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FIRE BEHAVIOUR OF FRP WRAPPED SQUARE REINFORCED CONCRETE COLUMNS

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ABSTRACT

Numerous applications of fibre reinforced polymers (FRPs) have demonstrated good performance in retrofitting and repairing deteriorated reinforced concrete structures, both through research studies and through field applications. Due to lack of available information and the perceived susceptibility of these systems in fire, an experimental and analytical study is being conducted on the fire behaviour of FRP-strengthened square reinforced concrete columns. The ultimate goal of the study is to provide design recommendations and guidelines that can be suggested for these structural members. This paper presents the explicit finite difference procedure used in developing a coupled heat transfer and structural analysis behaviour in numerical fire models. The paper also discusses the procedure for fire endurance tests on two FRP-strengthened square concrete columns which will be performed in an attempt to validate the numerical models.

1. INTRODUCTION

In recent years, existing concrete structures in North America have reached a state where many of them can no longer safely resist the loads acting on them. This is due to deterioration caused by electro-chemical corrosion and to increased load requirements, among other factors. Demolishing and rebuilding these structures is not an economically viable option, therefore new repair methods and materials such as fibre reinforced polymers (FRPs) are being used in retrofitting many of these structures. Due to their numerous advantages, which includes high strength-to-weight ratios in comparison to steel and resistance to electro-chemical corrosion, FRP materials have been already successfully used in the rehabilitation of bridges in Canada, such as Champlain Bridge, Webster Parkade, Country Hills Boulevard Bridge and Ste-Émélie-de-l'Énergie Bridge [1]. However, the sensitivity of FRP materials to elevated temperatures, as in the case of fire, and lack of information on their behaviour in fire, has thus far limited the use of FRPs in buildings and parking garages. A research study has been ongoing for more than 5 years at Queen's University, Canada in collaboration with the National Research Council (NRC) of Canada and industrial partners to investigate the fire performance of FRPs and FRP-strengthened concrete structural members. The current paper presents an analytical model and details of an experimental study that is being conducted on FRP-strengthened square columns. Preliminary results and partial validation of the analytical component of this study are also presented in the current paper.

2. BACKGROUND

Several studies evaluating structural performance in fire have been conducted on concrete structures incorporating FRP materials in recent years. The following is a brief review of these studies.

2.1. FRP-Strengthened Beams and Slabs

Deuring [2], Blontrock et. al. [3], Williams [4], Chowdhury [5], and Bisby et. al. [6] have reported on fire endurance tests on FRP-strengthened concrete beams and slabs. Without supplemental fire protection applied to the exterior of the FRP strengthening system, FRP-strengthened concrete beams have shown marginally superior performance in fire in comparison to steel plate-strengthened concrete beams [2]. However, the fire endurance of reinforced concrete members strengthened with FRP can be considerably improved by providing supplementary fire protection systems of various types [3, 4, 5, 6], which can maintain the internal concrete and reinforcing steel temperatures at relatively low temperatures [4] at which the materials do not experience significant deterioration in their mechanical properties [7, 8]. Hence, loaded and insulated reinforced concrete beams strengthened with FRP are able to endure the elevated temperatures during fire for more than four hours in some cases [4, 5]. Furthermore, maintaining low internal temperatures in the concrete and reinforcing steel is beneficial to the post-fire (i.e., residual) behaviour of these concrete members [5, 7, 8]. By providing supplementary fire protection, the temperatures of the FRP could be maintained below its glass transition temperature for less than about one hour in all cases [4].

There is little available information on the temperature at which a specific FRP strengthening system will fail (i.e., cease to perform structurally) during heating. Blontrock et. al. [3] conducted fire tests on FRP-strengthened beams where the FRP was entirely protected by insulation and also where only the anchorage zone was protected by insulation. In this study, loss of bond between the FRP and the concrete was observed around temperatures between 66°C to 81°C [3].

2.2. FRP Wrapped Columns

Bisby et. al. [9] reported on fire endurance tests on insulated FRP confined reinforced concrete circular columns, which also endured a standard fire for more than four hours in some cases. The temperature of the steel reinforcement and concrete for the columns was maintained below 200°C in some cases, and therefore the column was able to maintain essentially all of its original room temperature strength during the fire test. This was evident in the fact that the column failed after more than five hours of fire exposure at a higher axial load than its predicted nominal (unfactored) compressive strength for the unwrapped condition. In this study, the insulation protecting the FRP confined reinforced concrete column was able to maintain the temperature of the FRP below 100°C, which was higher than the glass transition temperature of 91°C, for up to four hours during fire. However, without any supplemental fire protection, the FRP begin to combust within minutes of exposure to fire, thus raising the surface temperature of the structural member above the surrounding temperature [10]. This effect could potentially create a more severe fire exposure than the unstrengthened reinforced concrete member.

3. ANALYTICAL MODELLING

Previous experimental and modelling work on the fire performance of FRP-strengthened reinforced concrete columns has focused primarily on the performance of circular members. While this research has provided a wealth of useful information on the important factors to consider in designing fire protection schemes for FRP-strengthened columns, it must be recognized that the majority of columns in structures are rectangular and square, and very little information on the performance of these types of members when strengthened with FRPs is available in the literature.

In the current preliminary study, a numerical model was developed to predict the heat transfer and structural behaviour of FRP-strengthened square concrete columns in fire. An explicit finite difference method was used in predicting the heat transfer within the column, since a similar technique has been successfully used in the past for modelling the fire performance of square reinforced concrete columns and circular FRP-strengthened columns in fire [8, 9]. A numerical integration method presented by Chen and Atsuta [11] was used in determining the load-moment interaction diagram of the square column at elevated temperatures. A flowchart of the overall program logic is shown in Figure 1.

3.1. Heat Transfer Model

Initially, all required information is inputted into the analytical program. This includes cross-section details, concrete aggregate type, FRP thickness, etc. The fire temperature is then calculated at each instant for the required fire duration according to the standard temperature-time curve described by ULC S101 [12]. Because FRP-strengthened square columns should have rounded or chamfered corners, a different approach than that taken by Lie [8] or Williams [4] was used in discretizing the column cross-section in the current model. Note that round corners are approximated by the analysis as chamfered (refer to Figure 2). The cross-section is divided into a number of square and triangular elements at the fire-exposed chamfered corners, as shown in Figure 2. The maximum allowable time step to ensure stability of the explicit finite difference algorithm is then calculated. The heat transfer from the centreline to the column’s exterior surface is subsequently calculated using a series of two-dimensional explicit finite difference formulae based on elemental energy balance. The formulation of the finite difference equations and the maximum allowable time step were based on theory described by both Cengel [13] and Lie [8]. A series of slightly different heat transfer equations was developed for the insulation-fire interface, FRP-insulation interface, concrete-FRP interface, and inside the concrete, FRP and insulation, to calculate the temperature distribution throughout the column cross-section at any instant during exposure to the ULC S101 standard fire. Variations of the thermal properties of constituent materials with temperature and the effects of moisture evaporation from the concrete were taken into account using relationships described by Lie [8] and Bisby [14]. Once the column temperatures at each element in the cross-section are calculated, the time is stepped forward and the procedure is repeated. The temperature of the central node of each element is assumed to be that of the entire element.

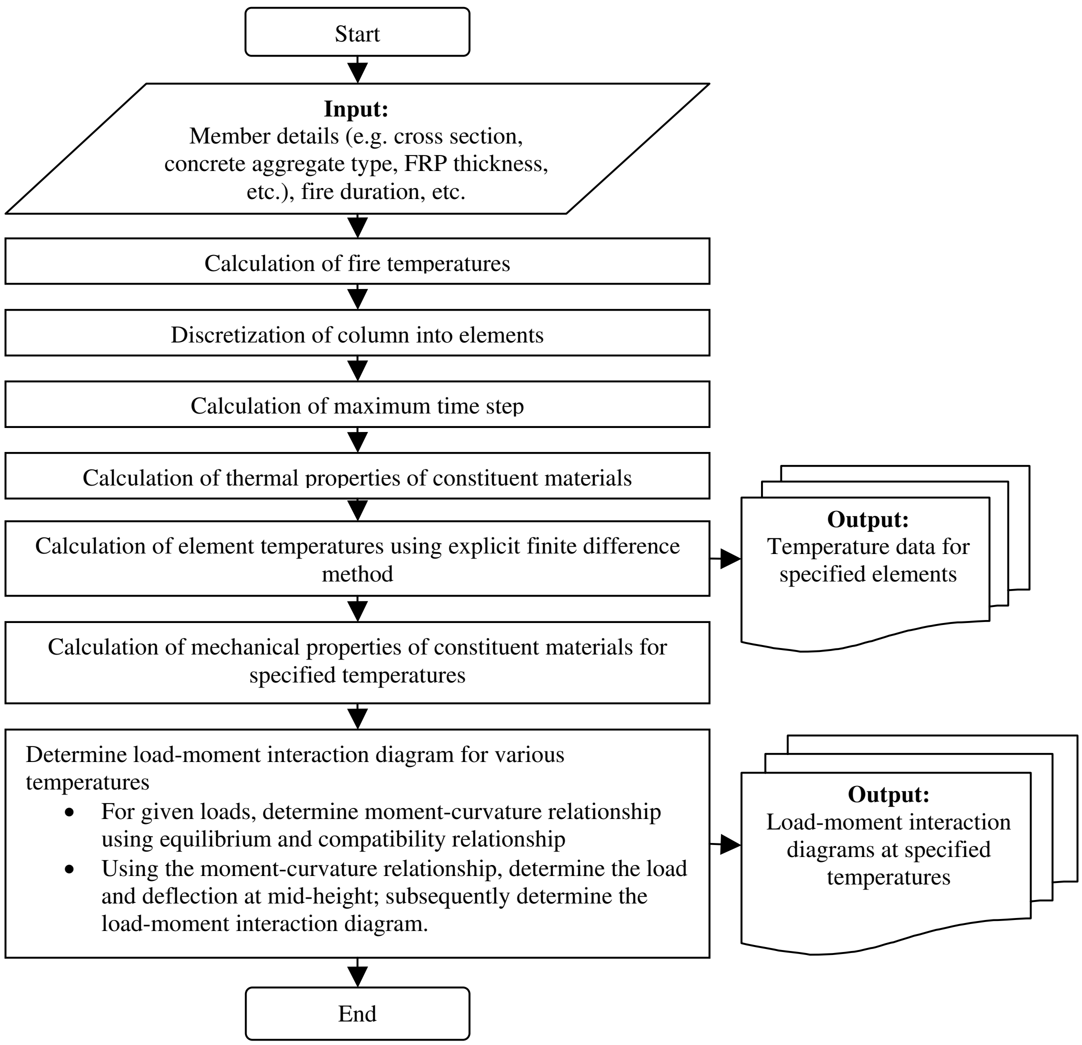

Fig. 1: Flowchart showing the procedures for the fire resistance calculation of columns

3.2. Load Capacity Model

After the temperature distribution of the column cross-section has been determined at each time step, the mechanical properties of the materials in each element are determined using relationship described by Lie [8] and Bisby [14]. The confinement pressure due to the FRP wrap is then determined using the FRP confinement model proposed by Lam and Teng [15] for square reinforced concrete columns. For each element, the stress and strain are assumed to be those at the nodes. The objective of the load capacity model is to determine the load-moment interaction diagram, from which the failure load of the column specimen can be approximated at any instant in time. This information can be used to predict the time at which the column will fail during fire under a given service load. The method of analysis is based on the following assumptions: (1) plane sections remain plane; (2) strain in the reinforcement is equal to the strain in the concrete at the same location, (3) longitudinal stress at any point in the section is dependent on the longitudinal strain; (4) the tensile strength of concrete is negligible and can be ignored.

Using an incremental iterative procedure, the moment-curvature for a given axial thrust is calculated. A strain profile is proposed across the section from which the axial thrust and bending moment are obtained; if the axial thrust is in close agreement with the given axial thrust being applied on the section, the curvature corresponding to the proposed strain profile is taken to be accurate. Otherwise, the strain profile is modified and the procedure is repeated. This procedure is repeated for increasing applied loads. Once the moment-curvature for a given load is determined, the slope and deflection are calculated along the longitudinal height of the column using the Column Deflection Curve method described by Chen and Atsuta [11].

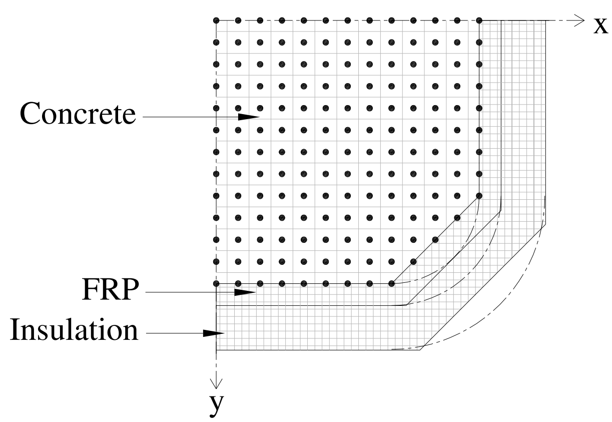

Fig. 2: Discretization of one-quarter cross-section of a square FRP-strengthened and insulated reinforced concrete column for the numerical model (nodes on the FRP and insulation layer not shown)

3.3. Initial Results

Preliminary results from the heat transfer model on square reinforced concrete column are shown in Figure 3, since experimental tests on FRP-strengthened square columns are planned for 2007 and have not yet been performed. Temperature variations at various locations within the column cross-section for a reinforced concrete column have been validated using experimental data presented in Lie and Woollerton [16] on a 305 mm square siliceous aggregate concrete column, which was reported to have a moisture content of 5% prior to its fire test. It was found that the predictions from the current heat transfer model agreed well with the experimental results from Lie and Woollerton. As shown in Figure 3, temperatures calculated along the line AC within the concrete were higher than along the line AB, as should be expected.

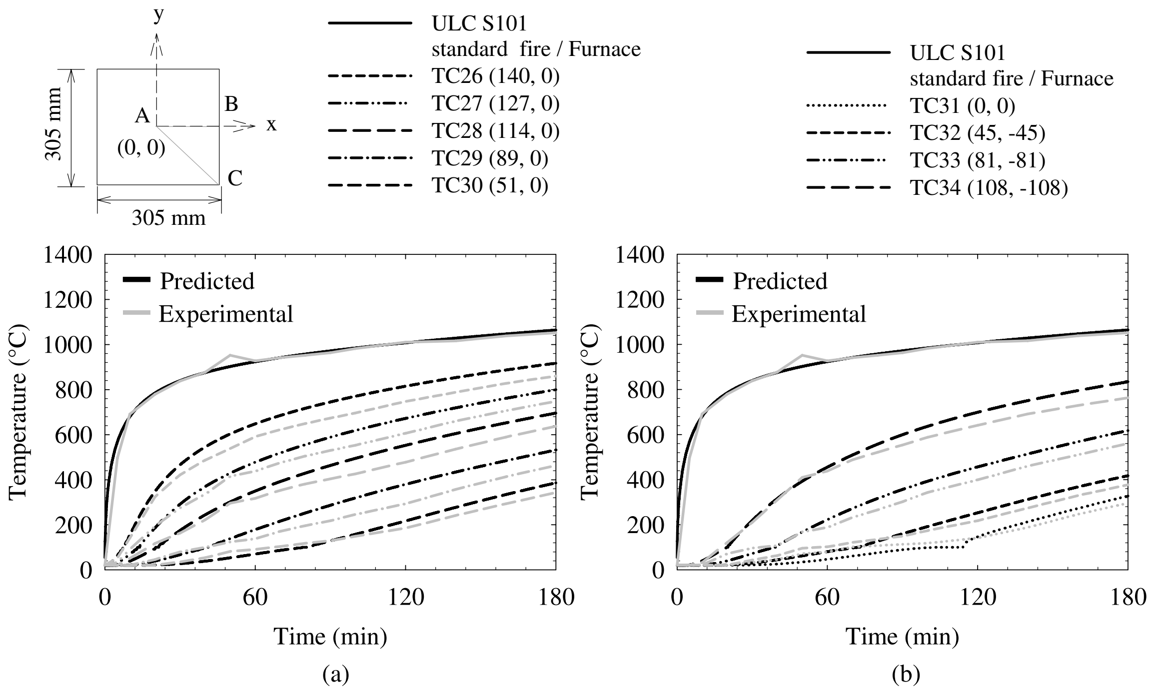

Fig. 3: Variation in temperature within a siliceous aggregate concrete column (a) along the line AB, and (b) along the line AC.

The temperature within the concrete rose steadily until 100°C, after which the rise in temperature increased more rapidly. This is due to moisture evaporation from the concrete as heat is consumed by the latent heat of evaporation of moisture within the concrete. Temperatures at greater depths within the concrete showed a slower heating rate, as well as longer duration of moisture evaporation near 100°C. In the heat transfer model, the effect of moisture was taken into account by assuming that, in each element, the moisture starts to evaporate when the temperature of that element reaches 100°C. Movement of moisture within the elements has not been accounted for in the heat transfer model. The emissivity of the concrete surface was taken to be a constant value of 0.9, as suggested by Lie [8].

4. EXPERIMENTAL STUDY

To gain further insight into the behaviour of FRP-strengthened square reinforced concrete columns, two full-scale square columns have been fabricated and will be fire tested under the ULC S101 standard fire [12] and full sustained service load. Details of the cross-section and reinforcements are shown in Figure 4. Prior to the fire tests, these reinforced concrete columns will be wrapped with FRP and insulated with a supplementary fire protection system. Both columns have been instrumented internally with Chromel-alumel (Type K) thermocouples and 5 mm high temperature electrical resistance strain gauges. These square column specimens will be tested in the column furnace at the National Research Council of Canada, Ottawa, Canada, using a fixed-end condition. Results from the fire tests will be used to validate as well as refine the numerical model.

There is little information on the mechanical and thermal behaviour of the materials used in these FRP-strengthened concrete members, especially currently available FRP systems and insulation. As part of this experimental investigation, tensile strength tests will be conducted on reinforcing steel and FRP, and compressive strength tests on concrete under elevated temperatures. Results from these tests will be used in developing analytical models representing the stress-strain behaviour of FRP and validating existing thermal-stress-strain models for concrete and steel. Further thermal analysis will be conducted through thermogravimetric analysis (TGA), thermal conductivity testing and differential scanning calorimetry (DSC) on concrete, FRP, and insulation materials.

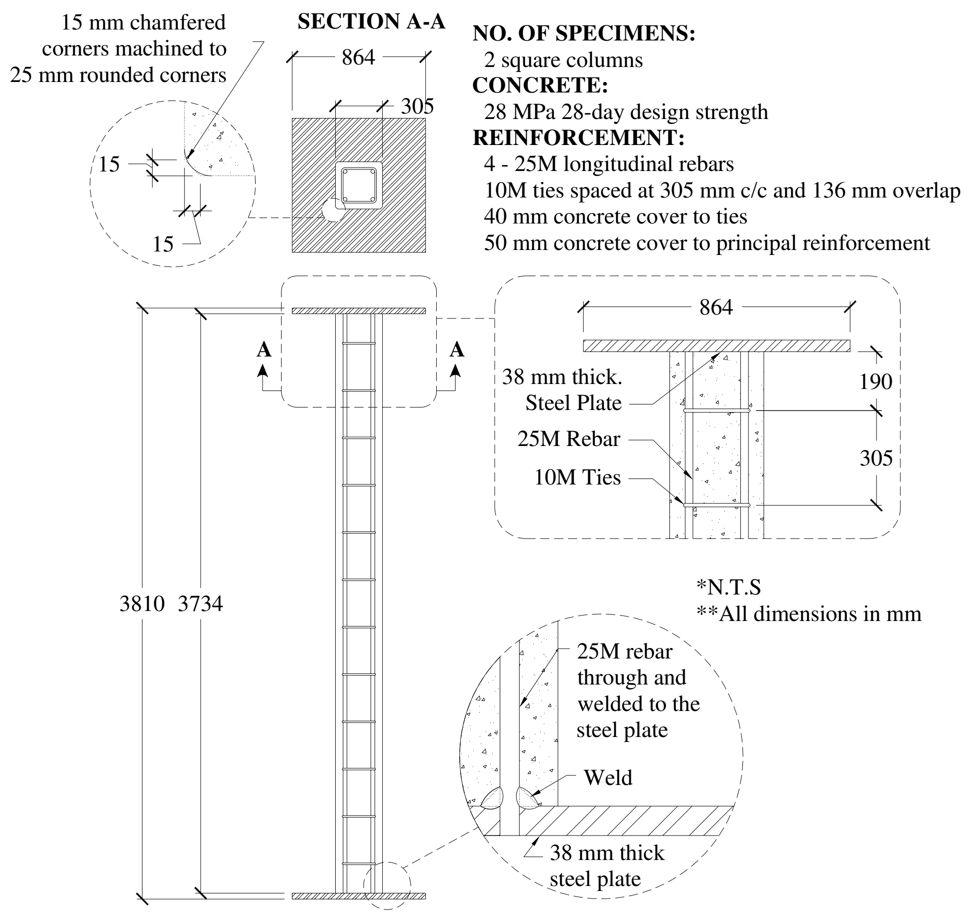

Fig. 4: Details of the reinforced concrete square column

5. SUMMARY AND FUTURE WORK

The discussion and results presented herein show preliminary study on a numerical model that has been developed to predict the thermal and structural behaviour of FRP wrapped square reinforced concrete columns under exposure to a standard fire. Experimental studies on FRP-strengthened concrete columns are necessary to validate and refine the numerical model before it can be used with confidence. Nonetheless, the numerical model is able to make reasonable predictions of the internal temperatures within square reinforced concrete columns. The key aspects of the numerical model that must be modified and evaluated relate to the moisture migration and thermo-mechanical properties of FRP and insulation materials. Therefore, further studies will be performed on these materials at elevated temperatures.

6. ACKNOWLEDGEMENTS

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