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Fire Behaviour of CFRP Strengthened Short SHS Steel Columns With and Without Insulation

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Abstract

Carbon Fibre Reinforced Polymers (CFRP) have been used as a potential strengthening material due to the many advantages they possess over conventional strengthening materials in recent times. Their successful applications in strengthening concrete columns have also led to CFRP being used as an external strengthening material in steel columns. However, the lack of knowledge of the fire performance characteristics of CFRP has hindered the CFRP usage in steel columns, which require structural fire ratings. Therefore, this two phase experimental investigation was aimed at investigating the effect of fire on the structural performance of CFRP strengthened short Square Hollow Section (SHS) steel columns. In the first phase, CFRP strengthened short SHS columns were exposed to steady state fire conditions and tested under axial compression until failure. The test results exhibited a severe degradation of the ultimate axial compression capacity beyond the glass transition temperature of the adhesive (66°C) and showed that the effect of CFRP has diminished completely at 225°C. In the second phase, CFRP strengthened short SHS columns were insulated with a spray applied insulation material and exposed to standard fire under three load conditions. The standard fire test results showed that the CFRP strengthened and insulated columns were able to achieve more than 60 min of fire rating under 0.2 load ratio suggesting satisfactory fire resistance level. This paper presents the details of the investigation and its results.

Keywords: CFRP Strengthening; Steel columns; Experiments; Standard fire; Insulation; Fire resistance level**.**

1. Introduction

Repairing or strengthening deteriorated steel tubular columns using Carbon Fibre Reinforced Polymers (CFRP), which is a composite material made of longitudinal carbon fibres impregnated in adhesive (resin), is increasingly accepted in the construction industry because of the many advantages associated with CFRP such as high strength to weight ratio, high stiffness, corrosion resistance and high impact properties. Recent research studies have proven CFRP to be successful in strengthening steel tubular columns, which are prone to local buckling failures, where applications of CFRP in short square hollow section (SHS) columns have resulted in axial compression capacity enhancements by up to 2.6 times [1-3]. Strengthening steel columns using CFRP increases the composite thickness and stiffness, which results in increased critical elastic buckling stresses [2], and thus higher axial compression capacities. However, several safety concerns including potential for smoke generation, flame spread, loss of strength and stiffness at elevated temperatures, and lack of knowledge in this research area has raised concerns over the fire performance of CFRP and hindered its usage in columns which require certain structural fire ratings to be satisfied [4,5]. Generally, load bearing steel columns should provide a minimum of 30 min of structural fire resistance level (FRL) and this requirement may increase to 240 min depending on the building type [6, 7].

Carbon fibres are very resistive to elevated temperatures and can maintain their tensile strength and stiffness at high temperatures [8]. For instance, experimental investigation conducted by Bisby [5] have shown that Carbon fibres retain almost all of their room strength even at 600°C. But, commonly used adhesives are sensitive to elevated temperatures and tend to lose their mechanical and bond strength properties significantly at around their glass transition temperature. Glass transition temperature of the commonly used adhesives lies in the range of 65 - 120°C [5]. This phenomenon results in the degradation of the important properties such as tensile strength and elastic stiffness when the CFRP composite is exposed to elevated temperatures. Thus, the adhesive's capability to transfer stresses between fibres decrease substantially resulting in overall strength reduction for the CFRP composite. Hawileh et al. [9] and Cree et al. [10] conducted tensile tests of CFRP samples at temperatures up to 250°C. Hawileh et al. [9] observed severe degradation in elastic modulus and tensile strength at 100°C, which accounted for reductions of 68% and 29%, respectively. Similarly, Cree et al. [10] observed around 23% and 56% of stiffness and tensile strength reductions at 200°C. In addition, Nguyen et al. [11] conducted a series of experiments on CFRP/steel double strap joints in tension to evaluate the bond strength degradation of CFRP strengthened specimens at different temperatures. The adhesive had a glass transition temperature of 42°C and upon testing the bond stiffness showed a gradual decrease of around 18% at T_g followed by a rapid reduction, where the bond stiffness was observed to be only 10% at 60°C. Similarly, the bond strength decreased gradually with increasing temperature till T_g, but followed by a rapid reduction where only 5% of ambient temperature bond strength was observed at 60°C.

Based on the above discussion, it is apparent that the effectiveness of CFRP may be lost significantly at low temperatures (below 100°C) and could eventually lead to structural collapse of CFRP strengthened steel columns. Despite this severe concern with regard to the fire performance of CFRP strengthened steel columns, no research has been carried out to date to investigate the level of deterioration that CFRP strengthened steel columns undergo in fire events and possible solutions to improve their performance.

However, a few studies exist on the behaviour of CFRP strengthened reinforced concrete (RC) columns in literature [4, 12-15]. Al-Salloum et al. [13] conducted experiments on short CFRP strengthened RC cylinder columns and investigated the effect of temperature and the duration of fire exposure on the axial compression capacity. CFRP was found to be performing outstandingly well at ambient temperatures where the capacity of RC column increased by 2.46 times as a result of CFRP wrapping. However, exposing them to 100°C and 200°C for 3 hours resulted in axial compression capacity losses of 5.1% and 27.1%, respectively. Nevertheless, the capacity of CFRP strengthened column exposed to 200°C was still twice higher than that of unstrengthened column exposed to the same condition. Al-Salloum et al. [12] further extended the study and found that the capacity of CFRP strengthened column exposed to 400°C was still 31.5% greater than that of unstrengthened column exposed to the same temperature. These results show that the strengthening effect of CFRP existed significantly even at 400°C. Additionally, Al-Salloum et al. [12] observed that only 13% of its initial strength was lost when RC columns were insulated with Sikacrete-213F insulation (with a thickness of 40 mm) and exposed to 500°C, which showed the effectiveness of an insulation system to protect the CFRP layers.

Chowdhury et al. [14] conducted two full scale tests to investigate the fire performance of FRP strengthened RC circular columns with and without an insulation system. One of the circular columns was insulated with a spray applied cementitious mortar based fire protection system with an average thickness of 53 mm. Both columns were loaded to the same load ratio (0.56) and tested under standard fire exposure prescribed in ASTM E119 [16]. The unprotected column resisted the load for 210 min before the failure and it was noticed that the FRP layers ignited quickly when exposed to the fire, resulting in early temperature rise within the FRP. This scenario demonstrates the sensitivity of FRP to combustion and requirement of a fire protection system for FRP composite. In contrast, the protected column was able to endure fire for more than five hours. However, the insulation material was able to maintain the FRP surface temperature below the glass transition temperature of the adhesive (71°C) for only 34 min. Yet, it was able to maintain the temperature of concrete and reinforced steel bars at lower levels, which resulted in increased FRL.

Similarly, Kodur et al. [4] conducted experiments on FRP strengthened and insulated RC circular and square columns. Two circular FRP strengthened columns were insulated with spray applied Tyfo VG insulation material with different thicknesses (32 mm and 57 mm) and provided with an additional intumescent and surface hardening coating. In addition, a single layer of galvanized steel plastering lath was mechanically clasped to the exterior surface of these columns to make sure that the insulation was intact with the FRP surface during fire exposure. Both these columns were loaded to a load ratio of 0.73 and tested under standard fire exposure [16], in which both columns showed FRLs of more than 300 min. In comparison, the unstrengthened circular RC column showed a FRL of 245 min. The insulation system was able to maintain the FRP surface temperatures of both these columns below 100°C for an extended period of time (up to 240 min), which showed the effectiveness of the combined insulation system. On the other hand, FRP strengthened square RC column was insulated with 38 mm thick Tyfo VG insulation and provided with non-intumescent and surface hardening coating. The column reached a FRL of 256 min compared to the unstrengthened square RC column's FRL of 262 min. In this instance, the FRP surface temperature exceeded 100°C within 30 min and visible cracks were noticed in the insulation system after test, which might have led to the lower FRL. This phenomenon shows the effectiveness of having a mechanism (galvanized steel plastering lath in circular RC columns) to hold the insulation system with FRP surface to achieve higher fire performance. It is worth noting that the result was still satisfactory because the FRP strengthened square RC column was able to sustain similar fire exposure as unstrengthened square RC column, but with increased serviced load.

Cree et al. [15] investigated the effect of the column shape by conducting experiments on FRP strengthened and insulated RC circular and square columns. Both columns were insulated with 40 mm thick Sikacrete-213F fire insulation system and tested under standard fire exposure, in which more than 240 min of FRL were observed under a load ratio of 0.76. However, the FRP surface temperatures exceeded the glass transition temperature (60°C according to [15] within 30 min into the test. Nevertheless, the insulation system was able to maintain the temperatures of concrete and reinforced steel at a lower level and protect the column for an extended period of time.

Interestingly an important conclusion can be made by comparing the results of unstrengthened circular RC column given in Kodur et al. [4] and the FRP strengthened unprotected (uninsulated) circular RC column given in Chowdhury et al. [14]. Test results showed that the unstrengthened column was able to achieve a higher FRL under a higher load ratio than the FRP strengthened unprotected column. These results raise concerns over the fire performance of FRP strengthened columns because a significant reduction in FRL was observed in FRP strengthened column compared to that of unstrengthened column. This result further emphasises the importance of an insulation system to protect the FRP strengthened columns in fire.

It should be noted that all past studies have shown around 240 min of FRL for FRP strengthened/unstrengthened RC columns with and without insulation systems [4, 14, 15]. Even though the test conditions, geometry and materials used in these studies govern the behaviour of the above mentioned columns, the low thermal conductivity and the low rate of mechanical property reduction of concrete have a significant effect in the observed higher FRLs. However, this phenomenon will be completely different for steel columns because of the higher thermal conductivity and strength reduction at elevated temperatures. In addition, apart from Kodur et al. [4], FRP surface temperature exceeded the glass transition temperature within 30 to 60 min into the fire tests and thus, higher reduction in strength can be expected for steel columns even with an insulation system within a shorter time frame compared to RC columns. Therefore, the behaviour and the deterioration characteristics of the CFRP strengthened steel tubular columns exposed to elevated temperatures and the temperature range in which the CFRP will be rendered ineffective were identified as the primary research gaps in this study. In addition, the fire performance of CFRP strengthened columns with an external insulation system is also unknown.

To address these knowledge gaps, a two phase experimental investigation was conducted using short cold-formed steel SHS columns subject to local buckling failures in the Wind and Fire Laboratory of Queensland University of Technology. In the first phase of the experimental investigation, CFRP strengthened short SHS columns were exposed to seven steady state temperatures (20, 66, 81, 100, 150, 200 and 225°C) and tested until failure to determine the ultimate axial compression capacity deterioration with increasing temperature. In the second phase, CFRP strengthened short SHS columns were externally insulated with a spray applied insulation material and exposed to standard fire condition to determine the structural Fire Resistant

Levels (FRLs). FRL refers to the time period (in minutes) that a structural element can withstand the applied load under standard fire exposure without a structural failure. These standard fire tests were conducted under three different load conditions (non-load bearing, 0.2 and 0.3 load ratios).

This paper presents the details and results of the experimental investigation conducted on CFRP strengthened steel tubular columns with and without a supplementary insulation system under steady and transient state conditions.

2. Experimental Investigation

The experimental investigation consisted of two phases. Phase 1 experiments were aimed at determining the ultimate axial compression capacity deterioration of CFRP strengthened, short SHS steel columns at elevated temperatures. Hence steady state tests were conducted at seven different temperatures (20, 66, 81, 100, 150, 200 and 225°C) and the elevated temperature behaviour of CFRP strengthened columns was investigated. Phase 2 experiments were aimed at determining the fire performance and FRL of CFRP strengthened and insulated SHS steel columns. Therefore, these columns were exposed to the standard fire time-temperature curve [17] and tested under three different loading conditions (non-load bearing, 0.2 and 0.3 load ratio). Here the load ratio is the ratio of the applied load in fire to the ultimate axial compression capacity at ambient temperature of 401 kN obtained from Imran [3]. This section of the paper presents the details of this experimental investigation.

2.1. Materials

Grade 350, 100×100×2 mm SHS columns with a height of 300 mm were used in this investigation. The section has a form factor of 0.706 based on AS 4100 [18] and thus CFRP was significantly effective in strengthening the column [3]. The average yield strength and elastic modulus were measured as 359 MPa and 207 GPa, respectively [19]. Unidirectional carbon fibre (termed as TU27) with high strength and high modulus produced by QuakeWrap was used along with J300SR adhesive (resin) in wet layup external strengthening process. In addition, a two-part epoxy tack coat (J201TC) was used as a binder between CFRP and steel surfaces. The tensile strength and elastic modulus of CFRP were measured and found to be 903 MPa and 88.6 GPa [3], respectively. The mechanical properties of adhesive, tack coat and carbon fibres were obtained from the manufacturer and are given in Table 1 [20]. Vermiculite and Gypsum based CAFCO 300 insulation supplied by Promat Australia were used for the Phase 2 test columns.

2.2. Test columns

Table 2 shows the details of the test columns used in this study. Phase 1 included two ambient temperature tests of unstrengthened (bare steel) and CFRP strengthened columns, referred to as columns SS-CC and SS-20, respectively, followed by six steady state (SS) tests conducted at different temperatures varying from 66 to 225°C. The steady state temperatures were selected based on the glass transition temperature (T_g) of the adhesive, which was found to be as 66°C. Differential Scanning Calorimetry (DSC) tests of adhesives were conducted in this study to examine the thermal behaviour, based on which the above T_g value of the adhesive was determined [21]. CC refers to the unstrengthened bare steel SHS Control Column and the rest of the seven columns in Phase 1 (SS-20 to SS-225) were strengthened with 1T1L CFRP configuration. T' and 'L' refer to transverse and longitudinal CFRP layers and 1T1L CFRP wrapping configuration means a column strengthened with one transverse layer followed by one longitudinal layer. 1T1L configuration was chosen in this experimental investigation because it was found to be very effective in restricting local buckling failures [3].

Phase 2 included three standard fire (SF) tests conducted under three different loading conditions. These columns were strengthened with 2T2L CFRP configuration and insulated with CAFCO 300 insulation material with a thickness of 30 mm. Authors' recent ambient temperature experimental investigation showed that SHS column strengthened with 2T2L CFRP configuration, consisting of two layers of transverse and longitudinal CFRP layers, provided up to 2.6 times of enhancement compared to unstrengthened bare steel column [3]. This means that SHS column strengthened with 2T2L CFRP configuration is likely to perform worse than 1T1L configuration under standard fire exposure. Therefore, 2T2L configuration was used in the standard fire tests of Phase 2. The axial compression capacity of the unstrengthened bare steel column was 169 kN [3] and therefore the standard fire tests were conducted at load ratios of 0.2 (80 kN) and 0.3 (120 kN). These load ratios were chosen so that the applied load was less than the ultimate compression capacity of the unstrengthened column. A thermal analysis was conducted by the authors by developing a heat transfer model to determine the most suitable insulation thickness for the Phase 2 columns, which led to the choice of 30 mm [21].

2.3. Fabrication of column specimens

Initially the short cold-formed steel SHS columns were welded to 16 mm thick Grade 250 carbon steel end plates at both ends. The end plates were made with bolt holes to facilitate connection to the test set-up so that fixed end conditions can be achieved. The columns were sand blasted to a white metal finish and cleaned with acetone to achieve a perfect bonding between steel and CFRP surface (Fig. 1). The geometric imperfections of the columns were measured using a digital dial gauge before the strengthening process.

Two-part tack coat (Parts A and B) was mixed with a volumetric ratio of 2:1 according to the manufacturer's guidelines [20] and applied to the acetone cleaned sand blasted column surface using a putty knife (Fig. 2). Then the tack coat applied surface was allowed to cure for 15 min.

In the meantime, the two-part saturated adhesive was mixed (2:1) using an electric mixer for about 3 min and used to saturate the carbon fibres, which were cut to the desired lengths (Figs. 3a-b). Adhesive was applied to both surfaces of the carbon fibre using a roller brush, which ensured that the carbon fibres were fully saturated with resin. Then the saturated composite was placed on the column and the roller brush was moved along the composite thoroughly to achieve a good finish (Fig. 3c). Each CFRP layer was overlapped at the round corner for about 40 mm to avoid premature failures. The measured average CFRP composite thickness was 1.3 mm. The strengthened column was allowed to cure under room conditions for about 60 min before the application of the next CFRP layer. CFRP strengthened columns were then allowed to cure for at least 14 days under room conditions, followed by testing of Phase 1 column specimens and insulating in the case of Phase 2 column specimens.

Fig. 4 shows the thermocouple locations for Phase 2 columns. K type thermocouples were attached on each side of the CFRP surface to obtain the temperature variation of the CFRP-insulation interface. Moreover, eight additional thermocouples were attached to both inner and outer steel surfaces of the SF-NB test column to obtain the temperature profiles of steel column. However, thermocouples were only attached to the inner steel surface for load bearing test columns due to the understanding that thermocouples between steel and CFRP interface will affect the bonding and eventually result in ineffective strengthening (Fig. 4b). Then the column specimens were insulated with spray applied CAFCO 300 insulation material until the desired thickness (30 mm) was reached in two steps using a shotcreting rig. The two step (two lifts) application process ensured that the insulation was properly bonded to the CFRP surface. After the curing period, which took at least 2 months, the insulation surfaces were filled to ensure that the desired insulation thickness (30 mm) was achieved with a smooth finish (Fig. 5). Prior to the test, thermocouples and thermal sensing rods were attached to the insulation surfaces.

2.4. Test set-up

Both Phase 1 and Phase 2 column specimens were tested using the electric furnace facility which had an internal height of 1 m (Fig. 6). Since the test columns are 300 mm in height, a 253 MA high temperature resistant adopter shaft with a height of 550 mm was used in the test set-up to facilitate the loading. The end plates at both ends were bolted to the test set-up using high tensile bolts to achieve fixed end conditions (Fig. 6).

Eighteen mm thick compressed cement fibre insulation sheets were placed between the loading shafts and the end plates of the column specimen to avoid any heat transfer via the shafts to the column. Additional layers of Cerachem fibre insulation blankets were placed for Phase 2 column specimens, and both these insulation layers ensured that the inner core of the SHS column specimen was thermally insulated (Fig. 7). Thus, the heat transfer to the steel surface of the column only occurred through the spray applied CAFCO 300 insulation material.

The electric furnace consisted of heating elements on three sides of the furnace and the temperature was controlled by a Eurotherm control system. The control system used an L type thermocouple to maintain the temperature in the furnace according to the desired temperature program. In addition, K type thermocouples were attached to the exterior surface of the column specimens to determine the temperature as the control system mostly measures the air temperature within the furnace. The compression load was applied by means of a hydraulic jack using a hydraulic pump. A pressure transducer was used to measure the applied pressure and the pressure was then converted to obtain the applied load. The axial displacements of experimental columns were measured using two LVDTs which were connected to the bottom shaft via a horizontal steel frame (Fig. 6). The applied pressure, load, axial displacement and temperature readings were recorded against time using a universal data acquisition system (UDAQ).

2.5. Test procedure

Phase 1 – Steady state tests

The CFRP strengthened SHS test column was placed between the top and bottom loading shafts with compressed fibre insulation sheets at both ends, and bolted firmly to achieve fixed end condition. Initially, the column was preloaded for about 20% of the ambient axial compression capacity and unloaded to remove any misalignment. Then the furnace door was closed and tightly bolted before the furnace was switched on.

The test column was heated up to the target temperature (Table 2) by setting the predefined temperature on the control system. Thermocouples were placed on the CFRP surface and using their readings the furnace temperature was adjusted to incorporate any heat loss. Once the CFRP surface temperature reached the target temperature, the test column was allowed to remain for 15 min to ensure a uniform temperature distribution throughout the column. The loading rate was maintained at 10 - 20 kN/min until failure.

Phase 2 – Transient state tests

The CFRP strengthened and insulated SHS test column was placed between the top and bottom loading shafts with compressed cement fibre insulation and two layers of Cerachem fibre insulation sheets at each end. The top adopter shaft was wrapped with Cerachem fibre insulation blanket in order to avoid temperature increment that may occur through radiation (Fig. 7). An axial compression load about 5 kN was applied to the non-load bearing column to ensure both insulation layers were compressed and thus heat was not transferred to the inner core of SHS column via loading shafts. Both load bearing columns were loaded to 80 kN and 120 kN to achieve the target load ratios of 0.2 and 0.3, respectively. Then the furnace door was closed and the furnace was switched on.

The test columns were exposed to the standard fire conditions using the Eurotherm control system, which was programmed to follow the standard fire time-temperature curve [17]. However, the thermocouples connected to the external surface of the insulation system showed a slight lag in temperature increment compared to the program because of heat loss. Hence the temperature was manually controlled to achieve the best possible time-temperature curve that resembled the standard fire curve. The applied load of the column had to be released slightly during the test in order to incorporate the effect of thermal expansion of the loading set-up. Yet, care was taken to maintain the applied load closer to the target load until failure.

3. Results and discussions - Phase 1

3.1. Load versus axial displacement

Fig. 8 shows the load versus axial displacement curves of CFRP strengthened test columns in Phase 1, which show that the elastic stiffness and the ultimate failure load are significantly affected by the temperature rise. It is to be noted that the ambient temperature test and elevated temperature tests were done using different test set-ups and in the elevated temperature test set-up, the LVDTs to measure the axial displacement of test columns were placed beneath the furnace (Fig. 6).

Therefore, slightly lower stiffness values were noticed for elevated temperature tests because the axial shortening measurements might have included the axial shortening of several test rig components (compressed cement fibre sheets, loading shafts and end plates).

An apparent trend in elastic stiffness and ultimate failure load of column specimens is observed where they reduce with increasing temperature, primarily because of the reduction in CFRP's mechanical properties at elevated temperatures. Apart from a few exceptions, it was observed that the columns behaved in a more ductile manner with increasing temperature and thus showed higher axial displacements at the peak loads. All test columns, except SS-20, failed in local buckling and it was evident from the load versus axial displacement curves, where the axial stiffness started to reduce gradually before the failure.

3.2. Axial compression capacity

Table 3 shows the axial compression capacities of tested columns and their corresponding capacity reductions with respect to the ambient temperature CFRP strengthened column (SS-20). CFRP showed its great ability to enhance the strength, where column SS-20 failed at 281.5 kN demonstrating significant strength increase (1.66 times) in comparison to the unstrengthened bare steel column (SS-CC), 169.4 kN. The test column exposed to glass transition temperature (T_g) of the adhesive (SS-66), failed at 263.4 kN exhibiting 6.4% capacity reduction. However, severe reductions in axial compression capacities were noticed even in columns, which were exposed to slightly higher temperatures than the T_g, where columns SS-81 and SS-100 displayed 19.0% and 29.8% capacity reductions, respectively. This phenomenon is clearly visible in Fig. 9, which shows the reduction in the axial compression capacity of CFRP strengthened columns with increasing temperature. Beyond 100°C, columns lost their capacities gradually and at 225°C, 41.6% of its initial capacity was lost. Moreover, the temperature dependent capacity variation of the unstrengthened columns obtained from Imran et al. [22] is also plotted in Fig 9, which shows that the capacity of SS-225 column has reduced to unstrengthened column capacity at 225°C. Thus, CFRP is considered to be completely ineffective beyond 225°C.

In addition, Fig. 9 illustrates that unstrengthened columns show negligible capacity reductions in the given temperature range. Therefore, when both these columns are under the same load ratio, CFRP strengthened columns are more likely to fail at a low temperature than the unstrengthened columns because of higher ultimate capacity reduction. This phenomenon suggests that the fire performance of CFRP strengthened columns is worse than the unstrengthened columns under the same service load ratio.

3.3. Failure modes

SS-CC (bare steel column) displayed local buckling failure at its mid-height, where two adjacent sides of the column buckled inward and other two outward (Fig. 10a). Application of CFRP led to yielding failure at room temperature demonstrating CFRP's exceptional ability to restrain local buckling failures (Fig. 10b). However, as the temperature increases, yielding failure shifted back to local buckling failure and the location of the failure gradually moved towards the mid-height of the column (Figs. 10c-h). SS-66 and SS-81 columns exhibited local buckling failures at the top region of the column with less deformation suggesting that the effect of CFRP still remains to a certain extent. However, both SS-100 and SS-150 columns displayed similar local buckling failure and deformation as the bare steel column, SS-CC. This phenomenon was attributed to the rapid mechanical property degradation of CFRP at the given temperature range which eventually led CFRP strengthened columns to behave like the unstrengthened column.

Soon after the test, a tackiness was observed in both SS-200 and SS-225 columns, which might have been caused by the transition of adhesive from solid phase to the rubbery state. Additionally, in contrast to other columns, the CFRP layers were observed to be softer in these columns. Furthermore, SS-225 column displayed complete delamination of CFRP, suggesting that the strengthening effect of CFRP is completely lost at 225°C (Fig. 10h).

3.4. Discussion

Based on a numerical investigation, Imran et al. [3] proposed a design equation for the ambient temperature axial compression capacity of CFRP strengthened short steel columns by determining the theoretical critical elastic buckling stress of the section (Eqs. 1-13). As per this design model, CFRP is expected to increase the buckling stress as a result of its strengthening and subsequently the axial compression capacity of the column increases. In this section, this model is used to explain the effects of the relevant parameters together with the Phase 1 test observations.

$$P_u = 4\,\rho\, b\, t\, f_y + A_r\, f_y \tag{1}$$

$$b = b_w - 2\,r \tag{2}$$

$$A_r = A_g - 4\,b\,t \tag{3}$$

$$\rho = \frac{1 - \frac{0.22}{\lambda_C}}{\lambda_C} \tag{4}$$

$$\lambda_C = \sqrt{\frac{f_y}{f_{cr}}} \tag{5}$$

$$f_{cr} = \frac{k\, \pi^2\, D_t}{t_T\, b^2} \tag{6}$$

$$P_{cr} = A_g\, f_{cr} \tag{7}$$

$$D_t = \frac{D_1 D_3 - {D_2}^2}{D_1} \tag{8}$$

$$D_1 = \frac{E_S\, t}{1 - {\upsilon_S}^2} + \frac{E_{CE}\, (t_T - t)}{1 - {\upsilon_C}^2} \tag{9}$$

$$D_2 = \frac{E_S\, t^2}{2(1 - {\upsilon_S}^2)} + \frac{E_{CE}\, ({t_T}^2 - t^2)}{2(1 - {\upsilon_C}^2)} \tag{10}$$

$$D_3 = \frac{E_S\, t^3}{3(1 - {\upsilon_S}^2)} + \frac{E_{CE}\, ({t_T}^3 - t^3)}{3(1 - {\upsilon_C}^2)} \tag{11}$$

$$t_T = t + t_C\, (N_L + N_T) \tag{12}$$

$$E_{CE} = \frac{N_L\, E_{1C} + \xi\, N_T\, E_{1C}}{N_L + N_T} \tag{13}$$

When CFRP strengthened columns are exposed to elevated temperatures, CFRP stiffness reduces significantly, particularly beyond the glass transition temperature of the adhesive. As a result, the buckling strength increment is reduced, which then yields a lower compression capacity enhancement. This behaviour was clearly observed in Phase 1 tests, where beyond 66°C (the glass transition temperature of the adhesive used in the tests), the compression capacity of strengthened columns reduced significantly. Hence irrespective of the CFRP configuration and steel section sizes, a significant axial compression capacity reduction is expected when CFRP strengthened columns are exposed to temperatures beyond the glass transition temperature of the adhesive.

In addition, as the adhesive changes from a solid state into a rubbery state beyond its glass transition temperature, the bond strength will deteriorate, raising concerns of CFRP delamination and complete loss of strength enhancement. Phase 1 test results showed that strength enhancement at 200°C was minimal while complete CFRP delamination occurred at 225°C. Likewise, a similar behaviour is expected for all the CFRP strengthened columns at elevated temperatures, but the temperature at which the effect of CFRP is completely lost depends on the type of CFRP and adhesive used, which should be determined using an experimental investigation.

Temperature dependant axial compression capacities of CFRP strengthened columns also depend on the CFRP configuration, steel grade and section slenderness ratio, as evident from Eqs.1-13 [3]. Axial compression capacity generally increases with increasing number of CFRP layers because CFRP restricts the buckling deformations. However, a given column has a maximum attainable capacity and any addition of extra CFRP layers beyond this is unlikely to provide further enhancement [3]. As the strength enhancement increases with additional CFRP layers, subsequently they are expected to undergo larger strength reductions at elevated temperatures than the columns strengthened with lower number of CFRP layers. Similarly, high strength slender section columns show high capacity enhancements at ambient temperature and are thus expected to undergo larger strength reductions at elevated temperatures.

These phenomena as described above based on our previous numerical investigation [3] and this experimental investigation suggest that CFRP strengthened columns are prone to significant strength reduction at elevated temperatures and thus raise serious concerns over their fire resistance. It is primarily because, higher service loads are allowed in CFRP strengthened steel columns because of their increased axial compression capacity, but when they are exposed to fire, their compression capacities decrease rapidly and the columns would fail prematurely when their capacity drops below the applied fire limit state service load. Thus, a suitable insulation system is essential to maintain the capacity of CFRP strengthened columns above the applied service loads in fire.

4. Results and discussions - Phase 2

4.1. Thermal response

Time-temperature responses recorded at the insulation, CFRP and steel surfaces of all three columns during the standard fire tests are shown in Figs. 11-13. As illustrated in Section 3.3, four temperature readings were obtained for each surface and the average of those readings are plotted. During the non-load bearing test (SF-NB), dark black smoke emission was noticed after 50 min into the test and thus the test was stopped because of safety concerns. However, both the load bearing column tests were conducted until failure.

In all cases, insulation surface temperature closely followed the ISO 834 standard fire curve [17] apart from an initial deviation, which was attributed to the inability of electrical heating elements to provide the initial high temperature gradient. Both steel inner and outer surface temperatures of SF-NB column showed almost similar behaviour with increasing temperature because of high thermal conductivity of steel and low thickness of the section (Fig. 11). Hence, only the steel inner surface temperatures were measured in both load bearing columns. The steel surface temperatures showed slightly higher values than the CFRP surface temperature during the period from 20 to 40 min. This was attributed to the possible heat transfer through steel tube inner core. Hence, two layers of Cerachem fibre insulation blankets were used at the top and bottom steel end plates for both load bearing columns (Fig. 7).

As shown in Figs. 11-13, CFRP surface temperature exceeded the glass transition temperature of the polymer (66°C) within 10 to 12 min into the test. However, this phenomenon was followed up with a plateau, where minimal temperature increments were noticed suggesting that the insulation material is capable of maintaining the CFRP surface temperature less than 100°C for about 30 min. A significant rise in CFRP surface temperatures was noticed beyond 35 min and it was attributed to the formation of cracks in the insulation material, which enabled heat to transfer quickly. CAFCO 300 insulation starts to form cracks when they are exposed to temperatures above 800°C [3]. Another noteworthy observation was that, CFRP surface temperature reached 225°C, the temperature at which the effect of CFRP is completely lost, within 37 to 39 min into the fire tests, suggesting more protection is required to maintain the effect of CFRP for an extended period of time.

On the other hand, steel surface temperature showed a similar behaviour to that of CFRP surface temperature until about 35 min, beyond which slight variations in temperatures were noticed (Figs.

11-13). The average of maximum steel temperatures at the failure of SF-0.2 and SF-0.3 test columns were 691°C and 385°C, respectively. Figs. 14 and 15 show the comparison of both CFRP and steel surface temperatures in all three tests. Interestingly, both variations show a similar behaviour irrespective of loading conditions. Thus it was concluded that, for a given insulation thickness, thermal response of constituent interfaces are independent of the loading condition. Therefore, these time-temperature profiles can be used in finite element analyses to obtain the FRLs for higher load ratios (> 0.3).

4.2. Structural response

Figs. 16 and 17 show the variation of axial compression load and displacement during the fire tests of SF-0.2 and SF-0.3 columns, respectively. Although it was anticipated to maintain the axial compression service loads of both SF-0.2 and SF-0.3 at 80 kN and 120 kN throughout the test, the applied loads of the specimens were recorded as 79 kN and 115 kN, respectively, at the time of failure. The failure time was taken as the time at which the column was unable to withstand the applied load. The pressure was slightly released at various points during the test to incorporate the effect of thermal elongation of steel components of the test set-up and consequent load increment. Hence, minor anomalies were observed in the axial compression load versus time curves. Moreover, both axial displacement versus time curves exhibited slight increase in axial displacement beyond failure.

As shown in Fig. 18a, SF-NB test column displayed cracks not more than 5 mm after the test and visible black traces of carbon were noticed around the crack. However, insulation system remained intact with the column. In contrast, load bearing columns displayed wider cracks and spalling of insulation system after the tests. The combined effect of high temperature and applied load resulted in the initiation and widening of cracks which eventually ended up in insulation fall off (see Figs. 18b-c). Moreover, large black smoke traces, which might have been caused by CFRP combustion, were also observed.

Fig. 19 shows the inner surfaces of the load bearing test columns after the tests. Both CFRP surfaces experienced temperatures above 500°C at failure, and it is reasonable to assume that the adhesive had evaporated completely at the end of the test. Fig. 19 further proves this assumption where only the carbon fibre sheets are seen to be in contact with the columns. Both columns failed in local buckling where the two opposite sides of the column buckled outward and other two inward (Fig. 19).

Table 4 summarizes the fire resistance levels achieved by Phase 2 column specimens, where the fire resistance has been defined as the time period which the column was able to sustain the service load under standard fire exposure. SF-0.2 column specimen failed after 61 min while SF-0.3 specimen failed after 50 min. These results are significant in that they show that CFRP strengthened steel columns are capable of achieving more than 60 min of FRL and are able to certainly satisfy the minimum 30 min requirement. The application of an insulation system maintained the CFRP and steel surface temperatures at lower levels for an extended period of time and thus provided a satisfactory fire resistance level. Therefore, it can be concluded that fire performance of CFRP strengthened columns subjected to local buckling failures can be improved by having a suitable external insulation system. However, it should be noted that formation of cracks and falling-off of insulation at higher temperatures during the experimental investigation were considered as drawbacks, which should be addressed. As shown by Kodur et al. [4], a special mechanism that keeps the insulation system intact with the column during the fire test will certainly result in lower temperatures in CFRP and steel surfaces, which may improve the FRLs.

Another novel method to improve the fire performance of these steel columns is to use a suitable fire retardant in the CFRP composite which would delay the heat progression and eventual structural strength reduction at elevated temperatures and subsequent flame and smoke spread [23, 24]. However, future research is needed to explore these applications further.

4.3. Discussion

The results of Phase 2 experimental investigation showed that the fire performance of the CFRP strengthened steel columns can be significantly improved by using a suitable insulation material. An insulation system is capable of maintaining the temperature of both CFRP and steel at lower levels. As a result, the axial compression capacity of the CFRP strengthened steel column is expected to be maintained above the service load, which would eventually result in increased fire resistance.

Imran et el. [21] conducted a heat transfer analysis of CFRP strengthened steel columns protected using CAFCO 300 insulation material, in which the CFRP configuration, steel section size and insulation thickness were varied. These results showed that even though the insulation thickness significantly influenced the heat transfer behaviour and impacted the CFRP and steel surface temperatures, CFRP configuration and steel section size did not have a significant influence on the steel and CFRP surface temperatures. Therefore, it is concluded that only the insulation type and its thickness affect the heat transfer behaviour of CFRP strengthened and insulated steel columns. Provided that insulation types and corresponding thicknesses are tested to demonstrate that these insulation materials have the ability to maintain the stickability with CFRP strengthened columns, it is considered that the heat transfer results of CFRP strengthened and insulated steel columns can be used to determine their fire resistance performance.

For instance, Fig. 20 [21] shows the steel and CFRP surface temperature variations for various CAFCO 300 insulation thicknesses. In this figure, 30-CFRP refers to the CFRP surface temperature for 30 mm CAFCO 300 insulation thickness. Surface temperatures were reduced with increasing insulation thickness. Both steel and CFRP surfaces show a similar temperature variation because of the high thermal conductivity of CFRP.

If such steel and CFRP surface temperatures of a given CFRP strengthened and insulated steel column after a certain time are determined, the axial compression capacity of the columns after that same time period can be calculated using Eqs. 1-13. Consequently, if the determined axial compression capacity is greater than the applied service load in the fire limit state, the column is deemed to be safe and considered to have achieved the required fire resistance. As concluded above, these temperature variations are not expected to be affected significantly when the CFRP configuration and steel section size are changed. Therefore, this approach is suitable to use for any CFRP strengthened steel columns insulated with a suitable insulation system.

5. Conclusions

This paper has presented an experimental investigation on the fire performance of CFRP strengthened steel tubular columns, which are prone to local buckling failures. The investigation explored the fire performance of these columns with and without an insulation system. The first phase of the experimental investigation consisted of steady state tests of CFRP strengthened steel tubular columns at various temperatures. The results showed a significant reduction in the axial compression capacity when the columns were exposed to temperatures above the glass transition temperature of the adhesive and the effect of CFRP completely diminished at about 225°C. The reduction in axial compression capacity at elevated temperatures was primarily caused by the reduction of CFRP stiffness at elevated temperatures. In addition, since the steel columns with large number of CFRP layers, section slenderness and steel grade exhibit increased capacity enhancements, they are prone to severe axial compression capacity reductions at elevated temperatures. This has raised fire safety concerns and emphasized the need for a suitable fire insulation system to achieve the required fire resistance levels.

Accordingly, the second phase of the experimental investigation focused on evaluating the fire resistance of CFRP strengthened columns with an insulation system. Tests were conducted under different loading conditions with an insulation thickness of 30 mm. The investigation showed that the insulation system was capable of maintaining the CFRP and steel surface temperatures below 100°C for about 30 min and produced good results where more than 60 min of FRL was achieved. Furthermore, it was found that the minimum FRL requirement, which is 30 min for load bearing columns based on many design standards, can be achieved using a proper insulation system. In addition, for a given insulation thickness, thermal response of constituent interfaces were found to be less dependent on the loading conditions, CFRP configuration and section size. Therefore, time-temperature profiles obtained from heat transfer analyses for different insulation thicknesses and the design model proposed to determine the axial compression capacity of CFRP strengthened columns can be safely used to determine the fire resistance of CFRP strengthened and insulated steel columns.

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Table 1. Material properties of constituents

Material	Tensile strength (MPa)	Tensile modulus (GPa)
Carbon fibre	3800.0	231.0
Adhesive	49.3	1.995
CFRP composite	930.0	89.6
Tack coat	30.1	2.268

Table 2. Details of the experimental columns

	Specimen ID	Temperature exposure	Load ratio	CFRP configuration	Thermal insulation
Phase 1	SS -CC	20°C	Load increased until failure	-	No
	SS -20	20°C		1T1L	
	SS -66	66°C			
	SS -81	81°C			
	SS -100	100°C			
	SS -150	150°C			
	SS -200	200°C			
	SS -225	225°C			
Phase 2	SF -NB	Standard fire	0.0	2T2L	Yes
	SF -0.2		0.2		
	SF- 0.3		0.3		

Table 3. Axial compression capacity - Phase 1

Specimen	Failure capacity (kN)	Capacity reduction (%)
SS -CC	169.4	-
SS -20	281.6	0
SS -66	263.4	6.4
SS -81	228.1	19.0
SS -100	197.4	29.8
SS -150	180.1	35.9
SS -200	167.5	40.5
SS -225	164.5	41.6

Table 4. Fire resistance levels -Phase 2

Specimen	Load ratio [a]	FRL (min)
SF-0.2	0.198	61
SF-0.3	0.286	50
[a] Load ratios calculated with respect to ambient temperature capacity of 401 kN [3]		

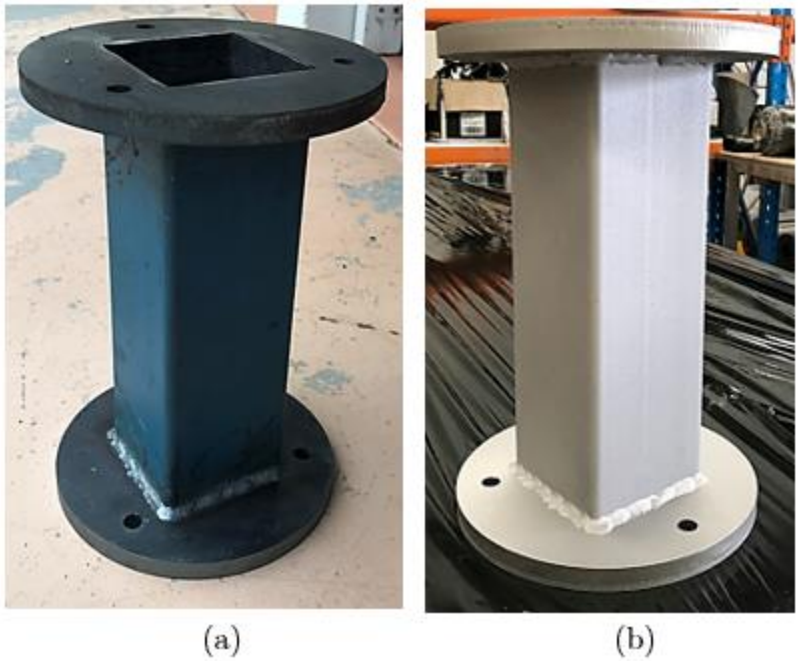
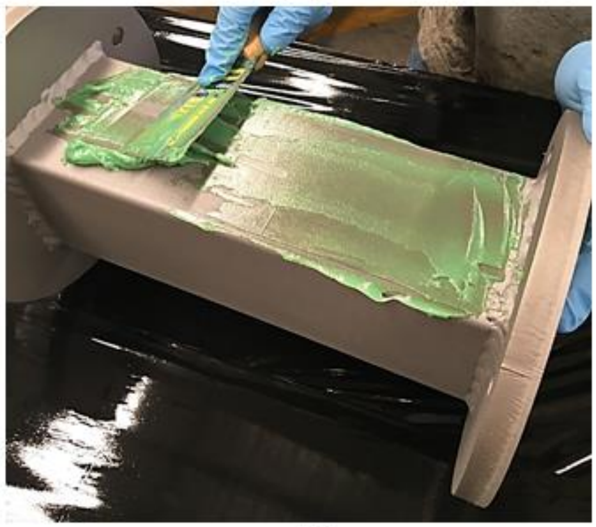


Fig. 1. Sand blasting process. (a) Before. (b) After.

(a)



(b)

Fig. 2. J201TC tack coat application. (a) Two-part tack coat. (b) Tack coat application.

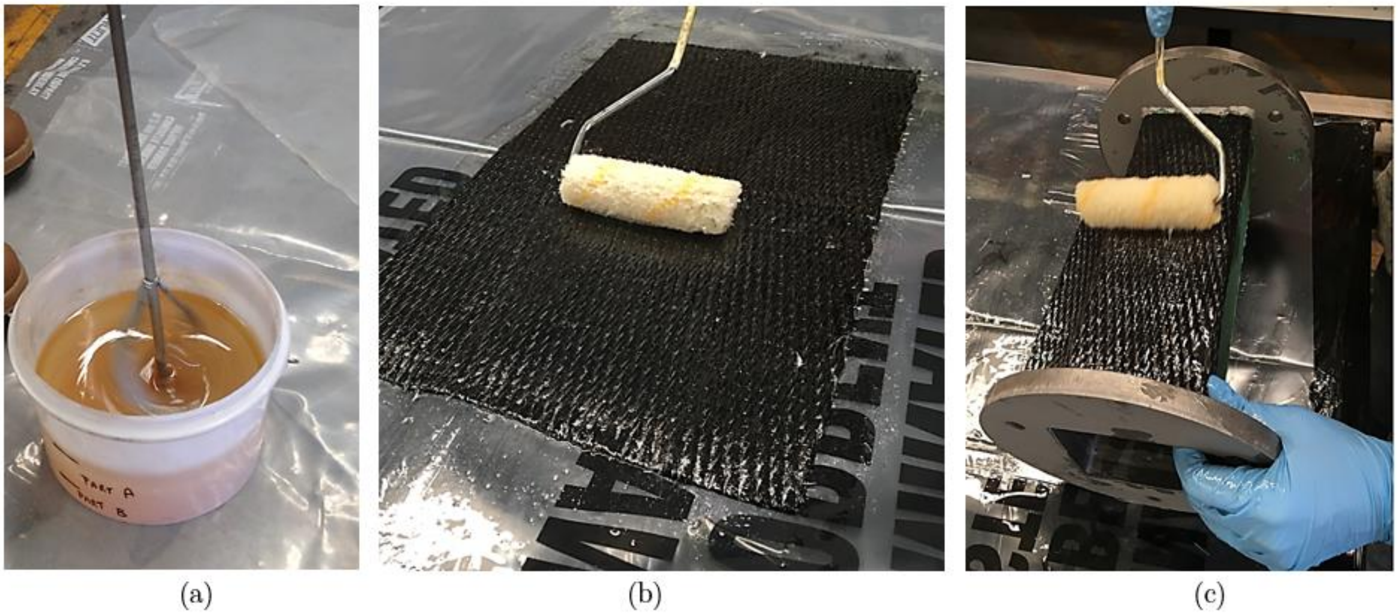


Fig. 3. CFRP strengthening. (a) Preparation of adhesive. (b) Application of adhesive on carbon fibre. (c) CFRP wrapping on column.

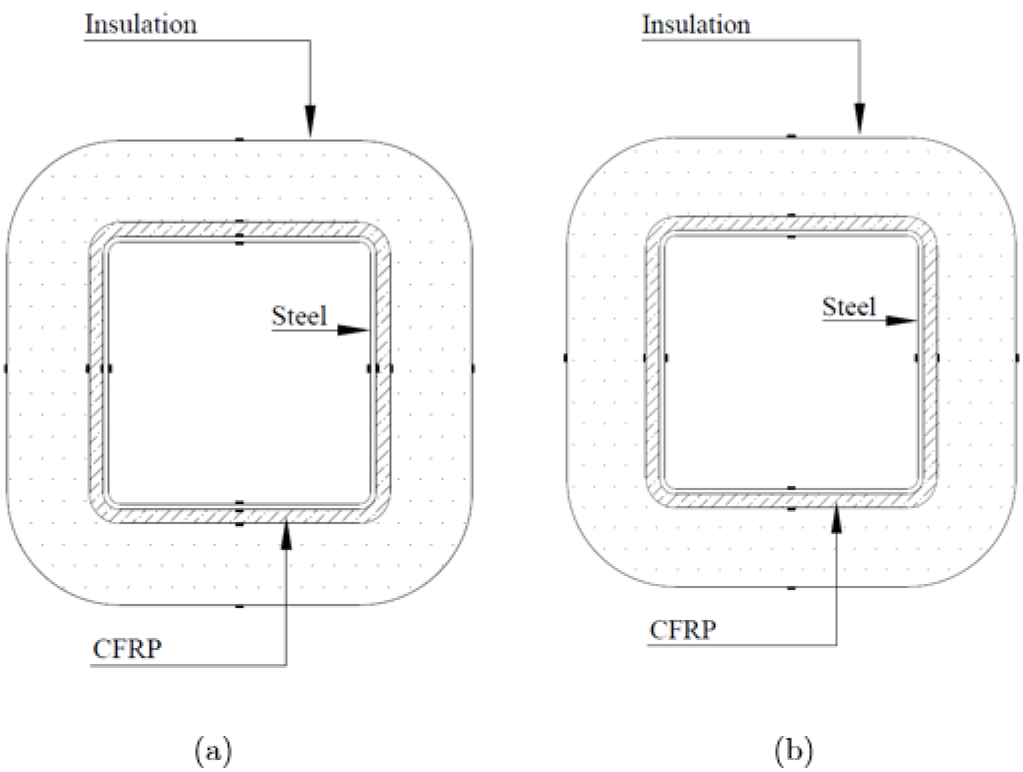


Fig. 4. Thermocouple locations. (a) SF -NB. (b) SF - 0.2 and SF - 0.3.

Fig. 5. CFRP strengthened and insulated column

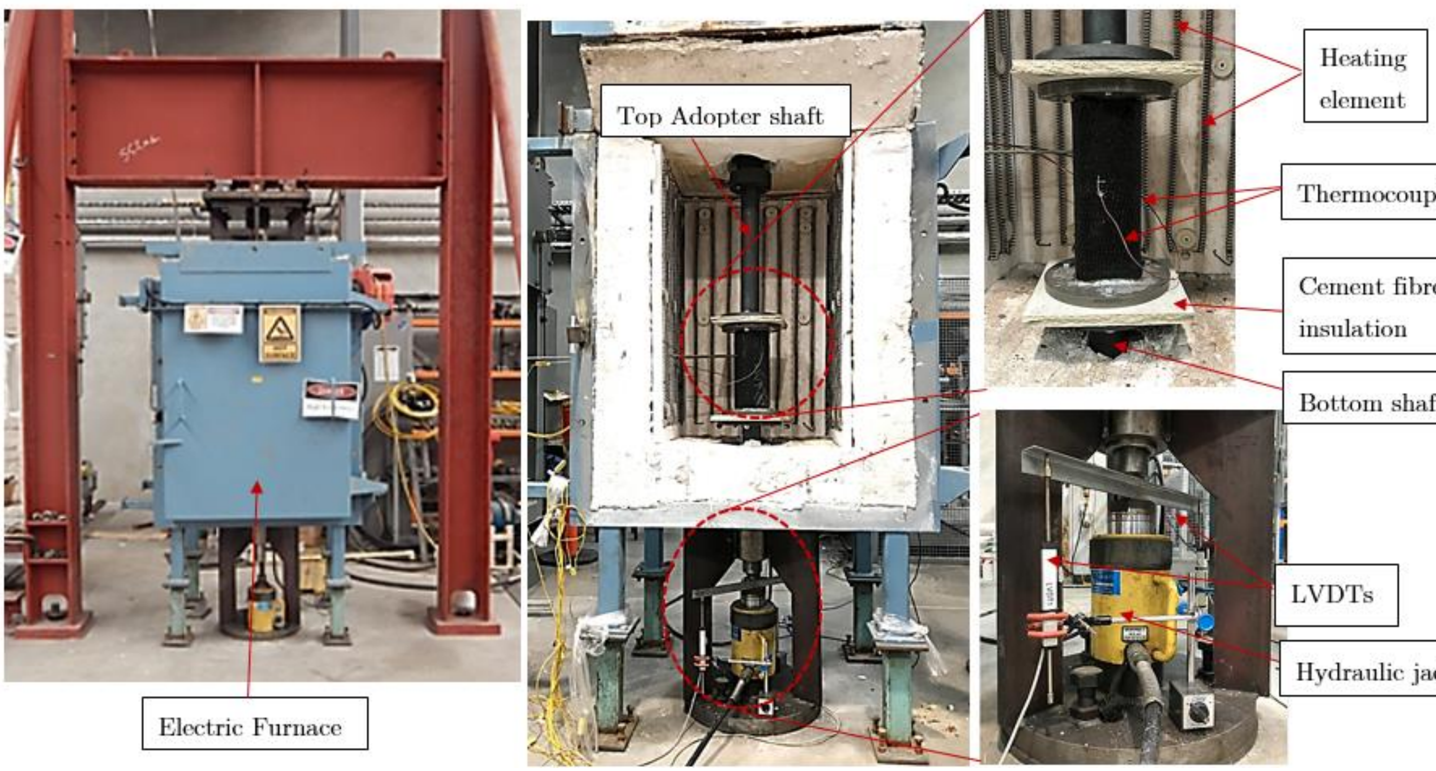


Fig. 6. Test set-up - Phase 1

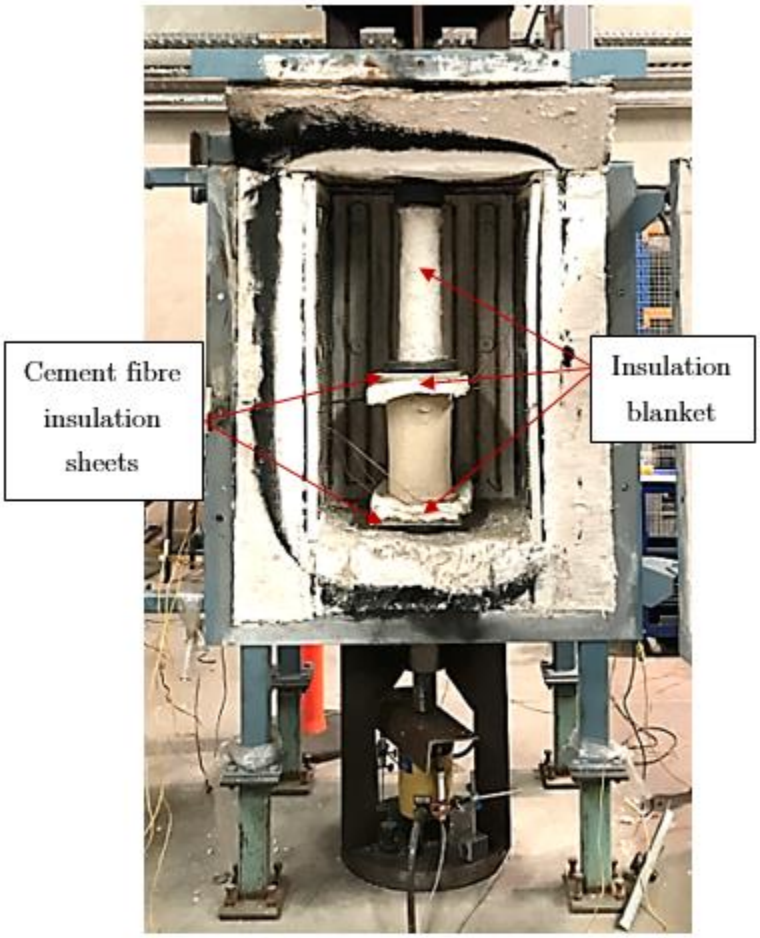


Fig. 7. Test set-up - Phase 2

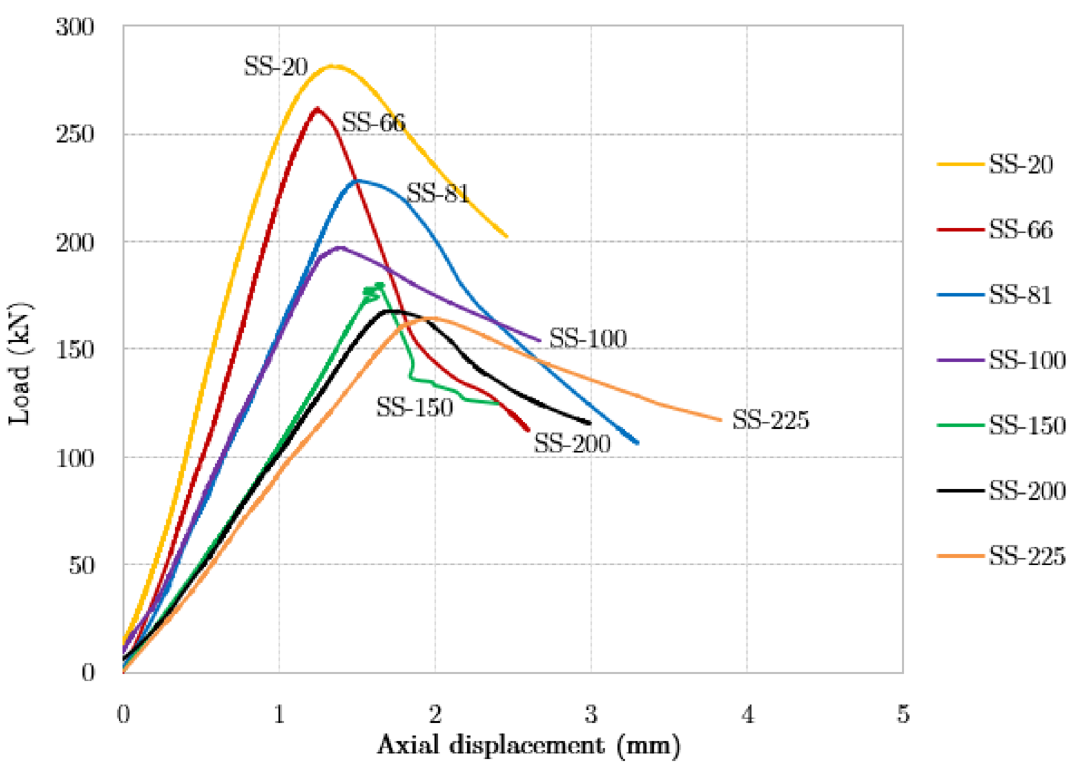


Fig. 8. Axial compression load versus axial displacement curves of CFRP strengthened columns

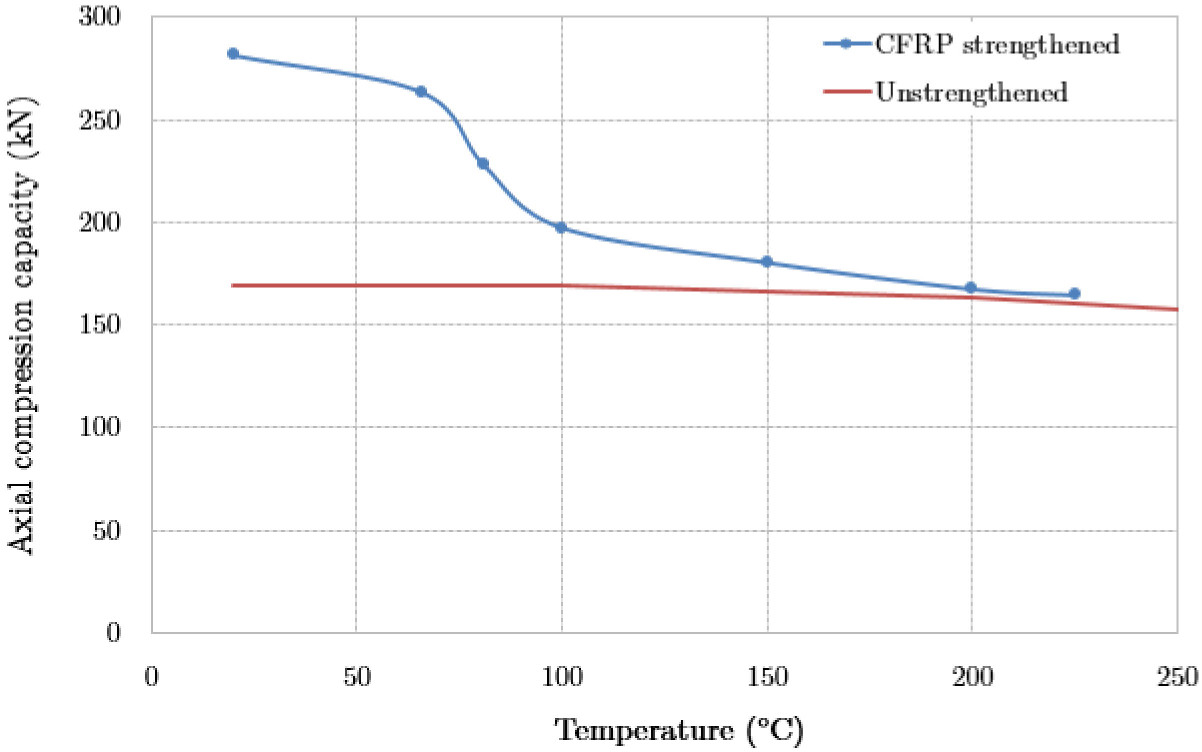


Fig. 9. Variation of axial compression capacity with temperature

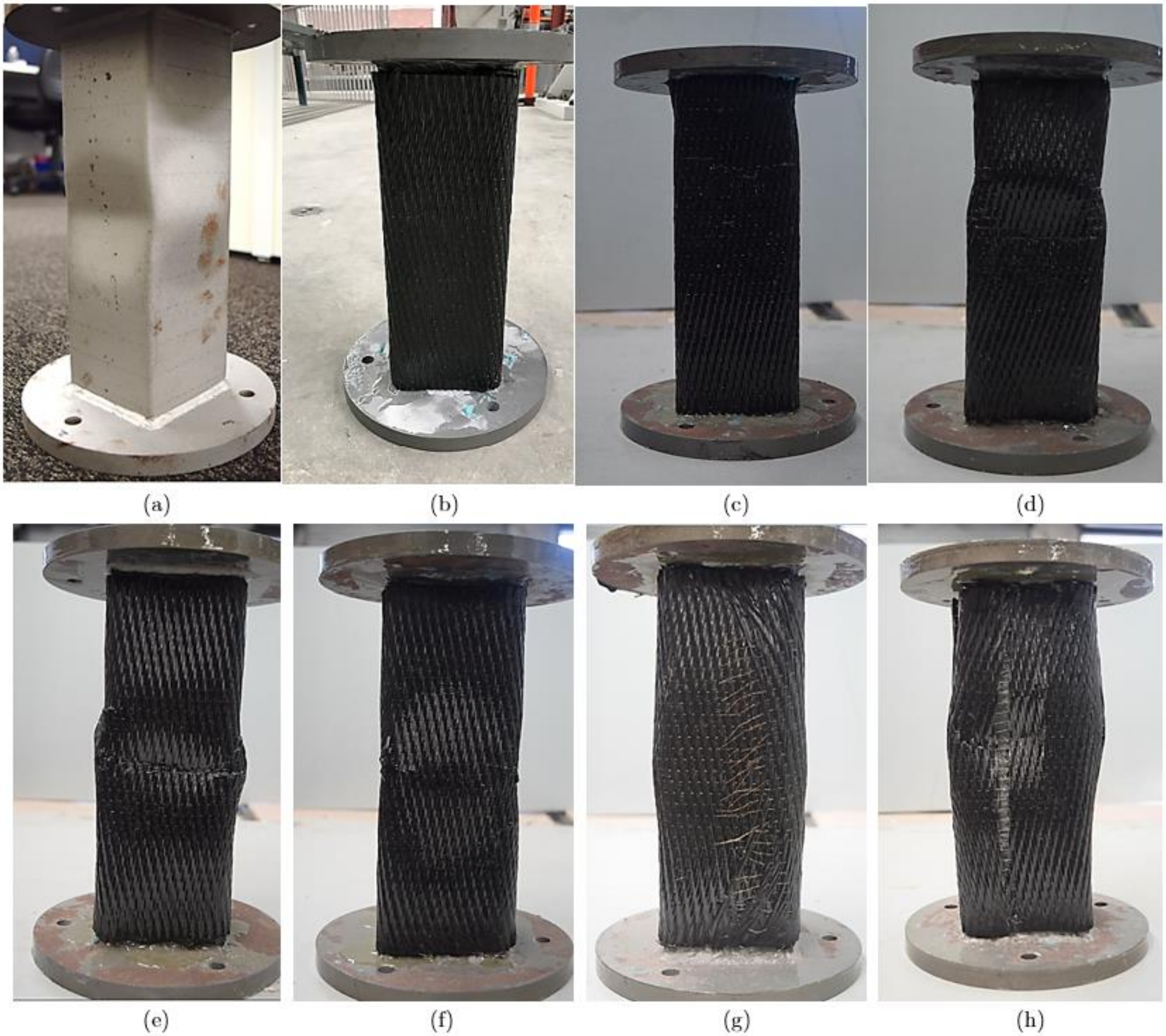


Fig. 10. Failure modes of Phase 1 columns. (a) SS -CC. (b) SS -20. (c) SS -66. (d) SS -81. (e) SS -100. (f) SS -150. (g) SS -200. (h) SS -225.

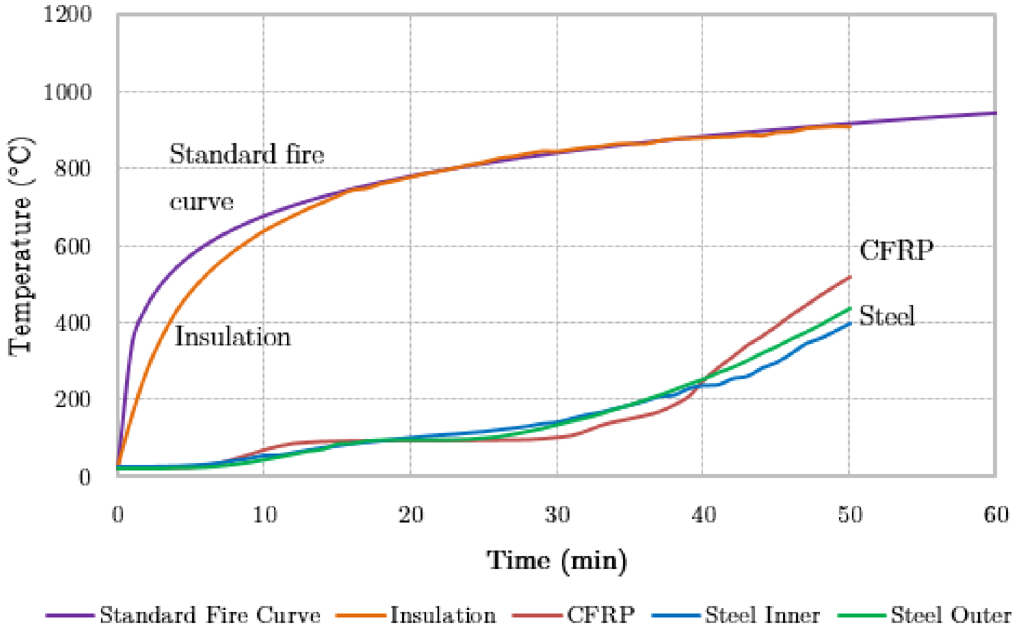


Fig. 11. Average time-temperature profiles of SF-NB column

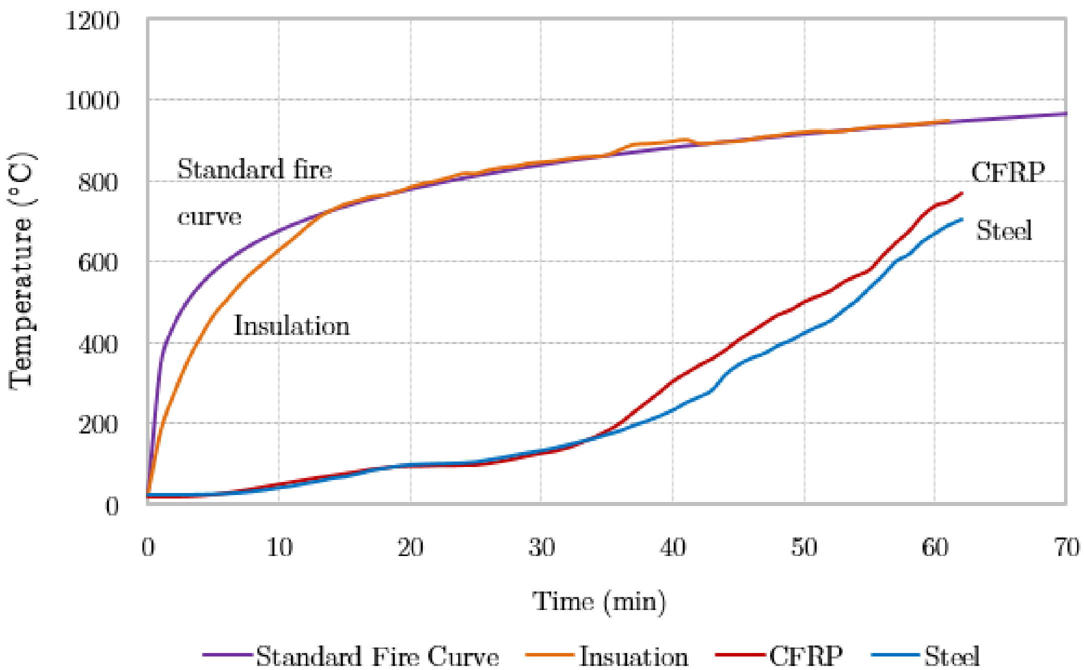


Fig. 12. Average time-temperature profiles of SF-0.2 column

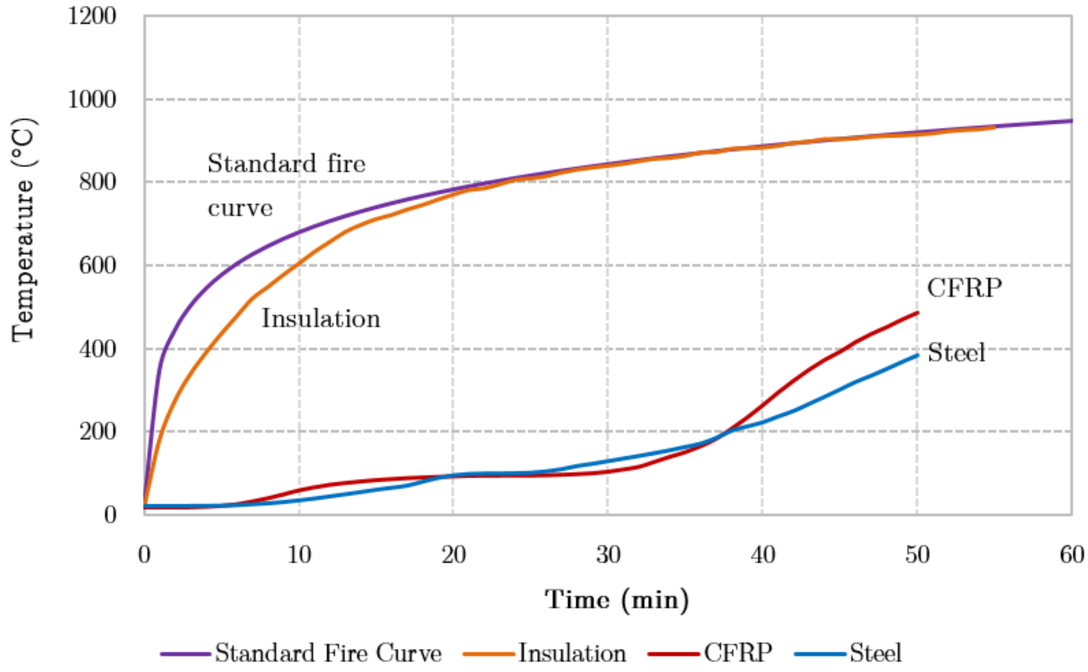


Fig. 13. Average time-temperature profiles of SF-0.3 column

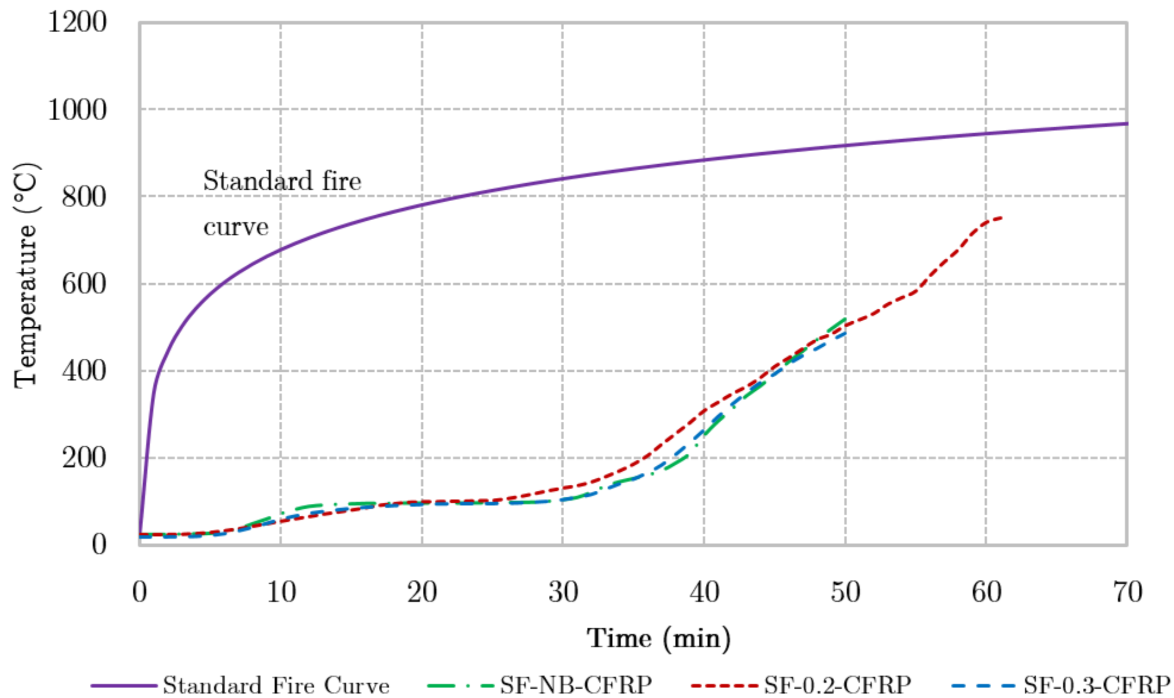


Fig. 14. Comparison of CFRP surface time-temperature profiles

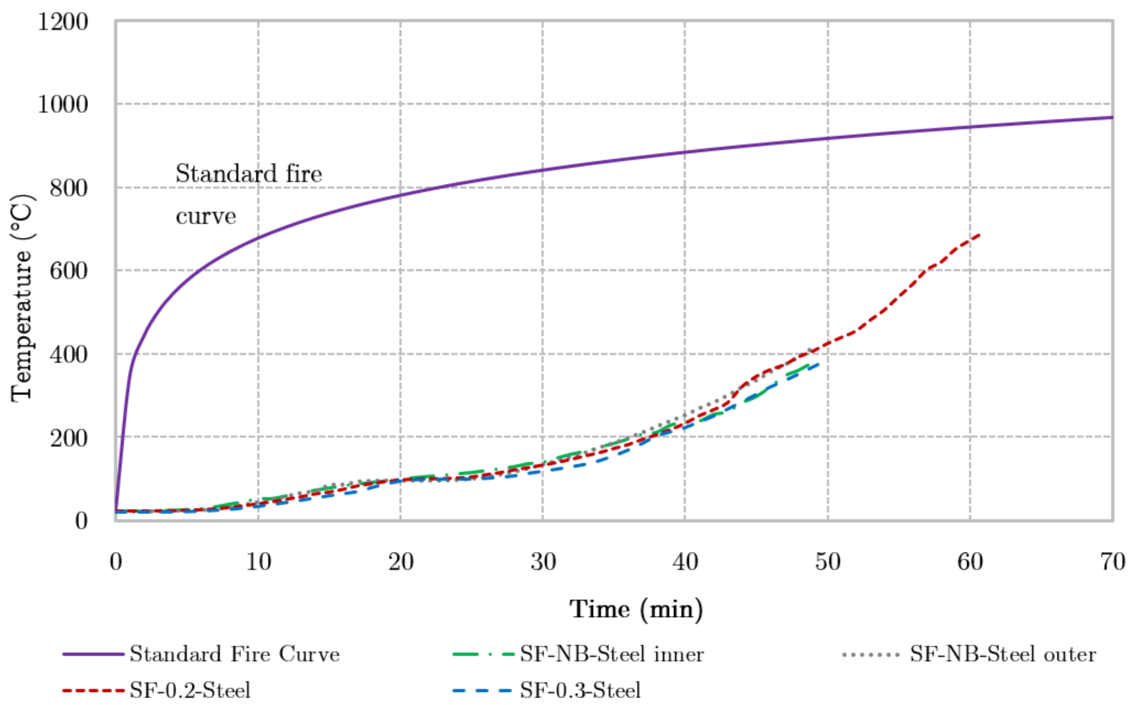


Fig. 15. Comparison of steel surface time-temperature profiles

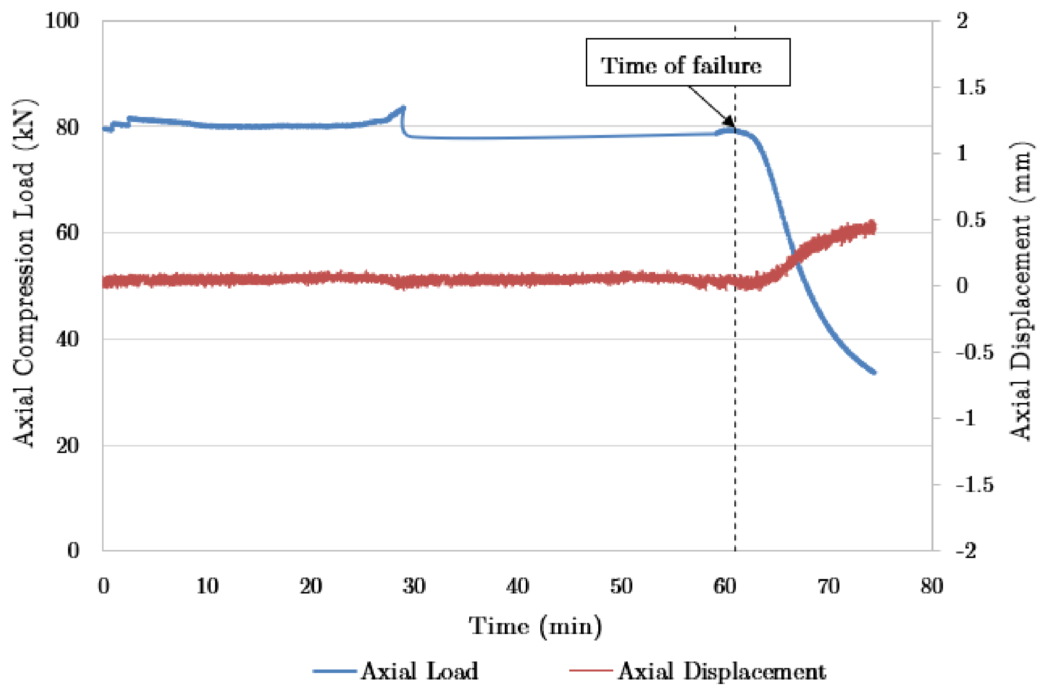


Fig. 16. Axial compression load and displacement variation of SF-0.2 column

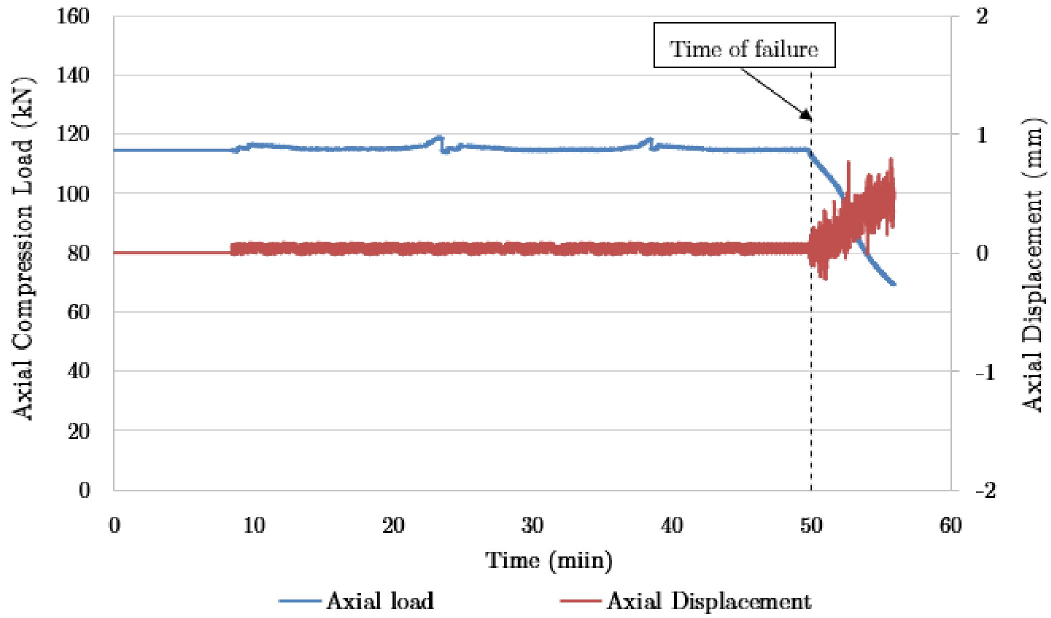


Fig. 17. Axial compression load and displacement variation of SF-3 column

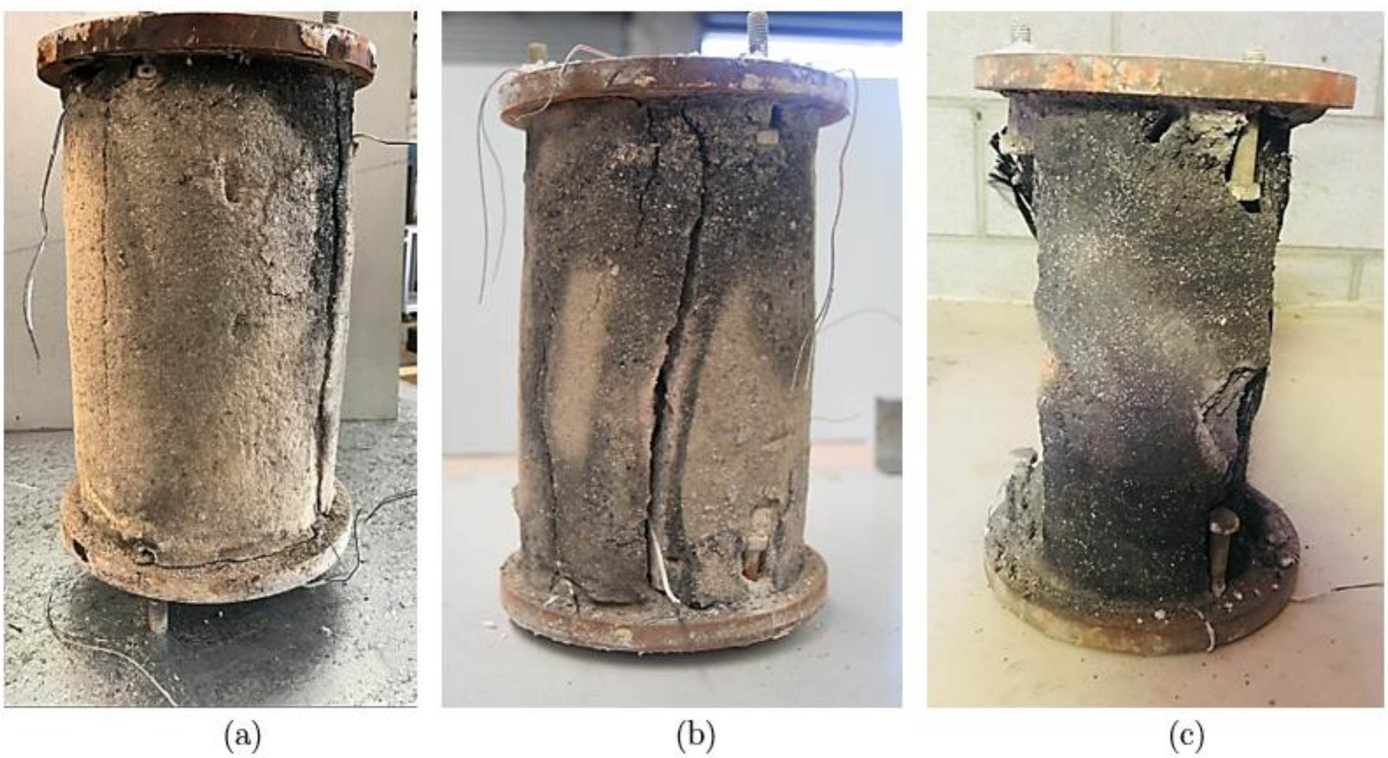


Fig. 18. Phase 2 columns after the test. (a) SF -NB. (b) SF -0.2. (c) SF-0.3.

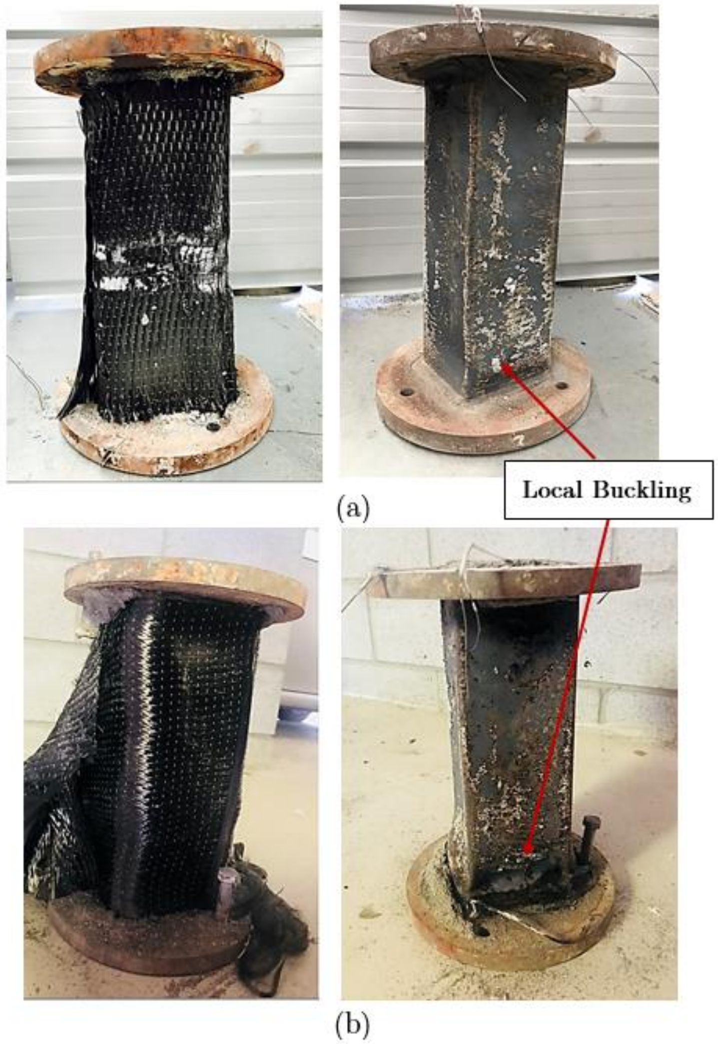


Fig. 19. Inner surfaces of Phase 2 columns after the test. (a) SF-0.2. (b) SF-0.3.

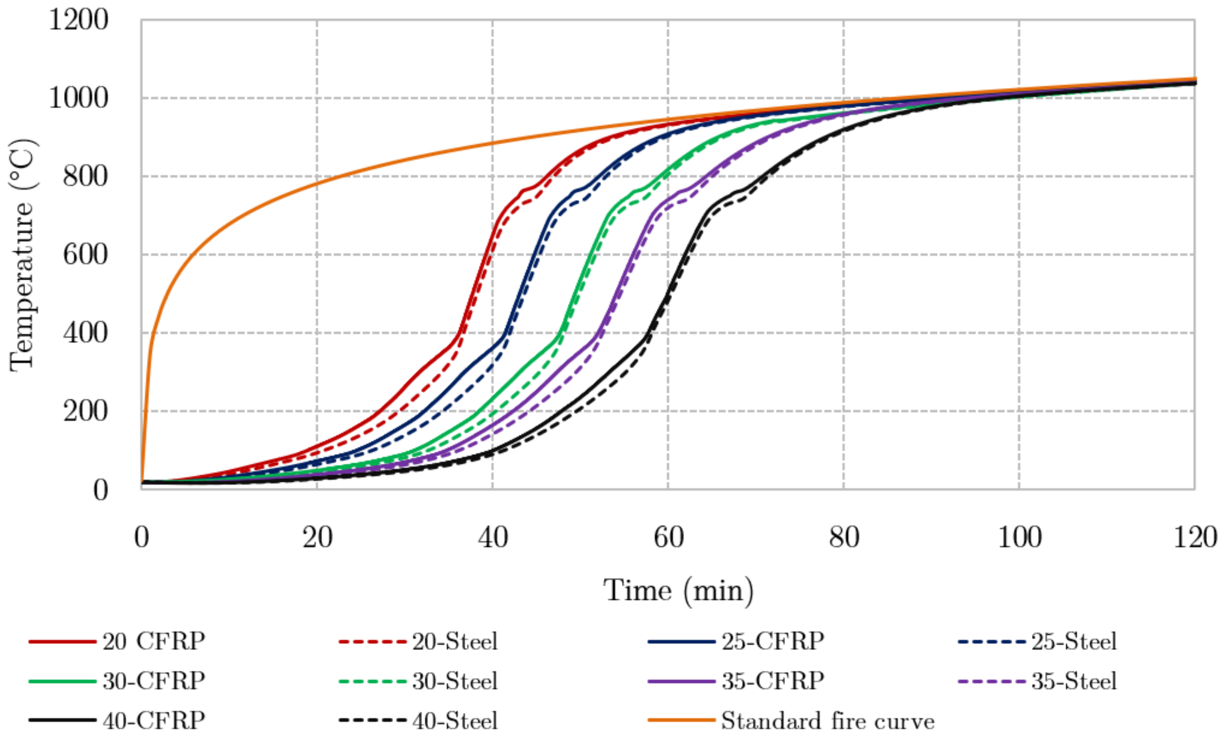


Fig. 20. Time-temperature curves of steel and CFRP surfaces with various CAFCO 300 insulation thicknesses