NUMERICAL INVESTIGATION OF CFRP RETROFITTED, QUARRY ROCK DUST, FLY ASH, AND SLAG BASED GEO POLYMER CONCRETE BEAMS

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Abstract- Geopolymers concrete (GPC) has gained popularity in the construction industry as a low-carbon, cement-free composite material with strong mechanical qualities that may be employed in various structural applications. In this paper, the behavior of simply supported geopolymer concrete beams employing symmetrical conditions is simulated using Abaqus (Finite Element Analysis) tool. A simplified version of the Concrete Damage Plasticity Model (CDP) is used as a nonlinear constitutive model. Using Abaqus (CAE), four geopolymer concrete beams were modeled with varying parameters depending on their compressive strength, and the experimental force-deflection curve. These beams were shear deficient and failed along the shear path experimentally, while the model followed the identical shear trajectory path in simulation. The same damaged beams were then strengthened by wrapping CFRP sheets around them and simulating the retrofitted beams using the ACI perfect bond condition method to validate the experimental force-deflection curve. The model has been validated against experimental load-deflection curves and shear trajectory failure paths for both controlled and CFRP-wrapped beams. The comparison of results from the experimental and numerical study suggests that the FEM is a good technique for the simulation and prediction of the elemental behavior under different loading conditions and restraints.

Keywords- Geopolymer, Concrete damage plasticity (CDP), Abaqus, sisal fibres, steel fibres, CFRP strips.

1 Introduction

In comparison to Ordinary Portland Cement (OPC) based construction materials, geopolymer concrete (GPC) has gained popularity in recent years due to its exceptional capacity to replace cement concrete and possessing improved mechanical and serviceability criteria. In terms of global warming, the GPC might reduce the CO_2 released into the atmosphere by the cement industry. Fly-ash (FA) and ground-granulated blast furnace slag (GGBS) are the industrial waste/by-products which are supplementary binding materials widely used for partial replacement of OPC due to their low cost and good binding or pozzolanic properties.

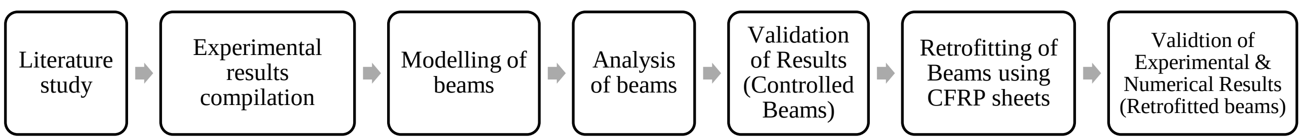
Develop a robust and efficient analytical/Numerical tools, such as the finite element method, by reducing the cost and time. The finite element approach can better simulate experimental conditions, including loads and deformation, as well as the support conditions of the actual test. Finite element analysis (FEA) is a significant tool in the study of fracture mechanics in elements. Linear elastic fracture mechanics (LEFM) has been well-studied, utilizing methods such as Damage for Traction Separation Laws (TSL) and Concrete Damaged Plasticity Model (CDP) [1]. Abaqus/CAE, or "Complete Abaqus Environment", is a three-dimensional finite element (FE) array with extensive modelling abilities that is mainly used as a research tool [2]. It offers a lot of commands for making different elements and a lot of material constitutive models for simulating the behavior of most common materials. Simulation with such models helps reduce the number of experimental tests required to determine an exact reaction of the materials.

As a result, any simulation research will save time, money, and exertion in the long run, especially when the material under consideration or the testing machine necessary is unavailable or demands a big budget. Because numerous tests have

already been performed, the tradition is shifting toward concentrating solely on the numerical model and avoiding any experimental testing. Only a few tests are required to identify constitutive model parameters in new materials [3]. To predict their behavior, it is necessary to have a detailed knowledge of the flexural behavior of building materials. The four-point or centre-point loading method can be used to examine this property. As the test progresses, it's hard to identify the crack spreading and load distribution [4]. Abaqus is a Finite Element Analysis (FEA) tool that helps in computer drawing, mechanical component analysis, and visualization of FEA results. Modelling features, processing options, and post-processing animation display options are all included in Abaqus, allowing users to simulate, and forecast the behavior of their complex product. This feature helps determine load-deflection behavior, cracking patterns, and stress-strain curves.
In this research work, a numerical investigation on geopolymer concrete beams has been carried out under four-point loading considering symmetrical conditions to minimize the analysis time and reduce the complexities in the model to make it easy to run [5-6]. The load deflection curve and shear failure trajectory results have been validated very well against the experimental test for both the controlled and retrofitted (wrapped by CFRP sheets) beams.

2 Methodology

The methodology for this study includes the modelling and analysis of the geopolymer concrete beams by using the finite element tool ABAQUS to perform. By using FEA Technique to reduce the analysis time and complexities of the model during analysis, Quarter symmetrical beams were modelled to run the analysis fast and smoothly. The Model beams then analyzed and validated the results with the experimental load-deformation curves. In total, eight beams were modeled (Table 1) in which four were analyzed under displacement-based loading, then these beams were retrofitted with CFRP sheets and analyzed again, simulated the beams, and validated with the experimental results. Different equations were used as per literature for the properties of these beams to input for the analysis as mentioned below.



3 Modelling and Analysis

3.1 Geometry modelling (Undamaged Beams)

Experimentally the dimensions of the beam were 1000 mm length x 150 mm depth x 150 mm width, while the beams for simulation were modelled as quarter symmetrical beams (dimensions 500 mm length x 150 mm depth x 75 mm width) & conditions to reduce the analysis time and minimize the complexities. Concrete is modelled as a 3D 8-Node solid brick homogenous element with reduced integration (C3D8R), while the steel bars (compression, tension & stirrups) have been modelled as a 2D truss element (T3D2) as shown in (Figure 1a, b). In the assembly part, the rebars are combined and embedded in the concrete beam by using the embedded region property. The beam has been restrained at the bottom by applying the support conditions, while at the sides of the beams symmetrical boundary condition has been applied. Displacement-based analysis was performed by applying the displacement to the experimental tests (load vs displacement) for all four beams. Meshing for the concrete beam and steel rebars was assigned in 25 mm and 15 mm, respectively. Four beams were modelled with the same geometry, but different compressive strength and different material properties input analyzed under displacement.

3.2 Geometry Modelling Retrofitted beams (wrapped by CFRP sheets)

The beams were modeled and analyzed under displacement control by obtaining the force-deflection curve, the beams failed in the shear path. These beams were then strengthened by wrapping the CFRP sheets. The CFRP sheets were modeled by deformable solid homogenous element as shown in (Figure 1c, d) having properties shown in (Table 2). Tie constraints were used between the beam and CFRP sheets & wrapping by considering perfect bonding between the sheet and concrete beam by following ACI perfect bond condition [7]. No debonding was considered between the CFRP and concrete beams.

Table 1 Modeled Beams Ids

Controlled Modeled Beams Ids	**Retrofitted (CFRP) Modeled Beams Ids**
GPC beam	Retrofitted (CFRP) GPC beam
0.75SF-R-GPC Beam	Retrofitted (CFRP) 0.75SF-R-GPC Beam
0.5SF+1SsF-GPC beam	Retrofitted (CFRP) 0.5SF+1SsF-GPC beam
2.4SsF-GPC Beam	Retrofitted (CFRP) 2.4SsF-GPC Beam

3.3 Beam properties

As for the geopolymer concrete (elemental study), some of the researchers [1], [2] suggest equations for the constitutive model for the CPD input parameters, the elasticity of the beam, density, and Poisson's ratio. These properties are a little bit different from the ordinary Portland cement concrete.

3.4 Constitutive model

The concrete damage parameters are used by default [10-11]

$$\sigma c = fcm\left({}^{\varepsilon c}/_{\varepsilon p}\right)\frac{n}{n-1+(\varepsilon c/\varepsilon p)^{nk}}\ (\text{MPa})\ \ [8–9] \quad (1)$$

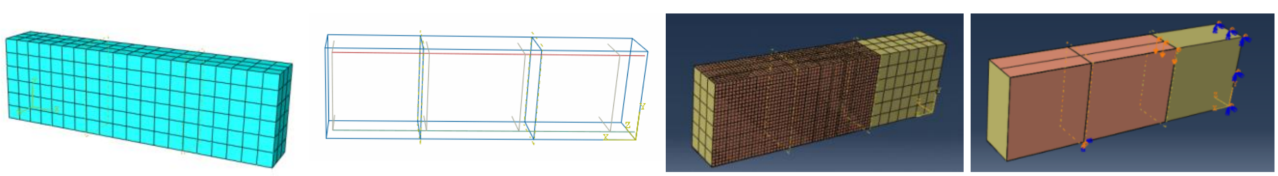
Where,

fc' = Peak / Maximum stress; εcp = Strain at peak / maximum stress, n = 0.8 + (fc'/17); k = 0.67 + (fcm /62) when εc /εcp >1 = 1.0 when εc /εcp ≤ 1.

For Steel Fiber Reinforced Concrete [5]: $n=\beta= 1.093 + 7.4818(3Vf\ \frac{lf}{df})^{-1.387}$; Vf = Steel fibre fraction in Volume; lf and df = length and diameter of the fibre, respectively; and η = Orientation factor of fibre which is taken as 0.5.

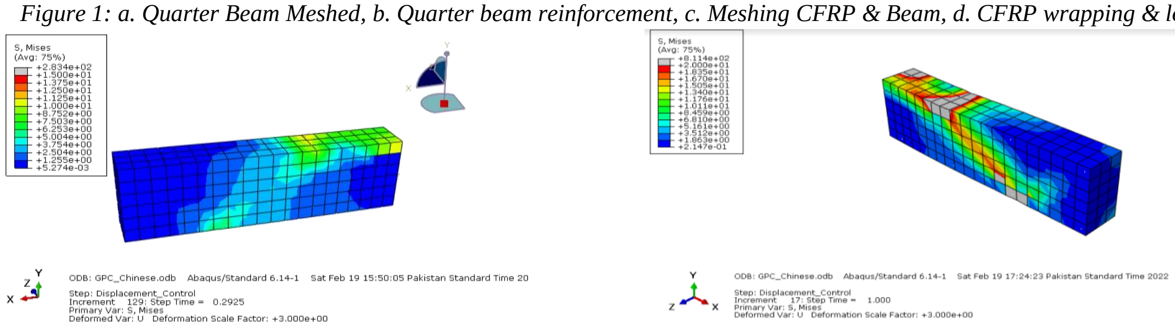
Modulus of Elasticity, $EcC_{GPC} = 4907.5\sqrt{fc'}$ [1]; Peak strain $\varepsilon = 1.65 \times 10^{-5}\ fcm + 0.00168$; Tensile Strength $= 0.7\sqrt{fc'}$ [7]; Cracking Strain, $\varepsilon_{cr} = 0.000065 f_{ct}^{0.54}$ [7]

For Steel Fiber Reinforced-GPC beams: $E_{cf\,(GPC)} = 21500 \times (\frac{fc'}{10})^{1/3}$ [8]; Tensile Strength $f_t' = 0.6\,\eta(fc')^{2/3}\,Vf\,\frac{lf}{df}$ [9]



a) b) c) d)

Figure 1: a. Quarter Beam Meshed, b. Quarter beam reinforcement, c. Meshing CFRP & Beam, d. CFRP wrapping & loading



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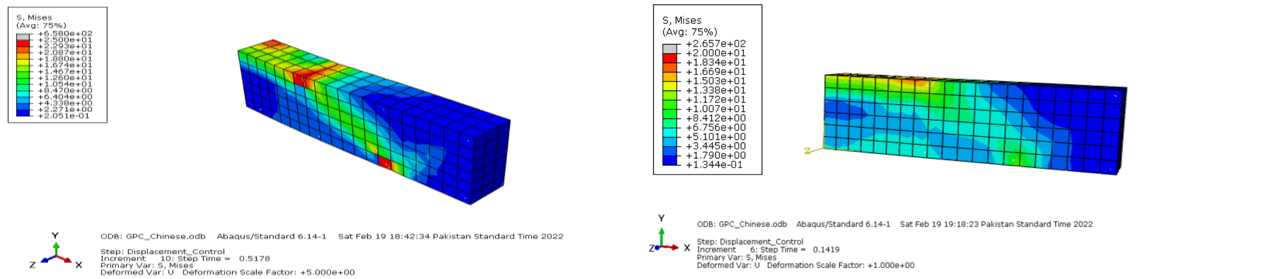
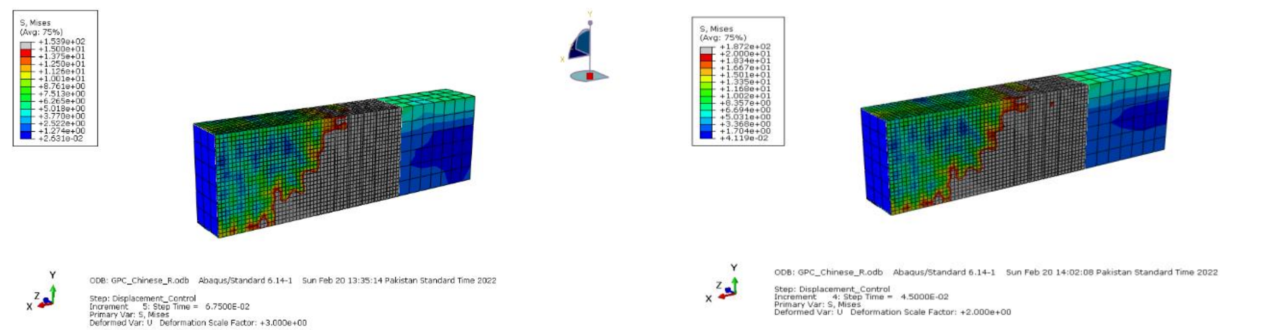


c) d)

Figure 2: a. GPC Beam stresses, b. 0.75SF-GPC Beam Stresses, c. 0.5SF+1SsF-GPC Stresses, d. 2.4SsF-GPC beam Stresses



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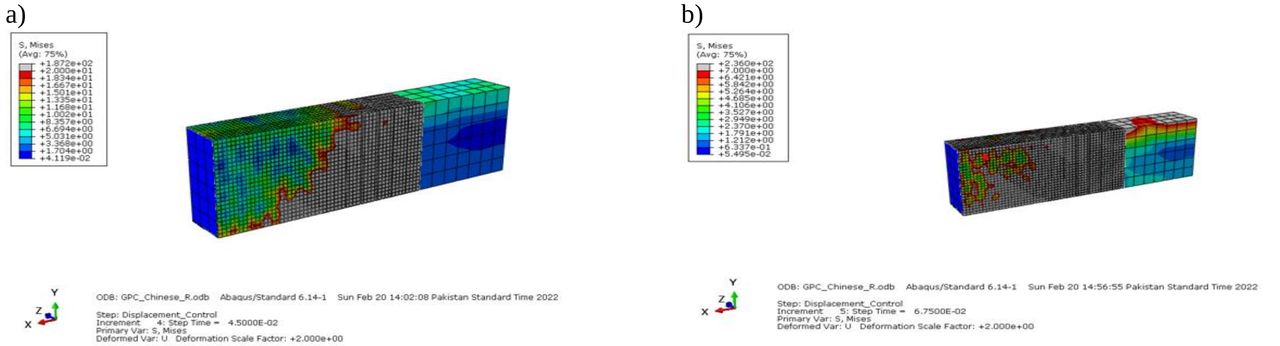


c) d)

Figure 3: a. Retrofitted GPC Beam stresses, b. 0.75SF-GPC Retrofitted Beam Stresses, c. 0.5SF+1SsF-Retrofited-GPC Stresses, d. 2.4SsF-Retrofited-GPC beam Stresses

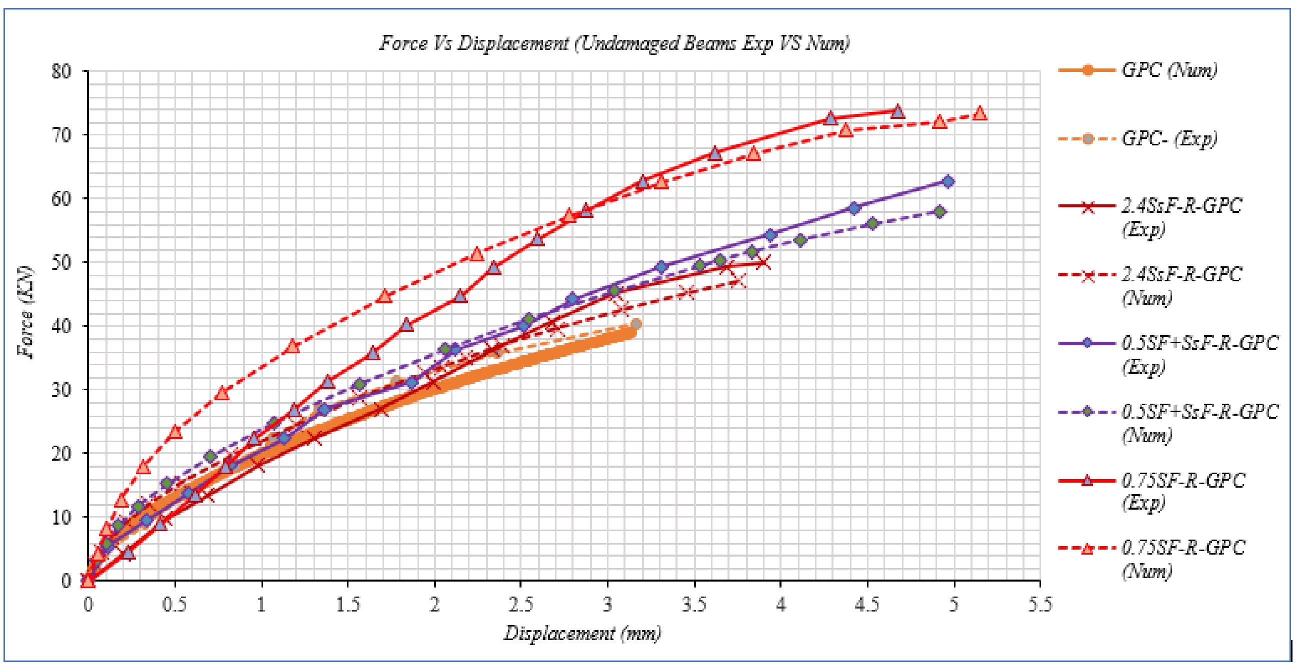
Table 2 CFRP Properties

Material	**Width (mm)**	**Thickness (mm)**	**Elastic Modulus (GPA)**	**Tensile Strength (MPA)**	**Elongation at break %**
CFRP Strip (S812)	80	1.2	165	3100	1.69
CFRP wrap (230C)	300	0.129	225	3500	1.59

4 Results and Discussion

The shear deficient beams were analyzed as a displacement-based & validate the numerical results with the experimental results for the four controlled & Retrofitted beams as the results shown in (Figure 4). The peak load and displacement were found to differ by less than 10 % as shown in (Table 3) when comparing experimental and numerical results, indicating a good agreement and validated results at the bottom of the beam and simulated for results. The predicted deflections were adequately close to the experimental results as by percentage difference less than 10% as observed by other researchers [10]. All the beams failed by the formation of diagonal cracks. Most stresses were produced near to the supports and no tensile splitting was noticed along with the main reinforcement. The shear failure occurred in the concrete due to its brittle nature. The load carrying capacity reached to the ultimate limits after which sudden failure was occurred. As in the (Figure 2, Figure 3) it can be noted that most of the stresses are in the shear path, which also indicates that the beams were shear deficient as simulated numerically.

The plain GPC beam exhibit a displacement of 3.16 mm at a load of 40.4 kN. 0.75SF-R-GPC exhibit more displacement of 5.15 mm at a load of 73.3 kN because of the inclusion of steel fibers in the beam, which interlocks the bond between the concrete and itself and gives more strength to the beam in the flexural behavior. The beam with the addition of Sisal fiber (SsF) and steel fiber (SF), gives a displacement of 4.9 mm at a load of 58.1 kN, and the beam having only Sisal fiber which exhibits a displacement of 3.75 mm at a load of 47.1 kN.
The shear failed beams were wrapped by CFRP sheet at the shear failure location and CFRP strips were adhered at the bottom to strengthen and check the displacement of the numerical model against the experimental results. The damaged beams CAE stresses and the damaged conditions were imported for the CFRP lamination analysis. The damaged beams were strengthened by wrapping CFRP sheets at the shear failure zone which enhanced the load-carrying capacity of the beams. CFRP sheets were modelled using linear elastic behavior by considering a perfect bond between concrete beams and CFRP sheets. CFRP sheets were modelled in such a way that no debonding occurs as per ACI 440.1R-15[11]–[13]. The strengthened beams have a steeper load-deflection curve and higher load-bearing capacity due to enhanced stiffness provided by the CFRP strengthening system. The CFRP sheets enhanced the load-carrying capacity of beams by 28.8 %, 20.40 %, 38.4 % & 39.0 % in the numerical model compared to the non-retrofitted model as observed by[14] Abdelrahman Mabrouk.



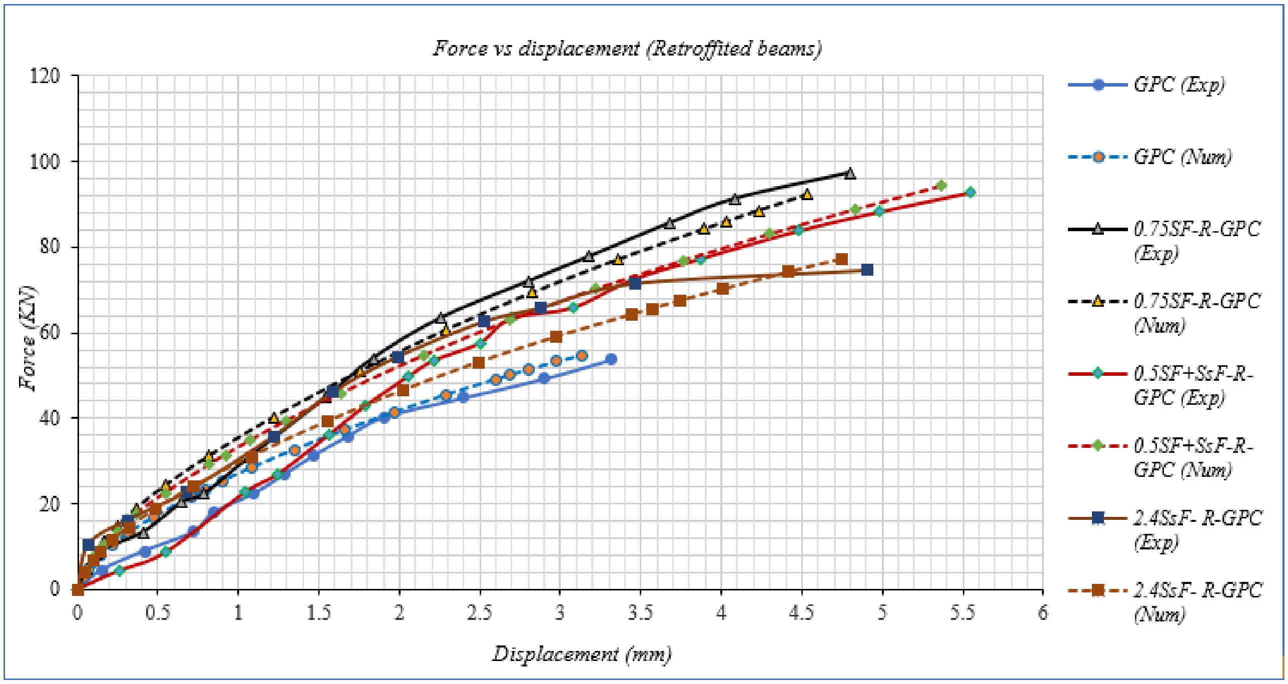


Figure 4: Load Vs Displacement (Controlled & Retrofitted Beams)

Table 3 Comparison between Experimental & Numerical results

		Controlled Beams		Retrofitted Beams	
Exp / Num	**Specimen**	**Load (KN)**	**Displacement (mm)**	**Load (KN)**	**Displacement (mm)**
Exp	GPC	40.465	3.17	53.76	3.32
Num		39.032	3.14	54.821	3.13
% Difference		3.67 %	0.98 %	1.94 %	5.91 %
Exp	0.75SF-R-GPC	73.872	4.678	97.429	4.797
Num		73.444	5.152	92.262	4.532
% Difference		0.58 %	9.20 %	5.60 %	5.83 %
Exp	0.5SF+SsF-R-GPC	62.791	4.96	92.779	5.545
Num		58.106	4.9164	94.408	5.364
% Difference		7.46 %	0.88 %	1.76 %	3.26 %
Exp	2.4SsF- R-GPC	50.023	3.900	74.679	4.903
Num		47.115	3.752	77.253	4.748
% Difference		5.81 %	3.788 %	3.45 %	3.17 %

5 Conclusion

1. The peak load and displacement were found to differ by less than 10 % as shown in when comparing experimental and numerical results, indicating a good agreement and validated results.
2. The CFRP sheets enhanced the load-carrying capacity of beams by 28.8 %, 20.40 %, 38.4 % & 39.0 % in the numerical model compared to the non-retrofitted model.
3. As the load increases on the beam, more stresses are generated in the concrete beams, which are transferred to the CFRP sheets that delay the beams' failure.
4. The comparison of results from the experimental and numerical study suggests that the FEM is a good technique for the simulation and prediction of the elemental behavior under different loading conditions and restraints.

5. The simulated results for all the beams are in good agreement to the experimental results. In some of the experimental curves, like in the retrofitted beam, there noted some humps in the curve; this may be due to the experimental errors, while in simulation, smooth curves are obtained.
6. As the beam 0.75SF-R-GPC beam shows a higher load capacity similar to in experimental, the inclusion of the steel fiber up to some extent increases their load-carrying capacity and does not let the crack propagate easily.
7. As in this study the numerical approach shows a good validation with experimental results also the finite element model is a time and money saving as compared to experimental testing/casting of concrete elements.
8. The Finite element model can be further used for more parametric studies and the shear deficiency in the beams may be excluded by confining the shear reinforcement at both end of beams.

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