Performance of Concrete Building Structure Exposed to Localized Fire

by Suryawan Murtiadi

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Abstract Concrete structures have a favorable position in the building industry with regard to their performance of fire resistance. The understanding of its behavior is essential for reliable analysis and design. This paper is mainly concerned with concrete building performance subjected to localized fire arrangement. Special attention has been given to the finite element model of a seven story concrete building representing a typical commercial office building designed to European Standard.Very large displacements happened on horizontal direction of the floor slabs due to thermal expansions. The large displacement induced lateral movement of the floor slabs and created additional moments to external columns. Design engineers should ensure that the external columns have ability to accommodate lateral displacements during fire. Although, the thin external columns of the model can withstand these movements due to beneficial effect of membrane action developed to the floor slabs. Present analysis indicates that the performance of the whole structure is substantially different to the single isolated structural member behavior during fire. Although the current design procedures are conservative, design engineers have to consider the detrimental and beneficial effects of lateral slabs thermal expansion in complete structure.

Keywords Building, Concrete, Displacement, Fire, Finite Element.

1. Introduction

Firecan occur caused by three essential materials such as fuel, oxygen and initial source of heat as an ignition. In a building fire, the fuel would be present in the combustible structure or furniture and other materials content in the building while oxygen is present in the air. In fire statistics, the initial source of heat is generally occurs by accident through a variety of mechanism from appliances fault, electrical wiring, overheating of mechanical plant etc. Arson, war and terrorism have also been the cause of many fires in buildings [1].

In order to achieve sufficient standard on fire safety and fire performance of structural building construction, there are two principal ways can be applied in the practice [2]. First is the simple prescriptive approach of the building codes and standards and secondly is performance based approach of fire safety engineering solution. The application of the building codes and standards gives little flexibility and require only a limited engineering approach. The second approach gives flexible design ability to achieve a special performance of the building and, therefore, needs greater skills involving engineering judgment.The integration of engineering judgment should be approached starting from the whole design to construction process and continued maintenance [3].

In recent decades, special consideration has been given to the use of structural building components as physical barriers to avoid or delay the growth and spread of fire [4-6]. The basis for the present study is to require special consideration by the designer for fire safety in buildings [7,8]. Since concrete is a good insulator and a non-combustible material, this also applies to concrete structures which conventionally have a favorable position in the building industry [9-12]. Consequently, the understanding of its behavior under elevated temperature is necessary for safe design and reliable analysis.

Fire can occur caused by three materials such as fuel, oxygen, and initial sources of heat as an ignition. When building in fire, the fuels would be present in the combustible structure, furniture, and other materials content in building, whilst, oxygen is present in the air. In fire statistics, the initial source of heat is generally occurs by accident through variety of mechanism from appliances faults, electricity faults, overheating of mechanical plants, etc.

Concrete is an fire-resistance material and good insulator. However, there is significant loss of concrete compressive strength when the temperature above 500 ^{o}C. In reinforced concrete structure, steel reinforcement can also loss its significant strength at this condition. As this temperature can be reached very early in fire, concrete cover and element size data are usually required to have an adequate fire resistance.

Behavior concrete exposed to fire depends on various concurrent interrelating factors have been reported in the literatures. The interrelating factors are ranging from the compositions of the materials to the characteristics of fire. The composition of the materials depends on the nature of aggregates and the characteristics of fire depend significantly upon the nature of fuel. Two main variables to be considered in the element concrete structures are the minimum dimensions of the member element and minimum concrete covers to the main reinforcing steel. The minimum dimensions specified to sustain temperatures on unexposed fire under 140 °C and to prevent spalling will not happen severely. Whilst, the minimum concrete cover specified to maintain the temperature of main steel reinforcement below a critical value as considered being around 500 °C [1,13].

2. Materials and Methods

2.1. Characteristic of Material at High Temperature

When the concrete temperature rises above 100 °C, the moisture is pushed out and the cement paste begins to dehydrate. Micro cracking of cement paste appeared because of large differential strains generated by expansion of aggregates particles. Even though without suffer any loses of strength, but the concrete begin disintegrate at this stage. The residual concrete strength is around 90 % of the initial strength happens when temperature increase to 200 °C. Further increases to 300 °C, some aggregates begin to break up and the residual concrete strength reduce to about 70%, whilst, the yield strength of reinforcing steel begins to reduce. When temperature rises between 500-600 °C, the strength of concrete and steel reinforcement are reduced significantly. At this temperature the residual strength of concrete is around 30-40 % and the reinforcing steel is about 50 %. In compartment fires, the temperature can rise above 1000 °C when most of the structures destroyed [13].

Loss of bond strength between the concrete and steel reinforcement under fire depend on the types of concrete aggregates and reinforcement. Cold deformed steel is likely to be more loss of bond than plain round. As there is no standardized test procedure, the loss of bond strength during fire will be depends on the test methods. In reinforced concrete, the bottom face of beam or slab will be carrying only a small proportion of the applied load. But, the reinforcement at the support will be able to carry full bond stress as they will only be slightly temperature affected. In general, there is not serious problem have been reported even though bond strengths are severely reduced in fire [14].

Loss in weight will be occurred when concrete is heated. The loss is caused by evaporation of both free and combined water. The loss of density as temperature increased exceeds 100 °C is mostly caused by the loss of free moisture. However, this loss is not generally enough to cause substantial change in density. Therefore, the effect of temperature is insignificant. However, consideration should be taken to ambient values and can be assumed constant up to 800 °C [15].

Mechanical properties of materials subjected to elevated temperatures are compulsory to determine structural response under fire. Comprehensive formulation is required to calculate deformations and displacements. However, to calculate load bearing capacity, more structured set of data should be employed. Considerably previous works were addressed to determine specific properties such as compressive strength of concrete and tensile strength of reinforcement steel at high temperatures.

It have been recognized that creep of concrete and relaxation of steel are much higher when exposed to elevated temperatures. Thus, the rate of loading applied in elevated temperature has enormously significant than at ambient conditions. The rate of heating performed to condition will also have significant affect to the results. The variation of temperature, duration and rate of heating will affect the concrete strength. High temperatures will result in concrete compressive strength reduction, disaggregation, spalling and cracking [1,16].

2.2. Concrete Building Model

Various research works have been carried out on the effect of high temperature on reinforced concrete building structures. Obviously, well design alone of the structure is not safe enough from fire damage. Equally important is the prevention of buildings from fire occurrence. Since concrete strength is directly affected to the elevated temperatures, increasing temperature and duration of fire will increase the amount of concrete damaged [17]. This paper presents a review of concrete building performance exposed to localized fire scenario.

Model of present analysis was seven-story reinforced concrete building at the laboratory of Building Research Establishment (BRE) in Cardington, UK [18]. The building was designed to European standard represented a commercial office building [19]. The completed concrete building was 25.20 m tall structure comprising 3 x 4 bays in plan, each square bay being 7.50 m x 7.50 m. The slab was constructed with nominally 250 mm thick flat floor slab supported by internal columns of 0.40 m x 0.40 m and external columns of 0.40 m x 0.25 m.

Constant cross-sections of the columns were applied through out of the building. Minimum reinforcement cover was 20 mm on the slabs and 40 mm on the columns. The building was constructed using normal-strength concrete for the floor slabs and high-strength concrete for the story columns and was designed to provide a minimum of 60 minutes fire resistance period.

All columns and floor slabs of the seven story building are modeled using 3D solid elements. The material properties were assumed that the structure has a concrete density of ρ_c = 2450 kg/m^3, Young's modulus of E_c = 32 GPa (for room temperature) and Poisson's ratio υ = 0.2. Reinforcement was not considered in the model. The applied loads of 3250 N/m^2 were acting on each floor. Temperature is as an input parameter, which is defined at each node. The boundary conditions of the ground floor columns are assumed to be ideally fixed.

2.3. Finite Element Model

Preliminary calculation indicated that the planned compartment fire had an equivalent fire endurance of about 60 minutes. It was then decided to examine performance at 0, 15, 30, 45, and 60 minutes. However, when the 45 minutes result compare to the room temperature result of 0 minutes at 20 °C there was no significant difference. Therefore, the examination of 60 minutes alone has been taken to this investigation and will be discussed in the following discussion.

All columns and the first floor slab of the seven story building are modeled using 3D solid elements, while the slabs in other six floors are modeled using plate elements [20-22].

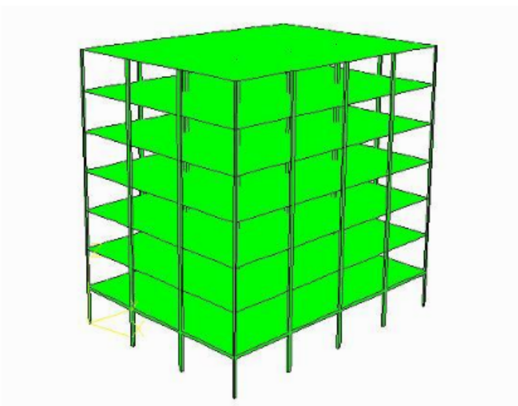

Figure 1. Seven story frame structure

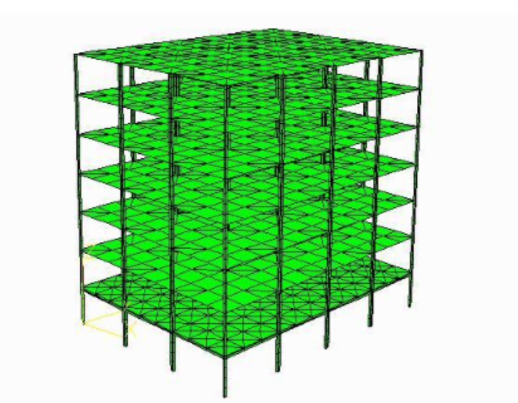

Figure 2. Corresponding finite element mesh of the structure

The concrete frame structure and detailed element mesh for the whole frame structure consist of 140 columns and 84 slabs. Figure 1 shows the seven-story frame structure and Figure 2 shows the corresponding finite element mesh of the structure.

2.4. Fire Compartment

Plannedcompartment fire had an equivalent fire endurance of around one hour. As explain in the previous discussion, at this duration it was then decided to examine performance at 60 minutes and assumed to have uniform temperature of 600 °C. In order to match the influence of temperature on Young's Modulus of concrete, the 0.375 reduction factor is applied [1].

The area fire compartment was 2 x 2 bays located at the ground floor. Location of fire compartment is shown in Figure 3.

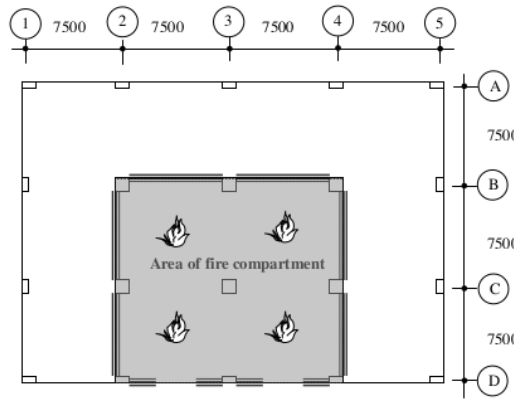

Figure 3. Area of fire compartment

2.3. Transient Analysis

Thermal strain during heating is a simple function of temperature and is not linier. This non linier behavior is in part due to chemical or physical change in the aggregates. The thermal expansion of concrete is dominated by thermal expansion of mineral aggregate.

When the exposure temperature is not high, the transient strain'saffect may not be significant. Under concrete compression, however, it is important to consider transient strains in the analysis. In one hour under fire duration of present model, temperature in the fired compartment assumed to reach 600 °C is analyzed using ANSYS computer package [23].

Constitutive model employed in this analysis is simple constitutive model that can easily be incorporated into various commercial finite element analysis codes [24, 25]. They developed an empirical formula based on the plotted results of the average Young's modulus. Figure 4 shows the normalized stress-strain curve with transient strain included.

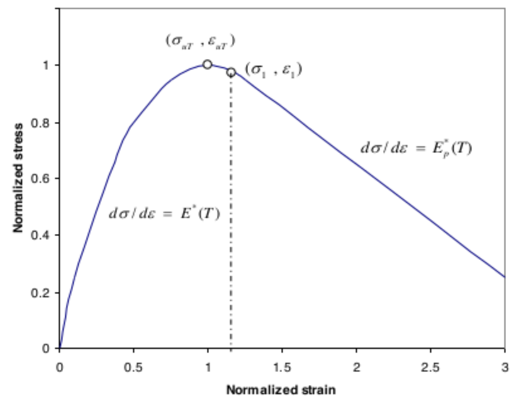

Figure 4. Normalized stress-strain curve with transient strain included

Temperature-dependent of Young's modulus in the elastic ranges suggested in (1) is applied.

$$E^*(T) = E_0 \exp\left[-\frac{(T - 20)^{0.65}}{25} \right] \quad (1)$$

Young's modulus in the plastic (2) range is recommended.

$$E_p^*(T) = E_0^- \exp[k_p (T - 20)^{2.15}] \quad (2)$$

Where: E_0 = initial Young's modulus,

$E_0^- = -0.045\,E_0$, and $k_p = 10^{-6}$.

3. Results and Discussion

Distribution of the stress and horizontal displacement (z-direction)of the structure are presented in Figures 5 and 6, respectively. Shown in Figure 5, as is expected, the maximum compressive stress is located at the bottom columns of the ground floor. The value of -21.02 MPa is found in which is close to the minimum principal stress. The stresses in horizontal direction perpendicular to the fire compartment (x-direction) and vertical (y) directions are not significant since the values of both directions of stresses are small compared to the z-direction stress.

Figs. 6a and 6b indicate that significant horizontal displacements are occurred to the heating slab by the movement of the floor slab due to thermal expansion. The horizontal movement of the slab caused maximum lateral displacement of 31.88 mm to the external columns of the ground floor. The horizontal displacement of 7.67 mm is also found to the unexposed fire external column at the opposite side. This large lateral displacement is significant and cannot be ignored in design. On the other hand, vertical displacements of the structure are relatively low. The maximum vertical displacement of 8.52 mm is found in the middle of the concrete slab.

Analysis from the model indicated that high compressive forces generated in the slab caused by restraint and thermal expansion. The horizontal displacements of the floor slab were significant, but, the vertical displacements of the floor slab found very low.

The compressive membrane action on floor slab can only occur at low vertical displacements. Usually, the amount of displacement is less than half thickness of the slab and can only occur in horizontal flat slabs. Provided the slab of the model does not achieve vertical displacements greater than half of its depth, then the effect of compressive membrane action will substantially improve the load bearing capacity of the slab [3,26,27].

Even concrete floor slab extensively spalling and exposed some bottom reinforcing bars to fire, the slab may remain stable. The applied static load of the slab was supported by compressive membrane action when the sagging moment capacity of the slab was extremely decreased [3]. In this case the floor slabs were survived due to beneficial effect of compressive membrane action as seen in Figure 7.

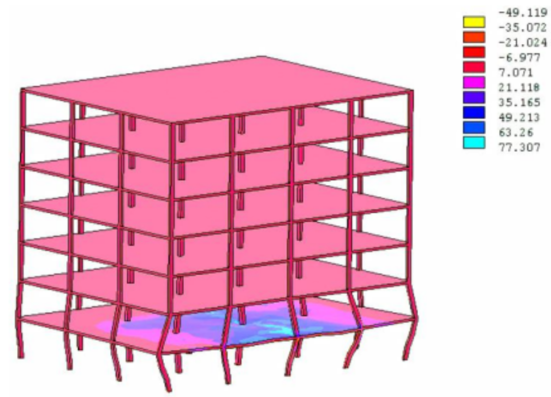

Figure 5. Distribution of the stress in horizontal (z) direction (MPa)

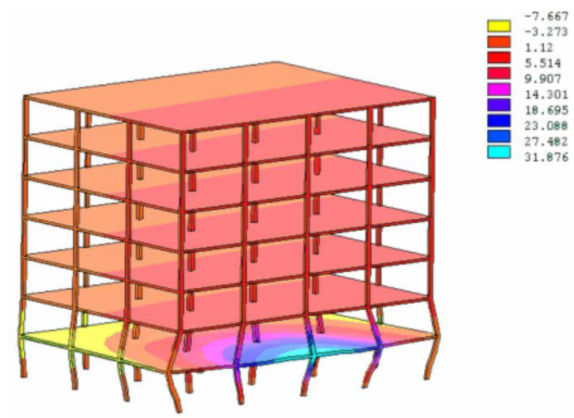

Figure 6a. Displacement of the structure in horizontal (z) direction (mm)

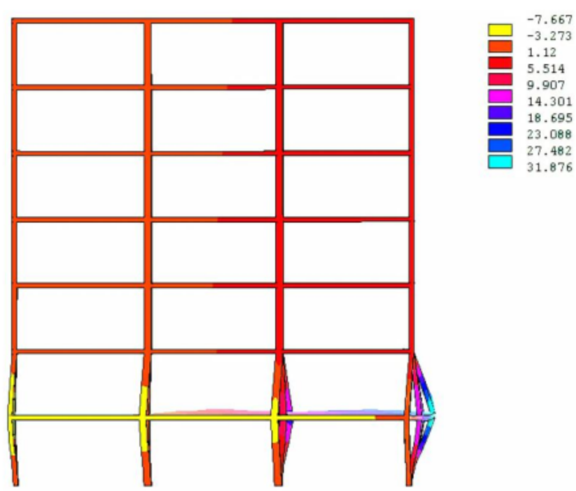

Figure 6b. Horizontal displacement of the structure viewing from the left side in 2D (mm)

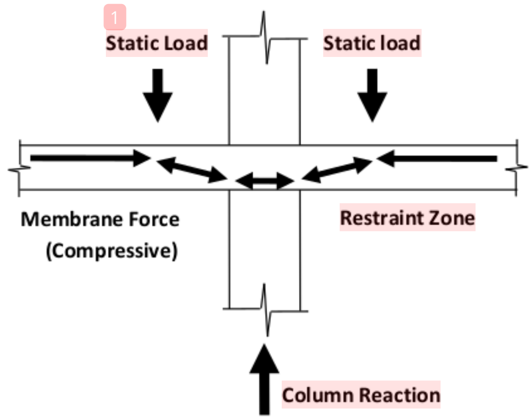

Figure 7. Compressive membrane actions

The European standard [14] does not require the actual displacement to be calculated explicitly in ambient conditions, but the standards recommend that the span/depth ratio should be satisfied. In this case, the beam span/depth ratio of 18.75, calculated from 7500/400, is satisfied. However, it should be noted that the significant displacements cannot be ignored.

Horizontal displacements caused by the floor slab's thermal expansion created additional moment to the external column. Previous failure of concrete structures has been identified as a result of this additional moment. Design engineers have to consider the behavior and ensure that the external columns have ability to accommodate the lateral displacement during fire.

4. Conclusions

Finite elementmodel with transient strain analysis using ANSYS demonstrated reliable analysis for the performance of reinforced concrete structure subjected to fire. The results indicated that the current design methods are based on an incorrect model of structural behavior without considering the beneficial and detrimental effects of the complete structure.

- The current design codes and design methods do not accommodate the compressive membrane action of the heated floor slabs as a beneficial effect.
- The current design codes have also not accommodates additional moment to the external columns caused by large lateral displacements of heated floor slabs as a detrimental effect.
- Therefore, the development of advanced fire engineering analysis from the complete concrete structure behaviour is required rather than from individual member behaviour.

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