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Investigation on the performance of reinforced concrete columns jacketed by conventional concrete and geopolymer concrete

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ABSTRACT

The objective of this investigation is to experimentally study the behaviour of reinforced concrete (RC) columns strengthened using RC and geopolymer concrete (GPC) jacketing by subjecting them to axial loading. The experimental results were analytically validated by the finite element model (FEM). For this investigation, six columns of M25-grade conventional concrete were subjected to more than 75% of the ultimate load. Then three columns were jacketed by using M40-grade RC and another three columns were jacketed by using M40-grade GPC. The interfacial behaviour of the conventional RC column and jacketed GPC columns was studied and compared. The 3D linear and FEM was employed to measure the effect of conventional RC and GPC-jacketed columns under increasing load by considering the concrete damage plasticity (CDP) and elastoplastic models with isotropic hardening. The validation against the experimental results confirmed 90% accuracy of the analytical model.

1. Introduction

Reinforced concrete structures undergo deterioration in a variety of ways due to wetting and drying cycles, freezing and thawing cycles, corrosion, chloride attack, tidal zones and other physical/-chemical causes. Therefore, there is a need to improvise the existing structures to meet the precise design requirements. Structural repair and strengthening of the structures have received worldwide attention [1,2]. Depending upon the type of distress, the techniques applied for the repair of damaged structures vary [3]. Some of the methods extensively used for strengthening of reinforced cement concrete (RCC) structures are patch repair, shotcrete, internal or external prestressing, jacketing by concrete and steel and externally bonded fibre-reinforced plastic (FRP) reinforcement [4].

Maintenance and repair work is estimated to account for about 85 % of the total expenditure in construction worldwide and there is always an increased need for upgrading the existing infrastructure to meet stern design necessities. Therefore, structural repair and strengthening have received considerable attention from researchers [5]. The premature deterioration of reinforced concrete structural members leads to the most critical problems in civil infrastructure. Reinforced concrete elements require repairs or strengthening when service loading causes excessive deflections and cracking. There is a necessity to enhance the service life of the RC element and incorporate the changes of design parameters to satisfy the stringent limits on serviceability and ultimate strength in accordance with the current codes. The replacement of such deficient structural members requires a huge amount of materials produced from natural resources, which is not environmentally feasible. Also, buildings of historical importance need to be preserved. In these cases, it becomes essential to strengthen the existing structural member depending on the type of construction and the condition of damage [6].

Concrete jacketing is a method for retrofitting or rehabilitation of RC structures damaged seismically or due to poor construction. In this method, a concrete and steel reinforcement is added to an existing column or beam [7]. Depending on the location and environmental conditions, suitable materials should be chosen for retrofitting to ensure the lasting performance of the structure after repair. Therefore, material selection and jacketing design play a major role [8].

The need for new materials with enhanced properties, which can provide higher performance, is imperative now than ever before in construction. The materials used to produce concrete structures should have four distinctive properties such as strength, workability, durability and affordability. To address the problem of the rapid deterioration of infrastructure and massive utilisation of

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construction materials (that consume natural resources), alternate materials have emerged, which include self-compacting concrete, engineered cementitious composite, fibre-reinforced concrete, reactive powder concrete, lightweight concrete, high-ductile fibre-reinforced concrete, geopolymer concrete and ultrahigh-performance fibre-reinforced concrete [3]. Concrete is the most ubiquitous material used for construction worldwide. It is a heterogeneous mixture consisting of cement, water, aggregate and air. Concrete consumption has been estimated to be one meter cube per person per year [9]. The manufacture of ordinary Portland cement (OPC) is known to cause heavy CO_2 emission [10]. So, environmentally friendly alternatives are being explored. One alternative is the substitution of OPC by a geopolymer concrete (GPC), which is produced from fly ash (a fine powder waste taken from the emissions of coal-burning power stations) and ground-granulated blast furnace slag (GGBS) (a powder waste product of iron and steel-making that is activated by an alkaline activator or reaction-generating liquid). This binder lowers carbon emissions when compared to OPC concrete [11]. It was noted that GPC possesses very high strengths and does not require conventional water curing like the Portland cement-based conventional concretes. GPC can set and harden at room temperature and can gain reasonable strength within a short period [12]. GPC thus led to the development of cost-effective, environmental friendly and innovative material for construction. This sustainable construction material has been used in a large number of applications, thereby contributing to an improved quality of life for humankind.

The advantage of strengthening a structure using RC jacketing over the steel bracing method is the uniform distribution of increased strength and stiffness of the column, in addition to fortification against corrosion and fire. Also, this strengthening technique does not require any specialist skills. All these factors make RC jacketing a tremendously valued choice in structural rehabilitation [13]. The rehabilitation of the deteriorated RC column is increasing due to the need for maintenance and severe exposure conditions. Hence the studies related to rehabilitation need to be undertaken to circumvent the social costs related to the demolition and reconstruction of new structures. As of now, there is no clarity on the interface behaviour of concrete jacketing. The high-performance materials such as ECC, FRP and UHPC in the applications of retrofitting of bridge columns [14], RC columns under cyclic loading [15], jacketing of RC columns using ECC [16], repairing of RC columns using FRC [17], strengthening of RC columns using high-performance FRC [18] and RC columns using CFRP [19] are widely employed in construction. The novelty of the present work is the analysis of the jacketing of low-grade RC column with high-grade concrete and GPC concrete using an analytical model based on FEA software and comparing the output with experimental test results.

2. Experimental studies

2.1. Materials

Ordinary Portland cement conforming to BIS: 8112–1989 was used in this investigation [20]. Manufacturing sand was used as the fine aggregate and satisfied the requirement for grading zone II of BIS: 383–1970. Its specific gravity and fineness modulus values were 2.64 and 2.7, respectively [21]. Locally available gravel less than 10 mm in size for the M40 mix and 20 mm in size for the M25 mix were used as the coarse aggregate. Its specific gravity was 2.75 and fineness modulus was 6.87 [21]. Conplast SP430 is a chloride-free, super plasticising admixture prepared from selected sulphonated naphthalene polymers. It is a brown solution that instantly disperses in water [22]. While reinforcing steel of 8 mm diameter was used as stirrups, the reinforcing steel of 12 mm diameter was used as the main reinforcement. Table 1 shows the mechanical properties of the reinforced steel. For geopolymer concrete, reaction-generating liquid is required for initiating chemical reactions in GSM and it consists of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate solution (SSS) or potassium silicate solution (PSS). SSS/PSS are available in different molar ratios whose chemical natures vary widely based on geopolymerisation considerations. In this study, the adopted molar ratio of SSS was 2.

2.2. Test specimen and mix design

Six identical scaled RC short columns prepared using M25 concrete ratio with a cross-section of 180 mm × 180 mm and a height of 1500 mm were cast and designed as per BIS 456:2000. The six columns (C1, C2, C3, C4, C5 and C6) were artificially weakened by subjecting them to more than 75 % of the ultimate load. Out of the six specimens, three (C1, C2 and C3) were jacketed conventionally (cement concrete) and the other three (C4, C5 and C6) were jacketed with GPC using eight numbers of 12 mm diameter rebars confined with 8 mm diameter rebar links. The jacketing of these six columns was carried out using M40 grade conventional concrete for C1, C2 and C3 and geopolymer concrete for C4, C5 and C6 mixes. The mix proportion of M25 and M40 concretes are tabulated in Table 2 [23]. The mix proportion for M40 grade GPC concrete is shown in Table 3.

2.3. Compressive strength test

The test for compressive strength of concrete was performed on standard cubic specimens of 100 × 100 × 100 mm dimensions after curing for 3, 7 and 28 days according to BIS 516:1959 [24]. Using an universal testing machine of 1000 kN capacity, the concrete cubes were placed precisely in the centre of the spherically seated upper block of the loading head and the compressive load was applied with displacement controlled rate of 0.5 mm/min until the specimen failed. The values were documented, and the compressive strength was calculated. The results are given in Table 5. While comparing the compressive strength of the conventional M40 mix and the GPC M40 mix, the GPC M40 concrete cubes were found to have a better strength as can be observed from the data provided in Table 4.

In order to find the modulus of elasticity, the cylinder specimens were tested using a universal testing machine of.

1000 kN capacity with speed displacement of 0.5 mm/min as shown in Fig. 1. The cross-section of the concrete cylinder used was 100 mm in diameter and 200 mm in height. The concrete cylinders were placed precisely at the upper block of loading head and the compression load was applied until the specimen failed. The values were recorded, and the modulus of elasticity was calculated. The values are provided in Table 5. Fig. 2 shows the stress–strain graph of different grades of concrete.

Table 1
Mechanical properties of reinforcing steel.

Diameter (mm)	Yield stress, f_y (MPa)	Yield strain (ε_y)	Elastic modulus, E (MPa)
8	525	0.0024	210,060
12	540	0.0024	210,060

Table 2
Mix Proportion for M25 and M40 Concrete.

Description	M25	M40 (CC)
Cement	320	420
Fine Aggregate (kg/m^3)	910	750
Coarse Aggregate (kg/m^3)	1050	1055
Water (kg/m^3)	165	160
W/C ratio	0.45	0.4
Admixture (litre/m^3)	–	2.2

Table 3
Mix Proportion for GPC M40 Concrete.

Description	M40 (GPC)
GGBS (kg/m^3)	246.54
Fly Ash (kg/m^3)	238.59
Fine Aggregate (kg/m^3)	741.02
Coarse Aggregate (kg/m^3)	801.30
RGL (kg/m^3)	225.47
W/C ratio	0.46
Admixture (litre/m^3)	–

Table 4
Compressive Strength results of Concrete Cube Specimens.

Compressive Strength (MPa)	3 days	7 days	28 days
M25	10.2	22.3	29.2
M40 (CC)	26.8	32.3	46.4
M40 (GPC)	30.5	42.4	50.1

Table 5
Test results on concrete cylinder.

Properties	M25	M40 (CC)	M40 (GPC)
Modulus of elasticity (GPa)	12	18	20
Poisson's ratio	0.20	0.22	0.22

Fig. 1. Compression test on concrete cylinder.

2.4. Testing setup and instrumentation

The details of the column dimensions for analysis are given in Fig. 3. The cross-section of the jacket is 280 × 280 mm and its height 1500 mm. The thickness of the jacket is scaled down to 50 mm as per BIS 15988:2013. A minimum spacing of 100 mm was provided [25].

The RC column specimens were tested using an axial loading frame. The deflection along the x, y and z directions was recorded using deflectometers. All the RC columns were loaded under a concentric axial load. Steel caps are provided at the top and bottom of RC Columns during loading to avoid the crushing failure of columns at the end supports. The bottom portion of the column was considered to be fixed and the top portion was kept free [26]. The load was applied on the top surface of RC column with due consideration to the kern point as shown in Fig. 4. The formula

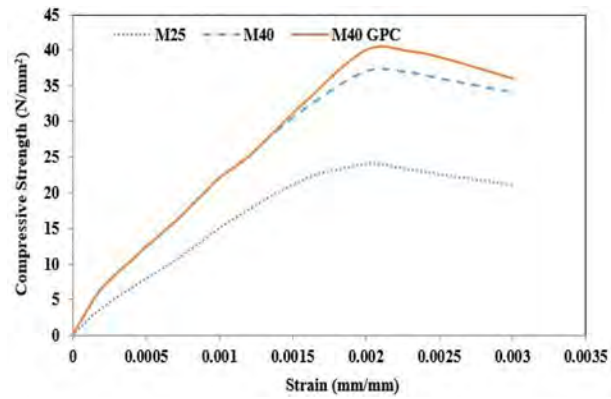

Fig. 2. Stress–strain plot for different grades of concrete.

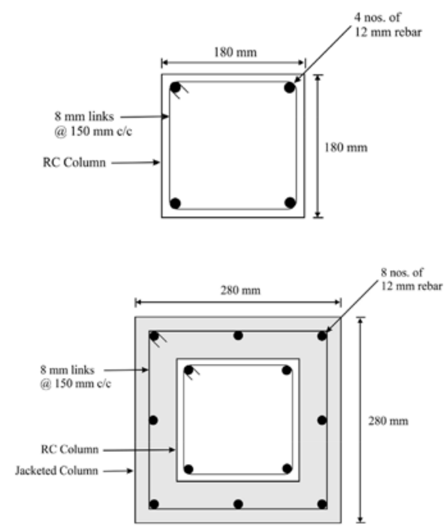

Fig. 3. Reinforcement detailing of non-jacketed and jacketed columns.

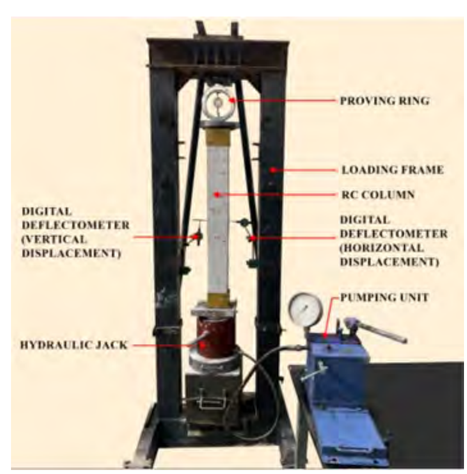

Fig. 4. Laboratory test setup.

for calculation of the axial bearing capacity of the jacketed columns is.

$$Pu = 0.4 f_{ck}A_c + 0.67 f_y A_{sc} \quad (1)$$

2.5. Repair and strengthening by concrete jacketing

Jacketing is the addition of concrete and steel reinforcement in both longitudinal and transverse directions to an existing column. Concrete jacketing is done to strengthen the damaged or poorly detailed RC columns. The repair method consists of first removing the concrete from the distressed zone by hand chipping, jack hammering or electric hammering. The column is then anchored with additional longitudinal reinforcement while maintaining adequate spacing as shown in Fig. 5.

The section to be repaired is then modified with suitable form work for pouring the repair concrete. It is to be noted that the concrete used for jacketing should have a maximum aggregate size of about 2–10 mm because of the volume occupied by the added steel reinforcement. A better interface bond is provided between the column and jacket shear keys at equal intervals as shown in Fig. 6. Based on the literature, an additional layer is provided over the core column to avoid the shrinkage of new RC jacket [27].

3. Analytical investigation

3.1. Material properties

The low-grade column is made of M25 grade concrete with a modulus of elasticity (E) of 12 GPa and a Poisson's ratio ($1/m$) of 0.2. The longitudinal reinforcements and stirrups are made of Fe500 grade concrete with E = 200,000 MPa and $1/m$ = 0.3. The high-grade concrete jacket is produced using M40 grade concrete with E = 20 GPa and $1/m$ = 0.22 [28]. The concrete damaged plasticity (CDP) model of concrete is used for demonstrating the non-linear retort of the mortar. It shows the combined effect of damaged elasticity by isotropic tensile and compressive plasticity [29]. This prototypical model is done based on a hypothesis of the two failures such as tensile cracking and compressive crushing. As per the linear response of concrete, E = 24 GPa and V = 0.2 is used. For generating accuracy, the retort of concrete needs damage constraints and tensile and compressive stresses are considered. The CDP prototypical model uses the yield function projected by Lubliner et al. (1989) and change by Lee and Fenves (1998) to interpret the diverse retort of concrete for tension and compression [30,31]. Also, it adopts a non-linked flow rule based on Drucker–Prager hyperbolic function [32]. Thus, a five-parameter model can be generated:

Fig. 5. Strengthening with steel reinforcement.

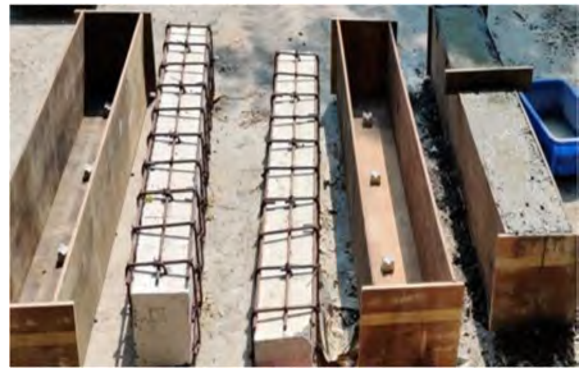

Fig. 6. Concrete jacketing process in columns with wooden moulds.

- A measure of angle in a meridian plane, between hydrostatic axis and yield function, known as dilation angle is taken as 38° [33].
- A small positive constant that explains the rate at which the hyperbole potential function approaches its asymptote known as eccentricity is taken as 0.1 [34].
- The ratio of mortar strength in biaxial state to uniaxial state (rb_0/rc_0) is considered. In 1973, Kupfer, from the experimental results, defined the default value of this ratio in ABAQUS user's guide to be rb_0/rc_0 = 1.16 [32].
- The ratio of the distance between the hydrostatic axis, the compressive meridian and the tensile meridian in a deviatoric cross plane is known as K_C, which is taken as a default value of 0.667 [34];
- The introduction of viscosity regularisation shows correction in the consecutive laws to increase the rate of convergence [32].

3.2. Geometry and boundary conditions

The design of the reinforced square column conforms to BIS 456:2000, where the column height is 1500 mm and cross-section is 180 mm × 180 mm. The main reinforcement of four numbers of the RC column with 12 mm diameter steel rebars and transverse reinforcement with 8 mm diameter steel rebars with a 150 mm centre-to-centre spacing is provided as shown in Figs. 7 and 8. The RC column used in this investigation is designed as a short column.

The design of reinforced concrete column jacketing conforms to BIS 15988:2013. The height is same as the inner reinforced concrete column (1500 mm) and its cross-section is

Fig. 7. Model Figure.

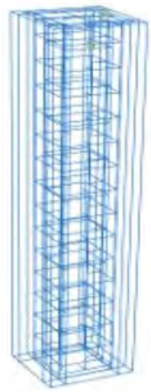

Fig. 8. Reinforcement Details in Model.

280 mm × 280 mm. The main reinforcement is done with eight numbers of steel rebars of 12 mm diameter. The minimum diameter of lateral tie must be 8 mm and not less than one-third of the longitudinal bar diameter. The spacing of the tie is provided as per BIS 15988:2013, To circumvent the flexural-shear failure of the column and its confinement to the longitudinal steel along the jacket, spacing is defined by the following equation:

$$\mathrm{S} = \frac{\left(\boldsymbol{F_y}\mathbf{xDh}^2\right)}{\left(\sqrt{\boldsymbol{F_{ck}} * \boldsymbol{t_j}}\right)} = 50.59\ \mathrm{mm}$$

Hence an 8 mm diameter tie bar with 55 mm centre-to centre spacing is provided. However, as per IS15988:2013, a minimum of 12 mm diameter bar and 8 mm diameter tie bar with 150 mm centre-to-centre spacing should be provided with 135° bends and 10 diameter length [25,35]. The thickness of strengthening layer used was 50 mm. The column length was 1500 mm while the concrete strength was 40 MPa and the reinforcement ratio of the strengthening layer was 1.96 %. The boundary conditions of RC column and RC jacketing column were to be hinged at the base and unrestricted at the topmost.

3.3. Interaction

Embedded element technique was used for the interaction between mortar and steel reinforcement by assuming a perfect adhesion between them [32]. The interface behaviour was defined between the M25 grade reinforced concrete column and M40 grade of conventional concrete jacket and GPC jacket using constant values for coefficient of friction as 1.55 [36] as shown in Fig. 9.

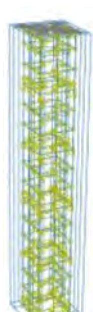

Fig. 9. Interaction.

Fig. 10. Meshing.

Fig. 11. End Conditions.

3.4. Elements and mesh size

The basic FEM analysis of low-grade RC columns with high-grade RC jackets primarily comprises low-grade internal column, external high-grade RC jacket and GPC jacket, and boundary conditions. These parts of the model were demonstrated by 3D eight-node continuum element. It also includes reduced hourglass control and integration point. Based on ABAQUS theory user guide manual, the 3D eight-node continuum element at each node encompasses a single integration point and three translation degrees of freedom [37]. A mesh convergence study was carried out to select a finest mesh size, which was chosen as 25 mm for the reinforced concrete column, 2 mm for reinforcements, 25 mm for jacketing and 2 mm for jacketing reinforcement as shown in Fig. 10.

3.5. Loading

The column is modelled as unrestricted at the top end and fixed at the bottom end. In this analysis, axial loading by equivalent uniaxial moment has been applied on the column by adapting it to an equivalent pressure as shown in Fig. 11 [28].

4. Results and discussion

4.1. Initial test on the RC column

The service load on the column was designed to be 430 kN as per BIS 456:2000. First, 75 % of the service load (322.5 kN) was applied on the RC column and afterwards the ultimate load of 429 kN was applied [4,38]. Fig. 12 shows the failure patterns of the RC column while testing.

Fig. 12. Failures of RC column after 75% loading.

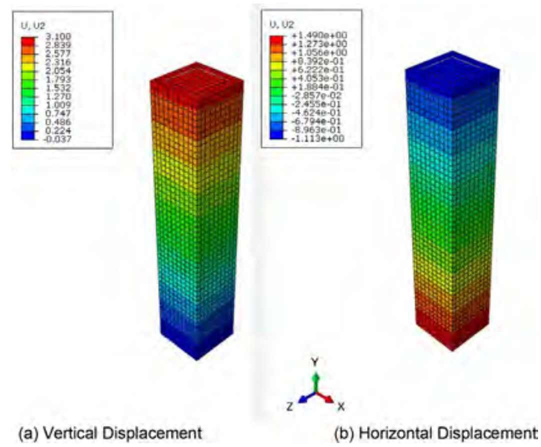

Fig. 15. Displacement of loaded RC-jacketed columns.

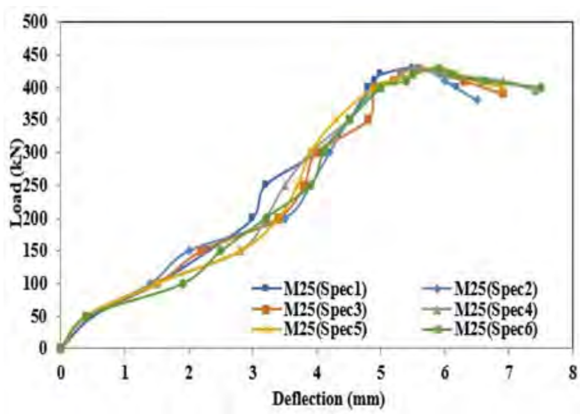

Fig. 13. Load vs deflection graph of RC column after loading.

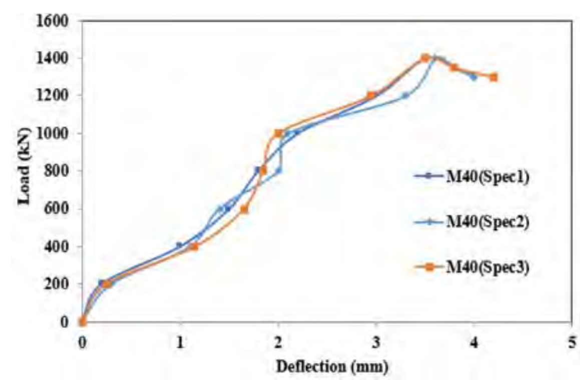

Fig. 16. Load vs deflection graph RC-jacketed columns.

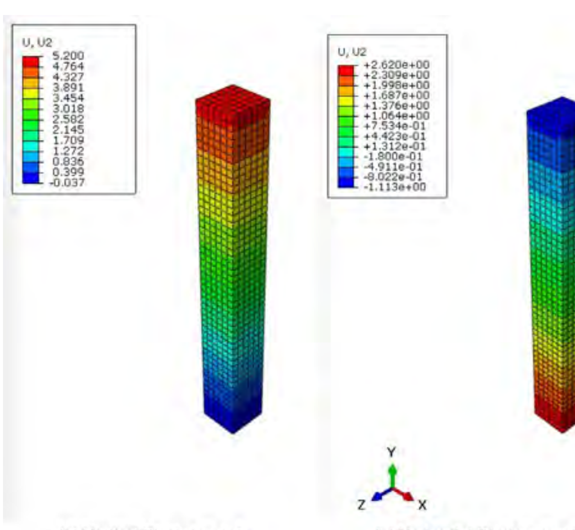

Fig. 14. Vertical Displacement of loaded RC columns.

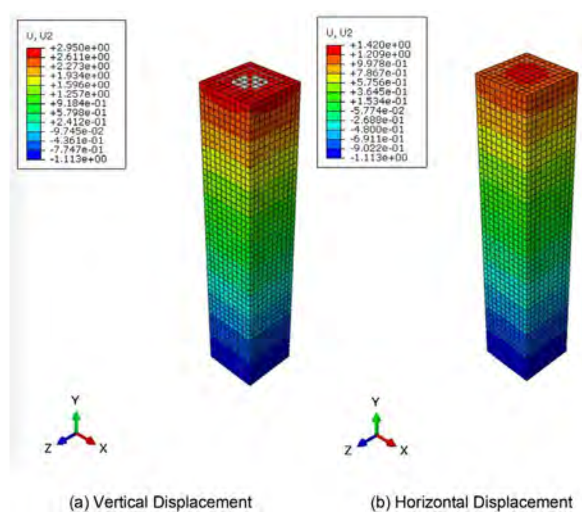

Fig. 17. Displacement of loaded GPC-jacketed columns.

The load versus deflection graphs of six columns (C1,C2,C3,C4, C5 and C6) after testing are plotted as shown in Fig. 13. The six tested RC columns show a deflection after an application of 75 % of the ultimate load as shown in Fig. 13 and the maximum vertical and horizontal displacement in RC Column using FEM is shown in Fig. 14a and 14b respectively. Thus, it leads to a conclusion that the analytical and experimental graphs are showing 90 % similarities similar to the results of Pavlo Krainskyi et al. (2019) [39] and Behrooz Dadmand et al. (2022) [40].

As per the analytical results, the RC column has a maximum reaction force of 412 kN, a maximum displacement of 5.55 mm and the corresponding stiffness is 74.23 N/mm.

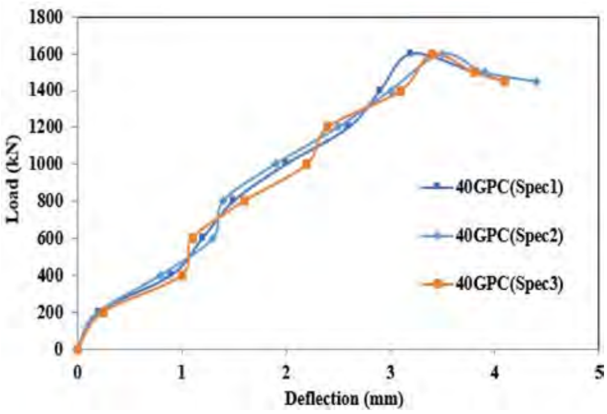

Fig. 18. Load vs deflection graph GPC-jacketed columns.

4.2. Final test on RC and GPC-Jacketed columns

The six tested RC columns were jacketed based on the design procedure for reinforced concrete column jacketing as per BIS 15988:2013 as mentioned in Section 3.2. The six columns were divided into two sets of three columns. The vertical and horizontal displacement of the RC Jacketed Column using FEM is shown in Fig. 15a and 15b respectively. Load versus displacement graphs were plotted for the RC conventionally jacketed column using the maximum displacement and maximum reaction force of the jacketed column as shown in Fig. 16.

The RC column has a maximum reaction force of 430 kN, a maximum vertical displacement of 5.9 mm and the corresponding stiffness is 72.88 N/mm. The RC-jacketed column has a maximum reaction force of 1400 kN, a maximum vertical displacement of 3.6 mm and the corresponding stiffness is 388.8 N/mm. On comparing with the RC column, the jacketed column has 1.28 times more stiffness. From the results, it was found that the jacketed column is more efficient in bearing the axial load as well as some amount of lateral forces compared to normal RC column. This finding agrees with the results of Julio et al. (2003) [13] and Dang Quang Ngo et al. (2020) [41]. While observing the load versus displacement graph, it's evident that the RC-jacketed column can take more load even beyond the ultimate load. The improved properties of jacketed columns are due to the enhanced properties of the jacketing (GPC) material. The vertical and horizontal displacement of the GPC Jacketed Column using FEM is shown in Fig. 17a and 17b respectively. Load versus displacement graphs are plotted for GPC jacketed columns using the maximum displacement and maximum reaction force of the jacketed column and the results are shown in Fig. 18 [42]. The RC column has a maximum reaction force of 412 kN, a maximum displacement of 5.55 mm and the corresponding stiffness is 74.23 N/mm. Whereas the GPC-jacketed column has a maximum reaction force of 1512 kN, a maximum displacement of 2.95 mm and the corresponding stiffness is 512.5 N/mm. The GPC-jacketed column has 6.9 times more stiffness than the RC column. It was clear that the jacketed column is more efficient for bearing axial load as well as some amount of lateral forces compared to the normal RC column. This finding is also similar to the results of Saif M. Salman et al. (2021) [43] and Sulaem Musaddiq Laskar et al. (2021) [44]. While observing the load versus displacement graph, it's evident that GPC jacketing column is capable of taking more load compared to the RC Jacketed column due to the improved bond interface between the RC column and the jacketed material. Table 6 shows the experimental values of deflection, reaction force and stiffness of columns.

From the equation (1) provided in BIS456 2000 the ultimate load of the column is determined to be 471 kN. But the crushing load was limited to be more than 75 % of the ultimate load carrying capacity to facilitate the yielding cracks in the specimen. After cracking, the specimens were jacketed using conventional RC and achieved a cracking load of 1400 kN and GPC jacketed columns sustains a load of 1600 kN. It was found that jacketed columns using RC and GPC have 3.25 and 3.72 times respectively more ultimate load-carrying capacity than the RC column. The jacketed columns were tested after interpolating the load versus deflection graph of C1, C2 and C3 with the RC jacket and C4, C5 and C6 with the GPC jacket as shown in Figs. 16 and 18 respectively. The failure of Conventional RC jacket and GPC jacketed columns is shown in Fig. 19 and it shows a 90 % agreement with the analytical results.

From the Fig. 19b, it is clear that the GPC jacket can withstand higher load compared to the conventional RC jacket. Table 7 shows the analytical values for deflection, reaction force and stiffness of columns.

In the experimental investigation, GPC jacket shows 12.5 % less deflection, 14.28 % more reaction force and 28.6 % more stiffness than the conventional RC jacket. This improved performance in GPC jacketing is due to the enhanced properties of geopolymer concrete under loading. In the analytical investigation, the GPC jacket shows 15.2 % less deflection, 14.11 % more reaction force and 31.25 % more stiffness than the conventional RC jacket.

4.3. Interface shear stress versus interface slip graph

The interface shear stress versus interface slip plot shows the interface crack and interface debonding between the RC column and RC jacket. Here, the interface shear stress is taken as the frictional shear stress (τ_{int}) from the analytical model and interface slip (δ_{int}) is the displacement of the column's outer surface and jacket's inner surface, which is also taken from the analytical model.

From Fig. 20, it is found that at the early stages of loading, the interface slip between the RC column and RC jacket is very low. After a point of time, the interface slip value fluctuates from negative to positive, that is, at the point of ultimate load, the interface shear stress also increases along with loading. And in the final stage of loading, the interface is showing same amount of slip for the column outer's surface and the jacket's inner surface. The maximum interface shear stress is 2.1 MPa and maximum interface slip is 0.6 mm for the column's outer surface and 0.68 mm for RC jacket's inner surface.

Table 6
Experimental values of Deflection, Reaction Force and Stiffness of Columns.

Column Designation	Maximum Deflection (mm)		Maximum Reaction Force (kN)	Yielding Load (kN)	Stiffness (N/mm)
	Vertical	Horizontal			
RC Column	5.9	2.74	430	380	72.88
RC-Jacketed Column	3.6	1.55	1400	990	388.8
GPC-Jacketed Column	3.2	1.46	1600	1010	500

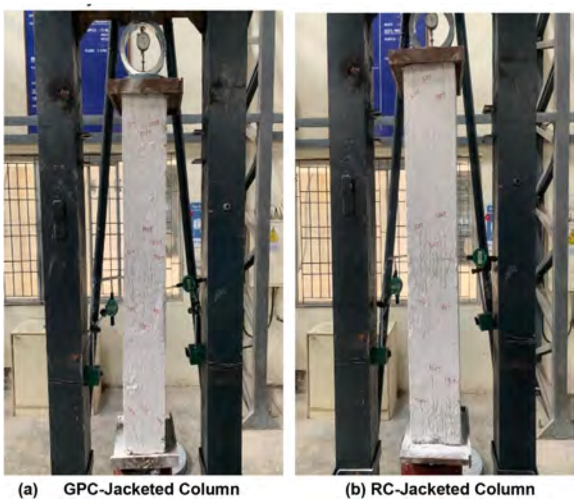

Fig. 19. Failure of GPC & RC-jacketed columns.

Table 7
Analytical values of deflection, reaction force and stiffness of columns.

Column Designation	Maximum Vertical Deflection (mm)	Maximum Reaction Force (kN)	Stiffness (N/mm)
RC Column	5.55	412	74.23
RC-Jacketed Column	3.4	1325	389.7
GPC-Jacketed Column	2.95	1512	512.5

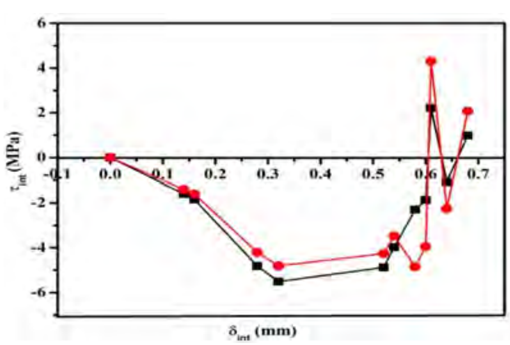

Fig. 20. Interface shear stress vs Interface slip graph of RC column outer and jacket inner surface.

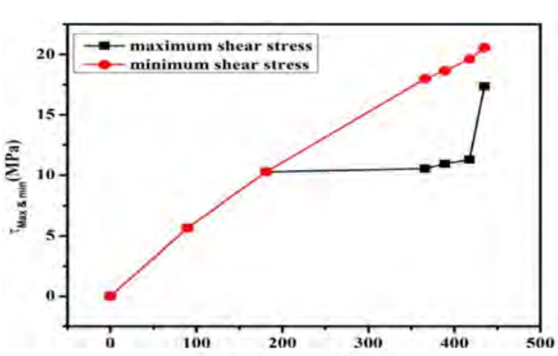

Fig. 21. Maximum and Minimum shear stress vs Contact pressure graph RC-jacketed column.

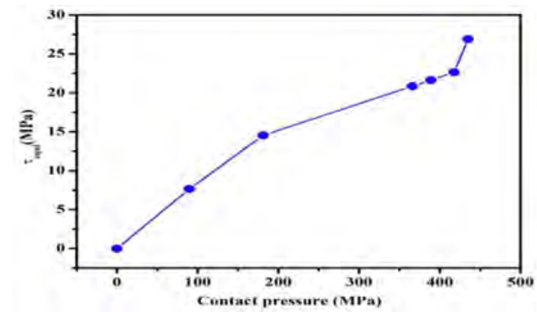

Fig. 22. Equivalent shear stress vs Contact pressure graph RC-jacketed column.

4.4. Equivalent shear stress vs contact pressure graph

The maximum permissible frictional or shear stress and contact pressure across the interface of the contacting surfaces is the elementary perception of coulomb friction model. Here the surfaces belong to low-grade RC column and high-grade jacket. Based on the coulomb friction model, the interface between the contacted body will initially have a shear stress. Then, the surfaces start slipping relative to one another, which can be termed as sticking. The critical shear stress, τ_{crit}, at which sliding of the surfaces twitches as a fraction of the contact pressure, *p*, between the surfaces ($\tau_{crit} = \mu p$) is defined by the coulomb friction model. The stick/slip determines the point of shift from sticking to slipping or vice versa. The fraction, μ, is known as the coefficient of friction. All the friction models commonly assume that μ is the equal in all directions (isotropic friction). For a 3D simulation, there are two orthogonal components of shear stress, τ_1 and τ_2, along the interface of the RC column and the RC jacket. The τ_1 and τ_2 components act in the local tangent directions to the interface [45].

In the ABAQUS software, the two shear stresses (τ_1 and τ_2) are combined into an "equivalent shear stress," τ_{Equi}, for the stick/slip calculations, where $\tau=\sqrt{\tau_1{}^2 + \tau_2{}^2}$. In addition, ABAQUS syndicates the two slip velocity components into an equivalent slip rate, $\tau_{Equi} = \sqrt{\tau_1{}^2 + \tau_2{}^2}$. The stick/slip concept describes a surface in the contact pressure versus shear stress space along which a point shifts from sticking to slipping [32–34].

From Figs. 21 and 22, which represent minimum shear stress versus contact pressure and maximum shear stress versus contact pressure, respectively, the combination of two shear stress components (τ_1 and τ_2) generated from these two graphs is used to calculate "equivalent shear stress," τ_{Equi}. A plot of equivalent shear stress and contact pressure is generated. The portion below the line in the graph depicts the slip/stick region.

5. Conclusion

In this research, two sets of low-grade RC columns were strengthened, one set with high-grade concrete jacketing and another set with GPC jacketing. The interface between the concrete and the jacket was analysed with a commonly available FEA package ABAQUS 6.14. The model was projected to forecast the compressive retort of low-grade RC column with high-grade RC and GPC jackets. A 3D nonlinear finite element method was advanced to explain the compressive response of low-grade concrete column by externally confining the high-grade RC jacket. The following inferences are drawn from the analytical studies:

1. The ultimate load-carrying capacity of the confined high-grade RC and GPC jacket in a low-grade RC column improves by 3.0 and 3.5 times than the normal RC column as per the analytical

results. In the experimental analysis, ultimate load-carrying capacity of the confined high-grade RC and GPC jacket in a low-grade RC column improves by 3.25 and 3.72 times than the RC column. The comparison of RC column with jacketed column is less important. But compared to the RC-jacketed column, the GPC-jacketed column shows 1.1 times more load-carrying capacity.
2. Using the embedded element technique in which the coefficient of friction was fixed at 1.55, an average displacement of 0.6 mm in column's outer surface and 0.66 mm in inner jacket's surface is obtained.
3. From the initial to the final stage of loading, the maximum interface shear stress is 2.1 MPa and the maximum interface slip is 0.6 mm for the column's outer surface and 0.68 mm for RC jacket's inner surface.
4. The stick/slip concept describes a surface in the contact pressure versus shear stress space in which there is a point of shift from sticking to slipping. The portion below the line in the pressure versus shear stress graph depicts the slip/stick region.
5. In the experimental investigation, the GPC jacket shows 12.5 % less deflection, 14.28 % more reaction force and 28.6 % more stiffness than the conventional RC jacket. In the analytical investigation, the GPC jacket shows 15.2 % less deflection, 14.11 % more reaction force and 28.6 % more stiffness than the conventional RC jacket.

The validation against the experimental test results confirmed 90 % accuracy of the analytical model. The advantage of strengthening the columns using GPC and RC jackets will increase the uniform distribution of strength and stiffness of the column.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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