, EH9 3FB, UK

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.

1. 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" (Fig. 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.

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 Fig. 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 (Fig. 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 Fig. 2a. However, the observed experimental deflections were in the opposite direction, resulting in a concave shape as shown in Fig. 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:

* Corresponding author.
E-mail address: rwayda.alhamd@manchester.ac.uk (R.K.S. Al Hamd).

https://doi.org/10.1016/j.firesaf.2018.02.004
Received 30 August 2017; Received in revised form 18 December 2017; Accepted 21 February 2018

- 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.

2. 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*, ε_{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 (Fig. 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:

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

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

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.

3. 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 (Fig. 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 (Fig. 4 and Fig. 5) was used. In this test, a concrete slab

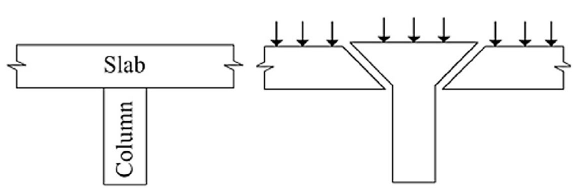

Fig. 1. Schematic diagram of a flat plate structure and the punching shear failure mechanism.

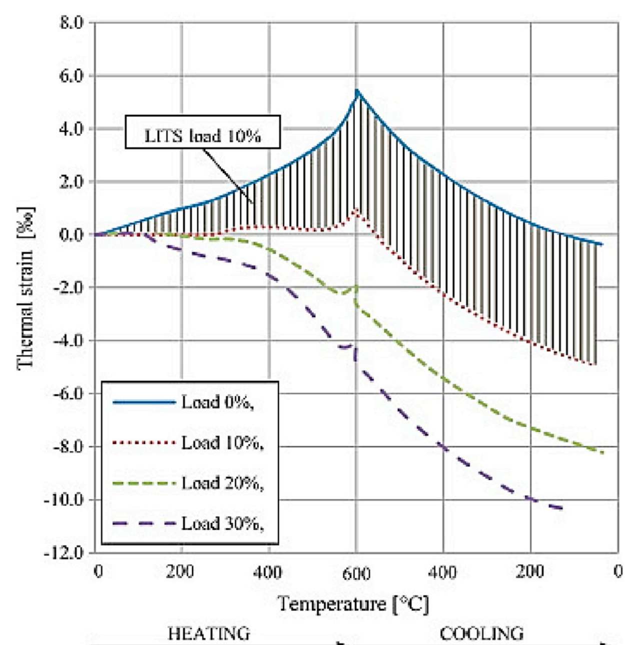

Fig. 3. Typical LITS behaviour expressed as a function of temperature for different load levels. (Adapted from https://doi.org/10.1016/j.engstruct.2016.08.021 under Creative Commons License).

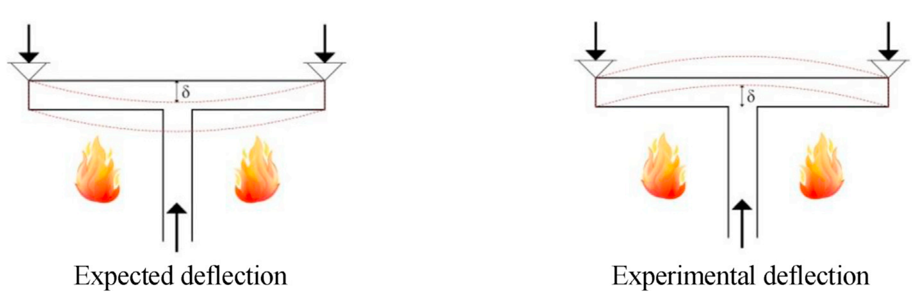

Fig. 2. Conceptual arrangement for testing heated flat plate beam-column connections. (a) Expected deflection response under heating and (b) Deflection response observed in Smith's tests [4–6].