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Abstract **-** Over the past decade, research has shown that fiber reinforced polymers (FRP's) can be efficiently, economically and safely be used for strengthening and rehabilitation of reinforced concrete RC structures. However little is known about the behaviour of FRP materials, at high temperature and this is a primary factor limiting the widespread application of FRP materials in buildings, parking garages and industrial structures. This paper presents the results of a numerical program to investigate the fire performance of FRP wrapped confined RC columns. The primary objective of this research paper is -: to develop numerical models to simulate the behavior in fire of these members; to investigate techniques to improve their behavior in fire; and to use data from numerical studies to provide fire design guidance. A numerical model is presented which is capable of predicting the thermal and structural response of FRP wrapped confined RC columns under exposure to standard fire.

Keywords*-FRP; numerical program; thermal and structural response.*

I. INTRODUCTION

Externally bonded fiber reinforced polymers (FRP) are now widely accepted as an effective and efficient means of repairing and upgrading deteriorated or under strength reinforced concrete (RC) structures. One of the most efficient and widely implemented, of these FRP repair techniques is circumferential wrapping (confinement) of RC columns, which has shown to increase both axial strength and ductility of these members. Design recommendations are now available for repair and upgrade of concrete columns with FRP wraps, and the technique has, in the last 10 years, been used in hundreds of field applications around the world. Despite the numerous advantages of the FRP wrapping technique, it has yet to see widespread applications in buildings, due in large part to uncertainties associated with the FRP materials during fire. This paper presents results of an ongoing numerical research program investigating the behavior in fire of FRP wrapped RC columns. The current discussion focuses on column strengthening applications, although slab and beam slab assembly strengthening applications are also being investigated within the overall program.

II. FRP'S IN FIRE

All structural materials, including concrete and steel, experience some degradation in mechanical properties and elevated temperature, and this is true also of FRP's. At elevated temperatures, beyond the GTT of the FRP's polymer matrix component, mechanical properties deteriorate rapidly, this results reduction in the strength and stiffness of the FRP. In addition, in extremely-bonded FRP applications, it is likely that exposure to elevated temperatures would lead to rapid and severe deterioration of the FRP/concrete bond, resulting in delamination of the FRP and loss of its effectiveness as tensile or confining reinforcement. To accomplish this goal, a database of results from tensile tests on FRP at high temperature was assembled from the literature. For each type of FRP, a sigmoid function was fitted to the data using a least squares regression analysis. As an example, the resulting curves for the strength and stiffness deterioration of carbon/epoxy FRP (CFRP) with temperature are shown in fig.1. also included in fig1 are equivalent curves for reinforcing steel and concrete.

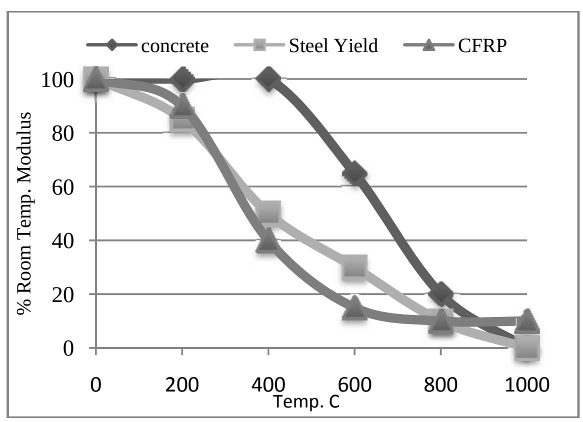


Fig. 1(a) Reduction of strength.

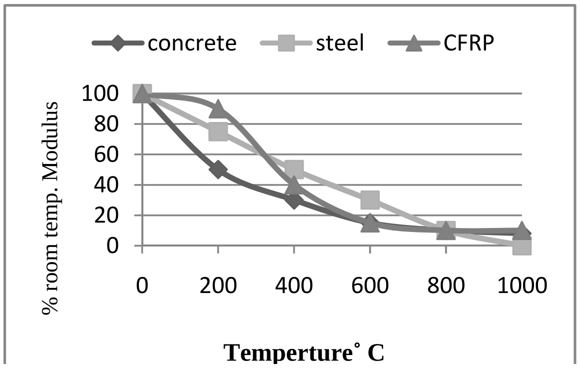


Fig 1(b) Reduction of stiffness of Carbon/Epoxy FRP at elevated temperatures.

III. NUMERICAL MODEL

Fire resistance experiments on loaded full-scale columns are relatively complex and costly to perform, with the advent of powerful computing capabilities, however, it is now possible to develop detailed numerical models which, once verified by relatively few full-scale experiments, can be used to conduct parametric studies and examine the influence of various factors on member behavior in a more cost effective manner. For current study, a numerical model has been developed to stimulate both the heat transfer and load capacity of FRP wrapped RC columns.

A. Heat Transfer

The transfer of heat within the column during fire is treated using an explicit finite difference methodology wherein the column is divided into a series of ring elements. For each ring, an energy balance is formulated such that the heat entering into minus the heat going out of the element (due to conduction) is equated to the energy stored in the element during some finite time interval. This allows the development of a series of equations which, once programmed into a computer, can be used to predict the temperature at any location within an FRP-wrapped and insulated RC column during exposure to fire following a known time- temperature curve. The thermal analysis ignores the contribution of the reinforcing steel to temperature propagation since its effect is negligible due to the small cross-sectional area of rebars.

B. Load Capacity

The load capacity of a structural member in fire can be evaluated once the distribution of internal temperatures is known (using heat transfer model described above). The analysis tools developed in the current program allow for the calculation of column strength based on pure axial crushing or on buckling. The buckling generally governs failure in fire for column lengths that would be encountered in practice. The analysis accounts for the thermal deterioration of mechanical properties of all materials involved, except for the insulation which is assumed to provide negligible strength to the column. The output of the load capacity analysis consists of curves showing the variation in axial strength, buckling strength, or overall axial elongation, with time during exposure to fire.

IV. RESULTS AND DISCUSSION

A. Temperatures

Figure 2 presents the temperature recorded at various key locations. Included also in figure 2a are equivalent temperatures as predicted by the numerical model. For both columns, the temperature at the level of the FRP is seen to increase fairly rapidly within the first 15-45 minutes of exposure, at which point the rate of temperature rise decreases and a temperature plateau is seen near 100 degree centigrade. The duration of this plateau, which can be attributed to the evaporation of both free and chemically combined moisture from the insulation at temperature near the boiling point of water is longer for column 2, which has greater insulation thickness, as should be expected. Indeed the FRP temperature in col. 2 remains less than 100 degree centigrade for more than 3 hours under fire exposure. Once all of the moisture has evaporated, the temperatures at the level of the FRP increase more rapidly until the end of the test. This behavior implies that one way to significantly improve the fire performance of the columns would be to increase the GTT of the polymer matrix to even slightly above 100 degree centigrade. The temperature at the level of the FRP remained less than the matrix ignition temperature for the full duration of fire exposure for col.2. For column 3, the ignition temperature was exceeded about 3 hours of exposure (a factor which may have contributed to its sudden failure at slightly more than 4 hours). For all 3 columns, the thermal insulation provided by the supplemental insulation was excellent, and temperatures within the concrete and reinforcing steel remained less than 350 degree centigrade for the full duration of the fire (until failure). Thus, it is likely that the columns retained essentially all of their unwrapped strength till the insulation was lost late in the fire exposure (beyond 4 hours for col.5 and beyond 5 hours for cols. 1 &2). Hence, the columns satisfied the ASTM E119 fire endurance requirement for 4 or 5 hours for the square and circular columns respectively.

Figures 2a and 2b show that, while the predictions of the numerical model generally is in agreement with test data, the model does not precisely capture the 100 degree centigrade temperature plateau exhibited in the experimental thermal profiles. This can be attributed to the fact that, while the model does account for the evaporation of moisture from individual elements at 100 degree centigrade, it does not account for the migration of free moisture in the concrete away from the fire.

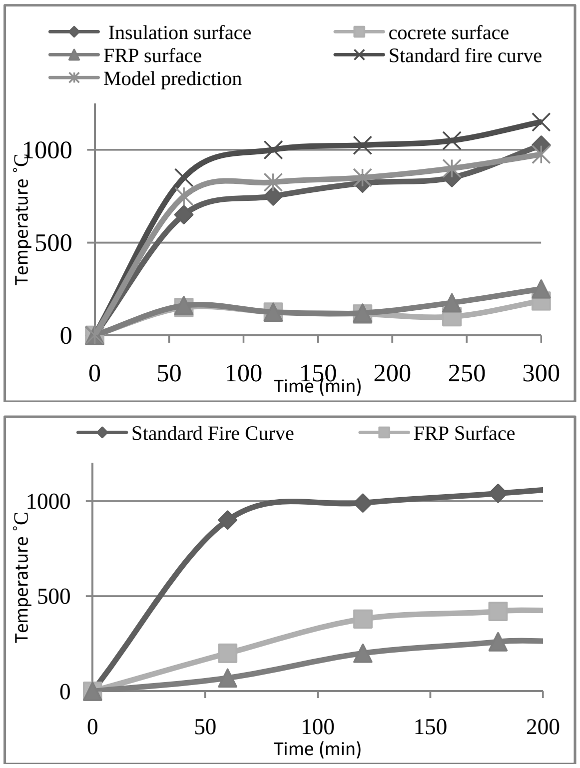


Figure 2 – temperature observed (or predicted) in (a) Col.2 (57mmVG) and (b) Col.3 (38mm VG).

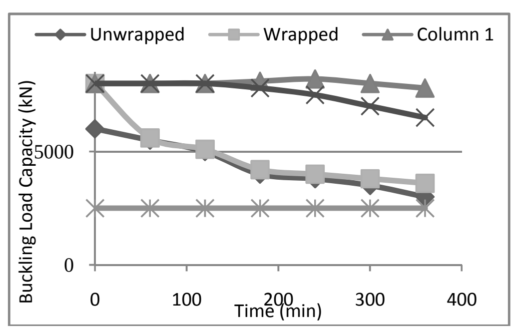
B. Fire Endurance

All columns tested were able to carry their full service load for at least 4 hours of exposure to the standard fire. Cols. 1 and 2 both failed at approximately 5.5 hours of fire exposure, and only once the applied load has been increased to about 1.8 times the required service load. Failure was sudden and explosive, and was accompanied by extensive spalling. Thus, as expected given the thermal profiles of concrete discussed above, these two columns indeed retained virtually all of their room- temperature unwrapped strength for the full duration of fire exposure. Col. 3(the square column) failed in an explosive manner at about 4.25 hours of fire exposure while under only its applied service load. The resulting combustion of the fire-exposed FRP directly exposed the substrate concrete, which had previously been at less than 400*C, to the full heat of the fire (at about 1100*C). This result in an extreme thermal shock to the concrete and caused explosive spalling resulting in rapid and catastrophic failure of column.

To demonstrate the use of the numerical model for the prediction of fire endurance of an FRP-wrapped RC column, Fig. 3a shows the predicted axial crushing strength of a concrete column with fire exposure time, and Fig. 3b shows a similar plot for the column's predicted buckling strength.

The following points are worthy of note with respect to fig. 3:

1. The model reasonably predicts the strength of the two circular FRP-wrapped RC columns tested to date after 5.5 hours of fire exposure (based on the buckling analysis).
2. For all cases shown the predicted axial crushing strength is greater than the predicted buckling strength for the full duration of the fire exposure (note that the buckling analysis assumes an initial eccentricity of 27 mm).
3. Loss of structural effectiveness of the FRP is predicted to occur very rapidly during the fire exposure for a wrapped but uninsulated column. Once the wrap is lost, the strength of the column is only slightly greater than that of an equivalent unstrengthened column. Loss of the wrap is seen to be more significant for the crushing strength analysis as opposed to the buckling strength analysis. This is because confinement of concrete with an FRP wrasp cannot be expected to significantly increase the concrete's modulus, and hence the buckling strength is not substantially improved by FRP wrapping.
4. Even a small amount of supplemental insulation (32mm for col.1) is predicted to significantly improve the retention of strength during fire. This is due primarily to the fact that the concrete and reinforcing steel in the column remain at sufficiently low temperatures to prevent degradation of their mechanical properties, and not to the effectiveness of the FRP warp being maintained. Thus, the columns are predicted to retain a significant portion of their unwrapped strength even if the FRP is lost.



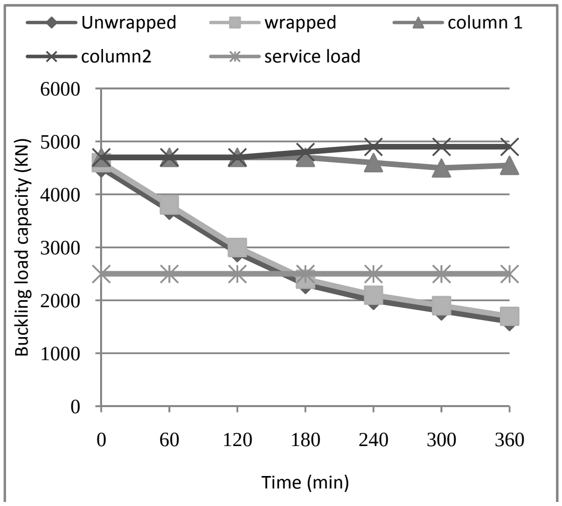


Fig.3 – Observed and predicted structural fire endurance for various column configurations based on (a) crushing strength and (b) buckling strength.

V. CONCLUSIONS

- FRP materials used as externally – wounded reinforcement for concrete structures are sensitive to the effects of elevated temperatures.
- FRP's experience degradation in strength, stiffness, and the bond at temperatures exceeding the GTT of the polymer matrix.
- Appropriately designed (and in the most cases supplementally- insulated) FRP wrapped circular RC columns can achieve satisfactory fire endurances in excess of 5 hours.
- The numerical models presented briefly herein can be used to predict the heat transfer within, and load capacity of, unwrapped and FRP wrapped and insulated RC columns under exposure to a standard fire.
- Parametric studies conducted using the model (not discussed here) indicate that the most important factors influencing the fire endurance of FRP wrapped RC columns are the thickness and thermal conductivity of the insulation applied to the exterior of the FRP wrap.
- While no explicit requirement currently exists that the temperature of an FRP wrap must remain below its matrix GTT during fire, it is not known what temperatures are allowable in the FRP such that it retains sufficient residual properties to remain effective after a severe building fire.
- Further work is required in this area.

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