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Thermal Behaviour of Damaged Reinforced Concrete in Fire

A. Ervine[1], *M. Gillie*[2], *T. J. Stratford*[2], *P.Pankaj*[2]

ABSTRACT

Safety and economic considerations dictate that structures are built to resist extreme events such as a major earthquake or fire, without collapse but some structural damage may be allowed. Fire following an earthquake is considered to be a major threat due to the risk of ignition of damaged gas and/or fuel services. The fire resistance of the structure may be compromised during the earthquake period. Hence the effect of a subsequent fire will be amplified and may lead to collapse of the structure.

This study examines the effect of tensile cracking on the thermal properties of reinforced concrete. Concrete beams in four-point bending are heated on their tensile faces. A comparison in made between the thermal response when a beam is under serviceability loads and major damage that may occur during extreme events. It is found that tensile cracking has a measurable adverse affect on the temperature profile through the cover of a reinforced concrete beam. Therefore, if a section is significantly cracked in tension, any heat applied will be allowed to propagate more quickly through the cracked region.

INTRODUCTION

Whilst the thermal conductivity of concrete is well documented, most available data relates to concrete that is undamaged. There are many scenarios (e.g. analysis of structures subject to fire following earthquake) in which knowledge of the conductivity of damaged concrete may be important. This is because the conductivity of damaged concrete may be significantly different to that of undamaged concrete and could lead to earlier structural failure in fire. The experiments detailed in this paper were designed to establish if tensile cracking resulting from damage alters the effective thermal diffusivity ($k/\rho c$) of concrete to a degree that can not be neglected in analyses of fire affected structures. Three hypotheses are considered

Hypothesis I

Tensile cracking does affect the effective thermal diffusivity of concrete so that heat transfer is more rapid; hence rebar layers will experience high temperatures more quickly than in undamaged concrete. This would cause the steel to be subjected to localised heating and elongation which could lead to failure of a member or structure more quickly than previously expected.

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[1] PhD, Dept Civil Engineering, University of Edinburgh, UK
[2] Lecturer, Dept Civil Engineering, University of Edinburgh, UK

Hypothesis II
Tensile cracking does not significantly affect the thermal diffusivity of concrete; hence rebar layers will experience similar temperatures in a similar time to those in undamaged concrete. This would mean that the effects are negligible and do not need to be accounted for in analyses.

Hypothesis III
Tensile cracking does affect the thermal diffusivity of concrete so that heat transfer is slower; hence rebar layers will experience high temperatures more slowly than in undamaged concrete. This would cause structures to perform better than previously expected in fire.

PREVIOUS WORK

There has been research into the thermal properties of concrete and how they vary with temperature. Similarly, there has been work on the cracking of concrete and reinforced concrete in tension. However, these research themes have yet to be combined to determine the thermal properties of cracked reinforced concrete.

Kong *et al* (2007), and Beeby. and Scott (2005) studied the behaviour of average tensile crack width with respect to the tensile stress within reinforcement. However the stresses and strains considered all fell into the elastic region of the reinforcement which corresponds to very small crack widths (of the order of $1x10^{-1}$mm). It would be inappropriate to extrapolate this information to situations where concrete members are damaged because in such cases the reinforcement steel may have yielded and cracks reached widths of the order of $1x10^{1}$mm or greater.

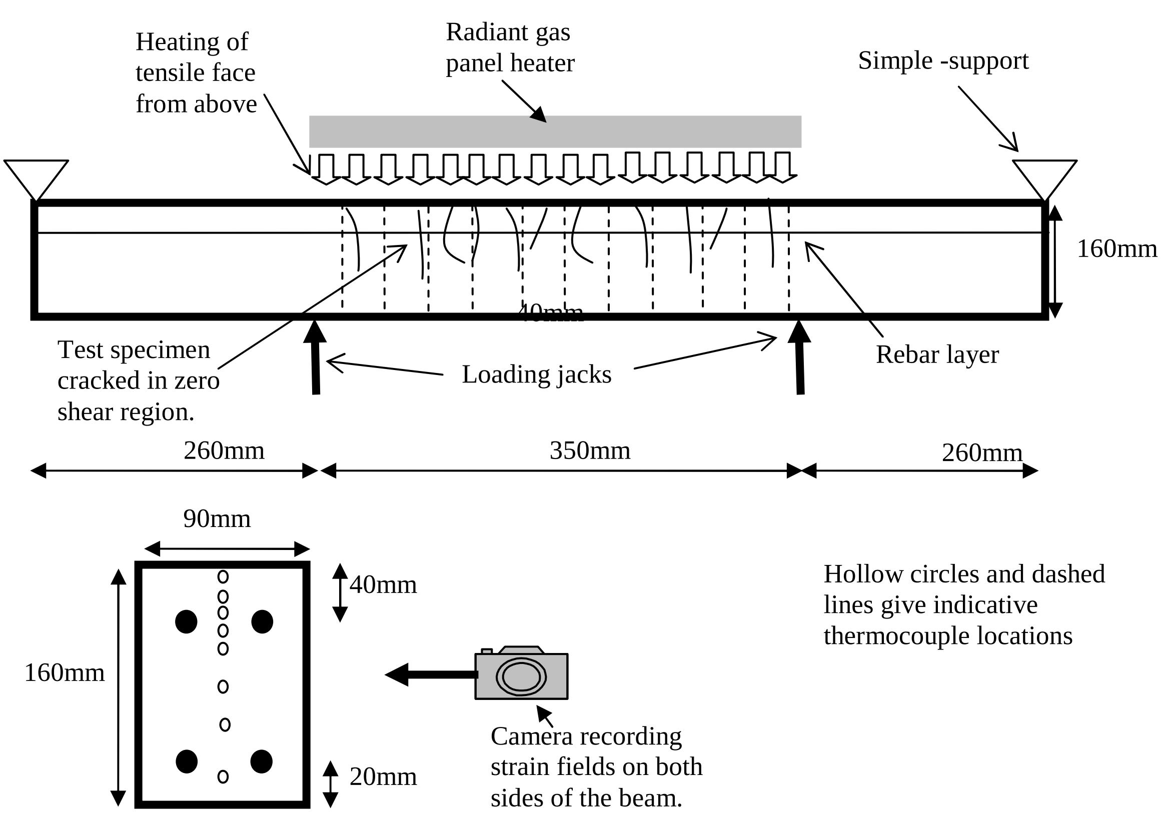
Vejmelková *et al* (2009) studied the effects of cracks on the hygric and thermal characteristics of concrete and obtained data suggesting the conductivity of cracked concrete decreases due to the increased porosity of the material and only increases with an increase in moisture content. They suggested that the air within cracks acts as an insulator and hence hinders the propagation of heat through the structure. A significant limitation of this work is the fact that the crack dimensions were not reported so the results cannot be combined with Kong *et al*'s work to find a relationship between crack width and conductivity. Furthermore, plain, not reinforced concrete was used so application of the results to real structures would be difficult in any case.

Thus, work aimed at determining the thermal properties of crack-damaged reinforced concrete is very limited. The work that has been undertaken has either been with un-reinforced concrete or within the elastic range of the reinforcement. The inclusion of reinforcement in the concrete during an experiment that considers cracking is vital because the reinforcement drastically alters the cracking pattern and crack propagation though a section. During extreme events such as earthquakes and blast it is unreasonable to assume that the reinforcement remains within its elastic range as these extreme events will cause larger cracks to form in the concrete. The larger the cracks within the concrete cover the more influential the buoyancy effects within these cracks become. The air within the cracks may no longer act as an insulator as Vejmelková *et al* suggest but may effectively allow heat to instantaneously penetrate the concrete to the reinforcement level.

EXPERIMENTAL DESCRIPTION

An experimental programme was undertaken to establish which of the three hypotheses detailed in the introduction is most representative of reality. To do this beams in four point bending were heated on their tensile faces and internal temperatures measured for different crack widths. The beams used were doubly reinforced 35MPa (nominal) concrete with dimensions of 90×160×870mm. The reinforcement was 10Φ mm 460MPa steel. Concrete cover was 20mm on all sides with the exception of the tensile face which had a cover of 40mm. Increased cover on the tensile face was designed to induce larger tensile cracks which would be representative of beams of larger, more realistic dimensions. The beams were then loaded vertically upwards as shown in Fig 1, either to failure or to the required deflection depending on the stage of the experiment (see permutations table below). Heating was applied from above via a radiant gas panel.

Loads were recorded from load cells placed under the loading jacks and deflections from gauges at mid-span and other key locations. Load and deflection data was recorded at 2s intervals. Strains fields within the area of zero shear were recorded using image correlation by taking photographs of both sides of the beam at 5s intervals and processing these with a program developed by Bisby et al (2007). Temperatures in the beam during both the heating and cooling phases were recorded using a large number of thermocouples within the heated section of the beam, with the highest density being in the tensile concrete cover. As the intestigation was to determine if tensile cracking has any effect on the effective thermal diffusivity, the majority of the thermo-couples were placed within the concrete cover on the tensile side of the beam. Details of this and other aspects of the experiments are shown in Figs 1 to 6



Hollow circles and dashed lines give indicative thermocouple locations

Figure 1. Experimental setup showing side view of loaded beam and a typical cross-section.

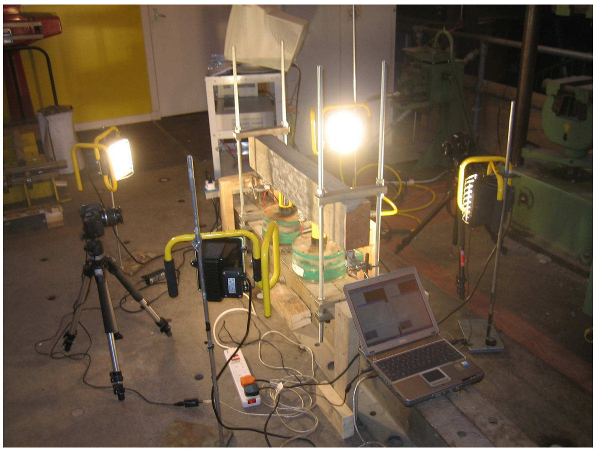


Figure 2. General mechanical set-up


Figure 3. General thermo-mechanical set-up


Figure 4. Loading set-up

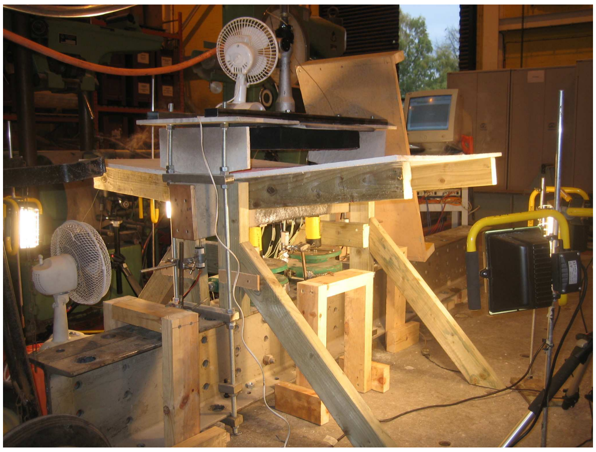


Figure 5. Testing in progress

Beams were tested with various heating and loading arrangements as detailed in Table 1. Critical to the test programme was comparing the heat-transfer in the beams when they were damaged to different degrees. The behaviour of beams with “minor” and “major” damage was compared. To allow damage levels to be defined, two beams were loaded without heating and their load-deflection behaviour recorded. Minor damage was defined as the crack width that occurred when an unheated beam was loaded to point at which it ceased to behave linearly. Major damage was defined as the crack width that occurred when an unheated beam was loaded to its ultimate load. Crack widths of these magnitudes were maintained during the thermal tests by controlling the deflections of the beams.

Table 1 Loading permutations examined during the test programme.

Permutation	Thermo-couples	Loading Phase	Heating Phase	Aim
1	-	√	-	Load incrementally to failure to determine crack widths and distribution as function of load
2	-	√	-	Repeat of permutation 1
3	√	√	√	To determine effect of minor damage on thermal behaviour.
4	√	√	√	To determine effect of minor damage on thermal behaviour.

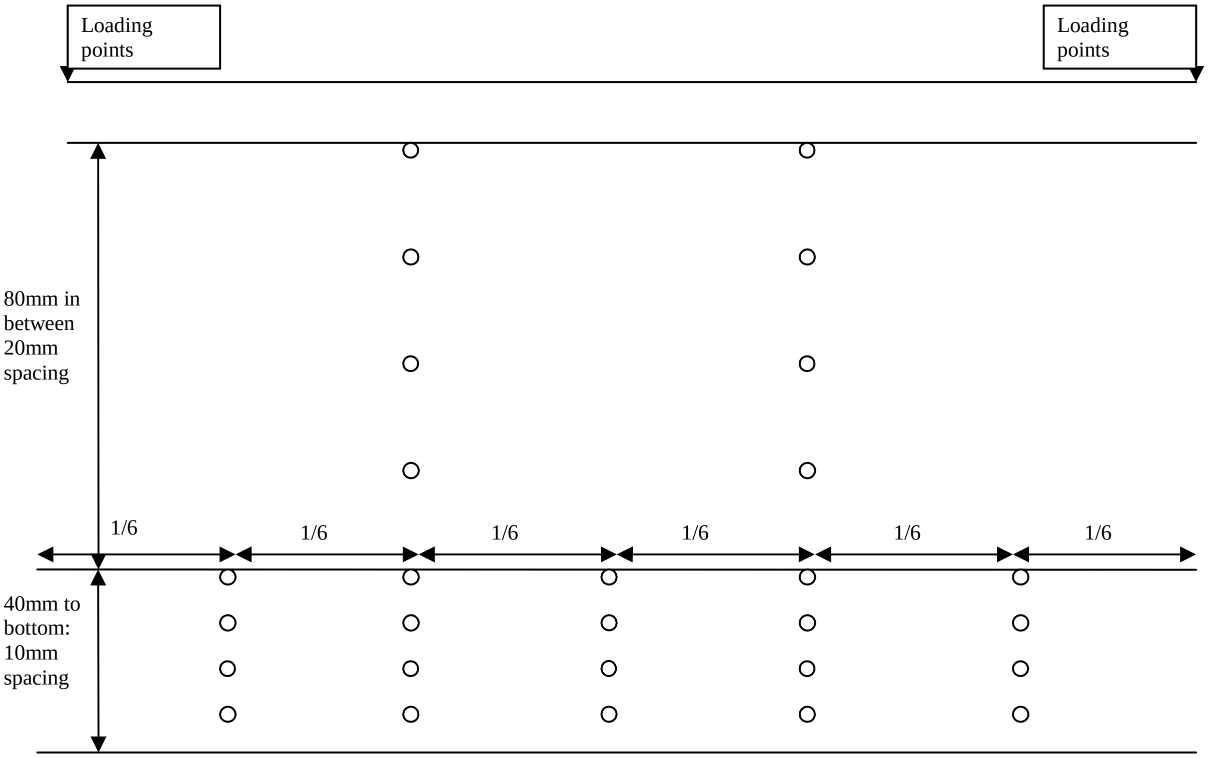


Figure 6. Placement of thermo-couples

EXPERIMENTAL RESULTS

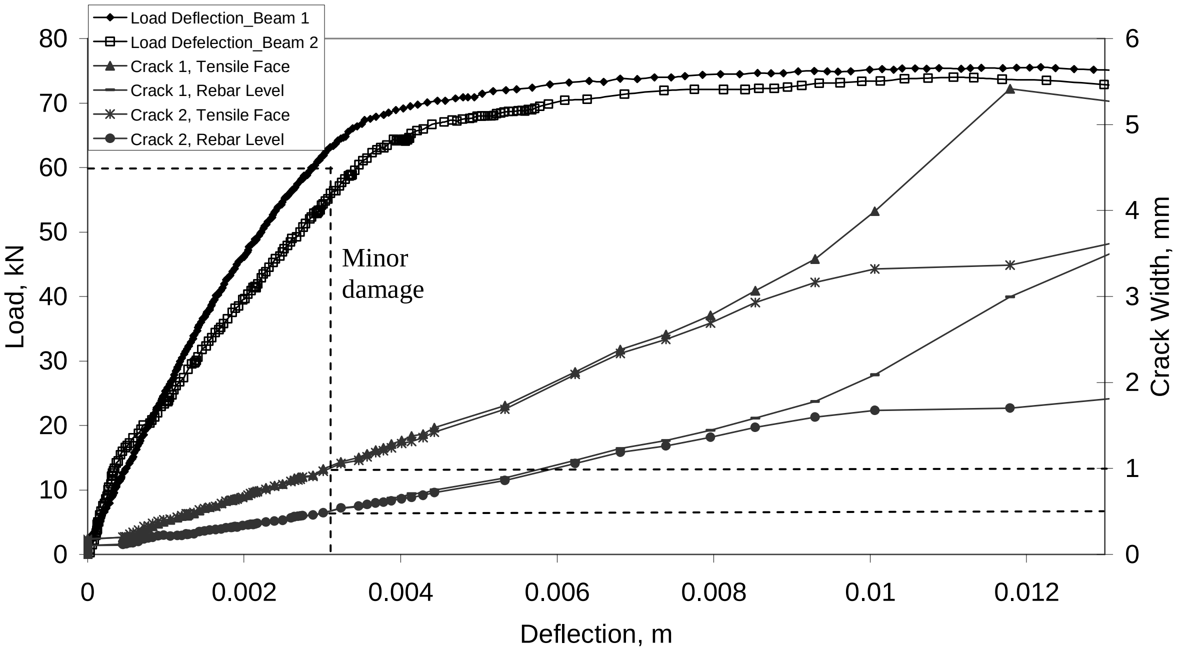


Figure 7. Load versus deflection (left axis); Load versus crack width (right axis)

Definition of Damage

From Fig 7 it can be seen that the beams subject to purely mechanical load behaved similarly. Transition from elastic to plastic behaviour occurred at approximately 60kN with a mid-span deflection of 3.5mm and the ultimate load was approximately 75kN (approximately 1.3 times the design load). These results therefore can be used as measures of minor and major damage states in terms of crack widths. The label “minor damage” will be defined as a state that occurs under reasonable serviceability loads; whilst “major damage” will be defined to occur some way into the plastic region. Therefore, the minor damage state will be set to experience loads in the region of 60kN and a mid-span deflections of 3.5mm; whereas the major damage state will be set to experience loads in the region of 74kN and a mid-span deflection of 12.5mm. Images of these states can be seen in Figs 8 and 9. When considering the major damage crack widths an average was taken of the cracks.

Table 2 – Damage State Summary

	Minor Damage	Major Damage
Load, kN	60	74
Mid-span Deflection, mm	3.5	12.5
Average Surface Crack Width, mm	1	4.5
Average Rebar Level Crack Width, mm	0.5	2.5

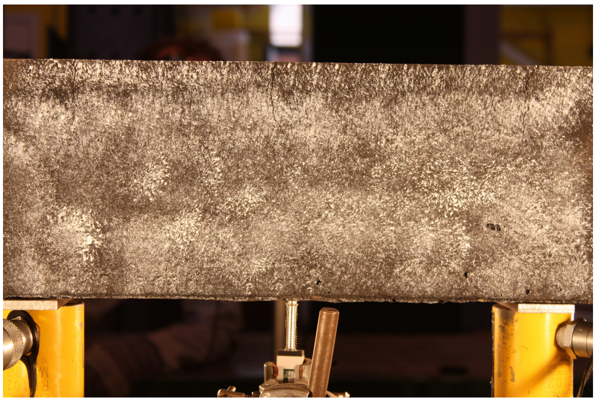


Figure 8. Minor damage image

Figure 9. Major damage image

Thermal Results

Figs 10 and 11 below illustrates the thermal profile from surface gas temperature to concrete temperature at reinforcement level (i.e. 40mm) for both minor and major damaged specimens respectively. It is to be noted that the when conducting the major damage experiment, the heater began to fail. Therefore instead of getting a full hour of heating and cooling the beam was only subjected to 35 minutes of heating and one hour of cooling. It should also be noted that during the major damage test, the surface gas temperatures experienced where, for the most part, lower than that of its minor damaged counterpart (this was dues to minor differences in the insulation arrangements). Despite this however, the average temperatures through the cracked section of the major damaged specimen are generally higher than those experienced by the minor damaged specimen. This is true at all depths through the concrete cover. However, at the depth where the reinforcement lies, there was no change in the recorded temperature between specimens.

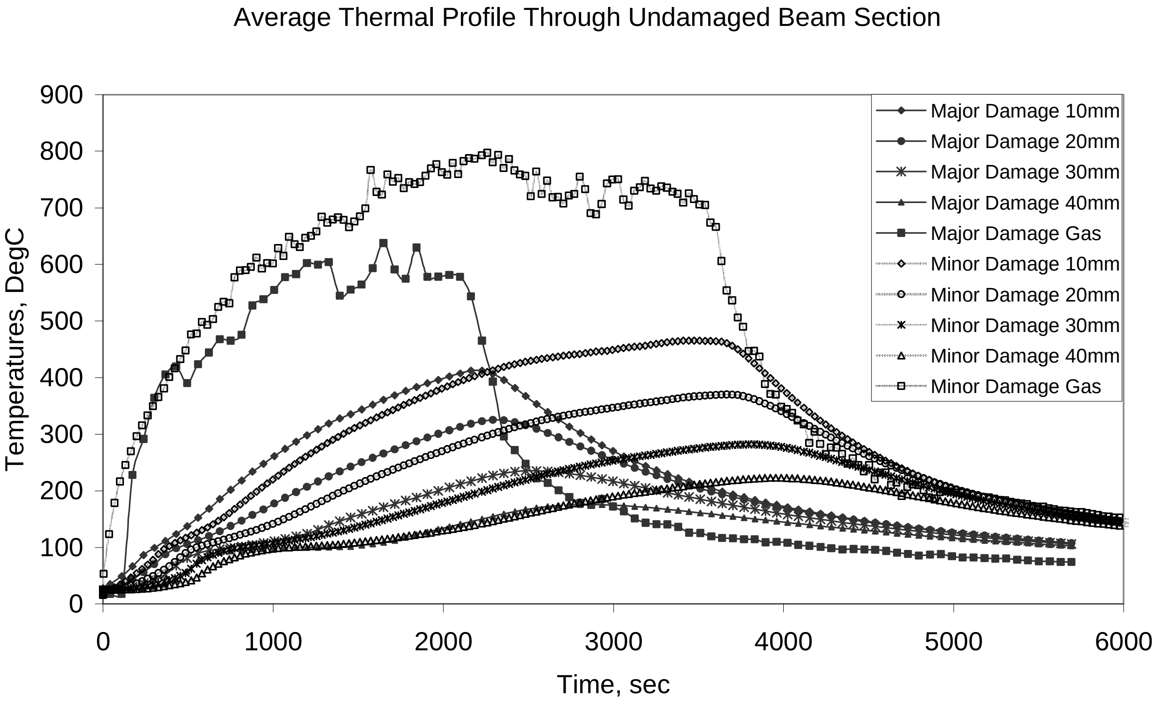


Figure 10. Comparison of thermal profiles for minor and major damaged sections

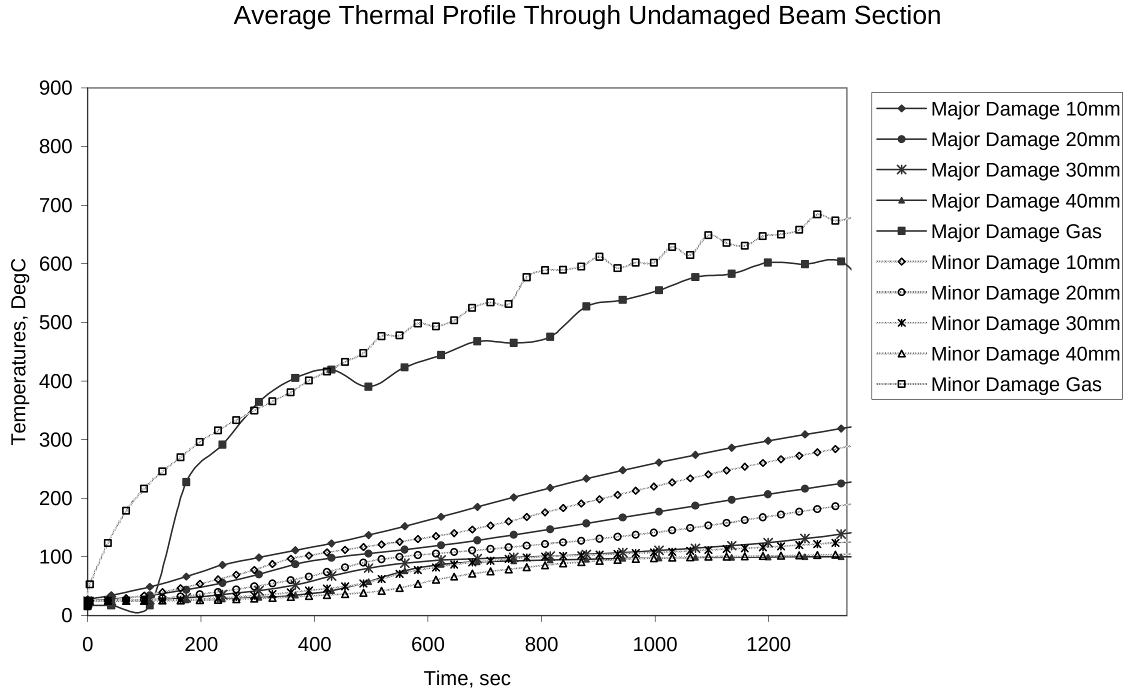


Figure 11. Comparison of thermal profiles for minor and major damaged sections

CONCLUSIONS

The results show that the thermal diffusivity of reinforced concrete increased when the beam was subjected to tensile cracking of the order of 10^1mm at the surface, and that this increase is apparent to depth of about 30mm within the concrete for a heating time of 30minutes. Therefore, the first part of Hypothesis I is accepted and Hypotheses II and III rejected. However, the rebar temperatures were not observed to be difference between major and minor damage tests. Consequently the effects of the increased diffusivity on structural failure times are not clear. In the tests conducted the rebar temperatures remained the same so the structural strength would not be altered. However, in real structures the increased cover temperatures that result from cracked concrete may well result in surface concrete spalling. In such cases temperatures at rebar level would thus increase more rapidly and early failure becomes probable. Moreover, the tests presented here are only comparable for a relative short period of heating. If heating had been maintained for a full hour, or longer, it is probable that the differences in temperature between the two samples would have been observed at the depth of the rebar. Further tests are planned to gain a more complete picture of the effects of cracking on diffusivity of damaged concrete.

ACKNOLEDGEMENTS

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REFERENCES

[1] Vejmelková, E., Padevět, P. and Černý, R., *Effects of cracks on hygric and thermal characteristics of concrete*, Ernst & Sohn (2009)

[2] Beeby, A.W. and Scott R.H., *Cracking and deformations of axially reinforced members subjected to pure tension*, Magazine of Concrete Research, (2005), 57, No.10, December 611-621

[3] Kong, K.L., Beeby, A.W., Forth, J.P. and Scott R.H., *Cracking and tension zone behaviour of RC flexural members*, Structures and Buildings 160 Issue SB3 (22/03/2007), 165-172

[4] Bisby, L., Take, A.W. and Caspary, A., *Quantifying Strain Variation in FRP Confined Concrete using Digital Image Correlation: Proof-of-Concept and Initial results*, Department Civil Engineering, Queen’s University, Canada