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Influence of loading ratio on flat slab connections at elevated temperature: A numerical study

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Abstract

For reinforced concrete members subjected to high temperature, the degree of in-service loading, commonly expressed as the loading ratio, can be highly influential on the structural behaviour. In particular, the loading ratio may be pivotal in relation to the phenomenon of load-induced thermal strain. Despite its potentially pivotal role, to date, the influence of the loading ratio on both material and structural behaviour has not been explored in detail. In practice, real structures experience variation in imposed loading during their service life and it is important to understand the likely response at elevated temperatures across the loading envelope. In this paper, the effect of the loading ratio is numerically investigated at both material and structural level using a validated finite element model. The model incorporates a proposed constitutive model accounting for load-induced thermal strain and this is shown to outperform the existing Eurocode 2 model in terms of accuracy. Using the validated model, the specific case of flats slabs and the associated connections to supporting columns at various loading ratios are explored. For the cases examined, a marked difference in the structural behaviour including displacement direction was captured from low to high loading ratios consistent with experimental observations.

Keywords: *concrete, finite elements, fire, load-induced thermal strain, punching shear*

1. Introduction

Flat slab structures represent the simplest form of reinforced concrete frame building since the slab is connected directly to the columns without the presence of beams. In view of this, the slab to column connection in a reinforced concrete flat slab is vital to the strength and stiffness of the slab system. Flat slabs are widely used in commercial and residential frame buildings due to the advantages they offer in situations that involve reduced storey heights, flat finishes, rapid construction and the need to place columns at arbitrary locations. However, despite the many advantages of flat slab construction, there is also a risk that the dangerous brittle failure mode known as ‘punching shear’ will occur if shear stresses at the slab-column connection reach critical levels.

Generally, reinforced concrete (RC) structures have a good reputation for fire resistance due to concrete’s low thermal conductivity. However, in some cases, this perception is not strictly correct as it ignores the implication of other aspects such as the effect of combined heating and loading conditions on the mechanical properties of concrete at high temperature. At elevated temperatures such as those occurring in fire conditions, RC structures lose a lot of their compressive resistance and since punching shear strength is influenced by the tensile strength and hence indirectly by the compressive strength, the slab-column connection would be adversely affected.

The first set of tests published on slab-column connections in a fire were by Kordina in the 1990s [1,2]. In 2004 following a fire-related collapse of a car park building in Gretzenbach, Switzerland [1], further experimental studies were carried out on punching shear in heated slabs by various researchers. The first of these post-2004 studies was by Salem et al. [3], a schematic of the test set-up is shown in Figure 1. The main focus of the work by [3] was the effect of the heating application on the tension side of the slab at the column connection. However, this would not normally be the most affected zone in a real-fire, as the fire will rise upward. To develop an understanding of the effect of heating on different sides

1 of the slab, compression side or tension side, Liao et al. [4] tested 12 slabs with dimensions of 1800
2 ×1800 ×120 mm, half of the test series were at high temperature, the other half were at ambient
3 temperature. It was concluded by [4] that the worst-case scenario occurs when applying the fire to the
4 tension side of the slab. This conclusion is due to several reasons: firstly, spalling occurs more severely
5 on the slabs heated on the tension side due to the cracks that form[4]. Secondly, the slabs heated on the
6 tension side failed after three to five hours while the slabs heated on the compression side failed after
7 eight hours. Finally, the deflection of the slabs heated on the tension side was far more significant than
8 the deflection of the slabs heated on the compression side. However, the performance of the slabs heated
9 on the tension side may be of less significance since this does not replicate the situation of actual slab-
10 column connections in flat slab frame buildings. One important point to note from Liao et al. [4] is that
11 the slabs heated on the compression side showed the same unexpected deflection behaviour noted first
12 by Kordina [1,2]. Subsequent to the aforementioned work, Smith et al. [5–8] investigated slab-column
13 connection behaviour under fire. They used 16 specimens of dimension 1400 x 1400 mm and depths of
14 50, 75 and 100mm; five of which were tested at ambient temperature to determine their punching shear
15 resistance. After applying static loading, the slabs were heated, most of the specimens clearly
16 demonstrated that the slab deflections when heated were in the opposite direction to that which had
17 been expected i.e. away from the heating source rather than towards it. A recent study by Al-Hamd et
18 al [9,10] concluded that the phenomenon of load-induced thermal strain (LITS), which is seen in heated
19 concrete, explains the observed behaviour.

20

Figure 1 Conceptual drawing for punching shear test set-up and the importance of the heating side

2. Background and motivation

Almost all of the tests conducted to date on flat slabs at high temperature, with the exception of those by Kordina [1,2], consistently applied loads between 60% and 80% of the ultimate punching shear capacity of the slab at ambient temperature. The relationship between the applied load and the nominal ultimate load capacity of the slab at ambient temperature is herein referred to as the Loading Ratio (LR). In the aforementioned existing studies, the nominal ultimate load capacity is either taken to be the theoretical value predicted by a design code or based on the experimentally derived value. Observations from the previously conducted tests showed that the higher LR's resulted in a marked change in deflection behaviour compared to that observed in the lower LR cases.

In Kordina's original work [1, 2] the effect of loading ratio (using three identical circular specimens A, B and C with a diameter of 2500 mm and thickness of 200mm) was examined. The three specimens were loaded up to 20, 40 and 70% of their ambient temperature ultimate design punching shear resistance (theoretically obtained from the German code DIN 1045:1988 [1,2]) respectively. The heating was applied according to the ISO-834 fire curve [1,2]. Slabs A and B experienced a downwards deflection (towards the heating source) until the slabs failed; however, slab C deflected downwards first

1 (towards the heating source) and then the deflection direction reversed after 30 minutes of heating, see
 2 Figure 2. This unexpected behaviour is noted by Kordina without explanation.

3

Figure 2 The load deflection profile for specimens (a) for A, B and (b) for C, based on Kordina [1,2]

4

5 Similarly, Smith et al. [5–8] implemented an LR of (70-80%) in all of the tested slabs and the deflection
 6 reported was again moving away from the heating source.

7 The level of loading directly affects the concrete behaviour at elevated temperatures and might result
 8 in the reversal of the expected deflection response due to the effect of LITS, (defined in detail in the
 9 next section), as shown in Figure 3. The effect of the loading ratio on the behaviour of the slab-column
 10 connections raises concerns about the design recommendations for heated reinforced concrete
 11 members. While some allowance for the effect of LITS is incorporated to some extent in current design
 12 codes such as Eurocode 2 (EC2) [11], the models are often limited. The main focus of the present study
 13 is to compare the EC2 constitutive model [11] for concrete at elevated temperatures with the novel
 14 model developed by Al-Hamd et. al. [9,10] which demonstrated more realistic results in capturing the
 15 structural behaviour of the slab-column connection. Although some limited experimental work has been

1 conducted to examine the effect of loading ratio, no numerical study incorporating accurate capture of
 2 LITS has been carried out to date in this particular application. Adopting a numerical approach allows
 3 additional insights into the structural behaviour to be gained beyond the practical constraints of physical
 4 experiments. In the present paper, the influence of the loading ratio is numerically investigated for the
 5 first time at both a material level and in terms of the overall structural behaviour of the connection,
 6 utilising a model which captures realistically the LITS effect.

7
 8 Figure 3 Typical LITS behaviour expressed as a function of temperature for different load levels, based on [12]

9 3. Effect of heating on the strain components of concrete

10 The combination of fire and mechanical loading results in the generation of different strain components.
 11 Therefore, the best way to understand the deformation of concrete at elevated temperatures is by
 12 splitting the total strain into its primary components, as shown in the following equation [13]:

$$\varepsilon_{tot} = \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{th}(T) + \varepsilon_{LITS}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) \quad \text{Equation 1}$$

13 Whilst the mechanical strain $\varepsilon_{\sigma}(\sigma, T)$ is a result of the static load, the thermal strain $\varepsilon_{th}(T)$ is due to
 14 the material expansion, the load-induced thermal strain (LITS) $\varepsilon_{LITS}(\sigma, T)$ is a result of the concrete

1 shrinking under a high level of applied loading and the creep strain $\varepsilon_{cr}(\sigma, T, t)$ is the strain that develops
2 in the material due to external loading over time[12]. Due to the time scale needed for creep strain to
3 develop, creep strain is often neglected in structural fire calculations[14–16]. This assumption
4 highlights the role of mechanical, thermal and load-induced thermal strain on behaviour of concrete in
5 fire. The effect of heat on concrete with these strain components being developed would increase the
6 loss of the concrete strength, which leads to substantial damage of the reduced cross-section [17–20].

7 Al-Hamd et al. [9,10] put forward an explanation for the unexpected behaviour reported in the
8 experimental tests conducted by [5–8] for the slab-column connections. The main reason for this
9 behaviour is found to be the activation of one of the strain components (LITS) of the heated concrete
10 generated under combined heating and high levels of loading conditions. Al-Hamd et al. also developed
11 a model that can capture the effect of LITS by adding its component separately to the Eurocode 2 (EC2)
12 constitutive concrete model [11]. The model proposed the implementation of the LITS component using
13 the formulation developed by Anderberg and Thelandersson [21,22] in the EC2 concrete model
14 explicitly to capture the effect of LITS. This was in line with the findings of Lange and Jansson [15]
15 that highlighted the weakness in the EC2 concrete model at elevated temperatures. The new model
16 proposed by Al-Hamd et al. that explicitly includes the effect of LITS in the compressive stress-strain
17 relationship of the concrete adopted in this study can be seen in Figure 4 where it is compared to the
18 standard EC2 model at different temperatures. As shown in Figure 4, the solid lines represent the stress-
19 strain behaviour for concrete without the addition of the LITS component and the dashed lines represent
20 the stress-strain behaviour for concrete with the LITS component added.

Figure 4 Stress-strain behaviour of concrete at various temperatures according to EC2 (solid lines) and EC2 plus load-induced thermal strain (dashed lines), (based on [9])

4. Modelling approach

There are several approaches for modelling reinforce concrete including the traditional mesh based approach and the relatively new approach of mesh-free methods that can capture directly the discontinuity of cracking in concrete members, [23–27]. In the present work, the traditional mesh based approach is adopted using the general finite element software Abaqus [30]. The concrete constitutive behaviour is modelled using the concrete damage plasticity model available in the Abaqus material library [31]. This model has been successfully adopted by Jansson and Lange for fire conditions [15]. All models in this study use three-dimensional solid elements (C3D8R) to represent the concrete slab, with truss elements (T3D2) embedded within them to represent the rebar. This approach has a number of advantages such as providing a better representation of the complex three-dimensional stress state that exists near the slab-column interface under punching shear, capturing the shear stresses at the connection in line with [28–30].

The modelling approach developed by Al-Hamd et al. [9,10,30] is adapted to produce a numerical model with different LR's at elevated temperatures. In all models, a full-bond between the concrete and

1 steel rebar is assumed[30]. Whilst this is a simplification of reality, the approach was implemented by
2 [30] for the specific case of punching shear and was shown to have a good agreement with
3 corresponding test results within the level of accuracy of (0.73-8.14%). Concrete uniaxial stress-strain
4 properties were initially made temperature dependent according to the recommendations in EC2. To
5 simulate high-temperature experiments, first a static load was applied and the effect of heating was
6 introduced using a thermal profile (see Section 5).

7 **5. Model calibration at elevated temperatures**

8 For the calibration of the numerical model, one of the test specimens (originally named as HU75)
9 reported by Smith [8] was simulated. The slab had dimensions of 1400 x 1400 x 75mm and was simply
10 supported along all edges (in a similar configuration to that shown in Figure 1). The concrete damage
11 plasticity model was used to model the concrete where the uniaxial compressive stress-strain
12 relationship was adopted from Eurocode 2 and the mesh size of 12.5mm was chosen as the macroscale
13 behaviour of concrete depends on aggregate size, the mesh size needed to be greater than the maximum
14 aggregate size [31] for accurate results. This slab specimen was chosen because it failed in punching
15 shear experimentally. Heating was provided in Smith's experiments by radiant panel heaters, with a
16 peak surface temperature of around 480°C, the thermal history was recorded using thermocouples [8].
17 Based on the heating data shown in Figure 5, a thermal profile was numerically developed using the
18 heat transfer model with heat transfer elements from the Abaqus library [32], then the static loading
19 was applied. In the numerical model, this procedure was carried out in two stages. The first stage is by
20 conducting a thermal heat transfer model to generate the thermal profile for the slab. The second stage
21 was implemented by incorporation of this thermal profile into a stress model to apply static load.

Figure 5 Temperature-time data through the depth of the slab (Adapted from [9] under Creative Commons License).

As explained in section 3, an additional strain component was introduced to the EC2 concrete model so that the effect of LITS could be captured numerically as shown in Figure 4.

In the current EC2 (EN 1992-1-2:2004) [11], some modification was made to the material behaviour, with the intention of including the additional strain component (LITS) implicitly [14]. The numerical model showed that the current EC2 model includes for the LITS effect in part but not fully. However, the model proposed by Al-Hamd et al. [9,10,30] is shown to capture the observed unexpected behaviour in the experiment, see figure 6. In the Al-Hamd model, the addition of the LITS component is made explicitly in line with research performed by Lange and Jansson [14,15] highlighting the poor inception of LITS in the current EC2.

Figure 6 Deflection-time response of Smith's slab, together with numerical predictions for the EC2 model (with LITS being incorporated implicitly) and Al-Hamd's model (with LITS)

In order to ensure the appropriateness of the mesh size, a sensitivity study was carried out with three different mesh sizes: a fine (10mm), medium (12.5mm) and coarse (15mm) mesh. The sensitivity study shown in Figure 7 suggests that the slab with the medium size mesh (12.5mm) is the best fit to the experimental results and more computationally efficient than the fine mesh; therefore, this mesh size would be adopted in all of the following analysis.

Figure 7 Mesh sensitivity study showing the deflection-time response for different mesh sizes against experimental results

6. Effect of continuous heating

This section examines the effect of a continuous heating scenario on the deflection response and the failure mode of the slab examined in Section 5. In this scenario, the initial heating regime measured by Smith was included and was then extended by assuming a linear increase in temperature after the experimental measurements were stopped. Figure 8 shows the predicted deflection behaviour plotted against time. The rapid increase in the deflection can qualitatively pinpoint the failure of the RC slab for both cases. However, the failure occurred earlier when the LITS component was included in the model. The model adopted by the current EC2 (that assumes the implicit inclusion of LITS) seems to over-predict the failure time (temperature) in comparison to the Al-Hamd model. The Al-Hamd model failed when the top surface temperature reached 710°C while the EC2 model resisted the fire loading up to about 870°C. Also, these models demonstrate a large difference in the deflection response due to the effect of the LITS component [15]. If we say that slab failure occurs when deflection reaches span

1 length/20 (=50 mm in this case) (based on the deflection limits for a reinforced concrete beam/slab
2 according to BS 476-23:1987 [33]), overlooking the effect of LITS can increase the exposed surface
3 predicted failure temperature by about 100°C. This difference might result in non-conservative design
4 recommendations.

Figure 8 Deflection response against time the continues heating scenario

7. Effect of different loading ratios

As stated earlier, the level of in-service loading in relation to structural capacity can affect directly the structural behaviour for a concrete building in fire as a result of the different strain components generated. In this section, this effect is investigated on a material level first, and its implication on structural behaviour is also discussed.

1 7.1 Material level (Simplified case)

2 To build a thorough understanding on the effect of the strain components in the adopted concrete
3 model in representing RC slabs, standard concrete cubes ($100 \times 100 \times 100$ mm) [34] were modelled
4 using the modelling approach previously described, see Figure 9 (the mesh size used is 12.5mm see
5 Section 5). Similar heating scenarios to that in the previous section were assumed. Different loading
6 ratios were explored to capture the initiation of the LITS component. Four different LRs, namely 25%,
7 50%, 70% and 80% of the ultimate compressive failure load at ambient temperature, was applied to
8 the specimens with and without LITS.

9
10 Figure 9 Conceptual diagram for the cube under the combined heating and loading scenario

11 Figure 10 shows the deflection of the concrete cube (indicating the strain) with two concrete models
12 one with LITS implicitly included (EC2) and one with LITS explicitly included (Al-Hamd). It can be
13 observed that increasing the LR magnifies the effect of the LITS component over the effect of the
14 thermal strain (thermal expansion). However, with low loading ratios (such as 20%) the effect does
15 not contribute to reversing the deflection direction of the concrete cube since the specimen still

1 deflects towards the heating source (i.e. (for the deflection response –ve deflection moving upwards,
2 +ve moving downwards)). On the other hand, at high LRs the effect of LITS can be substantial and
3 results in reversing the expected deflection direction of the cube. As discussed previously, this can
4 explain Kordina's [1,2] observation in the slab tests (Figure 2a and b). At the earlier stages of the
5 heating process, deflection at such lower temperature can be towards the heating source depending on
6 the test setup; this can be seen in the cube in Figure 9 LR 70%.

7 There is a clear difference between the implicit and explicit addition of the LITS strain component
8 and this might result in overestimating the fire resistance of the structural member. Therefore, the
9 explicit addition of the LITS component should be considered in order to ensure a more reliable design
10 is achieved.

1

2 Figure 10 Deflection-time response for different loading ratios at the centre of a standard cube (the solid lines represent the EC2 model and the dashed lines represent the

3 Al Hamd model)

1 **7.2 Structural behaviour of the slab-column connection**

2 Here the slab discussed in section 5 is subjected to 4 different loading ratios at high temperature. Using
3 the approach adopted by Smith [8], the loading ratio is taken to be (the applied load) / (80% of the
4 experimentally obtained punching shear capacity at ambient temperature). Load ratios of 25%, 50%,
5 70% and 80% were chosen.

6 From figure 10, it can be noted that a step change in deflection behaviour occurs when higher LR's are
7 applied triggering the load-induced thermal strain effect, this is in line with the previously described
8 work by [2] and the material level modelling (Figure 3). Figure 11 shows the maximum principal strain
9 in the section with different loading levels. From Figure 10 and 11 it can be clearly seen that the failure
10 profile was affected by the different loading ratios. The change in the loading level had a small effect
11 on the slab heat resistance as the specimen with a lower loading ratio (25%) had more heat resistance,
12 collapsing after 378 min (890°C) of heating, followed by the specimen with a 50% loading ratio, which
13 collapsed after 352 min (775°C), the specimen with 70% loading ratio, which collapsed after 330 min
14 (744°C) and, finally, the specimen with 80% loading ratio, which collapsed after 304 min (710°C), this
15 would seem to follow the intuitive pattern of results.

Figure 11 Deflection-time response for different loading ratios at the centre of the slab

1 According to the concrete damage plasticity theory used in the model, when the plastic strain exceeds
2 zero a crack will develop. The maximum principal plastic strains shown in Figure 11 can be used to
3 indicate the cracking pattern in the slab at the end of heating, where the characteristic cone shape of
4 failure by punching shear is noticeable. However, the influence of different loading ratios changes the
5 deflection profile due to the effect of thermal expansion and LITS. The cone-shaped failure profile of
6 punching shear is still noticeable in all of the cases, numerically demonstrating that all models failed
7 with the same failure mechanism.

Figure 12 Cracking pattern at the stage of anticipated failure for slab S75 with loading ratio (a) LR 25%, (b) LR 50%, (c) LR 70% and (d) LR 80%

1 The proposed failure profile, along with the failure envelope for the slab with different loading
2 ratios, is shown in Figure 12 where the assumed crack had travelled across half of the slab. The
3 failure envelope shows the maximum tensile stress that the concrete can sustain at each location,
4 taking into account the temperature-profiles and how the concrete material properties vary with
5 temperature. The failure profile shows the maximum principal stresses through the thickness of
6 the slab for the continuous-heating scenario (measured from bottom to top along with a crack
7 path at 45° degrees to the horizontal plane from the column face). Figure 12 demonstrates that
8 the different behaviour observed for each LR did not affect the failure mechanism for the slabs.

Figure 13 Failure envelopes along with the failure profiles for different loading ratios

1 **8. Conclusions**

2 This paper has explored via numerical modelling the effects of explicitly including load-induced
3 thermal strain on the behaviour of concrete at both material and structural levels. The effect of
4 modifying the concrete model can substantially affect the structural behaviour and improve
5 response prediction. The implemented model is able to capture the unexpected experimental
6 behaviour reported in the literature and offers some rationale for the observed phenomenon.

7 It has been demonstrated that the choice of LITS model has a significant impact on structural
8 behaviour at elevated temperatures. For the particular slab scenario examined, the Al Hamd
9 LITS model is able to capture the experimentally observed behaviour while markedly less
10 accurate results were predicted by the implicit LITS model from Eurocode 2

11 Exploring different loading ratios showed that this parameter can dramatically change the
12 deflection response for the same slab, yet this did not majorly affect the slab load resistance. The
13 change in the loading ratio especially when the loading ratio is more than 50% of the ultimate
14 tested capacity of the concrete slab at ambient temperature, directly affects the deflection
15 behaviour of the member at both material and structural levels. An understanding of the
16 structural system response at different load levels, accounting for the effects of LITS, is key to
17 developing strategies for safety in fire situations. The work presented here has concentrated on
18 one particular slab geometry and at a relatively small scale. Further work is required both
19 numerically and experimentally to understand the effects of LITS and loading ratio in full-scale
20 building scenarios.

21

22

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