Fire Endurance of Insulated FRP-Strengthened Square Concrete Columns

by V.K.R. Kodur, L.A. Bisby, M.F. Green, and E. Chowdhury

Synopsis: Increased use of fiber reinforced polymer (FRP) materials for strengthening of concrete structures has raised concerns regarding the behavior of such FRP systems in fire. Limited information is currently available on the fire endurance of FRP-strengthened concrete systems. This paper presents results from full-scale fire resistance experiments on two square reinforced concrete (RC) columns. A comparison is made between the fire performance of a conventional RC column and that of an FRP-strengthened and insulated RC column. Data obtained during the experiments show that the fire behavior of FRP-wrapped and insulated square concrete columns, protected using an appropriate fire protection system, is as good as that of unstrengthened RC columns. Factors that significantly influence the fire resistance of FRP-reinforced concrete columns are discussed. It is demonstrated that satisfactory fire resistance ratings for FRP-wrapped square concrete columns can be obtained through careful design and by incorporating appropriate fire protection measures into the overall structural system.

Keywords: fiber-reinforced polymers; fire endurance; reinforced concrete columns; strengthening

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INTRODUCTION

Interest in applications of fiber reinforced polymers (FRPs) for strengthening and rehabilitating reinforced concrete (RC) structures has increased significantly in recent years. This interest can be attributed to the numerous advantages that FRP materials offer over conventional materials. One particularly successful use of FRPs in structural engineering applications involves repair and rehabilitation of existing RC columns by bonding a circumferential FRP wrap to their exterior.

With increased applications of FRPs in structures, concerns have emerged regarding their behavior in fire, since FRP materials are known to be susceptible to deterioration of mechanical and bond properties at elevated temperature. Before FRP wraps can be used with confidence in buildings, the performance of these materials during fire, and their ability to meet the fire endurance criteria set out in building codes, must be evaluated and incorporated into design procedures. To date, relatively little information is available on the fire endurance of FRP-reinforced or strengthened concrete systems. This paucity of data is a primary factor hindering the widespread application of FRPs in buildings, where fire safety provisions are one of the major design requirements.

To develop information on the fire performance of FRP strengthening systems for RC members, a major research project, involving both experimental and numerical studies, is currently underway at the National Research Council of Canada (NRC) and Queen's University, Canada, in collaboration with the Intelligent Sensing for Innovative

Structures (ISIS) Research Network and industry partners (Fyfe Company LLC and Degussa Building Systems). The main objective of this research is to develop fire resistance guidelines for FRP-strengthening of reinforced concrete structures for possible incorporation into design codes and standards.

As a part of this research project, full-scale fire resistance tests have been conducted on square RC columns to investigate the behavior of loaded FRP-wrapped and insulated RC columns under exposure to a standard fire. The results of these experiments are presented in this paper.

MOTIVATION

Fire represents one of the most severe environmental conditions to which structures might be subjected, and hence the provision of appropriate fire safety measures for structural members is a major safety requirement in building design[1,2]. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defence for building occupants and emergency personnel.

The required fire safety measures for structural members are measured in terms of fire resistance. Fire resistance is defined as a duration during which a structural member exhibits resistance with respect to structural integrity, stability, and temperature transmission under standard fire conditions. The fire resistance of a structural member is typically dependent on the geometry of the structural member, the materials used in construction, the load intensity, and the characteristics of the fire exposure itself.

Generally, RC structural members exhibit good performance under fire situations. However, only limited studies have been conducted on the fire performance of FRP-strengthened RC systems[2,3,4]. A review of the existing literature in this area indicated that several concerns (including flame spread and smoke generation, loss of strength and stiffness, and loss of bond) are associated with the employment of FRPs as external reinforcement for concrete members in buildings[2,5,6]. FRP materials are, in comparison with conventional building materials such as concrete and steel, particularly sensitive to the effects of elevated temperatures. Deterioration in mechanical and/or bond properties can be expected at temperatures approaching the glass transition temperature (T_g) of the polymer adhesive/matrix[2,4,5,6]. For FRP-wrapped RC columns, this deterioration leads to a concern that loss of effectiveness of the FRP wrap during fire could lead to collapse under increased service loads. Furthermore, all organic polymer matrix materials are combustible and will burn when subjected to sufficiently high temperatures, leading to the potential for increased flame spread and smoke generation during fire.

RESEARCH SIGNIFICANCE

While some information is available on FRP-strengthened circular RC columns during fire[3,7], no data currently exists on the performance of FRP-strengthened square RC columns. It has been documented in the fire testing literature that the shape of cross-section of an RC column has an important effect on fire endurance of these members, and that circular columns typically have higher fire endurances when compared to square columns[8]. Hence, the focus of this paper is on the structural behavior of FRP-wrapped square RC columns under standard fire conditions. A key objective is to demonstrate that the performance in fire of appropriately designed and insulated square FRP-wrapped reinforced concrete columns is satisfactory, as has been previously demonstrated for circular FRP-wrapped columns[7].

FIRE ENDURANCE EXPERIMENTS

Column specimens

The experimental program consisted of fire endurance tests on two full-scale square RC columns: one unstrengthened RC column (SQ1) and one FRP-wrapped and insulated RC column (SQ2). Both columns were 3810 mm long and reinforced internally with conventional reinforcing steel. Details of the two columns are given in Table 1 and Figure 1.

Both columns were designed as per Canadian design procedures[9,10,11]. These procedures are similar to those used in the United States. Column SQ1 was fabricated as part of a larger program studying square reinforced concrete columns, whereas Column SQ2 was fabricated specifically for the current study. Hence, the columns, while similar, were not exactly the same. Column SQ1 had eight 25 mm diameter (No. 8) longitudinal bars and 9.5 mm diameter (No. 3) ties at 406 mm spacing. Column SQ2 had four 25 mm diameter longitudinal reinforcing bars and 10 mm diameter ties spaced at 406 mm. The main reinforcing bars were welded to steel end plates. The percentage of longitudinal steel in columns SQ 1 and SQ 2 was 2.47% and 1.21% respectively. The clear cover to the main reinforcing bars was 48 mm for Column SQ1 and 50 mm for Column SQ2. The main reinforcing bars and ties all had specified yield strengths of 400 MPa.

Both columns were made with normal strength, Type 10 Portland cement concrete. Column SQ1 was fabricated with siliceous aggregate while Column SQ2 was fabricated from carbonate aggregate. The mix proportions for both batches are given in Table 2.

The average compressive cylinder strengths of the concrete, measured 28 days after pouring and at the time of testing are given in Table 2. The moisture conditions of Columns SQ1 and SQ2 at the time of testing were approximately equivalent to those in equilibrium with air at room temperature of 80% relative humidity (RH), and 83% RH, respectively.

Column SQ2 was strengthened (confined) with an externally-bonded circumferential FRP wrap. The FRP strengthening system consisted of three layers of Fyfe Company's

Tyfo® SEH unidirectional glass/epoxy FRP system (SEH)[1] with a Tyfo® S epoxy adhesive/saturant/matrix. The wrap design called for a 300 mm overlap in the hoop direction and a 25 mm overlap in the vertical direction, and resulted in a theoretical design ultimate load capacity increase of about 5% based on the Teng et al.[12] confinement model for rectangular FRP-confined concrete columns (used in conjunction with the ACI 440[11] design equations for the pure axial strength of FRP-wrapped RC columns). Details of load calculations for the columns are presented in Reference 13.

Column SQ1 was not provided with any supplemental fire protection insulation, since conventional RC columns generally display adequate fire endurance without extra measures. However, the FRP-wrapped RC column, SQ2, was provided with a unique two-component fire protection system consisting of Fyfe Company's Tyfo® VG insulation in combination with Tyfo® EI-R paint. VG insulation is a spray applied cementitious plaster which has low thermal conductivity and is thermally inert up to temperatures in excess of 1000°C. The Tyfo® VG insulation was spray-applied directly onto the surface of the FRP wrap, without any mechanical anchorage between the FRP and the insulation. Tyfo EI-R was applied by trowel to the exterior of the Tyfo® VG insulation as a sealant and surface hardening agent. Column SQ2 was protected with 38mm of VG and a nominal coverage of 0.13mm of EI-R.

During fabrication of the specimens, thermocouples were installed within the concrete and on the internal reinforcing steel at column mid-height for measuring temperatures at various locations across the cross section. Column SQ2 was also instrumented with thermocouples to record the temperatures at the EI-R-VG interface, the VG-FRP interface, and the FRP-concrete interface (refer to Fig. 2). Details on material characteristics, column fabrication, and instrumentation are given by Kodur et al.[13].

Test Conditions and Procedures

The columns were installed in a specialized testing furnace, built for testing loaded columns under fire exposure[13], by bolting the steel endplates affixed to the columns to a loading head at the top and to a hydraulic jack at the bottom. This connection created essentially fixed end conditions. Figure 3 shows a picture of the test fixture with a specimen installed just before testing. The length of the columns exposed to fire was approximately 3000 mm, but at high temperature, the stiffness of the unheated column ends, which is high in comparison to that of the heated portion of the column, contributes to a reduction in the effective length of the columns. Thus, for the columns tested herein, an effective length of 2000 mm approximately represents the experimental behavior.

All columns were tested under sustained concentric axial compressive load. Column SQ1 was subjected to a load of 2418 kN, which was equal to 63% of the ultimate load according to ACI 318-95[14]. Column SQ2 was subjected a load of 3093 kN, which was

[1] Certain commercial products are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendations or endorsement by the National Research Council, nor does it imply that the product or material identified is the best available for the purpose.

about 69% of the ultimate load based on a combination of procedures recommended by Teng et al.[12] and ACI 440[11] for rectangular FRP-confined concrete columns. Details of the load calculations for these columns are discussed by Kodur et al.[13].

During the tests, the columns were exposed to heat according to the CAN/ULC-S101[15] standard time-temperature curve, which is equivalent to the ASTM E-119 Standard[16]. The columns were considered to have failed, and the tests were terminated, when the hydraulic jack could no longer maintain the load.

RESULTS AND DISCUSSION

In this section, results from the experimental studies are used to illustrate the comparative behavior of the two columns. The columns had reasonably similar overall dimensions, although they differed in terms of the type of aggregate used and the amount of internal longitudinal reinforcing steel. The type of aggregate did not significantly influence the behavior of Column SQ2 because the temperatures in the concrete remained well below the temperature (about 500˚C) at which differences in the type of aggregate begin to play an important role. Similarly, the temperatures in the reinforcing steel for Column SQ2 can be assumed (on the basis of the temperatures measured at the surface of the concrete, to have remained sufficiently low (below 450˚C) as to not have significantly reduced the mechanical properties of the steel during the fire test. The larger amount of reinforcing steel in column SQ1 is assumed not to have affected the comparative heat transfer behavior in the two columns (reinforcing steel is typically considered insignificant with respect to heat transfer in concrete members exposed to fire). No unprotected FRP-wrapped RC columns were tested, since results of previous fire endurance tests (unpublished) have shown that FRP-wrapped RC columns without fire protection tend to perform poorly, since the FRP wrapping is lost within less than 30 minutes of fire exposure.

Thermal Behavior

The temperature-time curves at various locations in the column are plotted for Column SQ1 in Fig. 4, which also demonstrates that the furnace temperature closely followed the standard temperature-time curve. The temperatures just beneath the surface of the concrete (at a depth of 6 mm for thermocouples (TCs) 13, 28, 29, and 44) rose rapidly until the onset of concrete spalling at a temperature of about 800°C, with the thermocouples at the corners recording higher temperatures (as expected). At the location of the reinforcing steel, the temperatures rose rapidly to about 100°C, after which point the temperature continued to increase, although at a decreased rate. This behavior is due to the evaporation of moisture from the concrete at temperatures close to 100°C and to thermally-induced migration of moisture toward the centre of the column[8]. The failure of the column occurred when the temperatures at the centre of the column reached about 800°C. The temperature of the longitudinal reinforcing steel was more than 700°C at failure, indicating that the reinforcement had lost more than 50% of its room temperature strength.

Figure 5 shows temperatures recorded at various locations in Columns SQ2 during exposure to fire. The figures show that that the temperature of the FRP wrap remained below 100°C for about 30 minutes due to the provision of the extremely effective VG/EI-R insulation system on the column. The temperatures in Column SQ2 were generally lower than those observed in Column SQ1, and this can be attributed entirely to the presence of the VG/EI-R fire insulation. In contrast to Column SQ1, no thermocouples were installed within the concrete for Column SQ2. Despite the absence of this temperature data, the temperatures of the steel reinforcing bars and internal concrete for Columns SQ2 can be assumed to have remained below the temperatures recorded at the level of the FRP-concrete interface. Temperatures inside the column thus remained below 300ºC for the full duration of the fire exposure. In the case of Column SQ1, however, temperatures in excess of 800°C and 700°C were observed in the concrete and steel, respectively. Since temperatures of less than about 350ºC are not structurally significant in terms of deterioration of mechanical properties for either concrete or steel, it can be stated with confidence that the FRP-wrapped square RC column maintained at least its full unwrapped axial load carrying capacity for more than 4 hours. It is difficult to state conclusively how long the FRP wrap remained effective during the tests. Material tests on the specific FRP materials themselves (at high temperature) are required to determine their effectiveness at elevated temperature.

Structural Behavior

The variation in axial deformation with fire exposure time is shown in Fig. 6 for both columns. The unwrapped RC column initially expanded, until the reinforcement yielded at elevated temperature, and then contracted, eventually leading to failure at about 4 hours, 22 minutes. The deformation during fire exposure results from several factors, such as load, thermal expansion, and creep. The initial expansion of the column was mainly due to the thermal expansion of concrete and steel. While the effect of load and thermal expansion is significant in the intermediate stages, the effect of creep becomes pronounced in the later stages due to the high fire temperature. The contraction of the column later in the exposure is mainly due to loss of strength and stiffness of the concrete and steel as the internal temperatures increase.

Column SQ2 does not expand at all during heating due to the relatively low temperatures in the concrete. An initial very slight contraction was observed within the first few minutes of fire exposure, probably due to seating of the column under load during the initial period of the fire exposure. The column remained essentially inert for most of the fire exposure, with sudden and severe contraction occurring just prior to failure (when severe cracking of the insulation exposed the FRP to the fire, resulting in sudden spalling of the concrete cover and failure at about 4 hours, 16 minutes of exposure. This behavior can be attributed to the beneficial thermal insulation provided by the fire protection, which resulted in minimal temperature increases in the concrete and internal reinforcing steel. Thus, no significant reduction in strength or stiffness was likely experienced by Column SQ2 until late in the fire tests. The observed superior behavior of the square insulated FRP-wrapped RC column is consistent with results of fire tests on circular insulated FRP-wrapped RC columns performed previously[7]. As expected however, the performance in fire of the circular columns was superior to that of the square columns for both the wrapped and unwrapped cases.

Load Capacity and Fire Endurance

Table 1 provides a comparison of the fire resistance ratings achieved for both columns, where fire resistance is defined in terms of the ability of the columns to maintain their sustained service load for the required duration during exposure to the standard fire. For Column SQ1, the fire resistance was 262 minutes, while for Column SQ2 it was 256 minutes, even under increased (wrapped) service loads that resulted in a significantly higher test load ratio for Column SQ2. The satisfactory fire resistance of the FRP-wrapped square RC column under increased loads, as compared to the conventional square RC column, can be attributed to the good thermal insulation characteristics of VG/EI-R fire protection system. Also, Column SQ1 was fabricated from siliceous aggregate concrete which typically results in lower fire resistances as compared with carbonate aggregate concrete[14], although this is not thought to have been a significant factor in the tests described herein.

Column SQ1 experienced sudden failure in compression under service load, with approximately 30% of the cover concrete spalling at that time. Column SQ2 failed by sudden combustion of the FRP wrap, crushing, and spalling of concrete, although only after more than 4 hours of fire exposure. Figure 7 shows an FRP-wrapped square RC column before testing and immediately after failure.

Insulation Effectiveness

Column SQ2 did not display any significant signs of failure for at least 4 hours of fire exposure under the 3093kN strengthened (increased) service load, which can be attributed primarily to the strong performance of the VG/EI-R fire protection system.

During fire testing, the EI-R surface hardening and sealing coating burned off within the first three to four minutes of the test. The EI-R coating acts as an impervious membrane and traps moisture inside the VG. Thus, the VG had a high moisture content when exposed to fire, and its insulating characteristics were enhanced. When exposed to flames, Tyfo® VG plaster releases chemically combined water in the form of water vapour, which helps to maintain the temperature in the plaster around 100°C until all of the water has been driven off as steam. Meanwhile, the insulating action of a vermiculite filler delays the release of steam and retards the transmission of heat, thus improving the overall fire-proofing characteristics. The VG insulation performed well under fire exposure, and remained intact until the end of the tests when explosive concrete crushing/spalling caused it to debond from the column over almost the entire column height. The only change that was observed in the appearance of the VG insulation during the fire exposure was the formation of cracks, generally less than 5 mm wide, which gradually appeared and widened as the test progressed. From a structural point of view, the fire-protected FRP-wrapped RC column behaved similarly to, or better than, the unwrapped RC column.

Current Studies

The main objective of the experimental studies reported above was to obtain test data for the development of computer models that can predict the behavior of FRP-wrapped reinforced concrete columns under fire conditions. In the past, the fire resistance of structural members could be determined only by testing. In recent years, however, numerical methods for the calculation of the fire resistance of various structural members have been gaining acceptance. These emerging calculation methods are far less costly and time consuming than full-scale fire endurance testing.

The development of computer programs for the calculation of the fire resistance of FRP-wrapped, reinforced, or strengthened RC members is in progress as part of this ongoing project. To validate the models, further fire tests will be conducted on full-size FRP-wrapped RC columns and FRP-strengthened RC beams and slabs, with and without supplemental fire protection systems. Once validated, the computer programs are being used to carry out parametric studies to investigate the influence of various parameters, such as concrete strength, supplemental insulation characteristics, and load intensity, on the fire endurance. Data from the parametric studies are being used to develop fire design guidelines for FRP-strengthened concrete systems.

SUMMARY AND CONCLUSIONS

Based on the experimental studies completed so far, the following conclusions can be drawn:

- Unlike conventional square RC columns, FRP-strengthened square RC columns require suitable fire protection, in most cases, to achieve the required fire endurance ratings under increased (strengthened) service loads. The performance of protected FRP-strengthened square RC columns at high temperatures can be similar to, or better than, that of conventional RC columns.

- FRP-strengthened square RC columns protected with the fire protection system discussed herein are capable of achieving fire endurance ratings of 4 hours or more according to CAN/CSA-S101 and ASTM E-119 requirements, under full service loads.

- The supplementary insulation described herein is an effective fire protection system. Visual observations made during the fire tests indicated that the insulation remained intact for more than 4 hours of exposure to the standard fire with only minimal cracking.

- Further studies, currently in progress, will generate additional data on the fire endurance of FRP-RC members and will identify the conditions under which these members can be safely used. Numerical models are under development and will be used in the future to develop design guidelines for FRP-strengthened concrete members.

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Table 1—Columns specifications and summary of test results

#	dim. (mm)	f'_c 28-d (MPa)	f'_c test (MPa)	FRP[a] wrap	supplemental insulation[b]	factored resistance, C_r (kN)	test load (C) (kN)	load intensity (C/C_r)	fire endurance (hr:min)
SQ1	406	38.4	38.8	none	None	3857	2418	0.63	4:22
SQ2	406	52	--	SEH	38mm VG 0.25mm EI-R[1]	5090	3093	0.69	4:16

[a] SEH – Tyfo® SEH Glass / Tyfo® S Epoxy, applied in three layers.
[b] VG/EI-R – Fyfe Company's Tyfo® VG/EI-R Insulation is a patented two-component fire protection system developed specifically for fire protection of Tyfo ® FRP wraps.

Table 2—Mix proportions for the concrete used to cast each column

Property	Mix 1	Mix 2
Cement content (kg/m^3)	307	280
Fine aggregate (kg/m^3)	871	980
Coarse aggregate (kg/m^3) (14 mm max. size)	1054	1070
Aggregate type	Siliceous	Carbonate
Water (kg/m^3)	154	152
w/c ratio	0.50	0.54
Slump (mm)	83	100
Specified 28-day strength (MPa)	35	44
Measured 28-day strength (MPa)	39	52

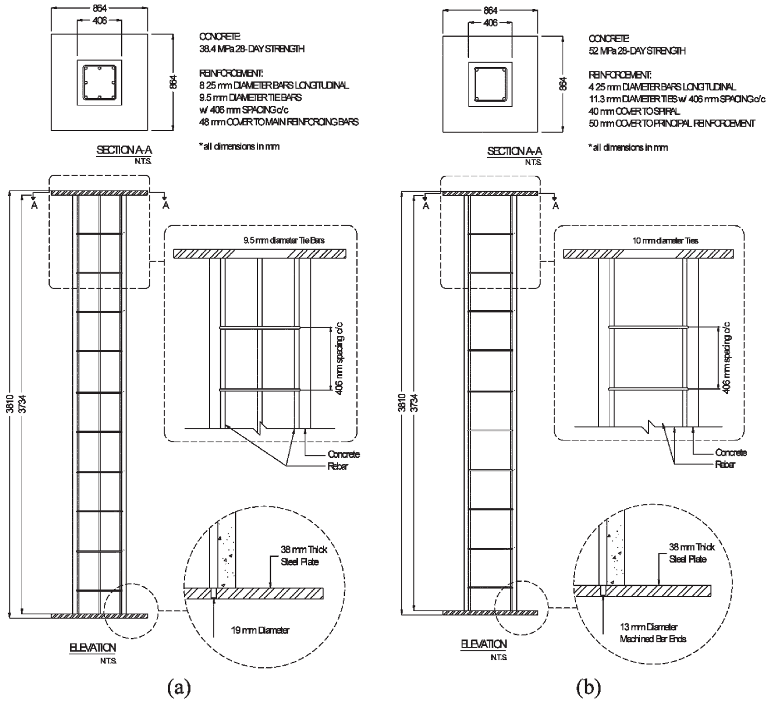


Fig. 1—Elevations and cross sections for Columns SQ1 and SQ2

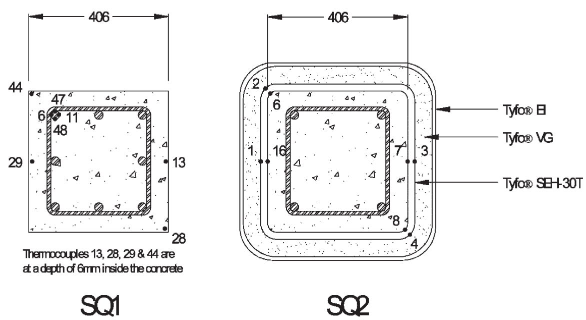


Fig. 2—Thermocouple locations in Columns SQ1 and SQ2 at mid-height

Fig. 3—The NRC Column Furnace with a columns installed prior to testing

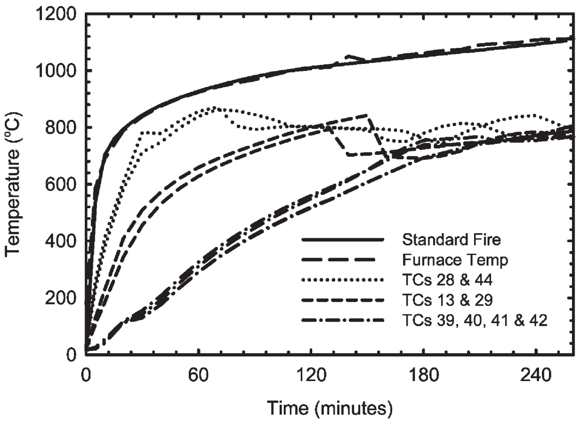


Fig. 4—Temperatures recorded at various locations in column SQ1 as a function of fire exposure time

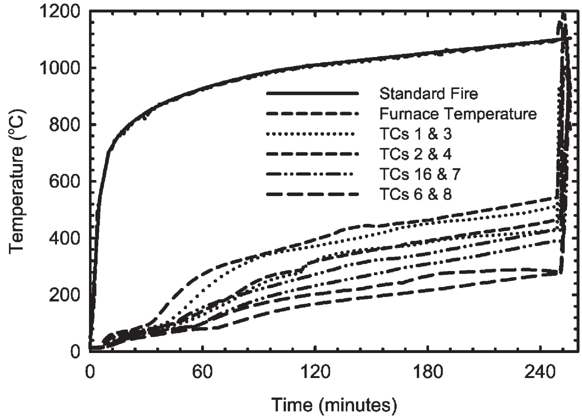


Fig. 5—Temperatures recorded at various locations in Column SQ2 as a function of fire exposure time

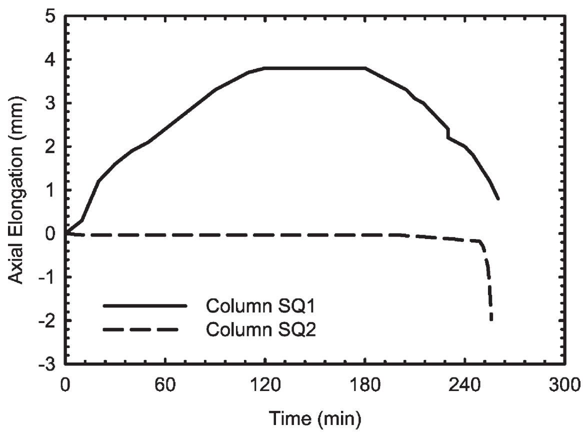
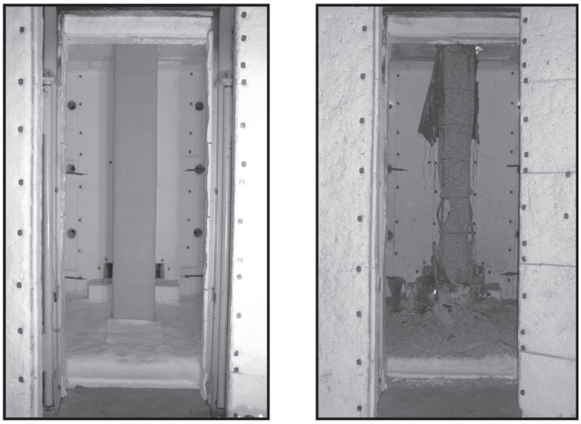


Fig. 6—Comparison of axial deformations as a function of time for Columns SQ1 and SQ2



(a) (b)

Fig. 7—FRP strengthened square RC column (Column SQ2) (a) before and (b) after fire testing