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Finite Element Modelling Of Compartment Fire Using ABAQUS

Mariyana A. A. K.[a]*, A. S. M. Abdul Awal[a], Mahmood Md. Tahir[b]

[a]Department of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bharu, Johor, Malaysia
[b]UTM-Construction Research Centre, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bharu, Johor, Malaysia

*Corresponding author: mariyanaida@utm.my

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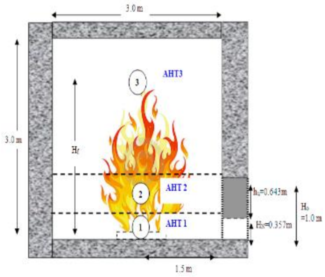
Graphical abstract



Abstract

This paper presents finite element modelling (FEM) of a reinforced concrete (RC) frame subjected to elevated temperature. The work presented is part of the UK-India Education and Research Initiative (UKIERI) project. In this project, an experimental test of sub-assemblage frame with elevated temperature has been performed at Indian Institute of Technology (IIT) Roorkee, India. The finite element model using ABAQUS software has been used to validate the increased in temperature distribution on reinforced concrete frame exposed to fire. The idea of this study is to design a compartment fire, and determination of emissivity value at different height. And composition of hot gases was calculated. Gas temperatures used was based on the average temperature-curve obtained in the fire test. The validity of the finite element model was established by comparing the predicted values from the FEM with test data direct from fire test results. The results obtained indicate that suggested FEM analysis procedure is capable of modelling temperature in compartment fires.

Keywords: Finite element model; heat transfer analysis; reinforced concrete frame; compartment fire; ABAQUS

■1.0 INTRODUCTION

The need to consider fire loading into structural design has been of great concern since the World Trade Centre disaster in 11 September 2001. An investigation carried out by the Building Performance Assessment Team has indicated that the fire issues were vital in the collapse of the twin towers. Reinforced concrete (RC) structures commonly exposed to fire have not been taken into consideration for thermal analysis during fire conditions. Rather, code provisions generally are considered relevant for detailing and cover requirements which provide an acceptable fire-rating in terms of the length of time that the structure can sustain its mechanical loads in the presence of fire without collapsing. Therefore, there has been a growing interest in research on the heat transfer analysis and design of RC structures subjected to fire.

A full scale fire test is not a practical solution as it is very expensive and need a state-of-the-art furnace with an appropriate capability. Therefore, a computer simulation is a better option for researchers to demonstrate the heat transfer in RC structures by modeling the specimen in a proper manner. The use of finite element modelling with high-speed electronic computers in heat transfer analysis began in the mid 1970's and has gained wide acceptance throughout most of major research works in fire engineering. Lamont *et al.* in their investigation of temperature distribution within steel slab of Cardingtion frame reveals using heat heat transfer mode is sufficient, efficient and gain results in the short time[1].

Compartment fires are defined as fire in enclosed spaces. Theoretically the fires are often discussed in terms of five growth stages-ignition, growth, flashover, fully developed fire and decay as shows in Figure 1 [2]. This idealization may provide useful information to understand further the compartment effect due to fire. Flashover is not a stage of development, but simply a rapid transition between the growth and fully developed stages. Sometimes the fire may fail just before the flashover without experiencing the development into all stages. Therefore, it is important to determine the stages of fire growth.

There are many factors that may affect the fire growth. For example, type of fuel, thermal properties, size of compartment and ventilation that influence fire to develop in a compartment fire. The type of fuel, indicated as a primary factor, can be defined as fire growth during ignition stage. Nevertheless, as the fire moves into the growth stage, it may be controlled by ventilation.

Compartment fires can be modelled to predict the temperature generation based on the type of fire and smoke movement. Klote and Milke have studied about smoke movement in a compartment [3]. Fire may occur at any parts below a ceiling in the compartment, furthermore this will releases energy and product of combustion. The hot products of combustion form a plume which rises towards the ceiling due to its buoyancy. As the plume rises, it draws cool air from within the compartment, decreasing the plume's temperature and increasing its volume flow rate. The interchange between the hot upper layer and the air in the lower part of the compartment assumed within the plume. As the hot layer moves and reaches ventilation in the compartment walls, hot gas flows out the ventilation and outside air flow into the ventilation. Figure 2 illustrate the compartment fire behaviour also known as a two layers or zone model which has been developed by Klote and Milke in 2002 [3]. In this model the compositions of the layers are assumed uniform and the temperature of the upper layer remain greater than the lower layer.

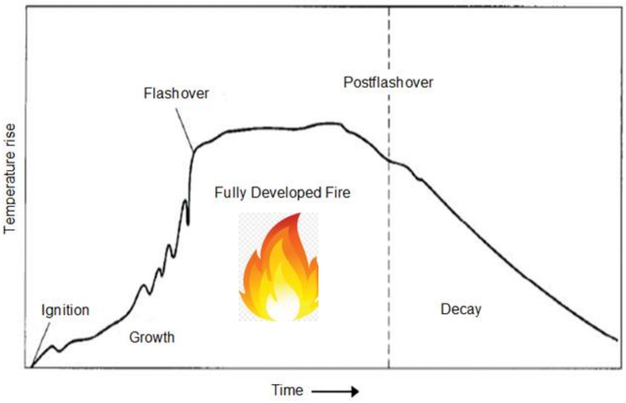


Figure 1 Compartment fires growth stages [2]

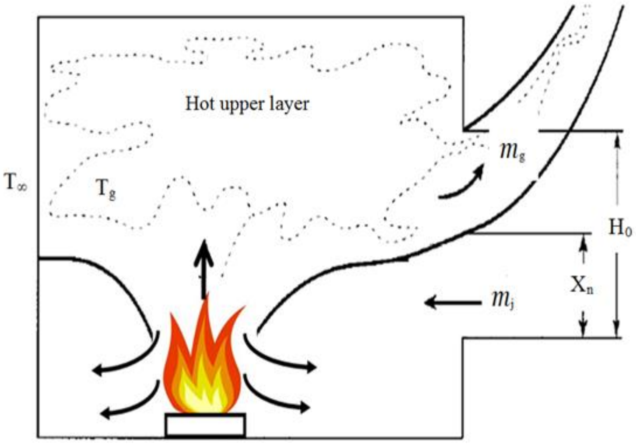


Figure 2 Schematic of the zone model [3]

Heat transfer analysis is a process of energy transmitted due to a temperature difference. The transmission of the energy happened in two mechanisms known as conduction and radiation. The conduction is a molecular energy transport which can be dominating mechanism for the heating up of small devices such as detectors. The radiation mode is very often dominated for transferring heat in enclosure fire in the case of higher temperatures of flames and fire gases. Babraukas showed in his study that pool fire with diameter is 1.0 m or bigger the radiation mode effect is more important than convection [4]. This mode of heat transfer is also important for a target which is located laterally of the exposure fire source.

Venkatesh Kodur in his studied, explained the concrete is best fire resistance properties compared to any building material due to unique characteristic of concrete which, when chemically combined from hydration proses it form a material that has low thermal conductivity, high heat capacity, and slower strength degradation subjected to elevate temperature [15]. However, the fire resistance rates of concrete vary as a function of temperature and depend on the composition and characteristics of concrete [5,6]. In practice, fire resistance of structural members used to be evaluated mainly through fire tests.

This paper attempts to implement the capability of 3D heat transfer analysis onto a finite element modeling program for single-storey of RC frame. The temperature-dependent material properties followed EC2 are considered in this heat transfer analysis [7].Taking advantage of zone model, mainly based on gas composition of each layers in compartment, transferred between a fires, the fire gases, the fuel bed and the surfaces in an enclosure can be estimated [8]. While, temperature in the finite element modelling is used based on the data from the UKIERI fire test [9, 10].

The following discussion will provide descriptions on calculation of emissivity values, finite element modelling procedure, and temperature distribution within elements of the UKIERI frame.

2.0 EMISSIVITY VALUE AND SOOT HEIGTH

Heat transfer analysis by means of radiation and convection mode is considered in this study. The convective mechanism in this study used a convection heat transfer coefficient of 25 kW/m^2. This is a typical value used in structural fire analysis [6]. Furthermore, Yung Lee *et al*. [11] have shown the convective components as coefficient in heat transfer modelling can be regarded as the crucial material property of concrete with respect to the prediction of behaviour of thermal cracking [12]. The radiation mode is affected by the soot height in the compartment fire. In real gas properties, combustion gases are complex in term of radiative properties due to the presence of gas, H_20 and $C0_2$, which radiate discretely over wavelength bands that can overlap while soot radiates continuously over a wide range of wavelengths.

When heat transfer in radiation mode is analysed using ABAQUS the emissivity, ε must be defined which simulates the behavior of soot in the compartment. In reality combustion gases are complex in terms of their radiative properties, however, due to the presence of gases such as H_2O and CO_2, which radiate discretely over wavelength bands can overlap and soot radiates continuously over a wide range of wavelengths. In a room smoke layer, the products of H_20 and $C0_2$ could contribute about ε_g ~ 0.3 and ε_s range from 0 to 0.7 taking ε up to 1.0. The total ε depends on the path length, if long enough it can take ε up to 1.0 [13]. Combining the soot, ε_s and the gas, ε_g together has contributed to the flame and smoke radiation, as shows in Equation 1.

$$\varepsilon = \varepsilon_{H_2O} + \varepsilon_{CO_2} + \left\lfloor \varepsilon_{correction} \right\rfloor \qquad [1]$$

In this analysis the emissivity is derived in accordance to Babraukas [2] as shown in Equation 2.

$$\varepsilon = (1 - e^{-\kappa\beta D}) \qquad [2]$$

The equation consists of an extinction coefficient, κ, a 'mean beam length corrector', β and D is the diameter of the pool fire. Particularly κβ is an empical constant (m^{-1}) in an area of fuel where effectively heats of combustible are known. Basically the emissivity value is defined depending on the fuel type used in a pool of fire and for this research the oil type is kerosene.

Based on Equation 2 where kerosene parameter was given by Blinov [14] and Kutcha *et al*. [15], which represent the emissivity in the whole compartment (highest point of smoke level) was taken as 0.9829 (AHT3). Figure 3 illustrates the behaviour of smoke of well-mixed case in an enclosure with uniform temperature, Tg, which is higher than the outside temperature, Ta. In this figure, ρa = ambient air density (kg/m^3) and ρg = gas density in enclosure (kg/m^3), H is the height of the window opening with 1meter height, H_o is the heat of combustion of the fuel (MJ/kg). From the figure, the height of smoke and air flow were then estimated using Equation 3 to determine the stages of fire started with the first stage; $H_1 = H_N$ with the reference point represent the bottom of the opening.

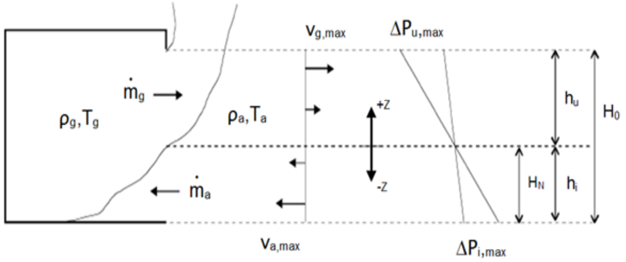


Figure 3 The well-mixed case: An enclosure with uniform temperature, T_g, which is higher than the outside temperature, T_a

$$h_1 = \frac{H_0}{1+\left(\frac{\rho_a}{\rho_g}\right)^{1/3}} \qquad [3]$$

The smoke layer in the compartment was calculated based on Equation 4 by Klote and Milke [3].

$$T = \frac{353}{\rho} \qquad [4]$$

Based on the frame configuration used in this study, values of T_g was 1400^{o}C and T_a was 20^{o}C. Therefore, according to Equation 4, the $H_N = h_1 = 0.357$m was obtained.

■3.0 FINITE ELEMENT MODELLING OF HEAT TRANSFER

The heat transfer analysis was performed using ABAQUS version 6.8 to get the temperature distribution within the elements of the RC frame. 3D continuum elements (DC3D8) defined as 8-noded linear (hexahedral) elements were used to model the UKIERI frame [16]. Temperature as a single degree of freedom at each node was defined in the modelling o recorded the temperature behaviour in the elements. The total nodes in the model is 4452 with 84 nodes at concrete columns, 672 nodes at the reinforced columns, slab contains of 3298 nodes, reinforced beam with 270 nodes and beams with 128 nodes respectively. Figure 4 shows the configuration of the 3D frame modelled for heat transfer analysis in ABAQUS.

Material properties of concrete at elevated temperature used was in accordance to Eurocode 2 [7]. In typical concrete it is known as non-homogeneous, anisotropic medium composed of aggregate, cement paste and water. For simplicity, concrete can be treated as a homogeneous isotropic material in heat transfer analysis. The temperature curves based on the fire test were applied at different height in elongation and area in plan.

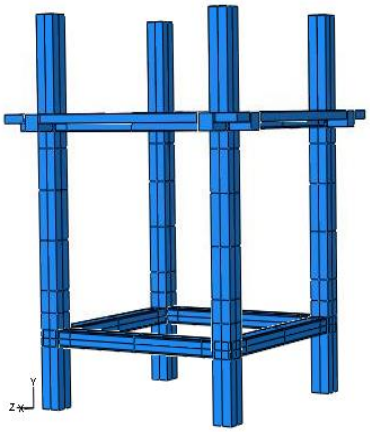


Figure 4 3D continuum brick element to model the frame using ABAQUS 6.8

The heat was introduced into the element uniformly since the flume is burned in the middle of the compartment.The compartment of the frame in this study is divided into three areas. The areas at different heights in the compartment are referred to as AHT1, AHT2 and AHT3, as shown in Figure 5, where AHT1 is the area located near to the opening, AHT3 is the area located at the top of the compartment and AHT2 is the area considered between AHT1 and AHT3. From Figure 5, AHT3 is assumed to be filled with smoke with estimation emissivity value to be 0.9829 at the highest smoke level for kerosene oil. Hence by considering AHT3 in this study, the area of AHT2 is then being estimated by assuming that the smoke only in its upper region (until the opening) and area AHT1 is assumed to contain little smoke. The emissivity value varies with different smoke layers as discussed earlier. Table 1 shows the emissivity values applied in the heat transfer analysis.

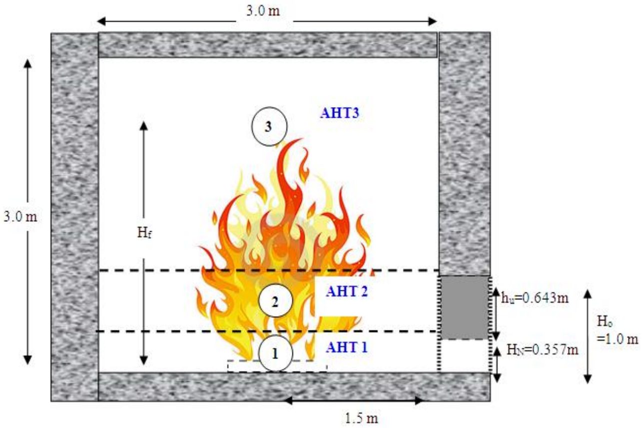


Figure 5 Compartment fire modelled in ABAQUS 6.8

Table 1 Parameter of emissivity for different areas used in heat transfer analysis using ABAQUS

Area in the compartment at different height	AHT1	AHT2	AHT3
Emissivity applied at each area , $\varepsilon = \varepsilon_g + \varepsilon_s$	0.3 ($\varepsilon_s = 0$)	0.6415	0.9829

■4.0 RESULTS AND DISCUSSION

The idea of this study is to design a compartment fire, and determination of emissivity value at different height. The temperature distribution within the frame from numerical analysis and test data on real temperature using thermocouples and data logger is then compared. The temperature distribution of the RC frame after 1 hour of fire is illustrated in Figure 6. Figure 7 shows the area where each time-temperature curve relates to, with the notation of the beam and column given for further reference. Due to failure of thermocouples at elevated temperature, most of the temperature distributions data within elements are not presented. Therefore, only temperature distribution on B1, B5, C4 and slab is compared with the test data.

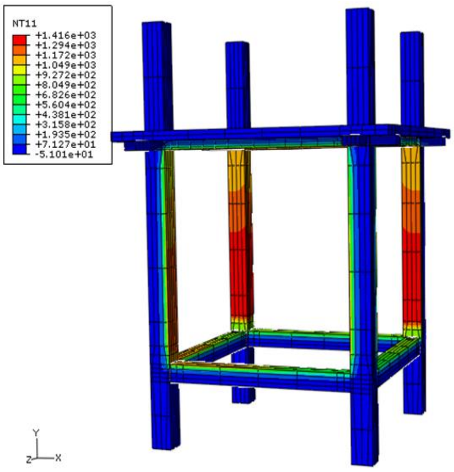


Figure 6 Temperature distribution of the frame from the heat transfer analysis

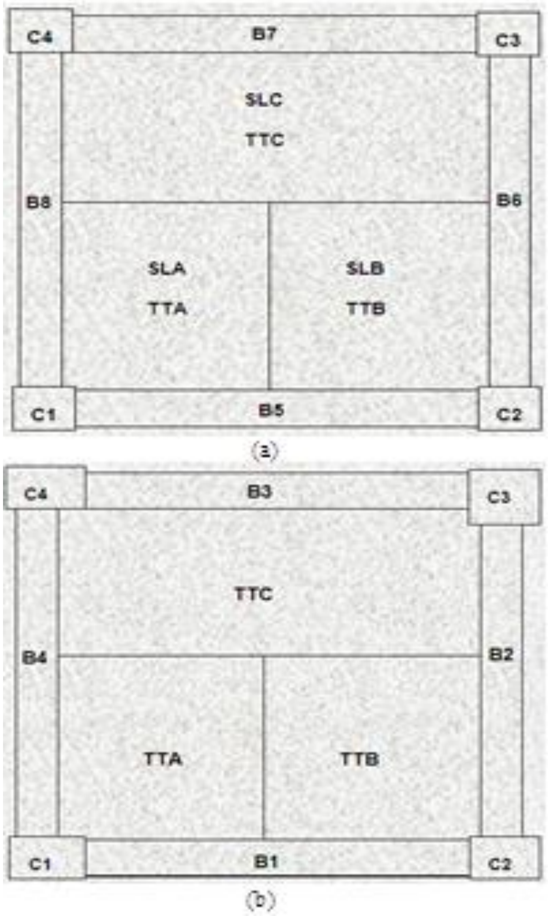


Figure 7 Notation of beams, columns and slab in a compartment (a) top floor (b) lower floor (Plan view)

The temperature distribution is recorded by thermocouples embedded at 5 points within the elements. The 5 points are measured as 5 mm, 25 mm, 115 mm, 205 mm and 225 mm from the base of the beam whiles the dotted lines represent test data and solid line for numerical analysis as shown in following graph. At lower floor, the temperature distributions though beam B1 provides the most detailed results obtained from the test; therefore, a comparison is made between the results of the test and the numerical analysis in this beam (Figure 8). From the graphs, the temperature distribution through beam B1 at mid span exhibit good agreement in both the numerical analyses and the test up to 50 minutes.

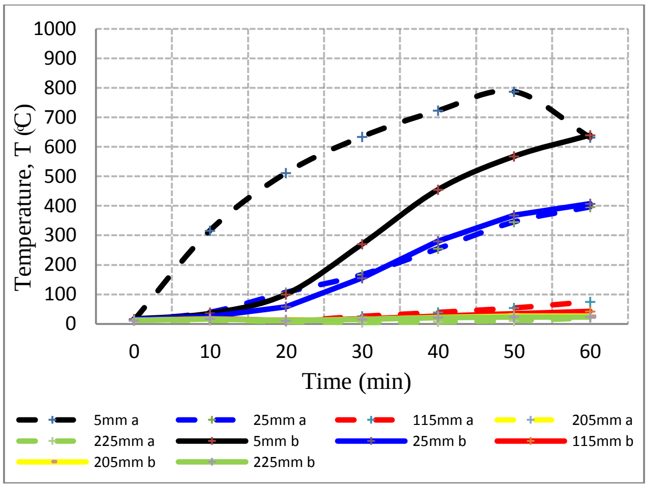
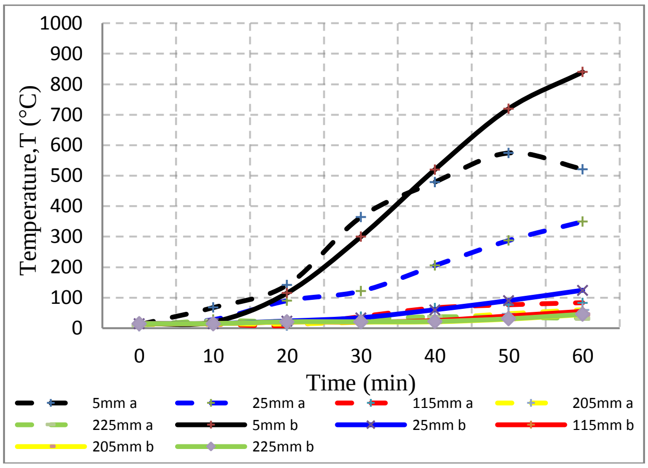


Figure 8 Temperature distributions in the beam, B1 at the middle side along the height (a) Test data (b) Heat Transfer using ABAQUS

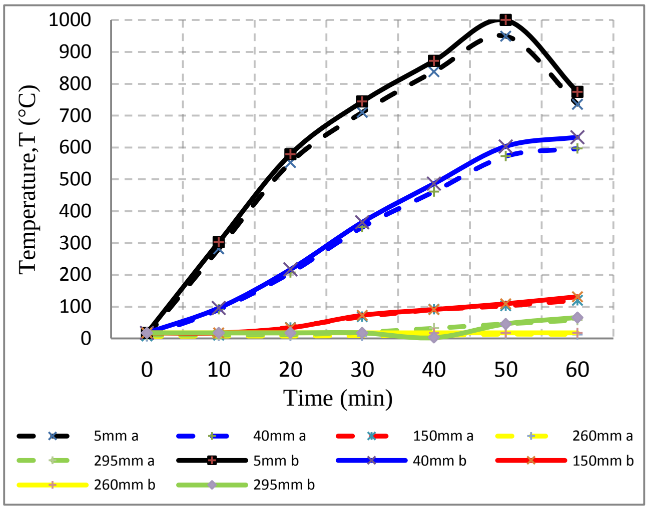
At the top floor, B5 is compared with the test data as shown in Figure 9. From the observation, the temperature distribution in the test slowly increased while in the heat transfer analysis increased about 50% faster than that obtained in the test. The temperature distribution as it can be seen there again very good aggrement between predicted and test data for the first 20 minutes.



(a)

Figure 9 Temperature distributions in the top beam, B5 at the middle side along the height (a) Test data (b) Heat Transfer using ABAQUS

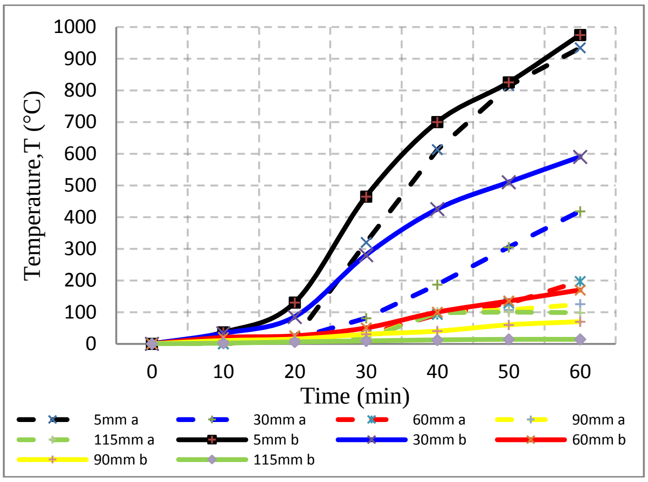
The temperature gradient in the columns obtained from the test shows a gradual increase as the time of exposure increased. Then, in the last 10 minutes, most of the points showed a decrease in temperature gradient (Figure 10). This may be due to the fuel running out at the end of the test. It is interesting to note that the temperature gradient in the column from the heat transfer analysis rises quickly from the beginning of the analysis until a time of 30 minutes. Then the temperatures remain steady until the end of 1 hour.



(a)

Figure 10 Temperature distributions in the column, C4 at the middle along the height (a) Test data (b) Heat Transfer using ABAQUS

Figure 11 reveals the temperature distribution through the slab SLA obtained from both the test and the heat transfer analysis. Increment pattern of the temperature distribution within the slab agree well between the test and the numerical analysis at the end of test. However, as it can be seen the temperatures obtained from the test are increased rapidly than those taken from the heat transfer analysis, after 20 minutes of heating.



(a)

Figure 11 Temperature distributions in the slab (SLA) (a) Test data (b) Heat Transfer using ABAQUS

■5.0 CONCLUSIONS

In this work, a compartment fire is developed and implemented into a 3D finite element analysis procedure for reinforced concrete frame. The gas composition within the compartment is calculated based on the emissivity values provided from soot height due to heat transfer analysis using general purposed analysis programs, ABAQUS. From the results, the temperatures from the heat transfer analyses are generally higher than that of corresponding temperatures from the test data. This is due to the fact that hot gases properties in fire test are higher as compared to the emissivity value calculated in the numerical analysis. The difference in results between finite element modelling and test may be due to the presence of thick smoke layer in the test as the emissivity value used in the heat transfer analysis is based on the effect of the smoke layer in the compartment. In other hand, moisture content of concrete in numerical modelling not properly defined caused the high temperature distribution in the numerical modelling of the frame elements.

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Nomenclature

Where:

ρ_g	density of gas in enclosure
ρ_a	density of gas at ambient
T_g	temperature in enclosure
T_a	ambient temperature
$\dot{m}_a$	mass of the gas at ambient temperature
$\dot{m}_g$	mass of the gas in enclosure
H_0	opening of enclosure
H_N	reference height of the gas
h_u	height of outgoing gas
h_1	height of incoming gas
T	temperature in Kelvin [K]
ρ	density in [kg/m3]
$\varepsilon_{correction}$	correction factor due to overlap wave length

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