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Structural Sustenance of Reinforced Concrete Elements Subjected to Fire Attack

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Abstract: Risk of accidents due to fire is more often caused due to electric short circuiting. The fitness of the structure after fire attack is to be issued by the structural engineer. In the present paper temperature propagation in concrete exposed to elevated temperatures is studied using finite element approach. A concrete column member of cross sectional dimensions 500mm× 300 mm is chosen for the study. The propagation of heat and the corresponding distress to concrete is evaluated from surface to the central core along the shorter dimension of the column. The temperature variation across the thickness of concrete is studied considering the variation of thermal conductivity with temperature and porosity. After completing the thermal analysis, the temperatures evaluated from the output are given as thermal inputs to find the thermal stresses and strains using the same package. With known values of thermal stresses and strains, the magnitudes of additional stresses that develop in the column member are evaluated. At present a large quantum of data is being generated by us, which shall be used later as training patterns to train a BOPN network to simulate the damage detection for any arbitrary inputs. The information thus obtained may be used for structural assessment.

Keywords: *Temperature, Thermal Stress, Thermal Strain, Thermal Conductivity, Porosity, Neural Network*

1. Introduction

The present day competitive environment demands the need of conceiving structures sustainable under all adversities keeping in tune with the financial needs of the nation. This puts pressure on the structural engineer to come up with advanced techniques to mitigate structures most competitively. The increased longevity of structures, even for a decade or half, results in substantial savings to the economy of the nation. In the present work the study pertaining to accidents due to fire attack has been taken up. Fire accidents and the resultant damages to the structure often leave doubts in the minds of the general public regarding their utility. Neither can the structures be dispensed off, as huge investments are involved in their demolition and reconstruction. In this scenario, active research in this field is considered most desirable. The present work is taken up in this backdrop. The fire accidents occur more frequently due to electric short circuiting in high rise buildings. The damage detection caused due to sustained fire attack on a portion of the building structure is investigated.

The source of fire emanates from electric panel boards in tall buildings; go unnoticed until it assumes larger proportions. Further, as the panel boards are more frequently located in the lower floors in buildings the distress occurring there is considered grave for the sustenance of the building. The inaccessibility of the origin of fire during fire attack further compounds any rational assessment of damage prediction. Though there are no known established methods to evaluate the extent of fire damage as on date, their sustainability assessment is considered most desirable. The frame members, located nearer to panel boards are more vulnerable to severe damage posing threat to the integrity of the structure. Since the columns are the primary load carrying members transferring the load of the structure to the ground, any damage to the columns is considered a disaster.

In the present study, a concrete column with sectional dimensions 500mm × 300 mm is considered subjected to fire on one of its larger faces. The propagation of heat and the resultant damages to the concrete is evaluated till the central core of the column using the finite element package MSC Nastran.

On this larger surface, only the central 200mm x 200mm square portion of the column is subjected to fire attack. The elevated temperature in this portion was considered 1000^0C lasting for two hours. The propagation of heat within the square portion of 500mm ×500mm around heated portion to a depth of 150mm is studied using the FEM package. Temperature all around the heated square portion was assumed as 27^oC, the room temperature. In the analysis, the temperature variation across the depth is studied considering the variation of thermal conductivity with respect to temperature and porosity.

Having completed the thermal analysis, the temperatures obtained at different locations from the output is given as thermal inputs to find out thermal stresses and strains generated in the concrete, again making use of the same package. With known values of thermal stresses and strains, evaluated as described above, the extent of additional stresses that develop in the column member after fire attack are evaluated. It is proposed to study the extent of damage due to C-S-H (Calcium Silicate Hydrate) gel failure as well. Due to the above two reasons, on one hand the strength of concrete gets decreased and on the other the resultant stress gets increased due to the thermal stress. This may prove grave for the sustenance of the structure. Making use of the present study, a rational assessment to work out the residual strength of the structure is possible.

The structural assessment after the fire attack is proposed to be carried out as given under. It is first proposed to evaluate the residual strength of all structural elements affected due to fire. Replace those elements alone with members of equivalent strength. The structural assessment made thereafter is considered acceptable. The thermal analysis using FEM is considered cumbersome and tedious. Hence, it is proposed to train a BOPN neural net with training patterns obtained from more cases of fire attacks. A BOPN neural net, developed already, will be used for simulating the training patterns. The information pertaining to the residual strength of elements subjected to fire will be obtained from the trained neural network.

2. Literature

During a fire attack, the temperature normally reach 1000^{o}C and above in buildings leading to severe structural damages. When concrete gets heated due to fire, the propagation of temperature to deeper layers happens progressively but at a slower rate. Therefore, significant temperature gradients are produced between the concrete surface and core inducing additional damage to concrete. The rate at which water gets evaporated from the heated concrete depends on the energy that binds the water with solid particles in concrete. Thus, free water evaporates first followed by capillary and physically bound water. The removal of water that is chemically bound with cement hydrates is the last to be initiated. Due to fire exposure the various changes that take place in concrete alters the physical, thermal and mechanical properties of concrete.

During heating, ettringite decomposition first takes place even before temperatures reach 100^{o}C. C-S-H gel decomposition is progressive and takes place from beginning of material heating. Structure of cement paste is partially damaged due to dehydration at a temperature of 105^{o}C; which is standard temperature for drying of materials. At about 500-550^{o}C, portlandite (calcium carbonate) rapidly drops as it decomposes to calcium oxide and water. Calcium oxide produced in this reaction makes the elements made of Portland cement practically redundant after cooling. Dehydration of C-S-H gel reduces volume which in turn increases porosity of the matrix. Moreover, during heating cement paste experiences a slight expansion up to 200^{o}C although intense shrinkage begins as soon as this temperature is exceeded. This contributes to the porosity in cement paste.

The fire response of reinforced concrete members is influenced by characteristics of constituent materials-concrete and reinforcing steel. The behaviour of concrete member exposed to fire depends on thermal, mechanical and deformation properties of concrete which substantially change within the temperature range associated with building fires. Thermal properties determine the extent of heat transfer to structural member. Mechanical properties determine the extent of strength loss and stiffness deterioration of the member, while, deformation in conjunction with mechanical properties determines the extent of deformations and strains in structural member. The mechanical properties are strongly affected by chemical bonds and cohesive forces between sheets of C-S-H gel. It is assumed that 50% of cement paste strength comes from cohesive forces. Thus, evaporation of water between C-S-H gel sheets strongly affects mechanical properties.

Since the temperature in excess of 200^{0}C turns steel reinforcement brittle, it needs to be protected against heat. Concrete and steel exhibits similar thermal expansion coefficients up to 400^{o}C. However, higher temperatures result in significant expansion of steel compared to concrete. If temperature of the order of 700^{o}C is attained, load carrying capacity of reinforcement gets reduced by 20% of its designed strength.

In design codes of RCC, the temperature variations across the depth of concrete cannot be considered to offer insulation effect to the structural steel reinforcement. Most of the studies in the past have been conducted with respect to certain predetermined heating regimes which might not be a representative of heating in real fire accident, that is, temperature-time curve used in fire tests; slow heating leading to reduced internal temperature gradients; using other temperature-time relationships appropriate only for specific applications.

One of the important aspects to be considered during a fire attack is spalling. Spalling is defined as breaking up of layers of concrete from surface when exposed to high and rapidly increasing temperatures. Spalling exposes deeper layers of concrete to fire temperatures thereby increasing the rate of transmission of heat to inner layers, including reinforcement. When reinforcement is exposed to fire, the temperatures in reinforcement rise at very high rate. This leads to faster deterioration in the strength of structural member. The loss of strength in reinforcement combined with that of concrete due to spalling significantly decreases the fire resistance of reinforced concrete structural member. Another impact is that due to reduction of cross-section of concrete available to support imposed loading, the stresses on remaining concrete members increase.

3. Method of Study

In the present study, a column member of dimensions 500mm×300mm is considered to be subjected to fire on one of its larger faces. A sample square portion of 500mm×500mm to a depth of 150mm is considered for this purpose. Within this area, the central portion of 200mm×200mm is subjected to an increased temperature of 1000°C on the exterior face for a period of two hours. For the purpose of study, the area is divided into nine parts such that the central portion is of dimensions 200mm×200mm.

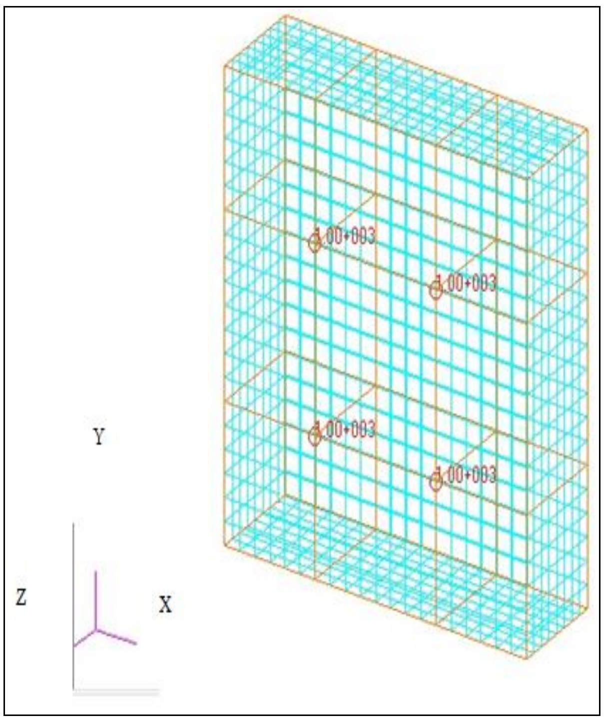
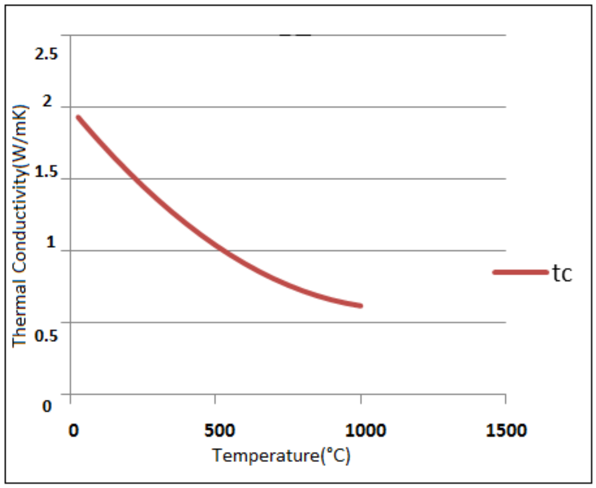


Figure 1 *Finite element model*



Graph 1*Thermal conductivity vs. temperature*

The model consists of total number of nine solids. A temperature loading of 1000°C is applied on the external face of the exterior central solid. The default initial temperature of all other faces of the model other than the temperature exposed portion is taken as 27°C. The temperature variation across the thickness is studied considering the variation of thermal conductivity with respect to temperature and porosity. The variation of thermal conductivity with temperature (θ) is computed as per the equation specified in Euro code 2.As per the code, the upper limit of thermal conductivity (λ_c) of normal weight concrete may be determined from the following equation:

$\lambda_c = 2 - 0.2451(\theta/100) + 0.0107(\theta/100)^2$ W/m°C for 20°C≤θ≤1200°C

The variation of porosity with respect to temperature is calculated using the following formulae:

$P = 0.0131\times T + 5.6929 \quad T \leq 500°C$
$P = 1.3978\times e0.0037\times T \quad T \geq 500°C$

For the purpose of study, the porosity is assumed to be inversely proportional to the thermal conductivity. Using the above equations, the increase in porosity with respect to temperature is calculated. The thermal conductivity values calculated as per the equation are reduced in proportion to that of porosity increase and then given as input in properties field. Other than the thermal conductivity, specific heat and density are specified and the values are as follows:

Specific heat **(C_p): 880 J/kg °C**
Density **(ρ): 2400 kg/m^3**

For the purpose of finite element analysis the model is suitably meshed so that the edges of the solid along the depth are divided into eight elements and then meshed. Transient thermal analysis, i.e. time dependent thermal analysis is carried-out on the model. The temperature is applied in time steps of 10minutes each for twelve times. Thus, the analysis of model exposed to a temperature of 1000°C for a period of 2 hours is carried-out to obtain the temperature distribution throughout the portion of the solid under interest.

Having completed the thermal analysis, with the known outputs of temperature readings as thermal loads at different locations, the structural analysis is taken-up. From this analysis the magnitudes of thermal strains and thermal stresses at different locations are evaluated. The grade of concrete considered is M35 and the material is considered to be linearly elastic and isotropic. In the properties field of the FE analysis, elastic modulus, Poisson's ratio, coefficient of thermal expansion and reference temperature are specified. Following are list of values specified:

For **M35** grade concrete:

Elastic Modulus: $5000\sqrt{f_{ck}}$ = 2.958 E10 N/m^2
Poisons Ratio: 0.15
Coefficient of thermal expansion: 14.5E-6/°C
Reference temperature: 27°C

The above given values of properties are assigned to the whole of the solid. The top and bottom faces of the model are considered to be fixed and the obtained temperatures are given as thermal loads on all faces of the model. Linear static analysis is carried out and thermal stresses and strains are obtained.

4. Neural Computing

Neural computing paradigm that is inspired by the functioning of human brain has attracted researchers from almost all disciplines of structural engineering for computerisation of ill conditioned tasks. This computing technology called neural computing, attempts at simulating the functioning of human brain very approximately in a mathematical form. The biochemistry of the neurons is not yet fully understood. Figure.2 shows the structure of a biological neuron. The main parts of a biological neuron are the cell body, the axon and the dendrite. The dendrite is responsible for carrying signals from the cell body to the other neurons. The axon on the other hand carries signals from the cell body to other neurons. The dendrite and axon meet at a point called synapses.

4.1. Artificial Neuron

The artificial neuron is an approximately simulated model of the biological neuron. The artificial neuron can carry out only a very simple mathematical function and/or can compare two values. Figure.3 shows the essential parts of an artificial neuron. An artificial neuron has a typical function associated to it, which is often called as threshold function or squashing function. A typical artificial neuron gets an input either from other neurons or directly from the environment (i.e. input nodes). The paths connecting the input nodes to the neurons and connections between the various neurons are associated with a certain variable weight, which represents a multiplying factor for the incoming signal representing the synaptic strength of the connections. These weights are initially set to some random values and are later adjusted in the process of training the net. The artificial neuron then sums this input which is actually a weighted sum of all the input signals. The input so obtained is used to calculate a node value according to the squashing function of the neuron. This node value is compared with the threshold value of the neuron and if the node value is higher, then the neuron goes to the "higher state" (excitation state) and a signal is passed on to the next layer of neurons. The three common types of non-linear nodal functions generally used are shown Figure.4.

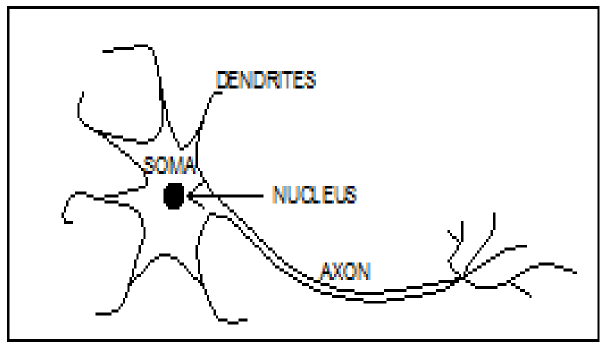


Figure 2 *Biological neuron*

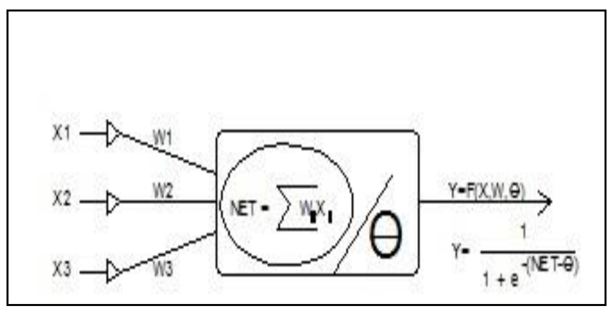


Figure 3 *Artificial neuron*

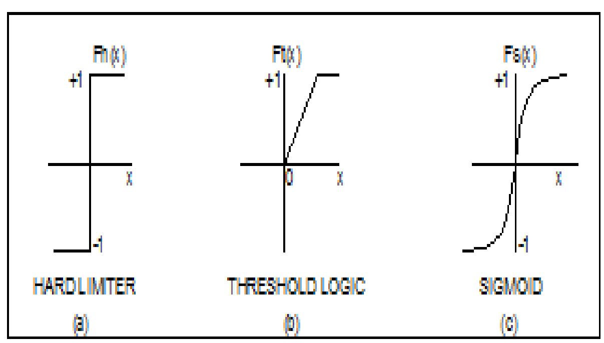


Figure 4 *Nodal functions*

5. Specimen Calculations

The stresses (in N/mm^2) for the four corner elements of the exterior central solid at the end of two hours of fire exposure are given in Table1. The corresponding strains for the four corner elements of the central solid are given in Table 2.The strains at the nodes on the exterior surface at the end of two hours are given in Table 3. In the table positive values indicate tension and negative values indicate compression.

***Table 1**: Thermal stresses in corner elements of the exterior central solid at the end of two hours*

Entity ID	XX (N/mm^2)	YY (N/mm^2)	ZZ (N/mm^2)	XY (N/mm^2)	YZ (N/mm^2)	ZX (N/mm^2)
1793	-160.53	-224.28	-0.92	-55.21	-5.51	-7.27
1800	-160.53	-224.28	-0.92	55.21	-5.51	7.27
1849	-160.53	-224.28	-0.92	55.21	5.51	-7.27
1856	-160.53	-224.28	-0.92	-55.21	5.51	7.27

***Table 2:** Thermal strains in corner elements of the exterior central solid at the end of two hours*

Entity ID	XX	YY	ZZ	XY	YZ	ZX
1793	0.006044	0.003565	0.012249	-0.002146	-0.000214	-0.000283
1800	0.006044	0.003565	0.012249	0.002146	-0.000214	0.000283
1849	0.006044	0.003565	0.012249	0.002146	0.000214	-0.000283
1856	0.006044	0.003565	0.012249	-0.002146	0.000214	0.000283

***Table 3:** Thermal strains at the nodes on the exterior surface at the end of two hours*

Entity ID	XX	YY	ZZ	XY	YZ	ZX
393	0.000228	-0.004066	-0.000025	-0.001560	-0.000272	-0.000000
399	0.000003	-0.003404	0.000126	-0.001880	0.000570	0.000000
435	0.000385	0.000989	0.000426	-0.000689	-0.000301	-0.000036
954	0.000003	-0.003404	0.000126	0.001880	0.000570	-0.000000
1032	0.000203	0.000064	0.000418	0.000099	0.000044	0.000033
1407	0.000228	-0.004066	-0.000025	0.001560	-0.000272	-0.000000
2010	0.000385	0.000989	0.000426	0.000689	0.000301	-0.000036
3312	0.000385	0.000989	0.000426	-0.000689	0.000301	0.000036
3336	0.000151	-0.000202	0.000302	-0.000039	0.000041	-0.000009
3747	0.000228	-0.004066	-0.000025	0.001560	0.000272	-0.000000
3785	0.000664	0.000322	0.000744	-0.000000	-0.000163	0.000000
4761	0.000228	-0.004066	-0.000025	-0.001560	0.000272	0.000000

6. Results And Discussions

As concrete is a heterogeneous material, gradient of temperature variation inside is very flat and irregular unlike metals. In the present work, the variation of thermal conductivity with changes in temperature values has been considered. Similarly, the variation of thermal conductivity due to porosity has also been taken into account based on available information. Magnitudes of temperature at different locations in concrete have been recorded at every ten minute intervals for two hours. Based on the FEM output, it is observed that the heat does not reach the core of concrete until one hour twenty minutes from the beginning of fire attack. From then on variation of temperature inside concrete core is found to increase significantly.

The variation in compressive strength of concrete with temperature for each grade of concrete as reported in Euro code is presented in Table 4. The information is found very useful for determining the residual strength of concrete. The magnitude of temperature in a few elements located in the central portion with corresponding compressive strengths after two hours of fire exposure is presented in Table 5. With these temperature readings as thermal inputs, the stresses and strains in the concrete are evaluated next using the same Finite Element Package. The thermal stresses calculated thus are acting in addition to the stresses caused due to the structural loads. The resultant stresses and strains obtained as described above shall not exceed the permissible strength of concrete for the sustenance of structure.

We are in the process of generating a large amount of data as mentioned already, where the time of temperature exposure, grade of concrete and area of temperature exposure are the likely parameters. Once such data is available it is proposed to train the BOPN neural network which shall be used to predict the temperature variation across concrete for an arbitrary accident.

Table 4: *Decrease in compressive strength with temperature*

Concrete Temperature(°C)	$f_{c\theta}$ / f_{ck}
20	1.00
100	1.00
200	0.95
300	0.85
400	0.75
500	0.60
600	0.45
700	0.30
800	0.15
900	0.08
1000	0.04
1100	0.01
1200	0.00

Table 5: *Decrease in compressive strength of central elements*

Element ID	Temperature (°C)	Compressive Strength (N/mm^2)
1361	121.17	34.63
1425	131.99	34.44
1489	154.72	34.04
1553	191.90	33.39
1617	248.46	31.55
1681	334.50	28.54
1745	473.27	22.40
1809	779.98	6.30

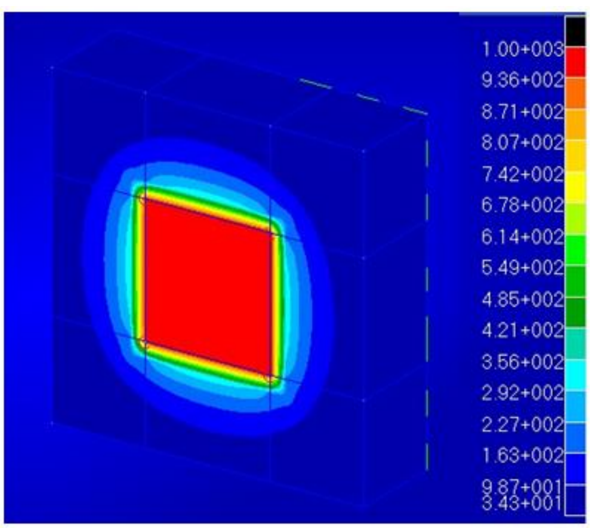


Figure 5 *Distribution of temperature throughout the solid*

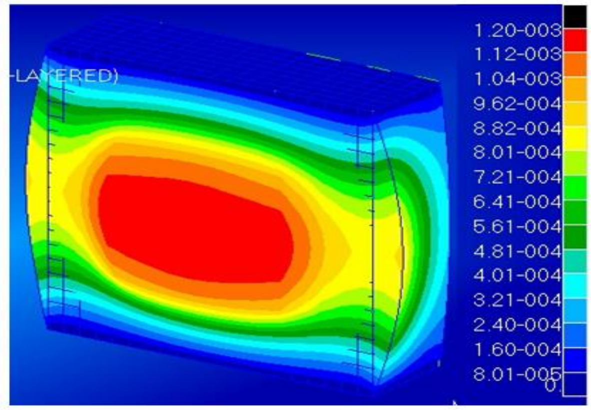


Figure 6 *Displacement profile for two hours duration*

7. Scope for Future

In the present study, the distress in concrete alone is investigated. The effect of temperature on the strength of steel, the bond between steel and concrete are to be explored. Consideration of geometric and material non-linearity would make the study more complete.

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