TEMPERATURE AND STRESS IN CONCRETE CYLINDER SPECIMEN SUBJECT TO UNIFORM HEAT FLUX: A NUMERICAL SOLUTION

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ABSTRACT

The outbreak of fire in a concrete infrastructure can have disastrous consequences, including severe structural damage, total loss of contents, and loss of life. Adequate structural fire design is therefore critical. Despite significant past studies, our understanding of concrete performance in fire remains inadequate. This paper will first highlight major limitations of conventional testing and accordingly of resulting constitutive models for concrete at elevated temperatures. The paper will then detail results of a thermal-stress coupling analysis as part of an ongoing research at The University of Queensland that aims to develop more realistic constitutive models through studying performance of concrete cylinders subject to known consistent heat flux boundary conditions. It is clearly shown that (i) Different levels of incident heat flux causes significantly different evolution of temperature and stress profiles within the specimen; and (ii) Such profiles and their nature may be considerably modified by mechanical loading. Accordingly, heat flux, and temperature gradient by extension, may have non-negligible influence on thermal and structural behaviour of concrete and concrete structures – Such influence has not been captured in currently available models.

KEYWORDS

Concrete, elevated temperature, fire, temperature gradient, heat transfer.

INTRODUCTION

The outbreak of fire in buildings and civil engineering structures can have disastrous consequences, including severe structural damage, significant loss of contents, and possible loss of life. Adequate design for fire is thus an essential requirement in the design process. Accordingly, knowledge of concrete performance in fire is critical.

Despite extensive research in the past decades, our current knowledge of fundamental properties of concrete at elevated temperatures remains largely based on data from conventional tests in which the thermal loading experienced by concrete specimens is very difficult to be consistently controlled (Cristian Maluk et al., 2014; C. Maluk et al., 2012; J. L. Torero, 2014). As a result, the effect of temperature gradients within concrete on its fire performance has not been adequately investigated. Accordingly, the influence of critical processes linked with temperature gradients, including thermal stresses, moisture transport, and pore pressures, has not been properly addressed. This knowledge gap is critical considering the likely significant temperature gradients within concrete in fires. As a result, revised knowledge of fundamental properties of concrete at elevated temperatures is required.

This paper will briefly highlight the limitation of thermal boundary condition in conventional test. On that basis, this paper will present some initial results of numerical modelling of concrete specimen (Φ100 × 200 mm) in fire condition that aims to study the effects of temperature and temperature gradient in concrete material/structural levels.

LIMITATIONS IN CONVENTIONAL TESTS AND THEIR EFFECTS

The increase of temperature in a test specimen depends on the heat flux imposed on the specimen. When conventional furnace/oven is used, the temperature evolution of the gases in the furnace is controlled if thermocouples are used and the heat-flux to a plate if a plate thermometer is used. In conventional furnace/oven, the imposed heat flux results from a combination of different forms of heat transfer (radiation, convection and conduction) between the furnace (gases/furnace walls/other test specimens) and the test specimen. Through consideration of energy balance at the cylinder surface, $q_S^{"}$ can be approximated as:

$$q_s^{"} = \varepsilon . q_{inc}^{"} - \varepsilon . \sigma . T_S^4 + h(T_H - T_S) \qquad (1)$$

where ε: thermal emissivity; T_H, T_S: temperature of gas and of specimen surface; σ: Stefan-Boltzmann constant; q''_{inc}: incident radiative heat flux (from gases, furnace walls and other test specimens).

The evolution of q''_s in time and space is thus highly complex, and accordingly very difficult to be controlled accurately and consistently. (In furnace/oven, the temperature evolution of the gases in the furnace is controlled if thermocouples are used and the heat-flux to a plate if a plate thermometer is used.) This inconsistent thermal loading imposed on test specimens has serious implications for the case of concrete with Biot number close to 1 (Figure 1b), where proper characterisation of thermal boundary conditions is required (J. Torero, 2014). On the other hand, for the case of plasterboard with Biot number much greater than 1, T_S approximates T_H - enabling the simple adoption of the monitored gas temperature (T_H) as T_S on the specimen surface. For steel with Biot number much smaller than 1, a single temperature can be assumed for specimen, also significantly simplifying the problem.

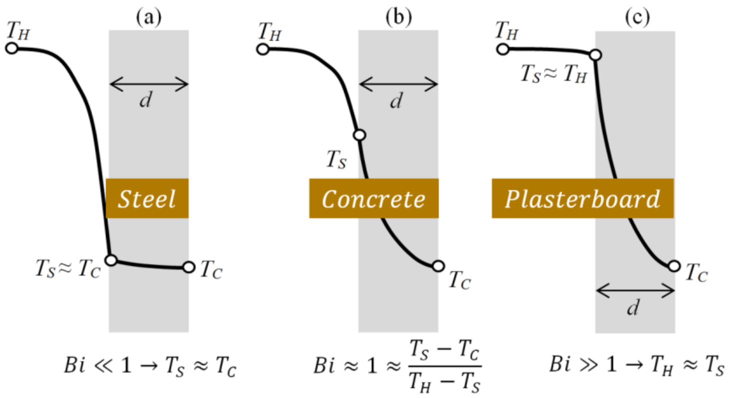


Figure 1 Typical temperature distributions for different materials.

The inconsistent q''_s means reliable control of the temperature evolution/gradient in test specimens is rather challenging, if not impossible, in furnace tests. This has caused, at least partly, the following:

a. Currently available constitutive models have been predominantly derived from “standardized” tests where temperature gradient within concrete test specimens is generally purposely minimized (Cheng et al., 2004; Phan, 1996). Limitations of these models include:
   - Mass transfer processes affected by heat are very different from typical real fire situations (with typically significant temperature gradients) because the very slow heating rates do not only allow dissipation of heat through the sample but also slow dissipation of water vapour with minimal pore pressure increase.
   - The temperature gradients while small remain undefined: Proper characterization of in-depth temperatures implies intrusive measurements that if introduced in sufficient quantity would affect the mechanical properties of the test specimen, and is thus normally not carried out.
   - Components of the model linked with temperature gradients have not been properly addressed. Neither have the couplings between different processes related to temperature gradients (including moisture transport, vapour pressure, and thermal gradient induced stresses).

b. Significant variation in test results regarding both strength deterioration and spalling of concrete upon heating (Khoury et al., 1984; Phan, 1996): Though small, different heating rates adopted have resulted in different heating histories for and thus variations in response of test specimens. These histories, however, are complex and generally undefined due to poor thermocouple/sensor resolution.

The above-discussed shortcomings can be effectively addressed if known heat fluxes representative of real fire scenarios can be consistently applied onto test specimens. A major research program is thus ongoing at The University of Queensland to carry out tests under well-defined and controlled conditions as subsequently outlined.

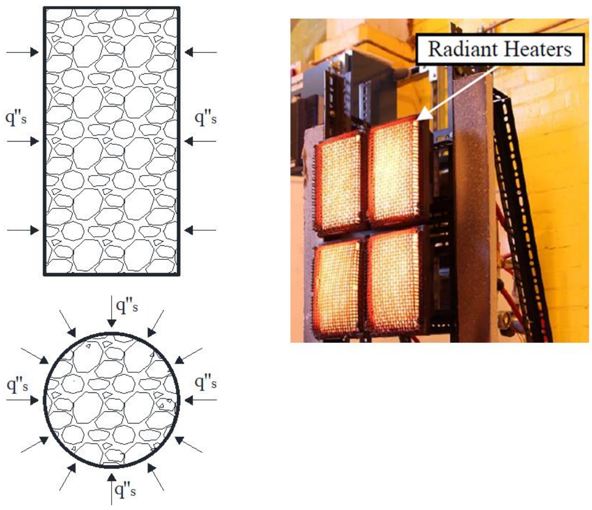


Figure 2 Novel fire test using radiant panels.

NUMERICAL MODEL FOR COUPLED THERMAL-STRESS ANALYSIS

There are essentially two different approaches for coupled thermal-stress analysis, namely (i) sequentially coupled analysis, and (ii) fully coupled analysis. Sequentially coupled thermal-stress analysis is performed by first solving the pure heat transfer problem, then reading the temperature solution into the structural model as a predefined field (Figure 3): The temperature field is thus assumed unaffected by the stress analysis solution. In fully coupled thermal-stress analysis, however, the coupling is two-way with iteration between thermal and stress analysis solutions.

In this study, the modification of the temperature field within the test cylinder specimen due to stress is deemed negligible. Accordingly, the sequentially coupled thermal-stress analysis – being simpler and less time-consuming than full coupling – is adopted.

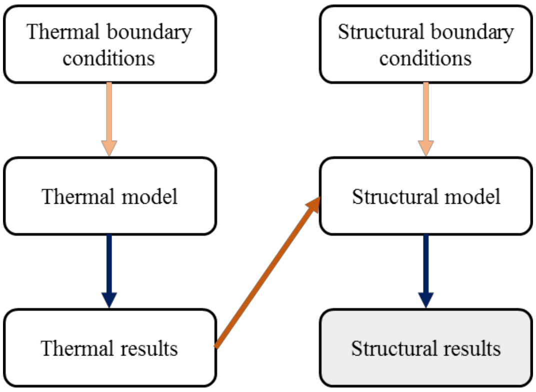


Figure 3 Sequentially coupled thermal-stress analysis.

To carry out such sequential coupling thermal-stress analysis, ANSYS is chosen due to its versatility and strong foundation for multi-physics. Within ANSYS, two models are performed:

- A thermal model to calculate nodal temperature evolution over time within concrete specimen under a specific thermal boundary condition – a known, uniform, and consistent incident heat flux;
- A structural model to determine the mechanical response corresponding to the input thermal and structural boundary conditions. The evolution of the temperature field from the thermal model is read into the structural model as inputs.

In the thermal analysis, a 3D eight nodes, SOLID70, was used to determine temperature distribution via heat conduction, while SOLID65 element was chosen to model the behaviour of concrete under thermal and structural loading. Figures 4 and 5 show the geometry of SOLID70 and SOLID65 in ANSYS, and Table 1 shows the details information of these two elements.

Due to the symmetry of thermal and structural boundary condition as well as the geometry symmetry of concrete, a quarter of the cylinder specimen is modelled, as in Figure 4. To facilitate the coupling, identical solid mesh systems are used for both thermal and structural analysis.

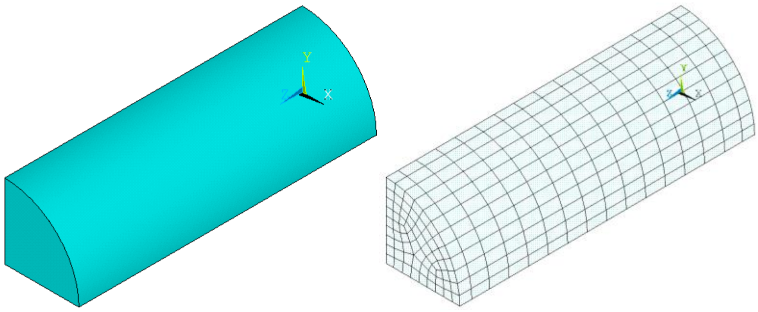


Figure 4 Physical and finite element models.

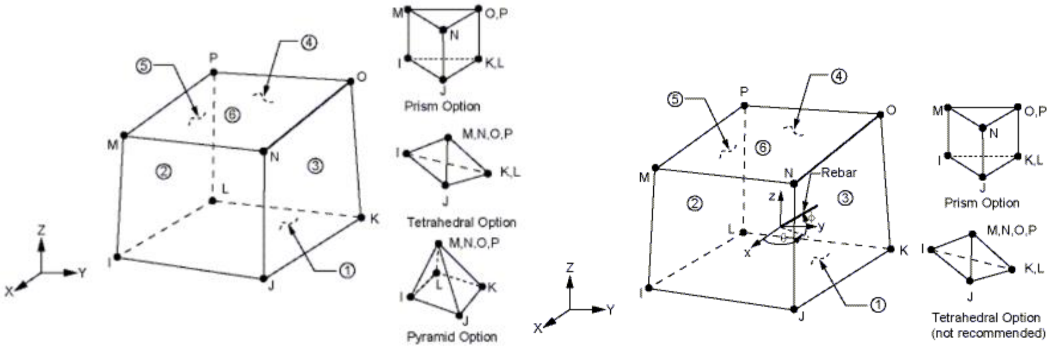


Figure 5 Thermal and structural elements, SOLID70 and SOLID65 (ANSYS® Academic Research, 2009).

Table 1 Properties of thermal and structural elements.

	Thermal analysis	*Structural analysis*
Element	SOLID70	SOLID65
Nodes	8 nodes	8 nodes
Degrees of freedom (DOF)	1 (TEMP)	3 (UX, UY, UZ)
Material properties	Thermal conductivity, density, specific heat	Young's modulus, thermal expansion coefficient, Poisson's ratio, density
Loading	Surface loads, body loads	Surface loads, body loads
Output data	Nodal temperatures	Nodal displacements, Stresses, Strains

The developed model is then used to determine the temperature and stress in a concrete cylinder of 50mm in radius. The boundary conditions, thermal and mechanical properties, and some notable results are presented as follows.

THERMAL ANALYSIS

Thermal Initial and Boundary Conditions

The cylinder has an initial temperature of T_o of 25°C and is subject to a uniform heat flux (q_s'') around the curve surface (Figure 6). There is no heat transfer through the two end faces and no internal heat generation. To model the heat transfer within concrete specimen under heat flux boundary condition together with heat loss, surface element SURF152 was used; the heat flux and convection loss were assigned to these two SURF152 elements.

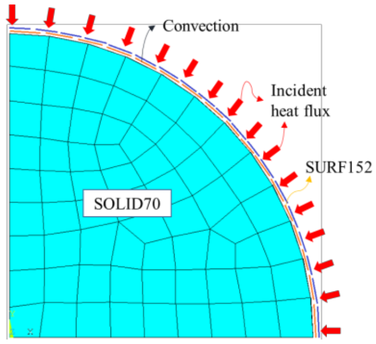


Figure 6 Model the heat transfer in the concrete specimen.

The initial and boundary conditions of concrete specimen are as follows:

$$T\big|_{t=0} = T_O \tag{2}$$

$$k\left.\frac{\partial T}{\partial r}\right|_{r=a} = q_s^{"} \tag{3}$$

$$k\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \tag{4}$$

where k: thermal conductivity of concrete; T: temperature; t: time; r: radial distance from specimen's centreline axis; and T_0 : initial temperature of the whole concrete specimen. Appropriate symmetric conditions are assigned to Line L3 and Surfaces S2, S3 (Figure 7).

For the pupose of this paper, concrete specimen was subjected to two levels of incident heat flux of 10 and 30 kW/m^2 to investigate the difference in temperature and stress response of the cylinder due to temperature gradient. The cylinder specimen had uniform initial temperature of 25°C and was then heated to an average target temperature of 400 °C. The evolution of temperature distribution over time was obtained using transient thermal analysis.

Thermal Properties of Concrete

Thermal properties of concrete - including thermal conductivity, specific heat, and concrete density (mass loss) – were assumed as functions of temperature, as suggested in (Kodur et al., 2003).

Weighted Average Temperature and Its Location

During heating, the temperature distribution is not uniform across the cross-section of the test specimen. The higher the heating rate, the more significant such non-uniformity. The temperature gradients are also dependent on the specimen geometry and thermal properties of concrete. The specimen thus generally does not possess a single temperature at any given time during heating but a temperature range. For practical purpose, it is desirable to represent a given temperature profile by its weighted average value. Analytical and numerical solutions for such a value were reported in (Khoury et al., 1984) for the case of concrete cylinder subject to uniform temperature on the boundary. Similar solutions were given in (Le et al., 2015) when concrete cylinder is subjected to heat flux boundary conditions. Interestingly, in both cases, the location of the weighted average temperature on a cross-section of concrete cylinder is at 0.58 times the cylinder radius from its centreline. Accordingly, the temperature at this location is taken as representative for the cylinder and used to determine whether a predetermined target temperature level has been reached.

STRUCTURAL ANALYSIS

Structural Initial and Boundary Conditions

The structural boundary conditions are as summarised in Table 2: The two end faces are restrained from axial displacement along Z-direction. The position of lines (L1 to L3) and surfaces (S1 to S4) of the physical model are given in Figure 7.

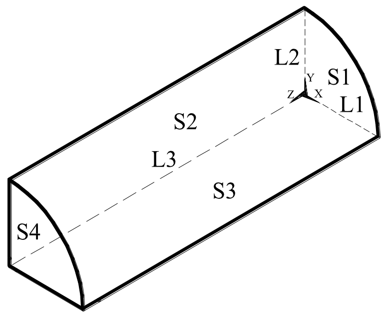


Figure 7 The position of lines and surfaces of the physical model.

Table 2. The constraints of lines and areas in the structural model.

Lines/Areas	*Constraints*
L1	*UY = 0; UX ≠ 0*
L2	*UX = 0; UY ≠ 0*
S1, S4	*UZ = 0*
S2	*Symmetric*
S3	*Symmetric*

Mechanical Properties of Concrete

Mechanical properties of concrete at elevated temperatures required include compressive strength, Young's modulus, compressive strain at peak stress, thermal expansion coefficient, Poisson's ratio, and general stress-strain relationship. Models for the above properties are chosen on the basis of their simplicity and generality and detailed as follows.

Stress-strain relationship of concrete at temperature T is as proposed by Lie et al. (1985):

$$\sigma_{cT} = f'_{cT}.\left[1-\left(\frac{\varepsilon_{oT}-\varepsilon_{cT}}{\varepsilon_{oT}}\right)^2\right] \qquad \varepsilon_{cT} \le \varepsilon_{oT} \tag{5}$$

where: σ_{cT} and f'_{cT} are compressive stress and compressive strength of concrete, respectively; ε_{oT} is strain at maximum stress of concrete; and ε_{cT} is concrete strain. These concrete properties are determined using a model proposed in (Li et al., 2005):

$$f'_{cT} = f'_c\left[0.00165.\left(\frac{T}{100}\right)^3 - 0.03.\left(\frac{T}{100}\right)^2 + 0.025.\left(\frac{T}{100}\right) + 1.002\right] \tag{6}$$

$$\varepsilon_{oT} = \frac{2.f'_c}{E_{ci}} + 0.21\times10^{-4}.(T-20) - 0.9\times10^{-8}.(\mathrm{T}-20)^2 \tag{7}$$

where: f'_c and E_{ci} are concrete compressive strength and Young's modulus at ambient temperature, respectively. Ascending branch of the resulting stress-strain curves at different target temperatures are plotted in Figure 8.

The coefficient of thermal expansion (α), assuming concrete using calcareous aggregates, was defined using Kodur's model (Kodur & Sultan, 2003):

- For 0 ≤ T ≤ 450 °C

$$\alpha = -0.0002 + 0.000008\times T \tag{8}$$

- For 450 < T ≤ 920 °C

$$\alpha = -0.0061 + 0.000021\times T \tag{9}$$

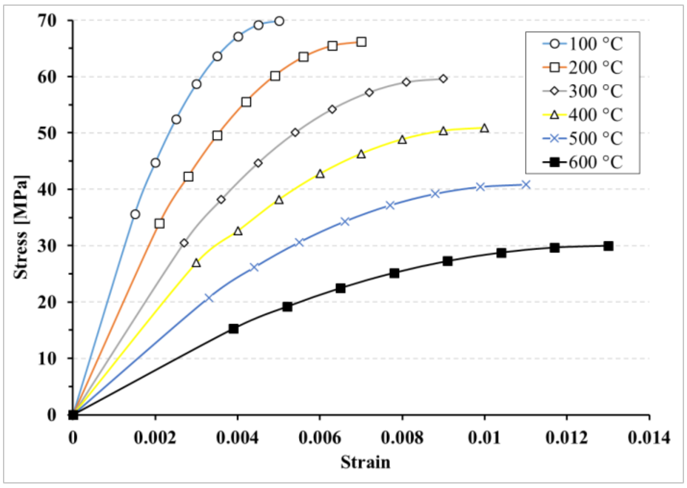


Figure 8 Stress-strain curves of concrete at different target temperatures.

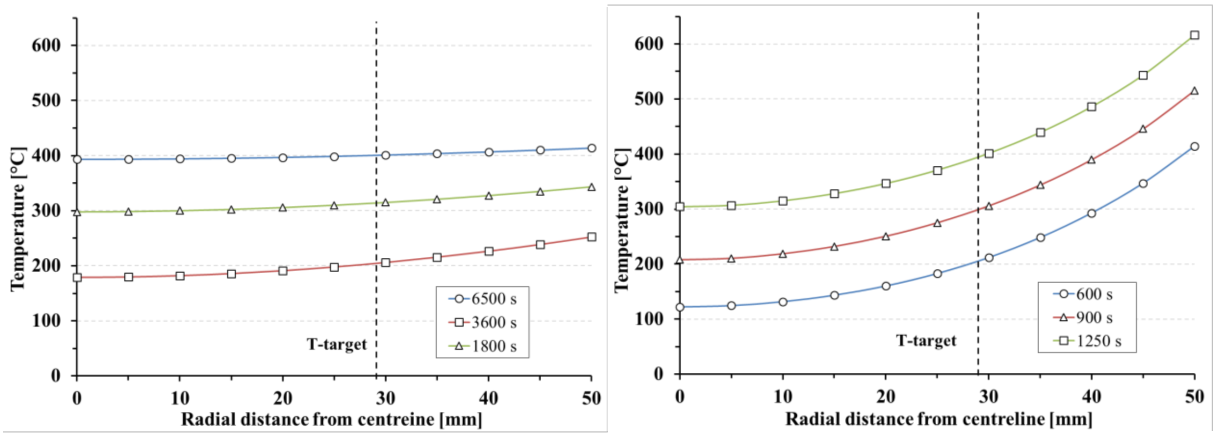
RESULTS AND DISCUSSION

To investigate the effect of temperature gradient, the temperature and stress in the concrete cylinder when subjected to two different levels of incident heat flux (q''_{inc}) of 10 kW/m^2 and of 30 kW/m^2 are studied. The cylinder, being fixed longitudinally at both end surfaces, is first subject to the imposed incident heat flux until the target temperature of 400 ºC is reached at 29 mm (being 0.58R where R is 50 mm (Le et al., 2015)) from the centreline of the cylinder. Once the target temperature is reached, a specified displacement (chosen as 0.5 mm, 1 mm and 2 mm) is imposed onto one end surface of the cylinder.

Evolution of Temperature Profiles

The evolution of temperature profile along a radius when the concrete cylinder is subject to an incident heat flux (q''_{inc}) of 10 kW/m^2 and of 30 kW/m^2 is shown in Figure 9. The following can be observed:

- The temperature profiles given by the numerical model are found to agree very well with the analytical solution (Le et al., 2015), suggesting both analytical and numerical models are appropriate.
- The time taken to reach the target temperature of 400 ºC is shorter for the case of an increased heat flux of 30 kW/m^2, compared to that of 10 kW/m^2; as expected.
- When subject to a given level of incident heat flux, the temperature gradient may change during the heating process. This is a result of the heat losses due to radiation and convection (Equation 1). Should a constant temperature gradient be required, the q''_s in Equation 1 can be kept essentially constant by manipulation of q''_{inc} through changing either the radiant intensity or position of the radiant panel system.



(a) (b)

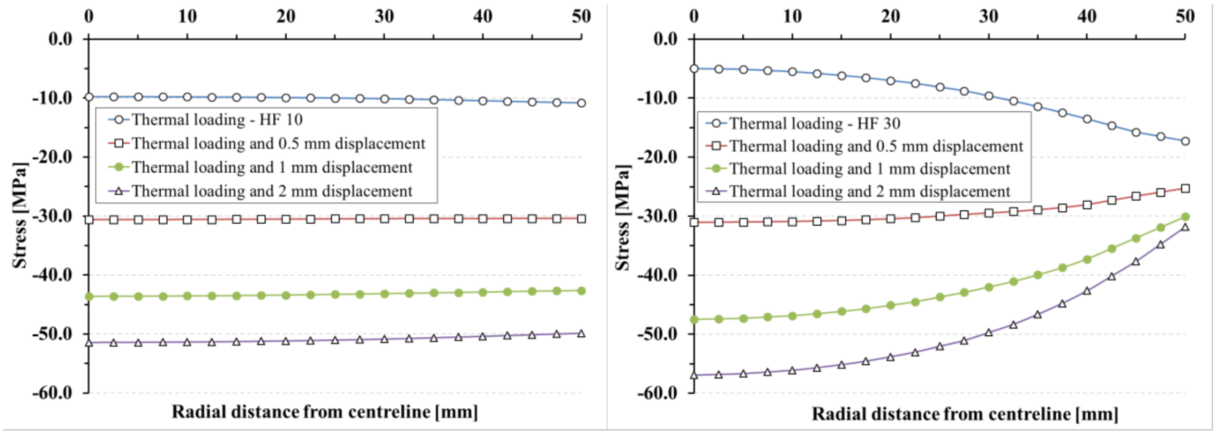
Figure 9 Temperature profiles in concrete at the different heating time of 10 and 30 kW/m^2 incident heat flux.

Stress Profiles due to combined Thermal and Mechanical Loading

As the cylinder is constrained at the two end surfaces, the different temperature distributions due to varied imposed heat fluxes in Figure 9 result in different stress profiles in the specimen, as clearly evidenced in Figure

10 (“*Thermal loading – HF10*” in (a) versus “*Thermal loading – HF 30*” in (b)): The higher the applied heat flux, the higher the compressive stress in concrete at the surface compared to that at the centre.

However, upon application of the imposed displacement, the stress distribution along a radius changes: The larger the imposed displacement and the higher the applied heat flux, the more significant the change. For the case of incident heat flux of 30 kW/m^2, the concrete stress at the surface become significantly less than that at the centre when the cylinder is subject to 2 mm imposed displacement.



(a) (b)

Figure 10 Stress profiles due to thermal loading combined with different levels of imposed displacement.

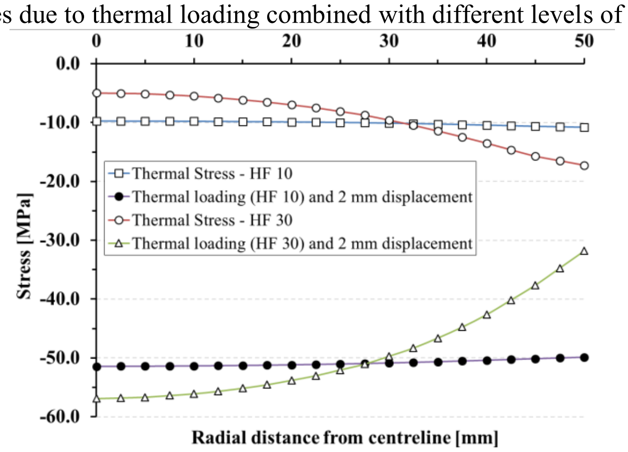


Figure 11 Illustration of stress profiles due to different applied heat fluxes.

The stress profiles along a radius due to different combinations of thermal and mechanical loadings are presented in Figure 11. It is clearly evidenced that for the same level of mechanical loading and at the same target temperature, different levels of incident heat flux may cause significantly different stress profiles, and thus potentially considerably different thermal and structural behaviour. However, such effect of heat flux, and of temperature gradient by extension, has not been captured in currently available models.

The temperature and stress profiles given by the numerical model presented in this paper will be compared to those to be obtained experimentally soon. Through such comparison, the model will be modified as appropriate. The better understanding of concrete performance in fire and improved numerical models would support the needed further transition to performance-based structural fire engineering.

SUMMARY AND CONCLUSIONS

This paper has first highlighted major limitations of conventional testing of concrete: (i) Thermal loading experienced by concrete specimens in conventional tests is very difficult to be accurately and independently controlled; and (ii) Currently available constitutive models have been primarily derived from tests with purposely-minimized temperature gradients, typically much lower than those experienced by concrete in real fires. Accordingly, the effect of temperature gradients within concrete on its fire performance has not been properly addressed – Neither has the influence of critical processes linked with temperature gradients, including thermal stresses, moisture transport, and pore pressures.

An ongoing research program at The University of Queensland thus aims to develop more realistic constitutive models through studying performance of concrete cylinders subject to known consistent heat flux boundary conditions. The numerical work for coupled thermal-stress analysis of concrete cylinder is subsequently presented in the paper. It is clearly shown that (i) Different levels of incident heat flux causes significantly different evolution of temperature and stress profiles within the specimen; and (ii) Such profiles and their nature may be considerably modified by mechanical loading. Accordingly, heat flux, and temperature gradient by extension, may have non-negligible influence on thermal and structural behaviour of concrete and concrete structures – Such influence has not been captured in currently available models.

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