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Software-based method for load capacity estimation of fire damaged RCC columns

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ABSTRACT: In this paper, estimation of non-homogeneous section capacity under axial compressive load is presented for various time of fire exposure for different column sections. To attain this goal, at first, thermal analysis of the column was done on finite element analysis software ABAQUS. ASTM E119 time-temperature relationship is used as standard fire. Result of this analysis in form of node temperatures for a certain fire exposure time was then exported to custom made software which was developed by the authors in Visual Basic programming language. This software considers the nodal temperatures and estimates corresponding thermal and strength properties of concrete and steel. Cumulative nodal compressive strength capacity is calculated for each scenario. It should be noted that strength calculation are done on 'hot' column, which is performance of the column during fire. Results are validated in two steps; at first, thermal analysis output from ABAQUS was validated with thermocouple recorded temperature recorded in test conducted in Canada and secondly plastic strength of columns with load eccentricity was collected from similar tests and was put into respective interaction diagrams. All these outputs show reasonably accurate results in most cases and somewhat conservative results in others. While this method is very simple, but it provides a valuable tool to engineers and fire fighters to estimate column capacity instantly provided that temperature history of that fire is known. Increase of cover on reinforcement shows significant increase of column capacity under fire. It is notable that reinforcement size and cover plays more significant roles in short duration fire but for long duration of fire exposure, these two factors are much less significant.

1 INTRODUCTION

Fire safety engineering for structures has been of tremendous interest in last decade as an aftermath of September 11 attacks on Twin Towers, New York in 2001. This followed much research on the field of structural response under fire. Sudden collapse of the structure was treated with greater concern. For this reason, column strength variations due to different lengths of fire exposure were dealt quite extensively. Researches concerning steel columns consists greater part of these efforts. It is because steel, with its high thermal conductivity, is much more prone to fire attack. Another cause is that the physical and thermal properties of steel are quite consistent and dependable. Hence it is easier to model with steel and predict fire resistance. Due to these reasons, concrete columns acquired lesser attention than steel columns. But concrete columns, due to its spalling phenomena, can be subjected to rapid failure when it is exposed to severe fire. Usual assessment methods of axial load capacity of the non-slender reinforced concrete column section lies on the idea of uniformity of material properties over the cross-section of the column. But, occurrence of fire around the column and propagated heat into the concrete will obviously create a non-homogeneous section regarding material properties that are temperature dependent. These non- homogeneous properties include strength, modulus of elasticity, specific heat, thermal conductivity, and ultimate strain of both concrete and steel. Such combination of factors makes it a very difficult task for field application in case of emergency. This paper provides a software based solution for fast solution. The software incorporates non-linear behavior of concrete and steel and provides fast estimation of strength. For this purposes, an initial analysis using finite element thermal analysis was conducted followed by use of the above mentioned software.

2 HEAT TRANSFER ANALYSIS AND VALIDATION

2.1 *Heat Transfer Mechanism*

As it is very commonly known, heat transmits by three means; namely, Conduction, convection and radiation. Concrete, due its flexibility and diversity, is difficult to characterize by single numerical value for any of its property. On top of that, damage extent by heat adds more degrees of unpredictability to its behavior. ACI 216.1R-89 provides guidelines for predicting thermal effected behavior of concrete. In this paper, the authors followed those specified values except tests showed otherwise.

Radiative heat transfer is taken as primary method of heat transfer between heating furnace and column. For radiative heat transfer, gray body equation by Stefan-Boltzmann equation is followed (1879, 1884).

$$q = \varepsilon \sigma (T_h^4 - T_c^4) A_c \tag{1}$$

Here, ε and σ stands for emissivity of concrete (assumed to be 0.8) and Stefan-Boltzmann constant ($5.670400 X 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$). Thermal Conduction by convection is not considered as its contribution to heat load is quite low (Lie 1977). Collected heat by column is propagated into the column solely by conduction being a solid and non-transparent medium.

Conductive heat transfer is dependent on thermal conductivity and specific heat of concrete.

$$\text{Rate of Heat Conduction} \propto \frac{\text{area} \times \text{temperature difference}}{\text{thickness}}$$

$$\Rightarrow Q_{conduction} = -kA\frac{dT}{dx} \tag{2}$$

Here, k represents thermal conductivity, a measure of material's capacity to carry heat. 'A' represents contact area between bodies and dT/dx indicates thermal gradient (Fourier 1822).

When temperature of a heated body is not in equilibrium (in steady state), temperature profile of that body changes with time. When time is a factor for heat conduction analysis, Transient heat analysis system is used. In other words, thermal equilibrium is not reached due to lack of sufficient time. A Transient analysis result with a comparative long span of time gives similar result as a Steady State analysis. As time dependant analysis is required for current problem, transient method is used.

$$\begin{pmatrix}\text{Heat transferred into}\\ \text{volume element from}\\ \text{all surfaces during } \Delta t\end{pmatrix} + \begin{pmatrix}\text{Heat generated}\\ \text{within the volume}\\ \text{element during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{The change in the}\\ \text{energy content of}\\ \text{element during } \Delta t\end{pmatrix}$$

$$\Rightarrow \Sigma_i(\text{all sides}) \, [Q] + E_i(\text{gen.element}) = (\Delta E_i \text{element})/\Delta t = (mc_p \Delta T)/\Delta t \quad [\therefore \Delta E_i \text{element} = mc_p \Delta T]$$

$$\Rightarrow \sum_{\text{all sides}} Q + E_{\text{gen.element}} = mc_p \frac{T_m^{i+1} - T_m^i}{\Delta t} \tag{3}$$

Here m and c_p represents mass and specific heat of the material. T_m^i and T_m^{i+1} are the temperatures of node m at times $t_i = i \times \Delta t$ and $t_{i+1} = (i+1) \times \Delta t$ respectively, and $T_m^{i+1} - T_m^i$ represents the temperature change of the node during the time interval Δt between the time steps i and $i+1$.

2.2 *Thermal Load*

Thermal load is applied on the column in form of ASTM E119 Time-temperature curve. It simulates standard household fire but "focus more on the control, measurement and specification of the heat flux condition rather than the ambient gas temperature history" (ASTM E119 Committee 2006). A similar curve of ISO 834 (BS 476) was also applied during simulation. But, for greater convenience for application in concordance with

BNBC 1993 and justification of results, only ASTM E119 data is presented here. Figure 1 shows ASTM E119 and ISO 834 (BS 476, EN 1992-1-2) curve.

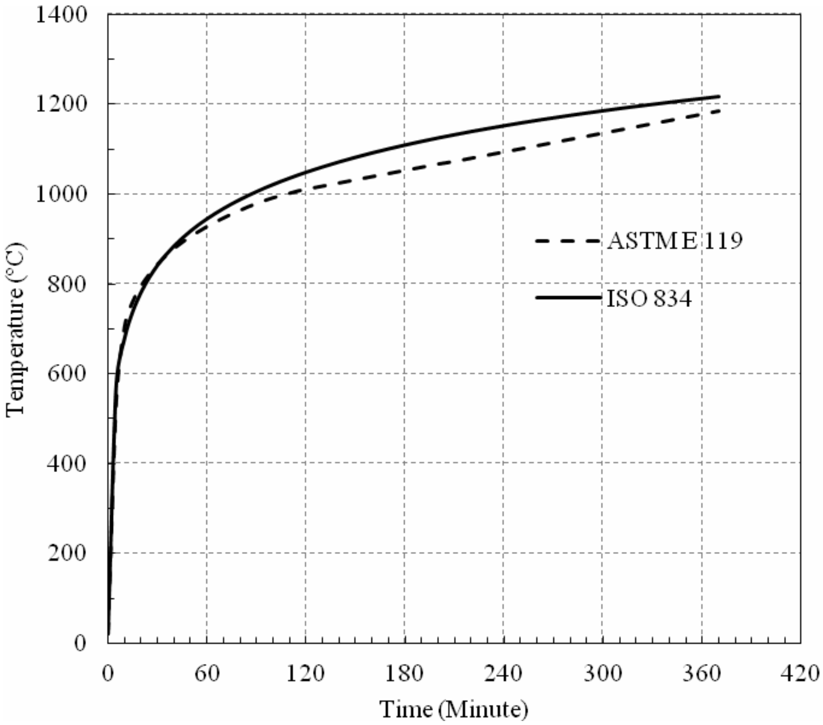


Figure 1. ASTM E119 and ISO 834 Time-Temperature curve

2.3 *Material Properties*

As mentioned previously, concrete properties are temperature dependent and for thermal analysis, conductivity and specific heat is of prime concern. Figure 2 and 3 shows their variation with increase of temperature.

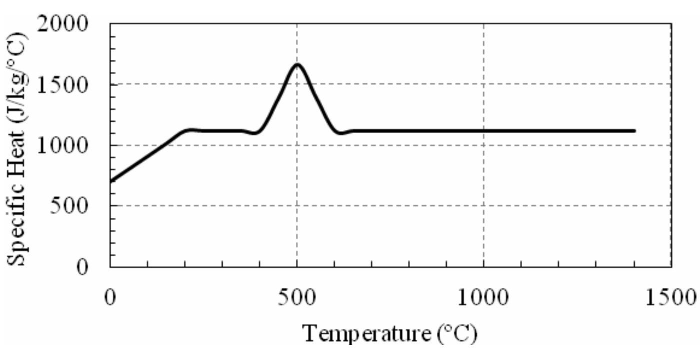


Figure 2. Concrete Specific Heat Variation with Temperature (Harmathy 1993)

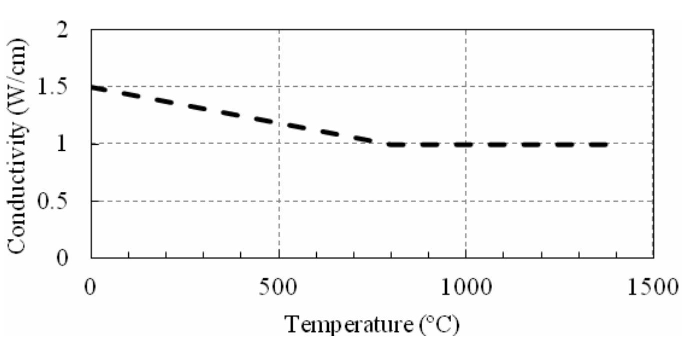


Figure 3. Concrete Conductivity Variation with Temperature (Harmathy 1993)

2.4 *Thermal Analysis*

General purpose finite element modeling software ABAQUS 6.10 is used for the thermal analysis. A two dimensional column cross section is modeled only for concrete. Steel reinforcements in the concrete are consciously omitted to simplify analysis and due to their negligible effect on over all thermal conduction process being about 50 time more thermally conductive than concrete. Concrete properties are taken for siliceous aggregate and moisture less concrete was assumed. It is also assumed that concrete will not suffer spalling. These two assumptions are necessary as moisture movement in the concrete is thought to be the major cause of concrete spalling. Simulation of pore moisture movement is still very difficult due to degree of crystallization, creation of Gel-tubes and other effects. It is also very interesting to note that for service load (not design load), spalling have lesser effect on reinforced concrete column performance during fire. This point is further explained at later discussions. Transient explicit analysis is used with 60 second time step. A 305mmX305mm column is used to compare with available test results. This model emulates a column in test furnace without considering convective heat transfer.

2.5 *Model Validation*

Results from this FEM analysis was compared with T.T. Lie and T. D. Lin (1985) test results for ASTM E119 fire curve. Output of FEM follows the thermocouple data closely. Figure 4 shows data acquired from test and FEA along the centerline of the column cross-section.

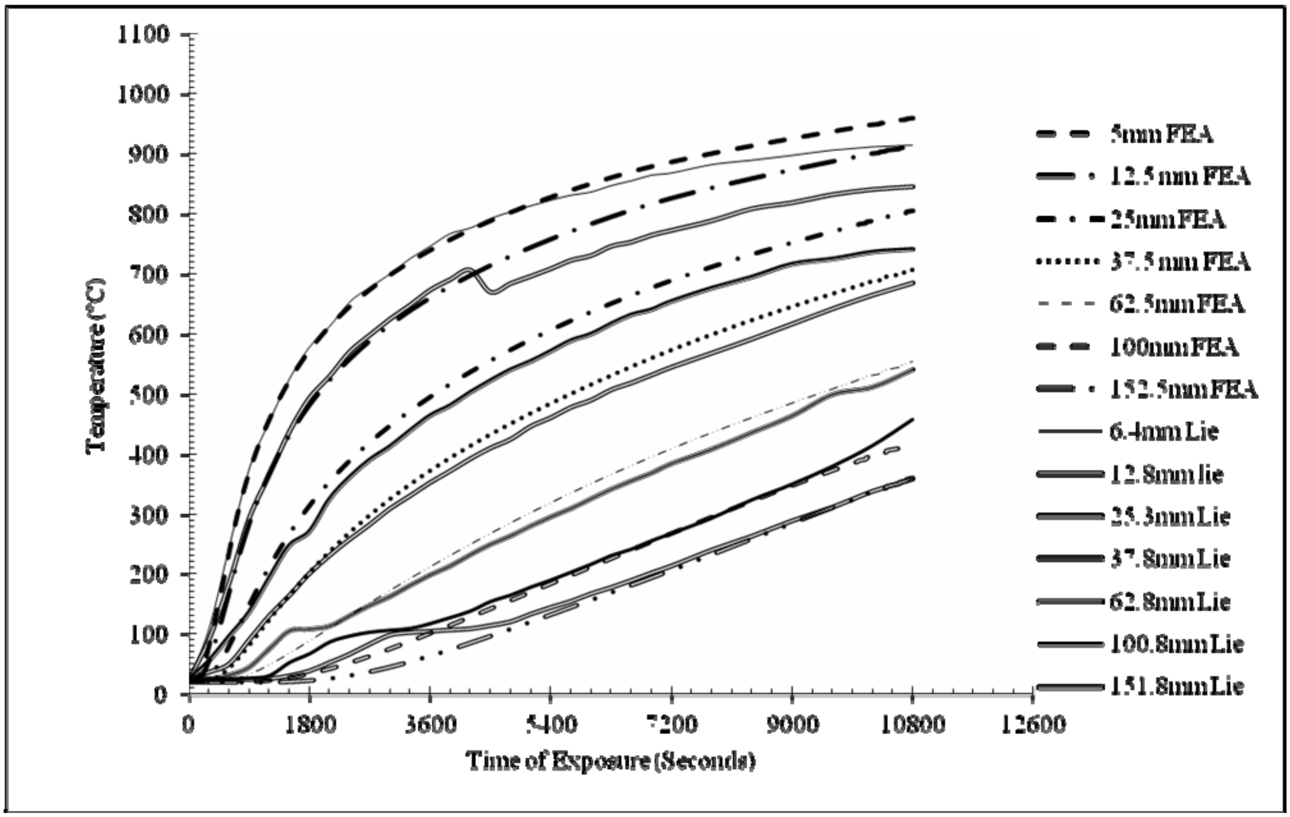


Figure 4. Time-Temperature curve for validation of FEM (Lie & Lin 1985).

Figure 4 validates the FE model and ensures that data acquired from this analysis mimics actual test condition. Variation at centre nodes at initial stage is due to unaccounted entrapped moisture at the core. This fact is further emphasized by flatness of the curve at 100ºC which indicated state change. After vaporization, test and FE curves showed a much closer match. As test results consistently stays below the FE model output curve, it can be said that actual test specimen had a lower emissivity and hence absorbed less heat than expected.

3 AXIAL STRENGTH PREDICTION

3.1 *Material Properties*

Material properties that effects reinforced column behavior under fire are compressive strength, modulus of elasticity, and ultimate strain for concrete and steel. Siliceous aggregate exhibits better fire resistance performance than calcareous aggregate concrete. Figure 5 and 6 shows percentage of concrete steel strength for increasing temperature.

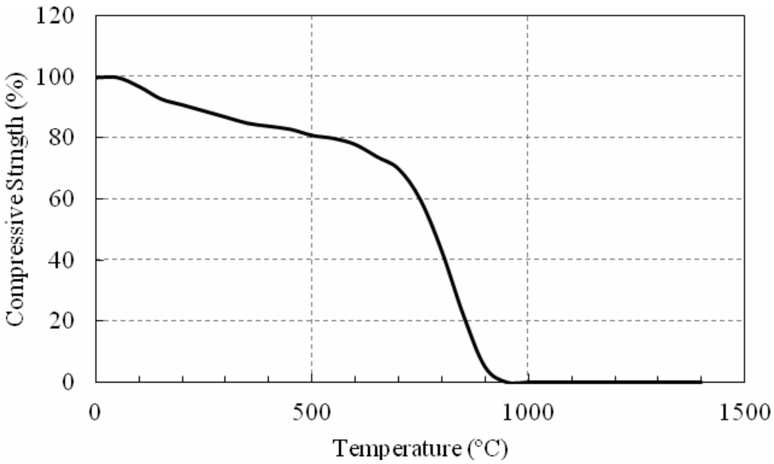


Figure 5. Compressive Strength Variation with Temperature as % of Initial Strength (ACI 216.1R-06)

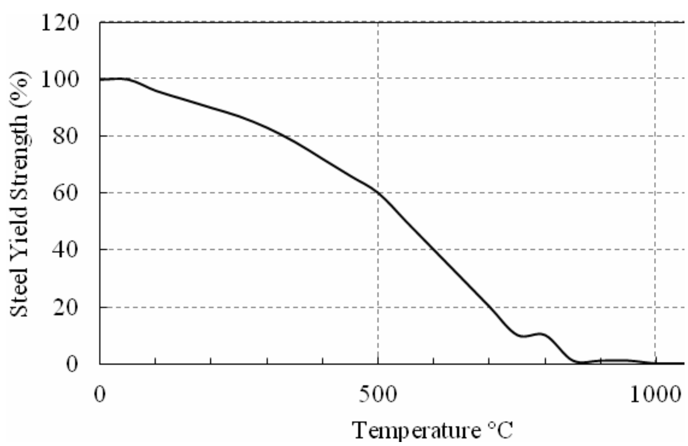


Figure 6. Steel Strength Variation with Temperature as % of Initial Strength (ACI 216.1R-06)

3.2 *Methodology*

These data was incorporated within the developed software for future direct application. The software takes nodal temperatures for a certain period of exposure (from previously mentioned analysis), concrete compressive strength in normal state, column dimension, and number, location, size, and yield strength of steel rebar. Then using the flow chart at figure 7 and 8, axial load capacity is measured. Temperature data is used to calculate strength of the 'contributing area' or element area. This block then contributes to overall strength calculation. Finer contributing area should make a more accurate prediction while it takes greater computing power. For this current problem, the authors confines their analysis to axial strength only but in can be emphasized that similar method can be used for finding moment; i.e. developing interaction diagrams of fire damaged column.

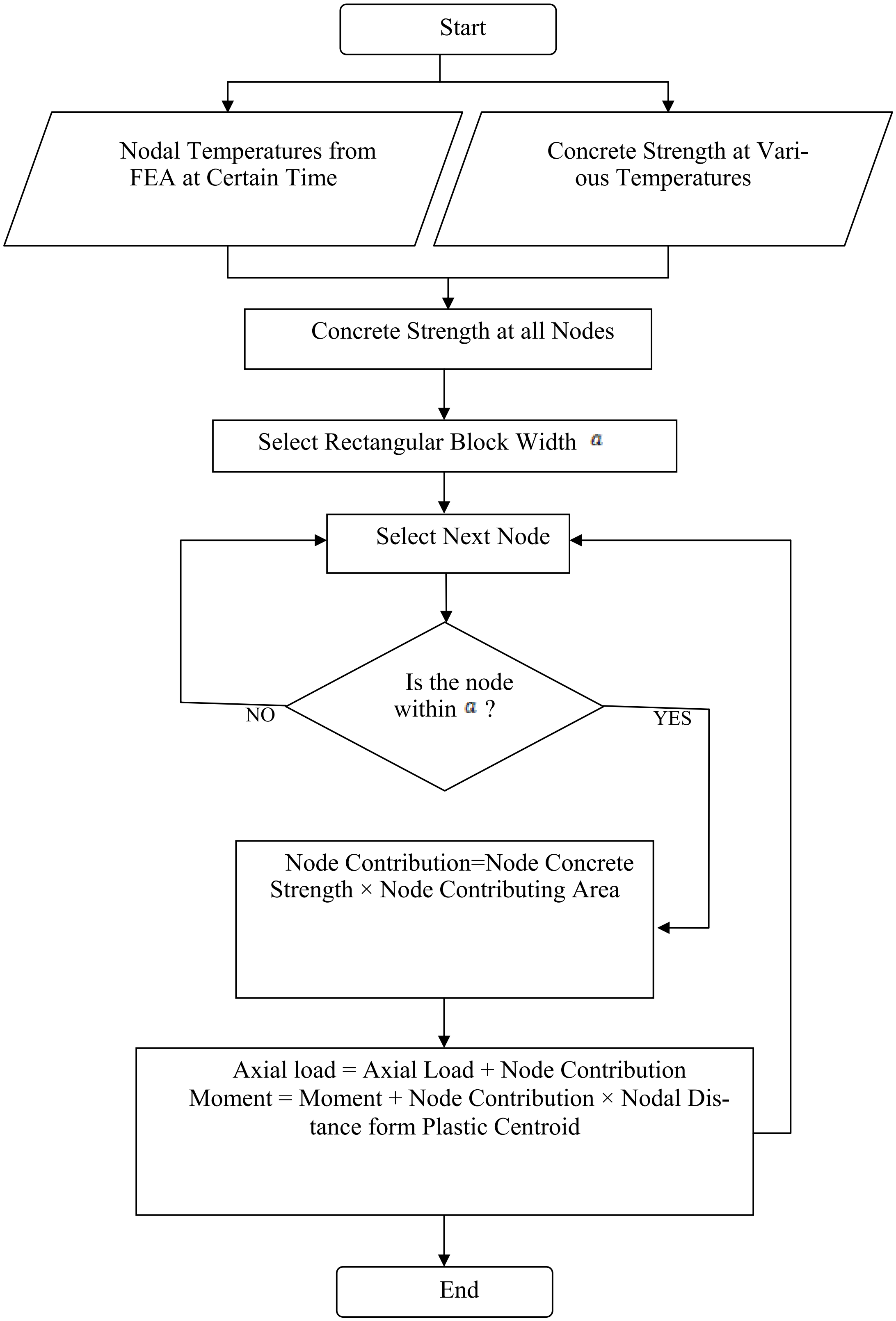


Figure 7. Flowchart for calculation of strength contribution of concrete to column

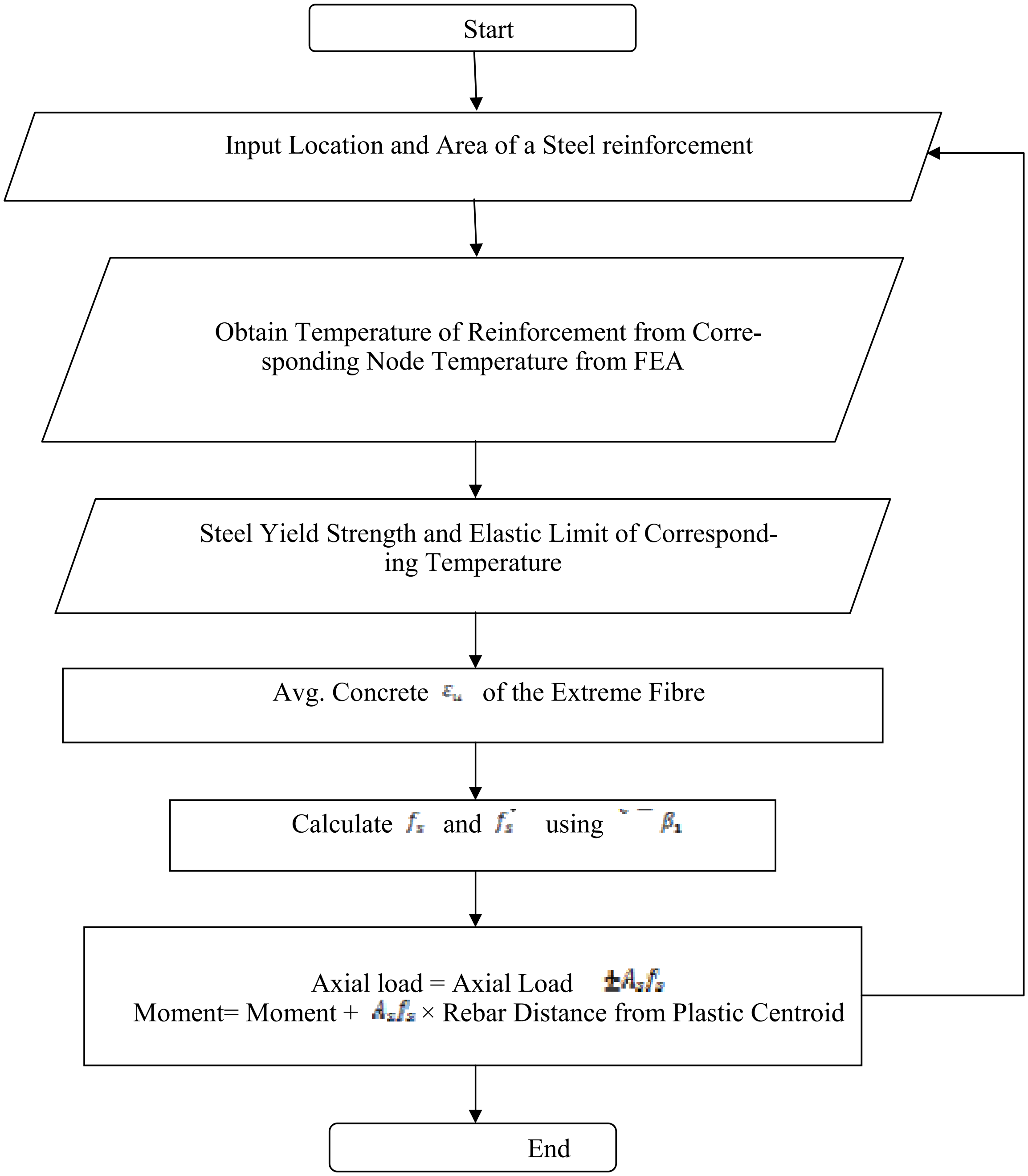
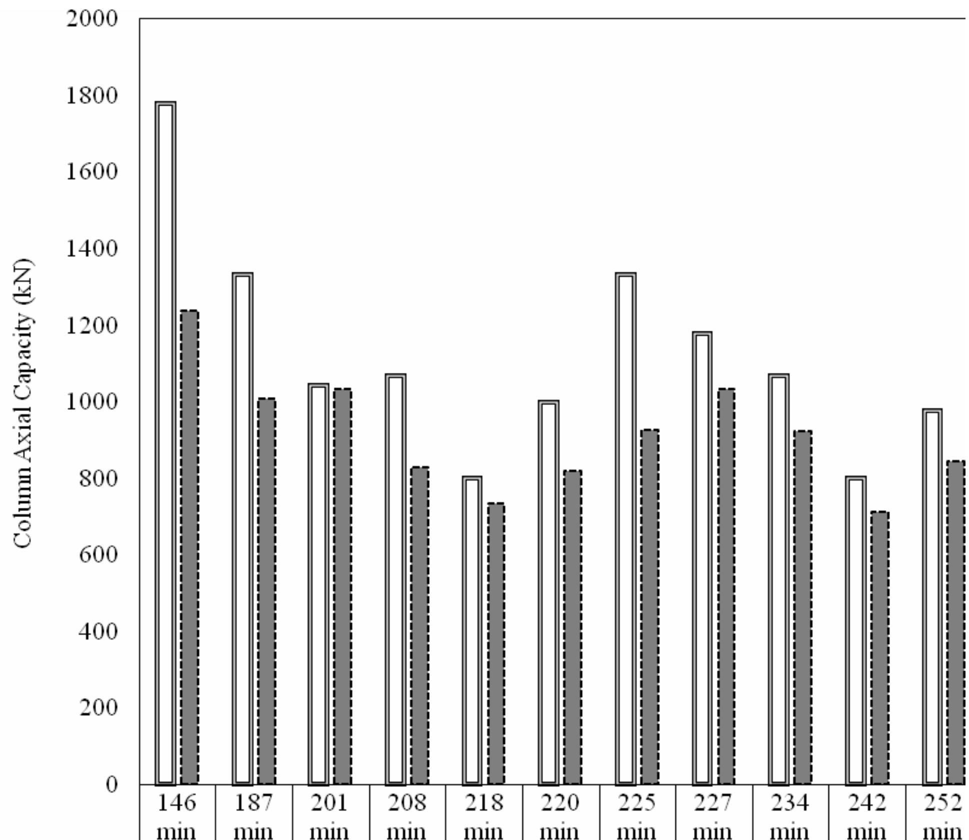


Figure 8. Calculation Steps of Strength Contribution of Steel to Column

3.3 *Validation*

Lie & Woollerton (1988) tested 21 RCC columns at National Research Council, Canada (NRCC). This test results were used for data validation. Some column had aspect ratio of more than one which are omitted from this validation. Columns with 305mm sides are taken for data validation. This comparison is summarized in figure 9. Lie and Woollerton test data is of column crushing point under a sustained load level. The software is used for predicting column capacity at that time. Figure 9 indicates reasonably good and conservative results between these two.



	146 min	187 min	201 min	208 min	218 min	220 min	225 min	227 min	234 min	242 min	252 min
Test data (Lie & Woollerton)	1778	1333	1044	1067	800	1000	1333	1178	1067	800	978
Softwere predicted strength for same exposure time	1239	1008	1034	828	733	818	927	1032	923	713	845

Figure 9. Comparison between column strength from test and software predicted strength.

3.4 *Result Interpretation*

Few data, especially those with earlier collapse time (higher load level) shows very conservative results (146 minute and 187 minute). Other reasonable matches of these two sources indicates that the software possess significant potential specially during a longer duration fire or low loading level compared to column capacity. Difficulty about predicting column strength accurately at earlier exposure time is due to the fact that steel contributes greater degree of strength during that period. So, in event of spalling, there is drastically higher temperature increase in rebars and subsequent strength loss. At higher load level on column, this loss of steel contribution initiates column collapse. To put it in short, for heavily loaded columns, performance of steel is the deciding factor. But, at lower load levels, steel is less loaded and concrete plays a more significant part in load bearing. Having greater thermal protection, concrete takes the greater share of such load and significantly increases column's performance. So, effect of spalling plays less important part. This is the cause of columns performing more predictably in such cases. For heavily loaded columns with steel carrying the lion's share of load, special consideration must be given for spalling. Effect of spalling was low in case of Lie & Woollerton test and hence their test yielded greater axial capacity then predicted by the software.

4 CONCLUSION

Predicting fire exposed concrete columns' behavior is difficult to predict due to the temperature dependant material properties and their significant variation among the samples. This paper dealt with a novel approach to solve this problem. Developed software showed substantial promise in this field. Potential research area involves predicting temperature profiles of the columns without FEA, incorporation of thermal stress and moment capacity prediction. It was also found that loading plays a more significant role in fire performance due to stress distribution pattern and strain compatibility between steel and concrete.

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