# Failure of Heterogenous Composites due to Thermal Stresses in Presence of Pre-Cracks†

**EL-SHEIKHY Refat* and NAKA Masaaki****

## Abstract

*Heterogeneous composite plates including inclined cracks were exposed to time dependent direct thermal stresses due to firing. The cracks were mixed mode cracks. The concrete heterogeneous composite plates were studied under the thermal stresses only and then studied under monotonic static loading after the pre-effect of the direct thermal stresses. The cracks were well observed during the effect of thermal stresses due to firing. The crack movements and failure resistance to thermal stresses were studied in addition to material strength effects. The heterogeneous composite plates were exposed to different degrees of temperature and different times of thermal effect. The results are important and useful for structural design, protection, repair and maintenance. The results can be applied for any heterogeneous composite. Concrete is a heterogeneous composite material involving the different solid materials bonded and joined together by cement.*

**KEY WORDS: (**Concrete composite), (Firing), (Thermal stresses),( Cracks), (Biaxial ratio)

## 1. Introduction

Some structures made of heterogeneous composites were destroyed completely during the firing exposure, especially concrete buildings, after very few hours and were less than the usual expected times of failure due to firing for heterogeneous composites such as concrete [1-8]**)** . We expected that the reason of reducing the resistance of concrete was accompanied by the presence of some defects and cracks. Therefore, in order to study this very important subject we studied the effect of firing on the concrete with cracks. This is because we supposed that these failed structures may have had some pre-existing cracks before firing exposure. In order to study this phenomenon we carried out the current research [9-12)].

Of course, the thermal effects on concrete composites are very serious, especially for fibrous concrete composites with longitudinal steel bars for reinforcement. But when the thermal effect on concrete elements becomes due to the direct fire exposure, the problem will be more serious because the concrete elements could be under the effect of concentration of very high stresses. Then, the stress concentration would cause serious cracks in addition to changing the mechanical properties and strength of the concrete material. It also would reduce the bond strength between the concrete composite materials which by a de-bonding process at the interface between different materials concrete composite which were (coarse aggregate, fine aggregate and cement). If there were other external loads on the concrete elements, it would produce more stresses on the concrete in addition to the stresses due to fires. This would lead to the propagation of cracks in presence of the changing mechanical properties. Concrete material is a brittle heterogeneous porous composite. The firing will make it more brittle with the extension of the pores sizes producing cracks. The thermal conductivity factor of each component is different from the others. These differences also create more internal stresses due to the different expansion sizes of the particles. Since the expansion will be homogeneous, if we consider that the thermal conductivity factors are same or if we neglect their effect, of course the chemical composition will be changed by heating especially for cement material and any additional additives. If concrete contains steel reinforcement as long steel fibers the problem will be different since the steel is a ductile material with high thermal conductivity.

The most serious problem is that the concrete composite has some pre-cracks before firing exposure. The cracks would have very high stress concentration around their tips. These cracks, under additional stresses due to thermal stresses of fires could propagate causing the failure of the structures. The stresses would be thermal stresses and stresses due to service loading in the presence of reduction of the material strength, mechanical properties and cracking properties such as fracture toughness and critical cracking load which would lead to fast unstable propagation of the cracks causing total failure of the structure.

We tried in this research to treat problems of effects on concrete due to firing by studying effects of firing on the pre-cracks. The study is concerned to most traditional

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and serious cracks which are mixed mode cracks. The experimental work was made in the laboratories of Housing and Building Research Center in Egypt. The results are important in the design of concrete structures.

## 2. Experimental

The experimental work for studying the effect of the firing on the cracked concrete is carried out in this research. This experimental work included concrete cubes without cracks and concrete plates including artificial pre-cracks.

### 2.1 Description of concrete test samples

The experiments consisted of two parts, one for the cubes and the other for the panels. The dimensions of the concrete cubes were (5cm length x 5 cm width x 5 cm height) for each cube. The total number of cubes was 15. The dimensions of the concrete panels were of (20 cm length x 20 cm width x 5 cm thickness) or (20 cm length x 20 cm width x 10 cm thickness). The total number of tested plates was four; two panels of each type. The cubes are divided into five groups. Each group contains 3 cubes. Each group is tested to certain degree of firing temperature and for different firing time. The concrete composites material is composed of dolomite as a coarse aggregate, sand as a fine aggregate and ordinary Portland cement in addition to the water content.

### 2.2 Testing procedures

2.2.1 Heterogeneous composites cubes

The experiment of the cubes was made to investigate mainly the effects of firing on the cube strength of the concrete. The cubes are divided into five groups. The first group is tested under compression loading without exposure to the firing effect. The other groups are exposed to the firing at 600℃ inside a closed oven. Group No. 2 is exposed to firing of 600℃ for only 1.0 hr. Group No. 3 is exposed to the firing of 600℃ for 2.0 hrs. Group No. 4 is exposed to the firing of 600℃ for 4.0 hrs. Group No. 5 is exposed to the firing of 600℃ for 6.0 hrs. All cubes are tested under compression loading to establish the average compressive strength for each group. The results are recorded in **Figs. 1 and** 2. **Figures 1 and 2** show the decrease of the concrete strength due to the relative firing time at firing temperature of 600℃.

2.2.2 Heterogeneous composites panels

The cracked concrete plates contain two groups. The dimensions of each plate of the first group are (20 length cm x 20 width cm x 5 cm height) while the dimensions of each of the second group are (20 length cm x 20 width cm x 10 cm height). . Each sample of the two groups has an inclined pre-crack with an inclination of 45 o . These cracks are made during the casting of the concrete panels. The artificial pre-cracks have inclination to represent the mixed mode cracks which are the usual cracks in the structures in order to examine the effect of thickness on the cracks during and after the firing process and studying of the size effect on the fire resistance of the cracked concrete.

The cracked concrete panels are exposed to direct firing on only one face. All of the test samples are exposed to firing at the same temperature degree of 600℃. Some samples of each group are exposed to firing for a time of only 1.0 hr while all of the other samples of the two groups are exposed to firing for 6.0 hrs. The results of the firing are recorded and shown in the **Figs. 1 to 1**5. The temperature of crack propagation, cracking time, propagation angle, propagation paths and fracture surface are recorded. Then, the samples are tested under compression loading using a computerized displacement control machine. These tests are made to check the fracture capacity of the concrete after firing. This is very important step to check what will happen to the fired structures to lead to the full collapse. This is shown in **Figs. 1 to 15.**

## 3. Analysis and Discussions

The experimental work in this research is intended to study the effect of the following points

1- Exposed concrete surfaces to the fire.
2- Exposed pre-cracked parts of the concrete element to the fire.
3- Effect of the fire on concrete surfaces.
4- Effect of the fire on the concrete composite.
5- Effect of the fire on concrete compressive strength ( $\sigma_c$ ).
6- Effect of the fire on the fracture properties of concrete.
7- Exposed free crack surfaces to the fire.
8- Exposed tips of the cracks to the fire.
9- Exposed side of the crack to fire.
10- Losses of the heat of applied thermal stresses due to firing.
11- Effect of firing time on the cracked concrete element.
12- Crack propagation direction explaining that crack will propagate in three dimensional fracture.
13- The stresses on the crack due to thermal loading are multi-axial stresses.
14- The crack will be in mode mixed (I +II+III)
15- Effects of the thermal stresses on the crack in all directions X, Y, Z.

To explain the above mentioned points, the results were discussed and analyzed as follows;

The experimental work was carried out on concrete cubes to study the effect of the firing on the concrete compressive strength ( $\sigma_c$). From the results shown in **Fig. 1** and **Fig. 2,** it was recorded that the concrete could resist the fire of 600℃ without bad effect on the compressive strength for 1.0 hr period. After period of 1.0 hr, the

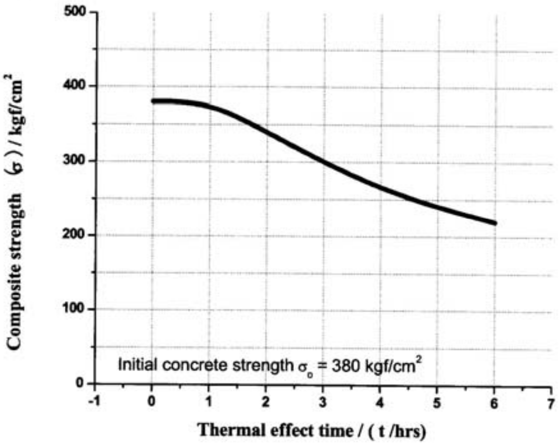


**Fig. 1** Composite strength and thermal time relation.

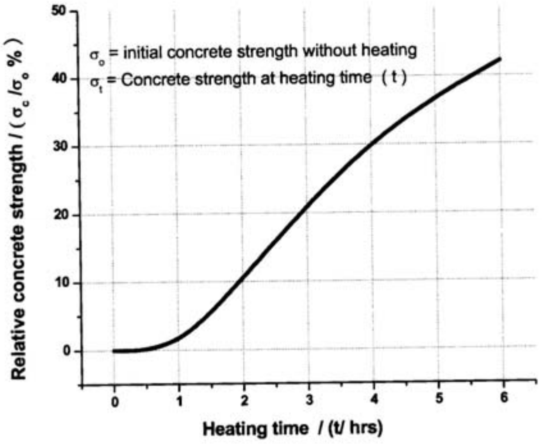


**Fig. 2** omposite strengtrh decreasing ratio and thermal time.

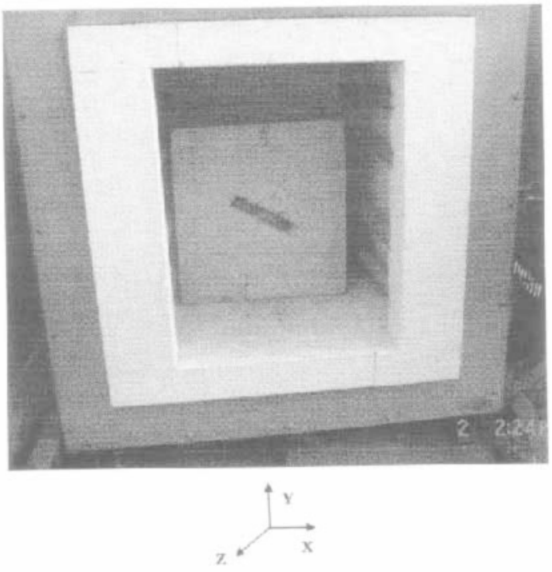


**Fig. 3(a)** Crack concrete panel with inclined pre-crack inside the oven during firing process.

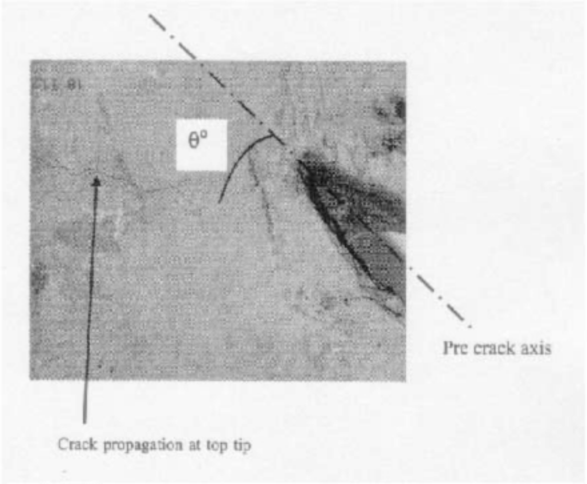


**Fig. 3(b)** Crack propagation at top of the pre-crack due to firing.

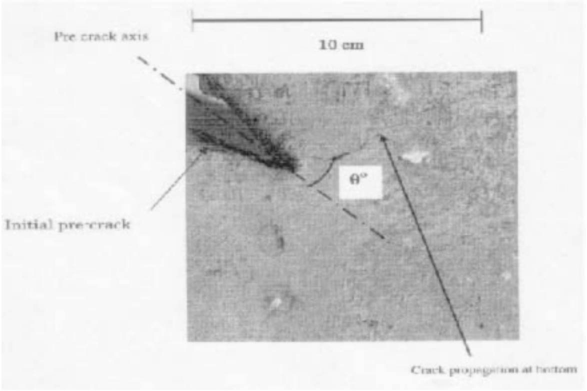


**Fig. 3(c)** Crack propagation at bottom of the pre-crack due to firing.

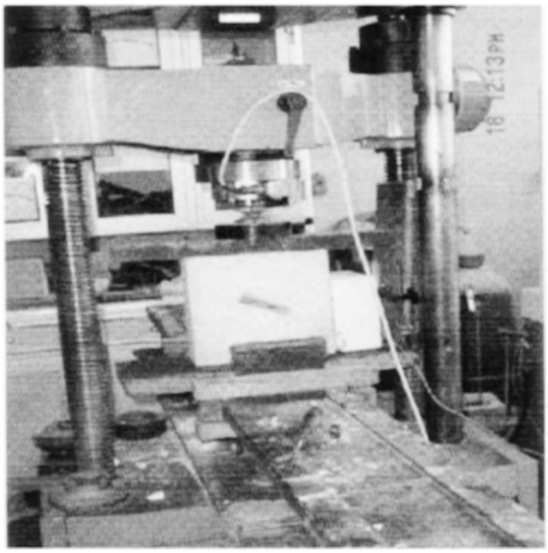


**Fig. 4(a)** cracked concrete sample under compression testing,

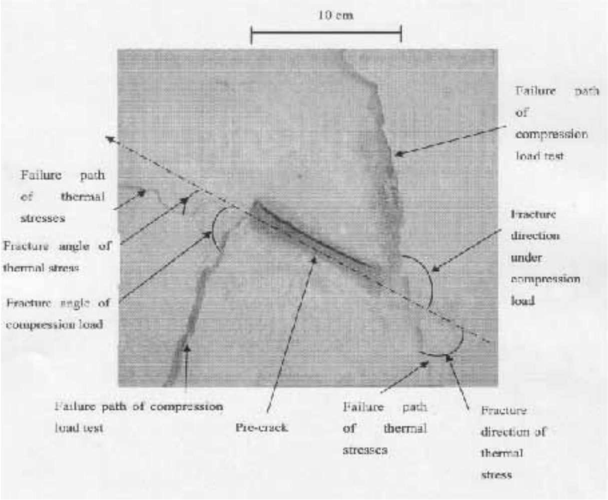


**Fig. 4 (b)** Failure of test sample showing the cracking path.

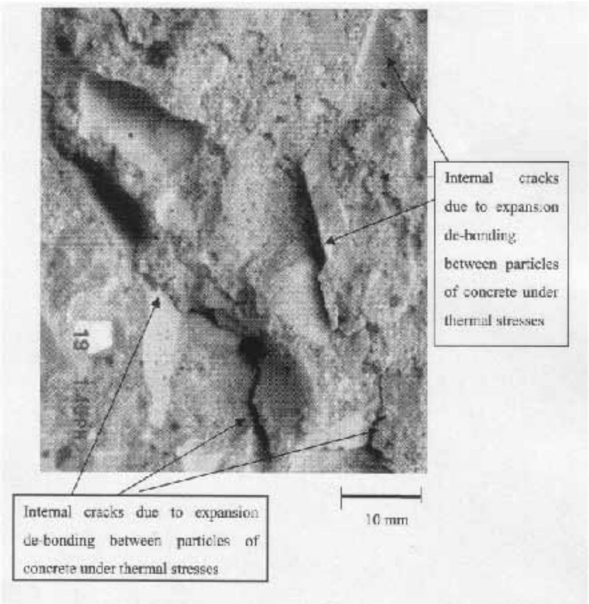
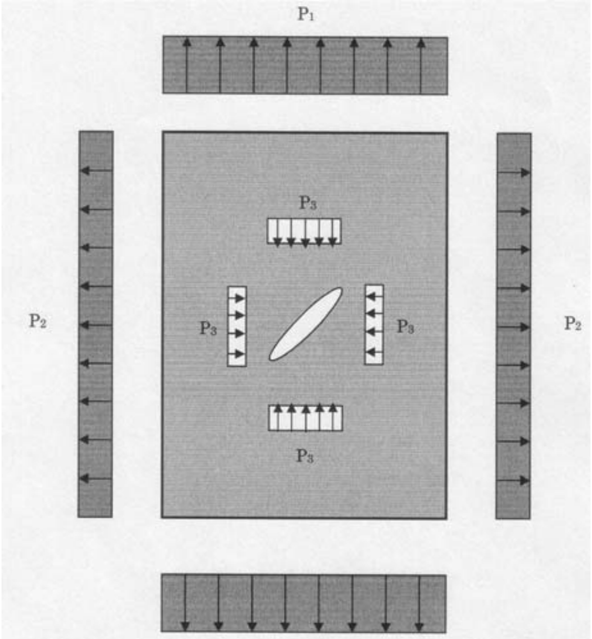


**Fig. 5** Concreate surface at failure zone indicating types of failure, fracture and de-bonding between composite components and particles.



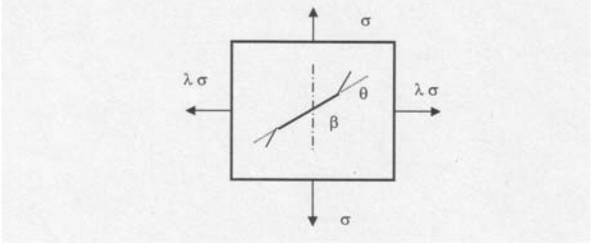


**Fig. 6 (a)** Equivalent stresses and displacements on lateral direction Z of test sample fired on only one face.

**Fig. 6 (b)** Equivalent stresses on test sample fired on only one face considering the heat losseses.

strength would be reduced sharply. In the case of period of (2.0 hrs) firing time the strength would be reduced by (10.5%). In the case of firing time of 4 hrs at 600℃ the strength would be reduced by (31.6%) while in the case of 6 hrs firing time at the same temperature 600℃ the strength would be reduced by (42.1%). This reduction of strength of non cracked concrete can led to failure of the structure due to sharp reduction of concrete compressive strength. But in these tests of the cubes, the firing was on all concrete cube faces and uniform in a closed oven without heat losses; while in the nature the firing may be only on some faces of the concrete elements while the other faces will not be exposed to the fire. Therefore, in the field the fire may be not uniform on the whole concrete element in addition to the open space which will increase the heat losses of the firing temperature. Also, the reinforced concrete element contains steel bars which are metallic ductile material with a high thermal conductivity factor and can be affected easily by temperature with high sensitivity producing de-bonding with the concrete and cracks with change of the properties of the steel reinforcement and reducing the design tensile strength. This will produce a severe effect on the concrete elements. In the case of the presence of pre-cracks or defects in the concrete elements, the state will be different. It will be more serious. Therefore, our study is carried out mainly for this reason.

As the results of studying the experimental work tests of the concrete cubes, it is found as indicated in **Fig.**

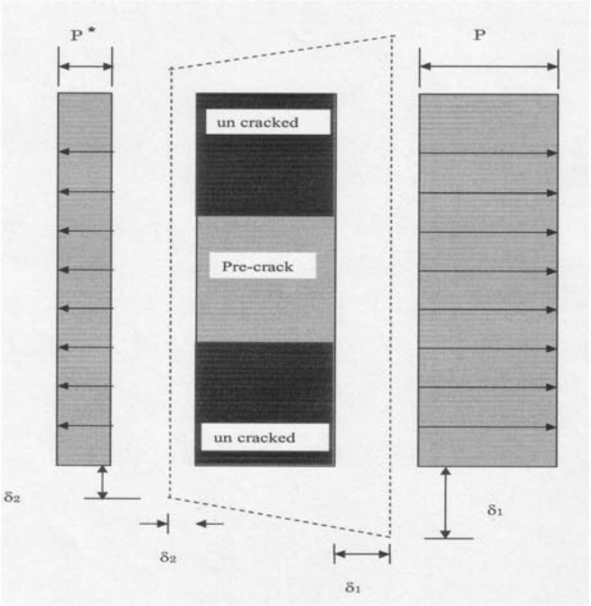


**Fig. 7** Equivalent stresses on test sample fired on all faces.

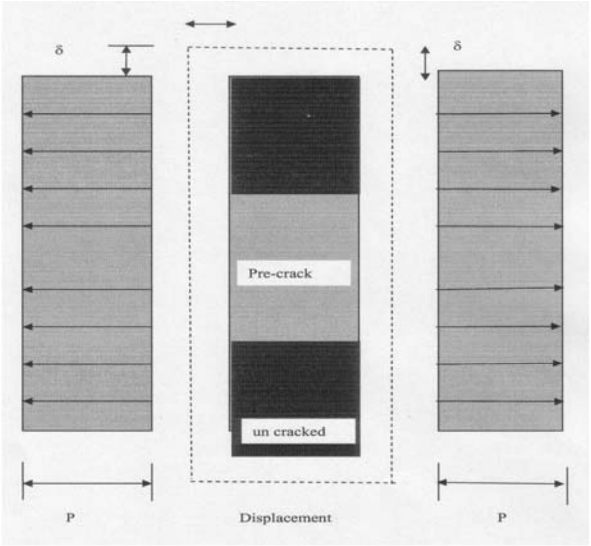


**Fig. 8** Crack in biaxial field of stress under tension-tension stresses respecting firing effects on test samples.

**1** and **Fig. 2** that the cubes of 1.0 hr firing time show no serious effect on the decrease in the concrete strength while the cubes of 6.0 hrs firing time have severe and worse effect and decrease in cube strength. Therefore the pre-cracked concrete panels are tested under these two firing time for the same firing temperature 600℃.

The cracked panels are shown in **Figs. 3** to 5. The schematic representations and the results obtained in the figures for the heterogeneous composites panels during and after firing are shown in **Figs. 6 to 1**0. Also, the results of the cracking due to firing are shown in **Figs. 11 to 1**5. The following points are recognized

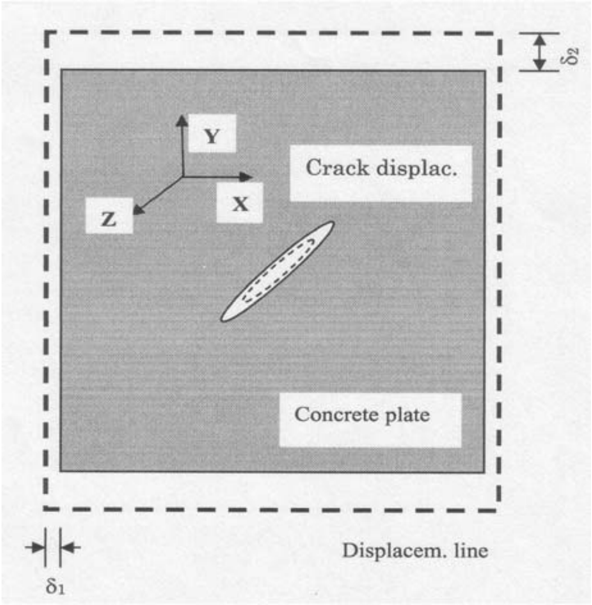


**Fig. 9** Schematic representation of displacements on test samples under non equal firing effects.

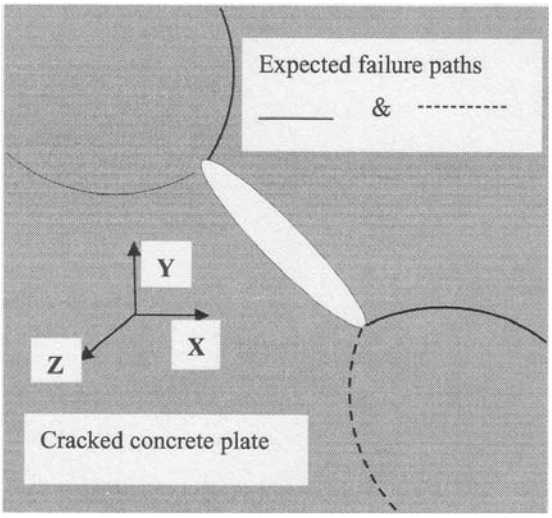


**Fig. 10** Theoretical propability of pre-crack propagation due to firing effects.

1- The thermal stresses are three dimensional as indicated in **Figs. 6 and 1**0, since temperature is not uniform or uniform on all faces, where:

**Figure 6** indicates schematic representation of expected stresses and resulting deformations of a concrete plate under non uniform firing exposure with the fire concentrated on the inner face of the concrete inside the oven as shown in **Fig. 3(a)** while the door of the oven is not closed. The outer face of the concrete plate will be exposed to fire stresses less than the inner face. Therefore, the displacement values of the two sides will be different ( $\delta_1$ for inner face > $\delta_2$ for outer face). The lateral side

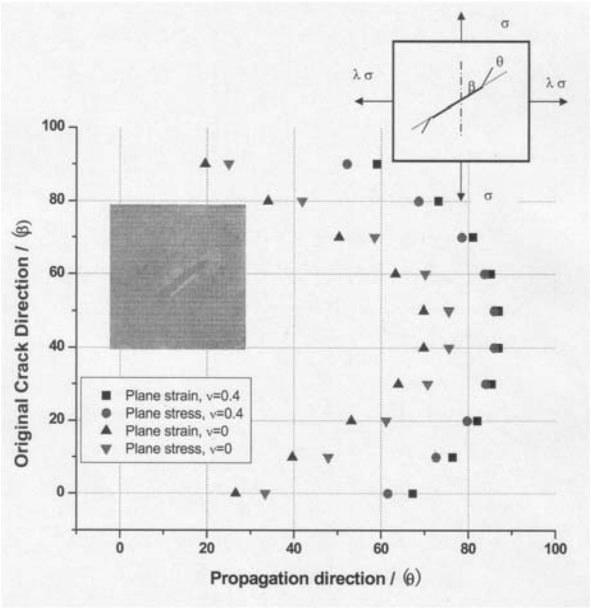


**Fig. 11** Cracking direction for bi-axial ratio ( $\lambda=(\sigma x/\sigma y)=1.0$).

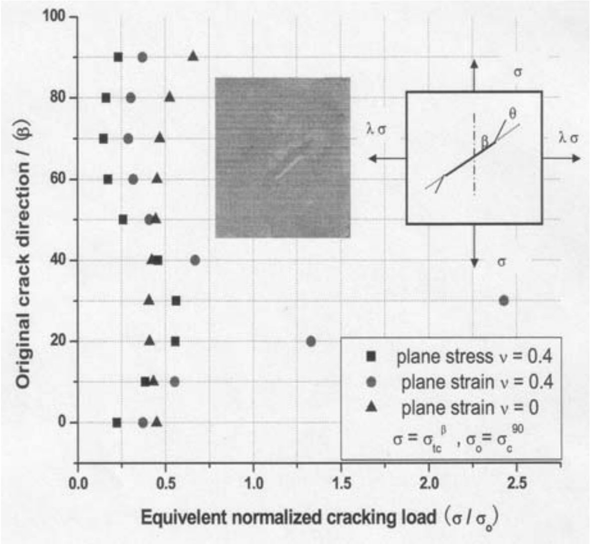


**Fig. 12** Equivalent cracking load for bi-axial ratio ( $\lambda=(\sigma x/\sigma y)=0.5$).

displacements also will be not equal ( $\delta_1$, $\delta_2$ values are on the same edge of the plate) depending on the non uniformity of applied stresses. **Figure 6** shows the side view of the concrete panel including the pre-crack and representation of tension stresses due to thermal effects on the two sides under non uniform firing.

**Figure 7** indicates a schematic representation of the stresses and deformations on concrete plate under uniform firing. The fire was concentrated on both the inner and outer faces of the concrete plate inside the oven and the door of the oven was closed. Then the stresses on the concrete plate will be uniform on all faces and sides of the concrete plate. Therefore, the displacements values of all sides will be equal ( $\delta$ ). The lateral side displacements also will be equal ( $\delta$ ). **Figure 7** shows the side view of the concrete panel including the pre-crack and representing the tension stresses due to thermal effects on the two sides under uniform firing.

**Figure 8** shows the expected thermal effects on the concrete plate and the pre- artificial inclined crack. The stresses on the sides and edges of the concrete panel $P_1$ and $P_2$ represent the thermal stresses on the sides of the concrete plates. The stress value ($P_3$) represents the direct stresses on the pre-crack. The final resultant stresses on the pre- crack will be ($P_1 - P_3$) in vertical direction and ($P_2$ - $P_3$) in horizontal direction. The resultant values of ($P_1 - P_3$) and ($P_2$ - $P_3$) will be equal or not equal depending on the relative dimensions of the concrete element and crack dimensions and position.

**Figure 9** represents the shape, dimensions and deformations of the pre-cracked concrete plate after firing. The values of ( $\delta_1$, $\delta_2$) represents the expected displacement in the vertical and horizontal directions due to firing which may be equal or not equal. ( $\delta_3$) represent the inner displacement of the crack surfaces.

**Figure 10** indicates the expected directions and paths of fracture and propagation of the pre-crack under thermal stresses due to firing loading. After the final path of the fracture and propagation of the pre-existing crack, the material of the concrete element will be separated and total collapse will occur. The fracture path will occur only as indicated by the solid lines or only as indicated by the dotted lines or both together as branched cracks. The safe time of the structures under firing before failure and collapse can be estimated based on the properties of this fracture path. The fracture path properties include the fracture direction at the first fracture initiation, fracture direction at each fracture step after the first start of the fracture, fracture load at each step, fracture length and time.

2- The thermal stresses are not uniform and the expansion of the concrete will not be uniform in all directions, as shown in **Fig. 6** and **Fig.** 9.

3- The expansion of the concrete will not only be towards the outer face of the concrete panel but also will be towards the inner faces of the cracks, as shown in **Figs. 3, 4** and **Fig.** 8.

4-Fire produced non uniform tri-axial stresses on the concrete plates and also other forces on the cracks in the opposite direction towards the inner, as shown in **Figs. 8, 9** and **Fig. 1**0.

5- The fire produced tri-axial stresses on the crack as shown if **Figs. 6** to **8.**

6- The crack will be under mixed mode ( I +II +III), which are normal stresses, in plane shear stresses and out of plane shear stresses, as shown in **Figs. 3** to 5.

7- The out of plane shear stresses will only affect the fracture surfaces which will have certain angles to (z) direction larger than zero ( $\theta° > 0$ ), as shown in **Fig.** 5.

8- The non equal biaxial stresses acting in direction Y, X of the crack will cause the fracture of the crack having

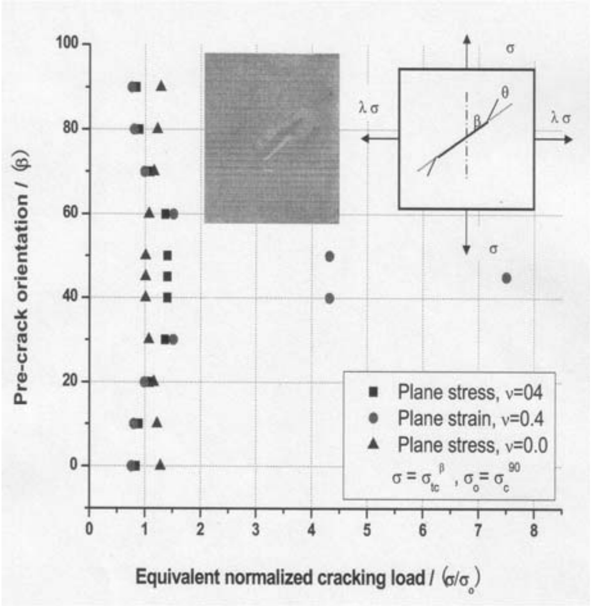


**Fig. 13** Equivalent cracking load for bi-axial ratio ( $\lambda = (\sigma x/\sigma y) = 1.0$).

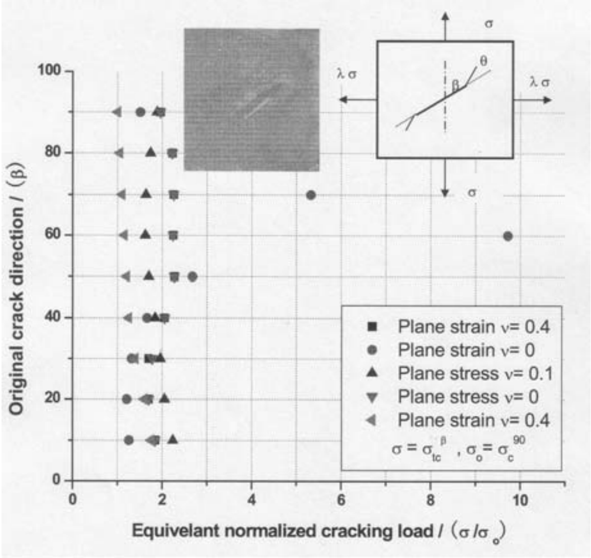


**Fig. 14** Eqivalent cracking load for bi-axial ratio ( $\lambda = (\sigma x/\sigma y) = 2.0$).

certain directions $\theta$ , as shown in **Fig. 3** and **Fig.** 4.

9- The non equality of thermal stresses was produced due to the losses in temperature because there was one closed direction of the oven Y while X direction was opened at the edges of the panel during the firing, as shown in **Fig. 3 (a)**.

10- The fracture path during firing was determined which was due to biaxial stresses as shown in **Figs 3, 4** and **Fig. 1**0, while the stresses in (Z) direction (mode III) effect appeared in the fracture surfaces as shown in **Fig.** 5.

11- It was recognized that the crack propagated during the first hour of firing while in the same period according to the cubes results the concrete strength would not be reduced. This meant that the concrete strength was not the controller of the safety of the structures but the pre-existing cracks would control the safety.

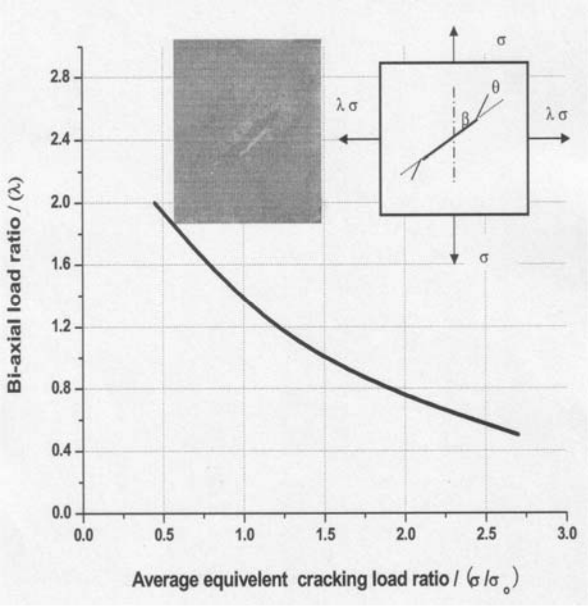


**Fig. 15** Comparison between bi-axial ratio and critical static equivalent cracking load.

12- In the structures and buildings, the cracks will be under service loads of the structures in addition to the thermal stresses due to fire but in the experiment the cracks were under only thermal stresses. This means that the cracks may propagate during a period of time less than 1.0 hour of firing beginning.

13- The cracks started propagation due to thermal stresses by the help of de-bonding process between the concrete composite materials i.e. between coarse aggregate and the matrix of cement and sand or in the matrix itself. In reinforced concrete the de-bonding may happen between steel and concrete composite.

14-The above results occurred in the tested panels of 5 cm thickness as shown in **Figs. 3(a), 3(b)** and **Fig. 3(**c). In the cases of the panels of 10 cm thickness the cracks started to propagate after a period of 1.0 hr and failed totally after 6.0 hrs firing as shown in **Figs. 3(a), 3(b)** and **Fig. 3(**c).

15- In the cases of tested panels of 10 cm thickness for only 1.0 hr the fracture started but stopped after stopping the firing without total failure of concrete. Then these samples are tested under static compression loading using a displacement control machine in HBRC as shown in **Figs. 4(a)** and **Fig. 4(b)**. The results are shown in **Figs 11** to **15** and the design and failure loads were determined where:

**Figure 11** indicates the fracture and propagation direction ( $\theta$ ) at the ends of the pre-existing crack in the concrete panel due to the thermal stresses of the fire. These fracture angles are plotted in a simple chart with

the relation to the pre-measured parameter of pre-crack orientation
(crack angle $\beta$). This chart is presented for biaxial thermal stresses with equal values in the two directions. So, the bi-axiality ratio ( $\lambda = (\sigma_x / \sigma_y) = 1.0$ ), where ( $\sigma_x$ = thermal stresses in horizontal direction), ( $\sigma_y$ = thermal stresses in vertical direction). Other similar charts for different values of ( $\lambda = \sigma_x / \sigma_y$ )can be presented. From this relation we can early predict and investigate the failure direction and position. Then we can protect the structure from the failure. The results of this chart also will be used in the calculation of the fracture path and time before failure. Then, we can predict the safe time of the fired structure before failure and collapse. The chart also will be used in the study of reliability of the structures under thermal stresses. It will be very important also in the repair and strengthening purposes of the structures.

**Figures 12, 13** and **Fig. 14** represent in simple form the equivalent critical tension load for the inclined cracks with angle ( $\beta$ ), ( $\sigma_{tc}$) of the effect of thermal stresses in normalized form ( $\sigma_{tc}^{\beta} / \sigma^{90}$ ) to the critical stresses of horizontal cracks ( mode I cracks) without inclination ( $\beta$ = 90) (s90) with comparison to the measurable fracture parameter of pre-existing crack orientation ( $\beta$ ). By measuring the crack angle ( $\beta$ ) the equivalent critical tension load ( $\sigma_t$) can be estimated directly from the charts without need for complicated calculations. The chart of **Fig. 12** is presented for case of ( $\lambda = (\sigma_x / \sigma_y) = 0.5$), such that ( $\sigma_y = 2\ \sigma_x$ ). The chart of **Fig. 13** is presented for case of ( $\lambda = (\sigma_x / \sigma_y) = 1.0$), such that ( $\sigma_y = \sigma_x$). The chart of **Fig. 14** is presented for case of ( $\lambda = (\sigma_x / \sigma_y) = 0.5$), such that ( $\sigma_y = 0.5\ \sigma_x$ ). From these charts, in addition to the chart of **Fig. 11**, we can early predict and investigate the failure load and its location. So, the structures can saved and protected from sudden failures. The results of these relations will be applied in the prediction of the failure trajectory and safe time of the firing process prior to total collapse. The reliability, repair and strengthening study of the structures will depend mainly on the data of theses charts.

As the last chart, **Fig.15** represents the comparison between the predicted bi-axiality ratios ( $\lambda = \sigma_x / \sigma_y$) of the equivalent stresses to firing effects and experimental work results of the critical load of oriented cracks in normalized form to the critical load of mode I crack ( $\sigma / \sigma_o$). This relation is very important to know and compares the cracking loads and ratios of loads to the critical load of mode I crack which is a material fracture intrinsic parameter.

## 4. Conclusions

The results of the experimental work on the non cracked concrete elements (concrete cubes) showed that the fire reduced the concrete compressive strength according to the firing time. The decrease of concrete strength and change of properties led to the total collapse of the un-cracked concrete. The problem is more serious due to the concentration of stresses at the crack tips and a change of fracture properties will led to sudden failure as shown in the concrete panels of the current research. In the case of reinforced concrete elements the problem will be more difficult due to presence of steel bars. In this last case, the failure will occur due to change of the properties of concrete and increasing of the stresses on the steel and concrete section until total failure. In the case of pre defected or pre cracked concrete elements, the fire would produce the failure at very early stage before changing of the compressive strength of concrete or decreasing the tensile strength ( $\sigma_t$) of reinforcing steel (which could be investigated and measured during and after firing) in addition to the de-bonding process between concrete and reinforcing steel bars. This is due to the pre existing cracks. Our current study did not include the effects of presence of embedded steel reinforcement in concrete. This research will be studied in the near future. It is very important to avoid this failure by maintenance of the structures and by repairing any defect or crack without delay.

Therefore, to avoid sudden failure due to firing we should avoid the presence of pre-cracks and design the structures against the cracking by means of fracture mechanics theories. In addition, it is very important to avoid any internal cracks in the concrete elements which can be produced during the manufacturing stages. Also, the recommendations of the design codes should
be followed.

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