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# Analyzing Performance of Partially Encased Composite Columns with Steel Wool and Carbon Fiber

**Manthri Shivaprasad[1], S. Bhoomesh[2]**

[1]P.G. Scholar, Department of Civil Engineering, Malla Reddy Engineering College, Hyderabad
[2]Assistant Professor, Department of Civil Engineering, Malla Reddy Engineering College, Hyderabad
Corresponng Author: shivadesignstudio69@gmail.com

***Abstract -*** *Partially encased composite columns (PECCs) combine a steel I-section with concrete placed between the flanges, but this concrete loses strength at high temperature. This study added carbon fiber (CF) and steel wool (SW) to M30 infill concrete and tested its strength and heat resistance. A mix of 0.50% CF and 0.50% SW gave about 19% higher compressive strength and 18–58% higher residual strength after heating to 400–800 °C. PECCs filled with this mix carried 14.9% more load than plain-concrete PECCs and deformed about 135% more. A finite element model matched the test results and showed slower heat transfer to the steel.*

***Key Words:*** partially encased composite column, hybrid fiber reinforced concrete, steel wool fiber, carbon fiber, elevated temperature, axial compression.

## 1. INTRODUCTION

Composite columns made of steel and concrete have the advantage over comparable reinforced concrete members of being able to support loads with smaller cross-sections and less self-weight than similar reinforced concrete members [1], [2]. A partially encased composite column (PECC) consists of a hot-rolled I-beam with concrete poured in the space created by the flanges. The concrete prevents local buckling of the flanges and protects the web from thermal effects, whereas the steel supports most of the tensile and bending demands. PECCs are lighter and less expensive than fully encased composite columns; also, their performance has been examined using both experimental and numerical methods [1], [2], [16] (Fig. 1).




**Fig -1:** Concept of a PECC: (a) cross-section with fiber concrete between the flanges; (b) fiber infill slowing heat flow towards the steel web (schematic)

Fire protection has been a significant issue for these types of columns. Although concrete does not burn, nor does it conduct heat very quickly; however, when subjected to extreme temperatures, concrete loses its ability to carry loads and will likely begin to break down into small pieces (spall). Due to these characteristics, designing for fire resistance is a critical part of high-rise building design [3], [4], [15]. Adding fibers into the concrete can slow down the development of cracks within the concrete, which in turn improves the overall tensile capacity, ductility and toughness of the material. When you use multiple types of fibers in the same mix of concrete, so that each type works best during a specific phase of cracking, you create what we refer to as Hybrid Fiber Reinforced Concrete (HFRC). This type of concrete has a synergistic effect [5]-[7]. Carbon fiber provides excellent strength-to-weight ratios and exhibits minimal shrinkage [13], [14]; whereas, steel fibers provide improved ductility and post-peak load-carrying capacity. Additionally, steel fibers have been shown to provide increased load-carrying capacity and improved fire performance [8]-[12].




**Fig -2:** Fibers used in this study: (a) chopped carbon fiber; (b) steel wool (photographs from the thesis)

The two fibers used here are shown in Fig. 2. This study investigates how concrete infill containing steel wool (SW) and carbon fiber (CF), both small enough to easily distribute between the flanges of a small I-beam, affects the performance of PECCs. Specifically, this study (i) evaluates the strength and thermal properties of concrete containing SW, CF and various combinations of them; (ii) determines the optimal proportioning of these materials based on multi-response optimization; (iii) conducts axial compression testing of PECCs with and without fiber reinforcement in the infill; and (iv) validates the experimental results using a finite element analysis to assess the heat transfer through the infill.

## 2. MATERIALS AND METHODS

### *2.1 Materials and mix proportions*

Portland Pozzolana Cement with specific gravity of 2.9, standard consistency of 34%, and initial and final setting times of 35 minutes and 130 minutes respectively, river sand of Zone II with fineness modulus of 2.48 and specific gravity of 2.7, crushed coarse aggregate with fineness modulus of 7.88 and specific gravity of 2.58 and the water reducing admixture CONPLAST SP 430 were used in the study. The control M30 mix was designed according to IS 10262:2009 [17] and consisted of 380 : 791 : 1000 : 183 kg/m3 (cement : fine aggregate : coarse aggregate : water), which translates into a mix ratio of 1 : 2.08 : 2.63 and a water-cement ratio of 0.48. In addition to the control mix, fibers were incorporated into the mixes based on their percent volume of the concrete. The

carbon fiber was chopped and PAN-based (diameter 10 µm, length 12 mm, density 1.76 g/cm³, tensile strength 3300–3850 MPa, Young's modulus 220–245 GPa). The steel wool consisted of low-carbon steel filaments of 0.10 mm diameter and density 7.18 g/cm³.

The first series consisted of 9 mixes of SW fibers having L/d ratio of 50, 70 and 90; and Vf of 0.1%, 0.2% and 0.3%. The second series was composed of CF fiber mixes at 0%, 0.3%, 0.6% and 0.9%. The third series was hybrid mixes of CF and SW fibers (0/1, 0.25/0.75, 0.50/0.50, 0.75/0.25 and 1/0 % by volume) and plain M30 concrete. All hybrid mixes are referred to as CF/SW in the text and figures.

### *2.2 Tests on concrete*

The specimens were removed from their molds 24 hours later, then cured in lime-saturated water for 28 days. A minimum of three specimens were tested for each mix. At both 7 and 28 days after curing, compressive strength (fc) was determined using 150mm cube specimens. Cylinder specimens (150 x 300mm) were used to determine splitting tensile strength (fst). Fst = 2P / (piLD) where P is the failure load, L is the cylinder length and D is the cylinder diameter. Cylinder stress-strain measurements were used to calculate Young's Modulus and Poisson's Ratio. Cube specimens were tested for ultrasonic pulse velocity (UPV) and graded based upon IS 13311 (Part 1) [18].

Thermal tests used 28-day cubes which were placed into a muffle furnace. The cubes were heated to temperatures based on the ISO 834 standard fire curve [19]. The CF series used temperatures of 300°C and 600°C, while the hybrid series used temperatures of 400°C, 600°C, and 800°C. The cubes were kept at these temperatures for 60 minutes. After the cubes cooled down, their residual compressive strength and mass loss were determined. The surface and internal temperatures of both the best performing HFRC and plain M30 cubes were monitored using a K-type thermocouple every 30 minutes for as long as 150 minutes after they had been taken out of the furnace.

exposure of the concrete cubes

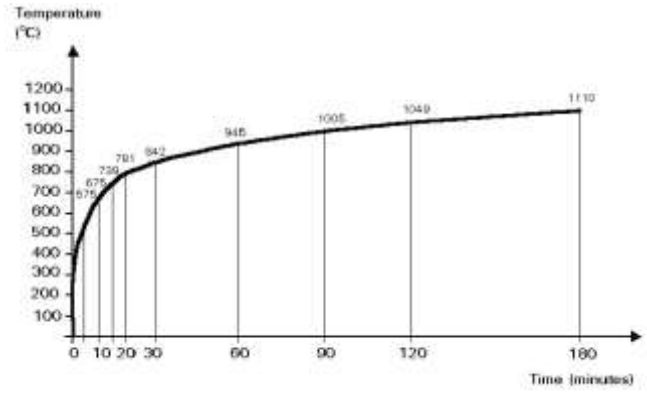



**Fig -3:** ISO 834 standard time–temperature curve followed during heating

surface and core temperatures

### *2.3 Optimization*

Amultiple-response, regression-based desirability approach was used. The inputs were the SW aspect ratio and volume fraction, and the CF volume fraction. Responses included compressive strength, splitting tensile strength, modulus, and UPV; and, in addition to those listed above, the hybrid series also had 7- and 28-day strengths, residual strength, and mass loss. Composite indices were developed from individual desirabilities and the optimal combination was identified by maximizing the composite index.

### *2.4 PECC specimens and testing*

The columns used an ISMB 125 x 75 section of E250 steel, which measured 800 mm in length. Concrete was placed into the column's flange areas (Fig. 6). One side was cast and cured overnight, and then the other side was filled the next day. Six columns were tested: the bare steel column (SS); the column with plain M30 concrete infill (CC1); the column with SW concrete (CC2); the column with CF concrete (CC3); the column with hybrid 0.50/0.50 concrete (CC4); and the same hybrid concrete as CC4 but with welded shear connectors designed according to Eurocode 4 (CC5). The columns were axially loaded using a 100-tonne UTM with its bottom end fixed and its top end free. Computer data collection included load, displacement and stress-strain responses.



**Fig -4:** Cross-section of the PECC specimen (dimensions in m)

### *2.5 Finite element model*

A 3D non-linear model was developed using ANSYS 17.2 software. Steel sections were modeled with SOLID185 elements and had bilinear isotropic hardening behavior (E=2*10^5 N/mm^2; fy=250 N/mm^2). Concrete was modeled with SOLID65 elements that allowed for both cracking and crushing. Contact between steel and concrete was modeled with a CONTA174/TARGE170 contact element. The base was constrained, the load was applied to the top face in increments (Newton-Raphson, large deflection), and an initial imperfection was added to the model based upon results from an eigenvalue buckling analysis. To conduct a transient thermal analysis (SOLID70 elements), the ISO 834 time-temperature history curve, T=T0+345log10(8t+1), was applied to all exposed surfaces. A convection coefficient of 25 W/m^2K and emissivity of 0.7 were used to represent heat transfer mechanisms as specified in EN 1994-1-2.

## 3. RESULTS AND DISCUSSION

### *3.1 Carbon fiber concrete*

In general, as the amount of carbon fiber (CF) added to concrete increases, the compressive strength of the concrete will also increase. However, if the amount of CF added to concrete exceeds 0.6%, the compressive strength of the concrete will begin to decrease (Fig. 10). At 0.6% CF, the 28-day compressive strength of the concrete is 38.25 MPa. This represents an increase of 15.9% over the control group. Similarly, at 7 days, there was a similar pattern in the compressive strength of the concrete. The decrease in compressive strength of the concrete with 0.9% CF can be attributed to the formation of fiber clusters or clumps. These fiber clusters or clumps create weakened areas within the concrete. The ultrasonic pulse velocity (UPV) of plain concrete

is about 4.3 km/s. On the other hand, the UPV of concrete with 0.6% CF is about 4.6 km/s. Therefore, adding CF to concrete increases its homogeneity and decreases its porosity. After exposing both types of concrete to thermal treatment, the concrete with 0.6% CF also demonstrated superior performance. When subjected to thermal treatment at 300°C, the compressive strength of the concrete with 0.6% CF was maintained at approximately 32 MPa. When subjected to thermal treatment at 600°C, the compressive strength of the concrete with 0.6% CF was maintained at approximately 25 MPa. Conversely, when subjected to thermal treatment at 300°C, the compressive strength of plain concrete decreased to approximately 25 MPa. When subjected to thermal treatment at 600°C, the compressive strength of plain concrete decreased to approximately 17.5 MPa.

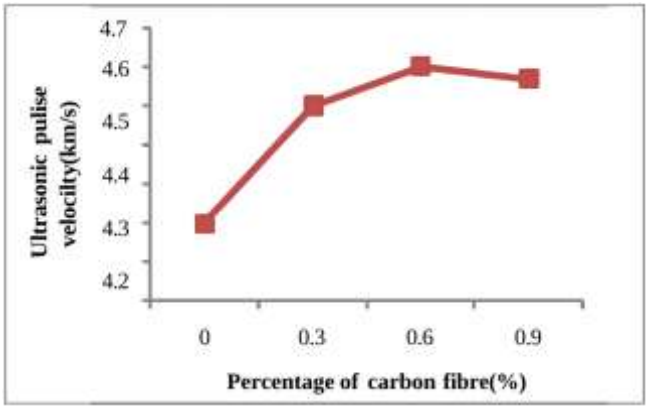



**Fig -5:** Ultrasonic pulse velocity of carbon fiber concrete

### *3.2 Hybrid fiber concrete at ambient temperature*

The 0.50/0.50 hybrid mix showed the greatest strength as compared to the other hybrid mixes. The 28-day strength of approximately 39.6 MPa for this mix represents an increase in strength of about 19% over the strength of plain concrete (approx. 33.2 MPa). In addition, the 7-day strength of the 0.50/0.50 hybrid mix is approximately 24% greater than that of plain concrete. Additionally, the hybrid mix exhibited a strength that was approximately 15% greater than that of the mix containing only 1% CF and approximately 29% greater than that of the mix containing only 1% SW. This suggests a synergy between fibers as opposed to simply adding together individual fiber contribution. Conversely, the 1% SW hybrid mix exhibited a lower strength than that of plain concrete. These results are consistent with what has been observed in Sec. 3.1 regarding the optimal single fiber content for SW being 0.3%, and the reduction in workability associated with increasing fiber contents.

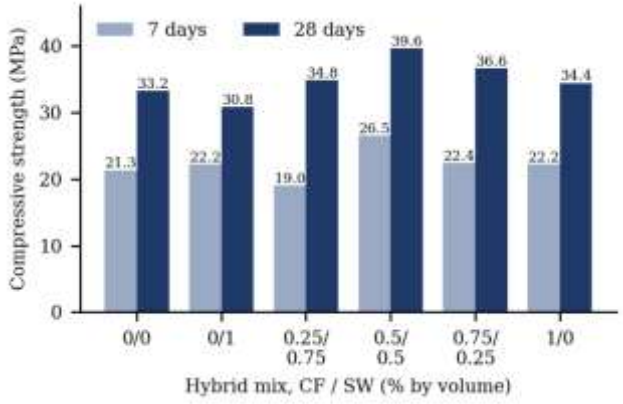



**Fig -6:** Compressive strength of hybrid mixes (values digitised from the experimental chart)

### *3.3 Behavior after exposure to elevated temperature*

After being heated, all of the mixtures showed decreases in both strength and weight; these decreases were due to the evaporation of free water and chemically bound water, as well as damage to the matrix by thermal effects. As illustrated in Fig. 14, the 0.50/0.50 mixture had the greatest remaining strength at all three temperatures studied: approximately 26.8, 24.2, and 20.8 MPa following heating to 400, 600, and 800 °C, respectively. Plain concrete exhibited much lower remaining strengths at those same temperatures: approximately 22.8, 17.6, and 13.2 MPa, which translates into 18%, 38%, and 58% more residual strength than plain concrete. Both mixtures retained approximately the same percentage of their initial strengths at 400 °C (approximately 68-69%); however, at 800 °C the hybrid mixture retained approximately 53% of its initial strength while plain concrete retained only approximately 40%. The 0.50/0.50 mixture exhibited the lowest mass loss among the three mixtures tested (approximately 1.0-1.1% versus approximately 1.1-1.25% for plain concrete), whereas the 1% SW mixture experienced the largest mass loss (approximately 1.7%). Therefore, the benefits of using a hybrid mixture increase with increasing temperature.

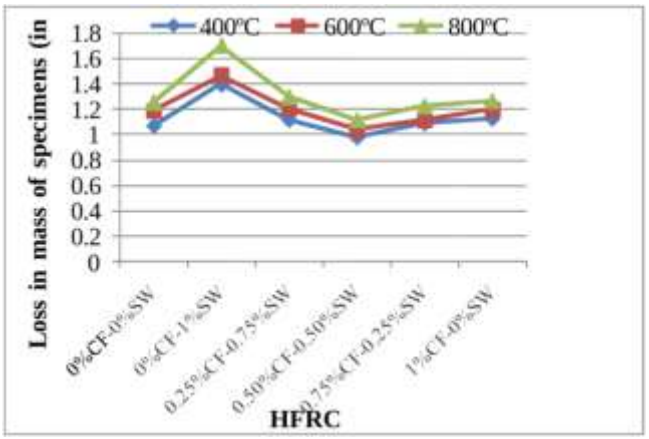



**Fig -7:** Mass loss of the hybrid mixes after exposure to 400, 600 and 800 °C

### *3.4 Heat transfer through the concrete*

Fig. 16 shows the core temperatures of the cubes when they were removed from the furnace. At all three exposure temperatures, the 0.50/0.50 HFRC core had a lower temperature (approx. 115–120 °C) than the plain M30 core, which indicates that the hybrid fibers delayed heat from penetrating the concrete specimen. Lower core temperatures of concrete are very important for PECCs since the infill acts as protection for the steel web.

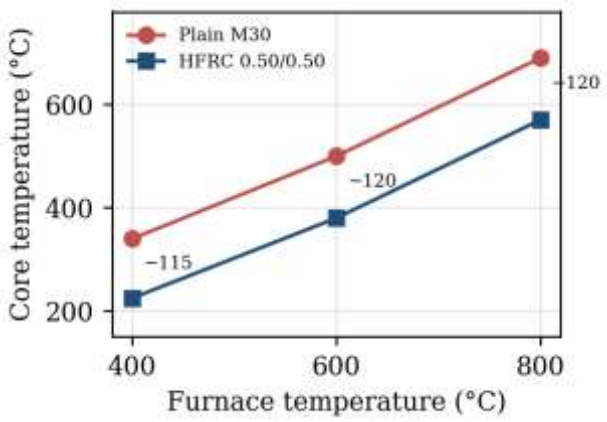



**Fig -8:** Approximate core temperature of plain M30 and HFRC 0.50/0.50 cubes immediately after removal from the furnace (read from charts)

### *3.5 Optimization results*

The desirability analysis gave an optimum single-fiber SW of aspect ratio 71.41 at 0.3% volume, in agreement with the best experimental mix (L/d = 70, 0.3%). For the hybrid series, 0.50% CF + 0.50% SW had the highest composite desirability, combining the best ambient strength with the best residual strength and lowest mass loss. This proportion was adopted for columns CC4 and CC5 and for the numerical study.

### *3.6 Axial compression of the columns*

Fig. 17 summarizes the results obtained from the column tests; the percentage increases for each test are presented relative to CC1. In addition to buckling after exceeding its elastic limit, the steel section of all five column specimens was found to separate from the concrete. The concrete also experienced crushing at the base of the columns when the maximum load was applied. As expected, the fiber-reinforced concrete had a significant effect on the column responses, primarily due to increased ductility and higher ultimate loads. Specifically, the ultimate loads of CC2 and CC3 were only increased by approximately 1% and 2%, respectively, however, their displacements at ultimate load were increased by 44% and 82%, respectively. The hybrid columns CC4 and CC5 had ultimate loads of 593.0 and 593.2 kN, respectively. Both hybrid columns had ultimate loads that were approximately 15% greater than that of CC1, and approximately 14% greater than that of the bare steel column (522.3 kN). Additionally, both hybrid columns experienced displacements that were approximately 135% greater than those experienced by CC1. Since the plain concrete column CC1 did not have a greater ultimate load than that of the bare steel column, it may be concluded that the additional strength provided by the hybrid columns is attributable to the inclusion of fibers within the concrete. This additional strength provided by the fibers is most likely attributed to the increased tensile strength of the fiber-reinforced concrete, along with the ability of the fibers to bridge cracks. It is possible that both types of fibers contributed to the increased strength, although this cannot be determined with certainty based upon the current testing program. The addition of shear connectors to CC5 did not contribute to any increase in the ultimate load of CC5, however, the shear connectors were effective in preventing the separation of the concrete from the steel section.

The load–displacement curves' elastic-limit loads that were read from the data, show that the elastic limits for the fiber column (276-402 kN) are less than the elastic limits for CC1 (407.9 kN). However, the fiber columns have higher ultimate loads than CC1. Therefore, the fiber columns deviate from linear behavior earlier than CC1, however, they can undergo larger amounts of deformation prior to failure (Fig. 18). It is important to note that the elastic limit is determined visually and can vary depending upon who determines it, and therefore the differences between CC1 and the fiber columns should be evaluated carefully and investigated further.

### *3.8 Numerical analysis*

ANSYS Model Validation: The ANSYS model successfully predicted the ultimate load carrying capacity (LCC) and general load vs displacement behavior of both the steel column sections and the composite columns. Additionally, the ANSYS model's predicted buckling mode was similar to what was observed during testing. Validation of Model for Transient Thermal Analysis: After being validated, the ANSYS model was employed to perform a transient thermal analysis on a PECC cross section filled with 50% fiber reinforced concrete (HFRC) and 50% plain concrete, subjected to the standard ISO 834 time-temperature curves. This analysis demonstrated a slower rate of thermal conduction through the composite infill material than would have occurred in a similar cross section that contained no fiber reinforcements. Additionally, the analysis indicated a time delay before temperatures reached the internal steel core. These findings support the lower measured core temperatures reported in Section 3.5. Numerical Assessment of Fire Resistance of Column: Only numerical analyses were performed to assess the fire resistance of the column. Therefore, experimental testing using full-scale furnace testing on loaded PECC columns is necessary to verify these results.

## 4. CONCLUSIONS

Steel wool (L/d = 70, 0.3%) and carbon fiber (0.6%) alone raised the 28-day compressive strength by 11.6% and 15.9%, but the hybrid of 0.50% CF + 0.50% SW performed best, giving about 19% higher strength, 18–58% higher residual strength after exposure to 400–800 °C, lower mass loss, and a core temperature 115–120 °C below that of plain M30. The PECC with hybrid infill carried 14.9% more load than the plain-concrete PECC and deformed about 135% more, while the ANSYS model matched the tests and showed slower heat transfer to the steel core. Load-bearing fire tests on PECCs are recommended as future work.

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