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Investigating the Shear Behaviour of Reinforced Concrete Beams during Fires Using Finite Element Analysis

Mazen Musmar[1], Anis Shatanawi[2]
Civil Engineering Department, The University of Jordan, Amman, Jordan.

Abstract

A detailed 3-Dimensional time domain transient thermal stress finite element analysis was carried out to investigate the shear behaviour of reinforced concrete beams exposed to fire attack. A FE model that represented a simply supported reinforced concrete beam was developed. The beam was subjected to BS574 standard fire exposure to the bottom and side surfaces, in the form of transient temperatures versus time, while maintaining constant transverse loading on top surface of mid span. Material nonlinearity was taken into account because of the changes in material properties experienced in fire. The more complicated aspects of structural behaviour in fire conditions, such as thermal dilation, cracking or crushing of concrete and yielding of steel were modelled. The validation of the applicability of the FE model was illustrated by comparing the finite element solution with the results of experimental testing carried out for similar RC beams within the same boundary conditions. The FE analysis gave acceptable results in terms of performance, development and progression of diagonal shear cracks, shear capacity, and mode of failure.

Keywords: Shear behaviour of RC beams, FE analysis of RC beams, shear capacity of thermal of RC beams during fires.

INTRODUCTION

Fire safety is an important design aspect. It ensures that the structure has sufficient capacity to support its loads for a period of fire exposure that guarantees safety, during the evacuation and fire extinguishing processes [1]. The current codes of practice include prescriptive provisions that are based on limited test data. Such provisions give minimum sizes of members and cover to the reinforcement for achieving the required fire rating.

The need to design durable concrete structures that ensures the structural integrity of buildings under fire exposure, leads evermore to understanding of deterioration phenomena. At the structural scale, elevated temperatures induce restrained thermal dilation due to kinematic restraints. At the material scale, thermal load induces strong micro-structural changes that alter the concrete behaviour [2]. According to Hertz [3], initially when the temperature of concrete rises, the free water inside the concrete evaporates. This evaporation causes a pressure build-up within the concrete. When the temperature reaches about 150ºC the water that is chemically bound to the hydrated calcium silicates, is released. At a temperature of 300ºC, the aggregates expand and the cement paste starts to shrink. When the temperature reaches a value between 400ºC and 600ºC, the calcium hydroxide $Ca(OH)_2$ breaks down into calcium oxide CaO and water H_2O, creating additional water vapour and more pressure. This pressure may be too high and may result in cracking and spalling of concrete.

Knaack et al [4] proposed temperature dependent material models for concrete. In addition Elgazouli et al [5] presented experimental evaluation of the mechanical properties of steel reinforcement at elevated temperatures. They also proposed temperature dependent material models for steel reinforcement. The availability of temperature dependent material models for the different constituents used in reinforced concrete, paved the way towards authentic fire behaviour modelling of structures by means of computer aided design, as the use of specialized computer codes can significantly increase the profitability of the project works and increase their efficiency. The weakness, in case of modelling is that the degradation of material properties is simplified [6].

At early stages, a number of researchers worked on developing structural modelling approaches such as Lie and Celikkod [7], who developed a model for the high temperature analysis of circular reinforced concrete columns. Huang and Platten [8] developed planar modelling software for reinforced concrete members in fire. The simulation of heat exposed RC structures in fire requires the solution of an hygro-thermo-mechanical problem. If spalling is disregarded, only the thermo-mechanical problem can be dealt with [9].

There is an increasing awareness that shear failure can be critical and may be the governing failure mode of RC elements during fire. This has been proved by actual past incidents [10]. Shear failure is catastrophic as it occurs suddenly without sufficient warning. Therefore, it is essential to evaluate properly the shear resistance of reinforced concrete elements during fire conditions in order to avoid such disastrous mode of failure.

Recent years have seen a gradual transition from the prescriptive approach to the performance based approach in the fire safety design of RC members since the latter provides a more cost effective, flexible and rational tool and allows designers to use multiple routes to achieve the required fire safety[11]. The performance-based fire safety design approach requires tools for the accurate fire analysis of RC members, which has motivated the development of numerical simulation tools with the desired capability. Such a numerical simulation tool is generally capable of a three-step analysis: (a) fire scenario analysis, (b) heat transfer analysis, and (c) mechanical response analysis [12].

The Finite Element method (FEM) is considered the most common tool to carry out advanced fire resistance analysis [13]. Predictions from FE modelling allow the complex distribution and evolution of stresses in the reinforcing steel and the concrete to be examined in detail, leading to a better understanding of the local responses of RC beams exposed to fire [14].

Although a large number of experimental and analytical research programs were conducted on the fire resistance of reinforced concrete, the majority of that research was focused on their flexural performance. The literature is lacking experimental and analytic work addressing the shear capacity of RC elements during fire conditions [15]. Thus, the objective of this paper is to perform a nonlinear finite element analysis that aims at estimating the shear capacity of RC beams under fire conditions.

SHEAR RESISTANCE MECHANISM

Prior to flexural cracking, uncracked concrete carries all shear forces, After developing flexural cracking, the shear is resisted by the following components [16]:

1. Shear in the compression zone "Vc"
2. Shear resisted by the dowel action of the longitudinal reinforcement that traverse a particular crack "Vd"
3. Interface shear transfer along the two surfaces of cracks (aggregate interlock) "Va".
4. After the development of inclined cracks, the stirrups play a noticeable role in resisting the applied shear forces. The shear reinforcement resists part of the shear forces "Vs".

Upon the yielding of stirrups, the inclined cracks widen rapidly, which decreases the contribution of the aggregate interlock. Eventually, the concrete element experiences failure either by splitting or by the failure of the compression zone of concrete. The shear failure of the concrete beams is brittle and occurs without sufficient warning. Thus, the main purpose of shear reinforcement is to ensure that the flexural capacity of the concrete is achievable.

Modelling the complex interaction of the shear resistance mechanisms at elevated temperatures is difficult. Fire increases the height of cracks, and thus reduces the depth of compression zone [17]. The reduced strength of stirrup reinforcement decreases the value of its resisted shear. The reduced bond strength reduces the effectiveness of the dowel action of tension steel.

ANALYTICAL METHODOLOGY

The simulation of heat exposed RC structures in fire requires the solution of an hygro-thermo-mechanical problem. If spalling is disregarded, only the thermo-mechanical problem can be dealt with [18].

The basis for thermal analysis, assuming no heat generation, is a heat balance equation obtained from the principal of conservation of energy [19].

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + q = \rho.c.\frac{\partial T}{\partial t} \qquad (1)$$

Where:

c: specific heat coefficient.

k: thermal conductivity coefficient.

q: rate of heat generated internally per unit volume.

ρ: density.

t: temperature.

T: time.

For heat transfer analysis of an RC beam exposed to fire, internal heat generation is inactive, thus q can be neglected.

The governing equation becomes

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} = \rho.c.\frac{\partial T}{\partial t} \qquad (2)$$

Assuming the temperature distribution in the structure as independent of the structural behavior, allows performing thermal analysis and structural analysis in two consecutive steps [20].

The objective of this work is first to find acceptable results for the shear capacity of reinforced concrete beams at elevated temperatures using finite element modeling. Calculation involves two analyses, each belonging to a different physical field. Coupling is made by applying results obtained from the thermal analysis, to the mechanical analysis. The numerical model development and transient thermo-structural analysis involved the following:

1. Constructing a 3-D finite element model of the RC beam. The model involves the geometry of concrete, main and shear reinforcement detailing, appropriate material models, meshing, and boundary conditions.
2. Apply the standard BS476 Part 20 [21] fire exposure to the bottom and side surfaces of the beam in the form of transient temperatures versus time. The top surface, being exposed to ambient temperature. Carry out transient thermal analysis to obtain the temperature distribution in the RC beam as a function of time.
3. Investigate the temperature distribution within the cross section. Obtain the predicted temperatures and the associated time at several locations within the beam cross section.
4. Determine the reduced strength properties of concrete and steel reinforcement.
5. Perform structural stress analysis based on thermal loading as nodal temperature, that was obtained by the

aforementioned heat transfer analysis, associated with the gravity load applied at the beam mid span, to obtain deflection, and stress and strain results.

6. Evaluate the deflection, the total strains comprising mechanical and thermal strains and the associated stresses within beam cross sections. Furthermore trace crack initiation, crack progression up to failure, and ultimately identify the mode of failure.

FINITE ELEMENT MODEL

A. Geometry

The FE model of the RC beam has the geometry, configuration, dimensions, material mechanical properties, and boundary conditions that are identical to those of the specimens tested by Desai [22]. The simply supported RC beam has a 1.40 m span. The rectangular section width is 200 mm, and depth is 300 mm. Bottom reinforcement is 3# 20 mm diameter steel bars, top reinforcement is 2#12 mm steel bars. Shear reinforcement is 6 mm stirrups at 200 mm c/c (Fig. 1, 2).

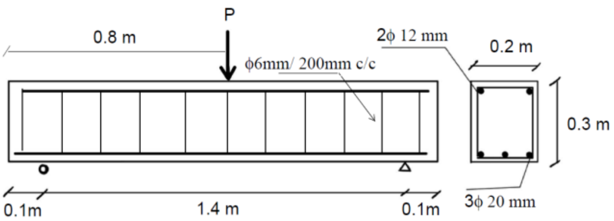
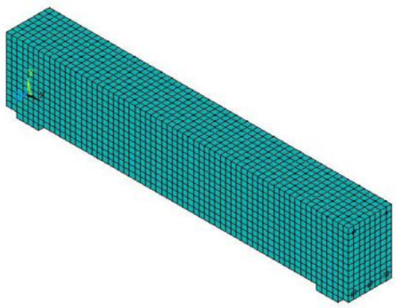
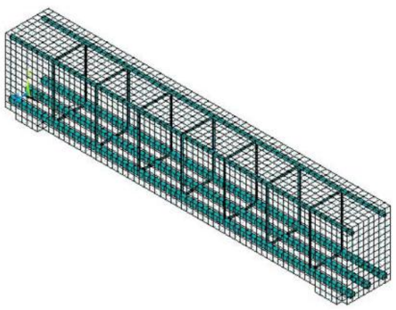


Figure 1. Geometry, steel reinforcement and boundary conditions for RC beam



a. Isometric view of the RC beam FE model



b. Isometric view of Rebars and Stirrups for beam FE model

Figure 2. FE Model of RC beam

The FE model was built in Ansys15 [23]. Concrete was represented by the solid70 element for heat conduction in thermal analysis. It is a three dimensional eight noded tetrahedral element having thermal degrees of freedom. The distributions of thermal elastic stress components were then calculated by switching the solid70 thermal element to solid65 structural element, when performing structural analysis. The solid65 element models the nonlinear response of concrete.

The behavior of the concrete material was based on a constitutive model for the triaxial behaviour of concrete after Williams and Warnke [24]. It is a nonmetal plasticity model with isotropic hardening and non-associated plastic flow. The criterion for failure of concrete due to a multi axial stress is expressed in the form:

$$\frac{F}{f_c} - S \geq 0 \qquad (3)$$

Where:

F: a function of principal stress state

S: failure surface

$f'c$: uniaxial concrete strength.

If equation 3 is satisfied, the material will crack or crush. Solid65 is capable of plastic deformation, cracking in three orthogonal directions at each integration point. The cracking is modelled through an adjustment of the material properties that is done by changing the element stiffness matrices.

Element Link180 was used to model the steel reinforcement. It is a uniaxial element with the ability to conduct heat between its nodes, and in thermal analysis was replaced by element link33, which has a single degree of freedom at each nodal point, as shown in table 1. A bilinear plasticity model that utilizes Von Mises yield surface with associated plastic flow and isotropic hardening, available in Ansys [23] was adopted for the constitutive modeling of reinforcing steel.

Table 1. Thermal and structural elements

	Switchable elements concrete		Switchable elements Steel reinforcement	
Element	Thermal	Structural	Thermal	Structural
Type	Solid 70	Solid65	Link33	Link180
Number of nodes	8	8	2	2
Number of DOF per node	1	3	1	3

Table 3. Material properties for concrete and steel at ambient temperature (20 °c)

Material	Concrete	Steel reinforcement
Compressive strength	28 MPa	
Tensile strength	3.28 MPa	460 MPa
Elastic modulus	24.870 GPa	200 GPa
Poisson's ratio	0.2	0.3
Density	2400 Kg/m^3	7800 Kg/m^3
Thermal conductivity (k)	1.2W/m°c	60W/m°c
Specific heat capacity (c)	1000J/kg°k	500J/kg°k
Thermal expansion coefficient α	1.2x10-5 /°c	1.08x10-5 /°c

B. *Temperature dependent material models*

Table 3 illustrates concrete and steel reinforcement material properties at room temperature. The temperature dependent Compressive stress strain curves of concrete are illustrated in Fig.3. There exists a linear elastic stage, followed by a nonlinear increase in stress, representing development of micro cracks in the concrete. Fig.3 illustrates the degradation of concrete stiffness and strength as the concrete temperature increases. The stress-strain relationship for concrete in tension is represented by a linear relationship, which is elastic up to failure. The temperature dependent stress strain relationship of steel reinforcement is presented in table 4.

C. *Thermal and structural boundary conditions.*

The bottom and side surfaces of the simply supported beam are subjected to thermal load in accordance with BS 476 fire exposure as shown in Fig.4, by convection with a film coefficient of 50 W/m^2/c. The top surface being exposed to ambient temperature. Ansys performs the numerical calculation for temperature, utilizing Galerkin finite element technique that is capable of performing heat exchange calculations [25]. The thermal conductivity of the materials forming the structure is taken into account. The RC beam is pin supported at the left end and roller supported at the right support.

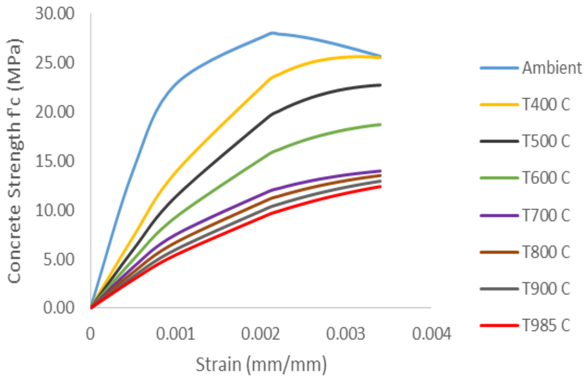
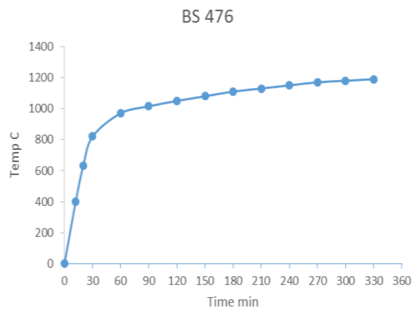


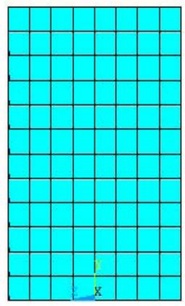
Figure 3. Temperature dependent conc. material model [4]

Table 4. Reduction factors at elevated temperatures for stress-strain profiles at elevated temperatures q relative to the value of f_y or E_a at 20°C [25].

Steel temperature (t)	Reduction factor for effective yield strength	Reduction factor for proportional limit	Reduction factor for the slope of the linear elastic range
°C	$K_{y,\theta}$ $(f_{y,\theta}/f_y)$	$K_{p,\theta}$ $(f_{p,\theta}/f_y)$	$K_{E,\theta}$ $(E_{a,\theta}/E_a)$
20	1	1	1
100	1	1	1
200	1	0.807	0.900
300	1	0.613	0.800
400	1	0.420	0.700
500	0.780	0.360	0.600
600	0.470	0.180	0.310
700	0.230	0.075	0.130
800	0.110	0.050	0.090
900	0.060	0038	0.068
1000	0.040	0.025	0.045
1100	0.020	0.013	0.023
1200	0.000	0.000	0.000



a. BS476 fire exposure [21]



b. Sides and soffit subjected to fire exposure

Figure 4. Thermal boundary conditions

RESULTS AND DISCUSSION.

A. *Model Validation*.

The proposed finite element method was validated by comparing the FE model solution with the experimental results of the specimens tested by Desai [22].Table 5 presents a comparison between the outcomes of the FE analysis in terms of the shear strength at fire exposure time of 101 minutes and the associated mid span deflection. It can be concluded that the outcomes compare well (Table 5). The shear strength in FE model at fire exposure time of 101 minutes is larger than that of the tested specimen. The recorded value of mid span deflection for the FE model is less than that of the tested specimen. This is attributed to the fact that the FE model does not include the bond degradation due to reduction in stiffness and strength of concrete and reinforcement. It also does not include the degradation of bond and slippage of tension steel due to crack formation and propagation at elevated temperatures.

Table 5

	Fire exposure time t: min	Shear force at failure kN	Max deflection mm
Tested specimen	101	55	12
FE Model	101	58.2	8.1

B. Analysis Results

The shear capacity of the FE model of the RC beam subjected to BS476 [21] fire exposure was investigated. The thermal load was applied to the soffit and the sides of the beam (Fig.4), the top face kept at ambient temperature while the FE model of the RC beam was under sustained transverse load. The diagonal shear cracks that resulted from the nonlinear thermal and mechanical strain gradients initiated near the supports from the tension reinforcement towards the compression face (Fig.5)

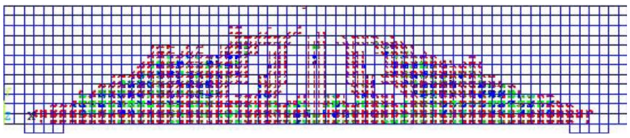


Figure 5. Cracks just before failure in the FE model

Fig. 6 illustrates the reduction in the shear strength in FE model of the RC beam according to the increase of fire

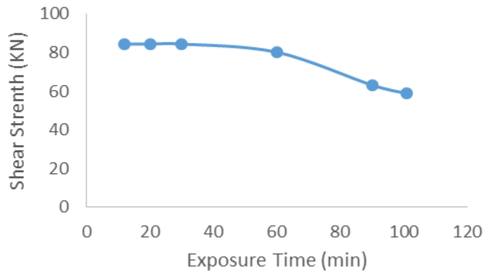


Figure 6. Shear strength versus fire exposure time

exposure time. Beyond fire exposure time of 101 min, convergence could not be attained, indicating that failure of the RC beam took place. It was a shear driven mode of failure.

Flexural tension cracks were harmless because adequate longitudinal reinforcement has been provided to resist the flexural tension stresses that cracked concrete is no longer able to transmit.

Fig. 7 illustrates the temperature evolution across the RC beam cross section as fire exposure time increases. Fig.8 also shows temperature evolution in flexural and shear reinforcement with respect to the increment in fire exposure time.

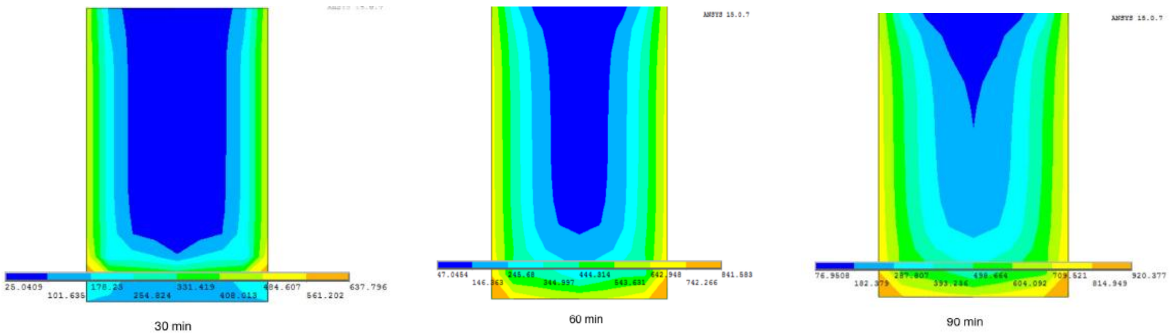


Figure 7. Temperature evolution across the beam cross section at different time periods of fire exposure.

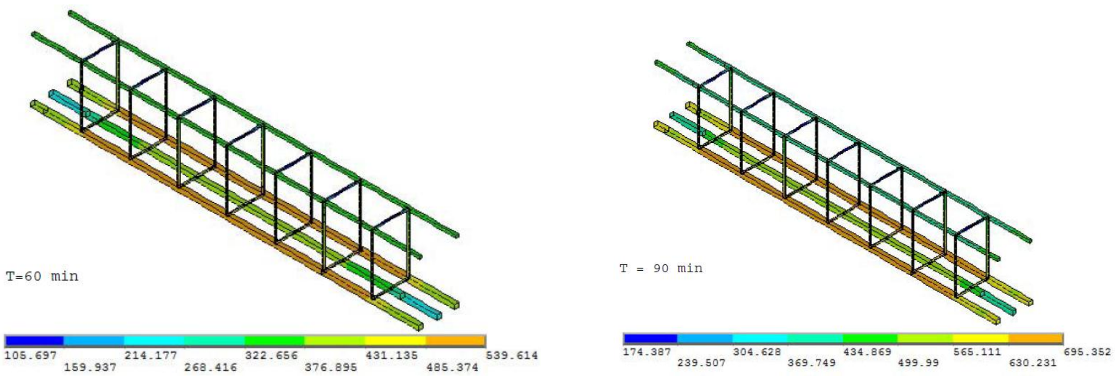


Figure 8. Temperature evolution in flexural and shear reinforcement at T= 60 min, T=90 min of fire exposure

CONCLUSIONS

A nonlinear three dimensional FE model was developed in this study. The model was validated against the experimental testing for six RC beams carried out by Desai [22], with similar parameters and boundary conditions. After validating the FE model, FE analysis was carried out to investigate the shear capacity of the RC beam exposed to BS574 fire, while under sustained transverse load.

The conclusions are as follows:

- FE modeling provides detailed results in terms of heat transfer and temperature distribution across the cross RC beam section and along the tension and compression reinforcement bars, and along the stirrups. A difficult task to accomplish in experimental testing.
- The test results have indicated that FE modeling is an efficient approach to determine the behavior of RC beams exposed to transient thermal load while under sustained gravity loading. The model simulates the progression of diagonal shear cracks as the fire exposure time increases and associated with a transient thermal load in accordance with BS574.
- The temperature dependent material models for concrete and steel reinforcement showed that concrete compressive strength and stiffness are less sensitive to variations in temperatures typically developed during fire than steel reinforcement.
- The shear strength of the Rc beam decreased as fire exposure time increased. Fire exposure time increment was associated with increment of the temperature distribution across the cross section and along the flexural and shear reinforcement, resulting in reducing of the compressive strength and stiffness of concrete in compression region. The yield strength and stiffness of shear and flexural reinforcement were reduced, thus the bond strength was reduced.
- The development and progression of diagonal shear cracks could be easily traced as fire exposure time increased. Shear cracks initiated near the end supports, they spread traversing the entire beam from the tension reinforcement towards the compression face. Ultimately, the beam failed in shear as the crack pattern and crack progression indicated.

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