



## Influence of Corner Rounding on the Axial Capacity of GFRP-Confined Square RC Columns: A Finite Element and Analytical Study

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### ABSTRACT :

Many reinforced concrete (RC) columns in older buildings no longer meet present load demands because of material deterioration, changes in occupancy or design shortfalls. Wrapping such columns with glass fibre reinforced polymer (GFRP) sheets is a fast and lightweight way to raise their axial capacity, but in square sections the confining action is weakened at the corners. This study examines how rounding the corners of a square column before wrapping changes the gain in axial capacity. A 200 mm × 200 mm short RC column with M20 concrete and four 12 mm bars was analysed with and without a single layer of unidirectional E-glass GFRP, for sharp corners and for a corner radius of 25 mm. Three-dimensional nonlinear finite element (FE) models were built in ABAQUS using the concrete damaged plasticity model for concrete, embedded beam elements for steel and shell elements for the jacket. The FE results were compared with nominal capacities obtained from the CSA A23.3 column equation, using confined concrete strengths from the fib Bulletin 14 confinement-effectiveness approach. The FE model predicted an increase in axial capacity of 15.1% for the sharp-cornered column and 31.9% for the rounded column, against analytical increases of 12.6% and 22.6%. FE capacities were 3–11% higher than the analytical values. The jacketed rounded column also sustained 66% more axial deformation before the onset of nonlinearity. The jacket material cost was about ₹1,820 per m<sup>2</sup> of wrapped surface, and corner rounding roughly halved the cost per kN of capacity gained. Rounding the corners before wrapping is therefore recommended when square columns are strengthened with GFRP.

**Keywords:** GFRP jacketing, square RC column, corner radius, confinement, concrete damaged plasticity, finite element analysis, retrofitting

### Introduction

A large share of the reinforced concrete (RC) building stock in India was designed before present loading and detailing rules came into use. Over time, many of these buildings face loads they were never designed for. Extra storeys are added, the use of a floor changes, reinforcement corrodes, or the concrete placed on site turns out weaker than specified. Columns are the most critical members in such cases, because the failure of one column can trigger the collapse of the floors it supports. Replacing deficient columns is costly and disruptive, so strengthening them in place is usually the preferred option.

Three jacketing methods are common for columns. In RC jacketing, a new layer of reinforced concrete is cast around the old column. It is effective but enlarges the section, adds weight and needs formwork and curing time. Steel jacketing is quicker and works well where shear capacity or lap splices are inadequate, but the steel needs protection against corrosion and fire (Sezen & Miller, 2011). Jacketing with fibre reinforced polymer (FRP) sheets avoids most of these drawbacks. The sheets are thin, light and easy to handle, they do not corrode, and they barely change the column size, so the building can often stay in use during the work (Jaya & Mathai, 2012; ACI Committee 440, 2017). Glass FRP (GFRP) is cheaper than carbon FRP and offers good strain capacity, which makes it attractive for ordinary buildings (Jaya & Mathai, 2012).

An FRP wrap strengthens a column mainly through confinement. Under axial compression, concrete expands sideways. The wrap resists this expansion and in turn presses inward on the concrete core. Concrete under such lateral pressure carries a higher axial stress and fails at a larger strain (fib, 2001; Mander et al., 1988). In a circular column the pressure is uniform around the perimeter. In a square column it is not. The wrap tends to straighten between the corners, so the confining pressure is concentrated near the corners while the middle of each face is poorly confined. Only part of the section is effectively confined, and the sharp corners also cause stress concentrations in the sheet, which can lead to early rupture (Lam & Teng, 2003; Al-Salloum, 2007).

Rounding the corners before wrapping is a simple remedy, and design guidelines link the effectively confined area to the corner radius (ACI Committee 440, 2017; fib, 2001). Experiments have shown that the strength gain rises as the corner radius grows (Al-Salloum, 2007; Benzaid et al., 2009). Most of these studies, however, tested small plain concrete prisms. Fewer studies have looked at full-height reinforced columns of the size found in buildings, and fewer still have compared numerical results with the design equations an Indian engineer is likely to use.

This paper addresses that gap for a typical short building column. The objectives are to:

1. Estimate the increase in axial capacity of a square RC column after wrapping with one layer of GFRP, using nonlinear FE analysis in ABAQUS.
2. Compare the FE capacities with nominal capacities from a code-based analytical procedure.

3. Quantify how a 25 mm corner radius changes the capacity gain, the deformation response and the cost-effectiveness of the jacket.

## Literature review

### 1.1. Experimental studies on FRP-confined columns

Tests over the last two decades have established that FRP wrapping raises both the strength and the ductility of axially loaded columns. Harajli et al. (2006) tested circular and square columns and proposed a stress–strain model for FRP-confined concrete that reproduced the measured load–deformation curves well. Hadi (2006) loaded wrapped columns both concentrically and eccentrically and found that an optimum number of layers improved strength, ductility and energy absorption together. Silva and Rodrigues (2006) studied size effects in GFRP-wrapped cylinders and reported that the benefit of confinement fell slightly as specimen diameter grew, even when the height-to-diameter ratio was kept constant.

For glass fibres in particular, Kumutha et al. (2007) wrapped rectangular columns with zero, one and two GFRP layers and showed that the strength gain dropped as the aspect ratio of the section increased. Silva (2011) compared carbon and aramid wraps and found that square columns gained much less than circular ones of similar size. Jaya and Mathai (2012) observed that GFRP gave a larger gain in ductility than CFRP, while CFRP gave more strength per layer at a higher material cost. Micelli and Modarelli (2013) tested 128 specimens and identified fibre type, number of layers and section shape as the main factors controlling confinement efficiency. Dave et al. (2014) compared tests on GFRP-wrapped M25 columns with the ISIS Canada design approach (ISIS Canada, 2001) and found reasonable agreement. Eid and Paultre (2017) proposed an effective confinement index that combines the contributions of internal ties and the external FRP wrap.

### 1.2. Effect of corner radius

The corner radius has received particular attention because it controls how much of a square section is effectively confined. Al-Salloum (2007) tested 20 specimens with corner radii varying from 5 mm up to values that made the section nearly circular. The strength gain rose steadily with the radius. Benzaid et al. (2009) tested 21 GFRP-wrapped prisms of 100 mm × 100 mm × 300 mm and reached the same conclusion. Lam and Teng (2003) used such test data to build a design-oriented model in which the effectively confined area shrinks as the corners become sharper. Both fib Bulletin 14 (fib, 2001) and ACI 440.2R (ACI Committee 440, 2017) adopt this idea.

### 1.3. Finite element modelling of FRP-confined concrete

Karabinis et al. (2008) modelled FRP-wrapped square and rectangular columns in ABAQUS with a modified Drucker–Prager plasticity model, eight-node solid elements for concrete and orthotropic elastic shells for the FRP, and obtained good predictions. Doran et al. (2009) used the Drucker–Prager approach in LUSAS to study how confining stresses spread over the mid-height section of 33 specimens. Yu et al. (2010) showed that the default concrete damaged plasticity (CDP) model in ABAQUS underestimates the strength of confined concrete, and proposed changes to its flow rule and hardening rule. Teng et al. (2015) later extended that work to RC columns with FRP and steel confinement. Piscesa et al. (2018) showed that the dilation behaviour of the concrete model and the stiffness of the confining material govern the predicted response. Zeng et al. (2018) applied 3D FE models to circular columns partially wrapped with FRP strips.

### 1.4. Research gap

The work reviewed above confirms that corner rounding improves FRP confinement, but most evidence comes from small plain concrete prisms. Studies on reinforced columns at building scale that combine an FE model, a code-based check and a cost estimate are limited. The present study is a step in that direction.

## Column details and analytical formulation

### 1.5. Reference column

The reference column is a 200 mm × 200 mm square RC column, 2000 mm long, designed to IS 456:2000 (BIS, 2000). The slenderness ratio based on the unsupported length is 10, so the column is treated as short and buckling is not considered. Longitudinal steel consists of four 12 mm bars ( $A_s = 452.4 \text{ mm}^2$ ,  $\rho = 1.13\%$ ), which satisfies the 0.8% minimum of IS 456. Lateral ties are 6 mm in diameter at 100 mm centres. This spacing is well inside the code limit, which is the least of the lateral dimension (200 mm), 16 times the bar diameter (192 mm) and 300 mm. A clear cover of 30 mm is provided to the main bars. Two corner details are studied: sharp corners, and corners rounded to a radius  $r_c = 25 \text{ mm}$  ( $r_c/b = 0.125$ ) before wrapping (Fig. 1). The jacket is one layer of unidirectional E-glass fabric, 1 mm thick, with fibres in the hoop direction.

**Table 1 - Material properties used in the analytical and FE models**

| Material       | Property                    | Value      |
|----------------|-----------------------------|------------|
| Concrete (M20) | Compressive strength, $f_c$ | 20 MPa     |
|                | Elastic modulus, $E_c$      | 21,000 MPa |
|                | Poisson's ratio             | 0.16       |

| Material             | Property                      | Value                  |
|----------------------|-------------------------------|------------------------|
| Steel (Fe 415)       | Tensile strength              | 3.15 MPa               |
|                      | Density                       | 2400 kg/m <sup>3</sup> |
|                      | Yield strength, $f_y$         | 415 MPa                |
|                      | Elastic modulus, $E_s$        | 210,000 MPa            |
|                      | Poisson's ratio               | 0.30                   |
| GFRP (E-glass/epoxy) | Density                       | 7850 kg/m <sup>3</sup> |
|                      | Thickness per layer, $t_f$    | 1.0 mm                 |
|                      | Elastic modulus (hoop), $E_f$ | 76,000 MPa             |
|                      | Tensile strength              | 1507 MPa               |
|                      | Fabric weight                 | 936 g/m <sup>2</sup>   |

### 1.6. Capacity of the unstrengthened column

The nominal axial capacity is calculated with the CSA A23.3 column equation (CSA, 1994), which Thériault and Neale (2000) also used as the basis for FRP-wrapped columns. All resistance factors are set to 1.0 so that the nominal capacity can be compared directly with the FE results:

$$P_0 = \alpha_1 f'_c (A_g - A_s) + f_y A_s, \quad \alpha_1 = 0.85 - 0.0015 f'_c \geq 0.67 \quad (1)$$

For  $f'_c = 20$  MPa,  $\alpha_1 = 0.82$ . For the sharp-cornered column,  $A_g = 40,000$  mm<sup>2</sup>, which gives  $P_0 = 836.3$  kN. Rounding the corners removes  $(4 - \pi)rc^2 = 536.5$  mm<sup>2</sup> of concrete, so  $A_g = 39,463.5$  mm<sup>2</sup> and  $P_0 = 827.5$  kN.

### 1.7. Capacity of the GFRP-wrapped column

The capacity of the wrapped column is found by replacing  $f'_c$  in Eq. (1) with the confined strength  $f'_{cc}$ :

$$P_j = \alpha_1 f'_{cc} (A_g - A_s) + f_y A_s \quad (2)$$

The confined strength depends on how much of the section the jacket confines effectively. Following fib Bulletin 14 (fib, 2001), the confinement effectiveness coefficient for a rectangular section with corner radius  $rc$  is:

$$k_e = 1 - \frac{(b - 2rc)^2 + (d - 2rc)^2}{3A_g(1 - \rho_{sg})} \quad (3)$$

where  $\rho_{sg} = A_s/A_g$ . The volumetric ratio of the jacket and the effective lateral confining pressure are:

$$\rho_f = \frac{2nt_f(b + d)}{bd} \quad (4)$$

$$f_l = 1/2 k_e \rho_f E_f \epsilon_{fe} \quad (5)$$

where  $n$  is the number of layers and  $\epsilon_{fe}$  is the effective hoop strain in the jacket at failure. A design value of  $\epsilon_{fe} = 0.002$  is used here. This is about 10% of the rupture strain of the fabric ( $1507/76,000 = 0.0198$ ) and is deliberately conservative, since square columns are known to fail at hoop strains far below the coupon rupture strain (Lam & Teng, 2003; Al-Salloum, 2007). The confined strength is then obtained from the Mander et al. (1988) equation:

$$f'_{cc} = f'_c \left[ 2.254 \sqrt{1 + \frac{7.94 f_l}{f'_c}} - \frac{2 f_l}{f'_c} - 1.254 \right] \quad (6)$$

**Table 2 - Analytical capacities of the columns (nominal, resistance factors = 1.0)**

| Column          | rc (mm) | Ag (mm <sup>2</sup> ) | ke    | fl (MPa) | f'cc (MPa) | P0 (kN) | Pj (kN) | Increase (%) |
|-----------------|---------|-----------------------|-------|----------|------------|---------|---------|--------------|
| Sharp corners   | 0       | 40,000.0              | 0.326 | 0.50     | 23.24      | 836.3   | 941.4   | 12.6         |
| Rounded corners | 25      | 39,463.5              | 0.616 | 0.94     | 25.84      | 827.5   | 1014.4  | 22.6         |

With  $\rho_f = 0.02$  for both columns, the 25 mm radius nearly doubles the effectiveness coefficient, from 0.326 to 0.616. The confining pressure and the strength gain follow the same trend.

## Finite element modelling

Four models were analysed in ABAQUS/Standard 6.14: the sharp-cornered and rounded columns, each with and without the GFRP jacket.

### 1.8. Geometry and parts

Each model has three parts. The concrete column is a 3D deformable solid created by extrusion. The longitudinal bars and ties are 3D deformable wires. The jacket is a 3D deformable shell that follows the outer surface of the column, with or without rounded corners. The parts were placed in a common global coordinate system in the assembly module (Fig. 3).

### 1.9. Material models

Concrete was modelled with the concrete damaged plasticity (CDP) model, which combines isotropic damage with plasticity to describe crushing in compression and cracking in tension (Lubliner et al., 1989; Lee & Fenves, 1998). The plasticity parameters were taken as the ABAQUS defaults (Dassault Systèmes, 2014): dilation angle  $\psi = 31^\circ$ , flow potential eccentricity  $\varepsilon = 0.1$ , ratio of biaxial to uniaxial compressive strength  $f_{b0}/f_{c0} = 1.16$ , shape factor of the yield surface  $K_c = 0.667$  and viscosity parameter  $\mu = 0.00001$ . Elastic properties are listed in Table 1. Steel was modelled as elastic–perfectly plastic with  $f_y = 415$  MPa.

The GFRP jacket was modelled as a linear elastic lamina with the fibres aligned in the hoop direction. Its stiffness along the column axis is negligible, so the jacket carries almost no axial load directly and acts only through confinement. Rupture of the fabric was not modelled.

### 1.10. Interactions, loading and boundary conditions

The reinforcement cage was embedded in the concrete, so the translational degrees of freedom of the steel nodes follow those of the surrounding concrete elements. This assumes perfect bond between steel and concrete. The jacket was joined to the concrete surface with a tie constraint, which assumes perfect bond between FRP and concrete; this simplification is common in FE studies of FRP-confined columns (Piscosa et al., 2018).

The base of each column was fully fixed (encastre). A monotonically increasing axial load was applied at a reference point at the centre of the top face. The load was ramped linearly from zero to its maximum in a single Static, General step solved with the full Newton method (Fig. 5).

### 1.11. Element types and mesh

Concrete was meshed with C3D8R elements (eight-node linear bricks with reduced integration and hourglass control). Steel bars and ties were meshed with B31 elements (two-node linear beams). The jacket was meshed with S4R elements (four-node shells with reduced integration and finite membrane strains). A structured hexahedral mesh was used for the concrete (Fig. 4).

A mesh sensitivity study was carried out on the unwrapped sharp-cornered column under a reference load, with element sizes from 10 mm to 35 mm (Fig. 6). The computed axial deformation fell from 1.174 mm at 10 mm to 1.132 mm at 20 mm and changed by less than 0.6% between 20 mm and 35 mm. An element size of 30 mm was adopted for all models.

### 1.12. Definition of capacity

The load–displacement curves from the analyses show a nearly linear branch followed by a clear change in slope. The load at this change in slope, marked on the curves in Figs. 7–10, was taken as the axial capacity of each column. It marks the onset of significant nonlinearity in the concrete. Because the analyses were load-controlled, the descending branch after peak load could not be traced.

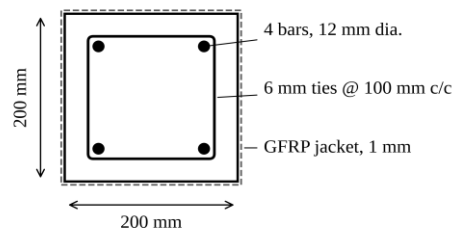


Fig. 1 - Cross-section of the column with sharp corners.

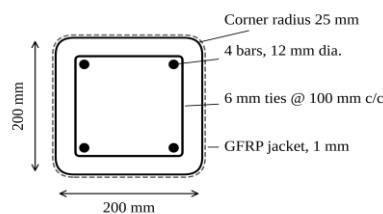


Fig. 2 - Cross-section of the column with 25 mm rounded corners.

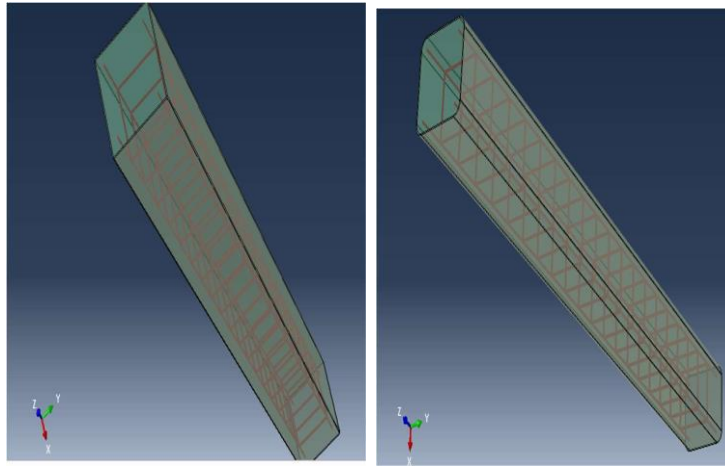


Fig. 3 - Assembled FE model showing the embedded reinforcement cage: (a) sharp corners; (b) rounded corners.

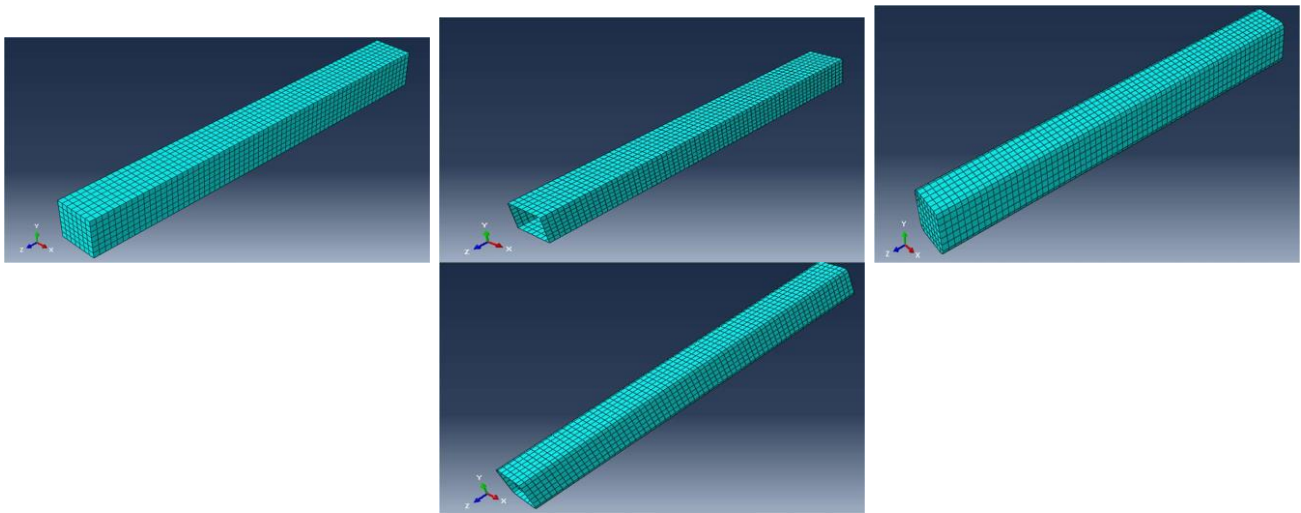


Fig. 4 - FE mesh: (a) column with sharp corners (C3D8R); (b) its GFRP jacket (S4R); (c) column with rounded corners (C3D8R); (d) its GFRP jacket (S4R).

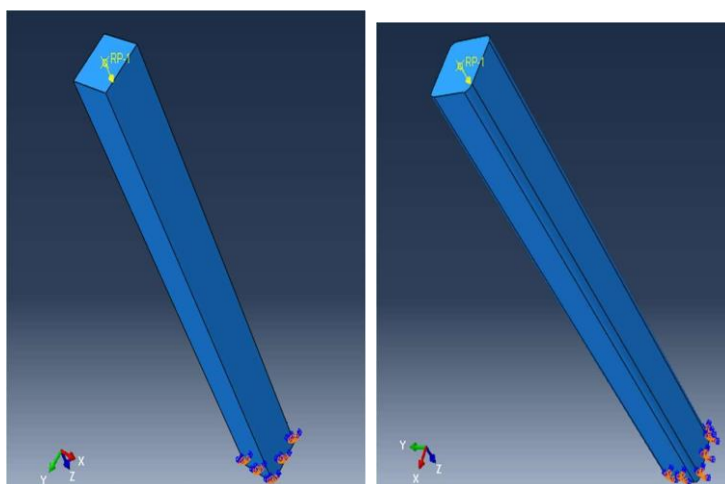


Fig. 5 - Loading and boundary conditions.

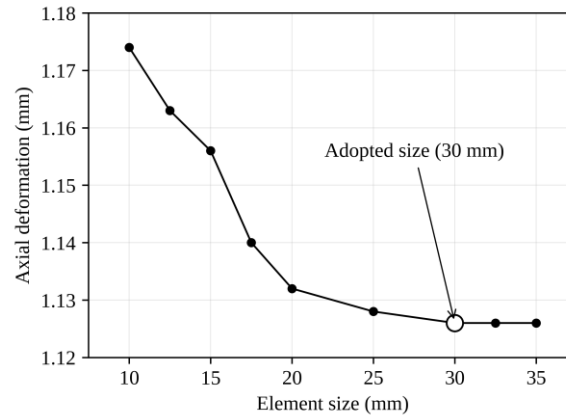


Fig. 6 - Mesh sensitivity of the axial deformation.

## Results and discussion

GFRP wrapping raised the FE axial capacity by 15.1% with sharp corners and by 31.9% with rounded corners. Table 3 summarises the FE results and compares them with the analytical values of Table 2.

Table 3 - FE capacities, axial displacement at capacity and comparison with analytical values

| Column             | FE capacity (kN) | Displacement at capacity (mm) | Increase due to GFRP (%) | Analytical capacity (kN) | FE / analytical |
|--------------------|------------------|-------------------------------|--------------------------|--------------------------|-----------------|
| Sharp, unwrapped   | 864.8            | 1.712                         | –                        | 836.3                    | 1.03            |
| Sharp, GFRP        | 995.0            | 2.190                         | 15.1                     | 941.4                    | 1.06            |
| Rounded, unwrapped | 857.4            | 1.681                         | –                        | 827.5                    | 1.04            |
| Rounded, GFRP      | 1130.5           | 2.786                         | 31.9                     | 1014.4                   | 1.11            |

### 1.13. Load–displacement response

All four columns showed a nearly linear response up to the capacity point (Figs. 7–10). Beyond it, the unwrapped columns followed a much flatter branch. The wrapped columns curved more gradually and kept gaining load, which reflects the growing confining pressure as the concrete dilates against the jacket. The wrapped columns also deformed more before reaching the capacity point. The axial displacement at capacity rose by 27.9% for the sharp-cornered column (1.712 mm to 2.190 mm) and by 65.7% for the rounded column (1.681 mm to 2.786 mm). The larger deformation of the rounded column suggests that its jacket engaged a larger part of the section before the concrete softened. The axial displacement contours at capacity are shown in Figs. 11 and 12.

### 1.14. Effect of corner rounding

Rounding the corners removes 536.5 mm<sup>2</sup> of concrete, about 1.3% of the section. Without a jacket, this lowered the FE capacity by only 0.9%, from 864.8 kN to 857.4 kN. With the jacket, the rounded column carried 1130.5 kN, which is 13.6% more than the wrapped sharp-cornered column (995.0 kN). The gain from wrapping more than doubled, from 15.1% to 31.9% (Fig. 14).

The reason is the shape of the confined zone. Around a sharp corner, the wrap restrains the concrete mainly at the corners, and the middle of each face is left almost unconfined. A rounded corner lets the wrap bend smoothly and press on a wider part of the section. In the analytical model this appears as a rise in  $k_e$  from 0.326 to 0.616. The FE results show the same trend, with a larger effect.

### 1.15. Comparison with the analytical approach

The FE capacities were 3–11% higher than the analytical values (Fig. 13), with a mean FE/analytical ratio of 1.06. The agreement is closest for the unwrapped columns (ratios 1.03 and 1.04), where both methods rest on the same concrete and steel properties. The gap widens for the wrapped columns, especially the rounded one (1.11). Two factors explain most of this. First, the analytical model uses a deliberately low effective hoop strain ( $\epsilon_{fe} = 0.002$ ), which caps the confining pressure. Second, the FE model assumes perfect bond, does not model rupture of the fabric and uses default CDP parameters, all of which tend to overstate the benefit of confinement (Yu et al., 2010). The analytical values can therefore be treated as a conservative lower estimate and the FE values as an upper estimate. Both methods agree that corner rounding clearly improves the efficiency of the jacket: the analytical gain rose from 12.6% to 22.6%, and the FE gain from 15.1% to 31.9%.

### 1.16. Material cost of the jacket

Material quantities were based on the SikaWrap-430 G fabric and Sikadur-330 epoxy (Sika India, 2014; Sika India, n.d.), with 5% added for wastage. At a fabric price of ₹37,642 per 40 m<sup>2</sup> roll and an epoxy price of ₹663 per kg, applied at 1.2 kg/m<sup>2</sup>, one layer costs about ₹1,823 per m<sup>2</sup> of wrapped surface (₹988 for fabric and ₹835 for epoxy). A 200 mm × 200 mm column wrapped over its 2.0 m length has a surface of 1.6 m<sup>2</sup>, giving a material cost of about ₹2,920 per column.

**Table 4 - Material cost per unit of capacity gained (single GFRP layer, FE capacities)**

| Column          | Jacket material cost (₹) | Capacity gain (kN) | Cost per kN gained (₹/kN) |
|-----------------|--------------------------|--------------------|---------------------------|
| Sharp corners   | 2,918                    | 130.2              | 22.4                      |
| Rounded corners | 2,918                    | 273.2              | 10.7                      |

The jacket costs the same for both columns, but the rounded column gains twice the capacity, so the cost per kN is roughly halved. These figures cover materials only. Labour, surface preparation and the cost of grinding the corners are not included, and prices should be updated for the year of application.

### 1.17. Limitations

The study covers one column size, one concrete grade, one corner radius and a single GFRP layer under concentric monotonic load. The columns were assumed undamaged before strengthening. The FE model was checked against the analytical procedure but not against test results. Load control prevented tracing the post-peak response, and the default CDP parameters are known to underestimate the dilation behaviour of FRP-confined concrete (Yu et al., 2010; Piscesa et al., 2018). The findings should therefore be read as comparative trends rather than design values.

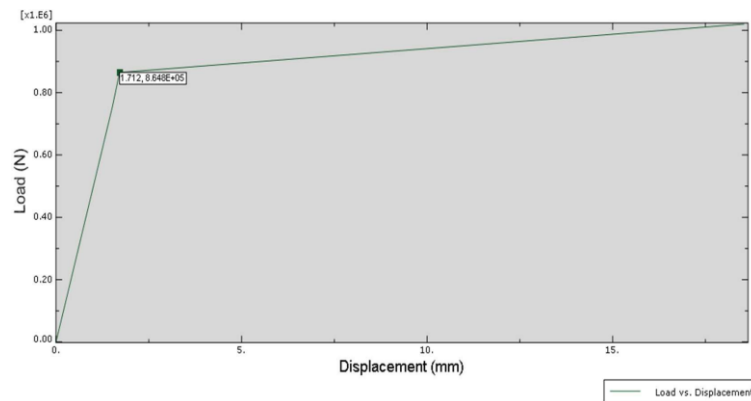


**Fig. 7 - Load–displacement curve of the unwrapped column with sharp corners.**

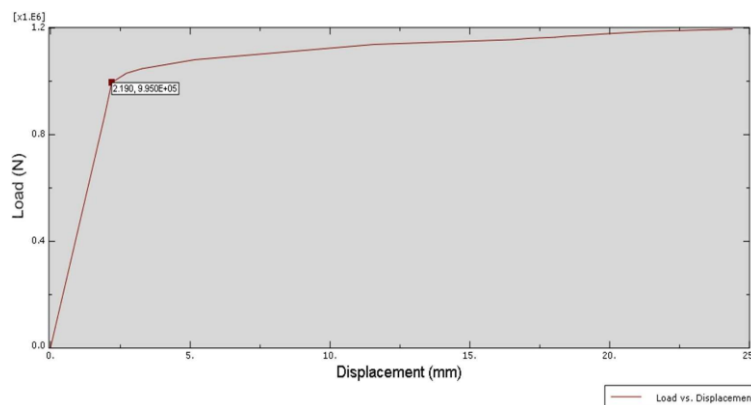


**Fig. 8 - Load–displacement curve of the GFRP-wrapped column with sharp corners.**

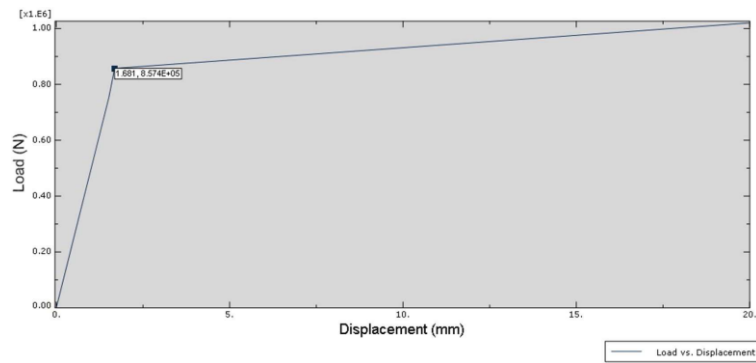


Fig. 9 - Load–displacement curve of the unwrapped column with rounded corners.

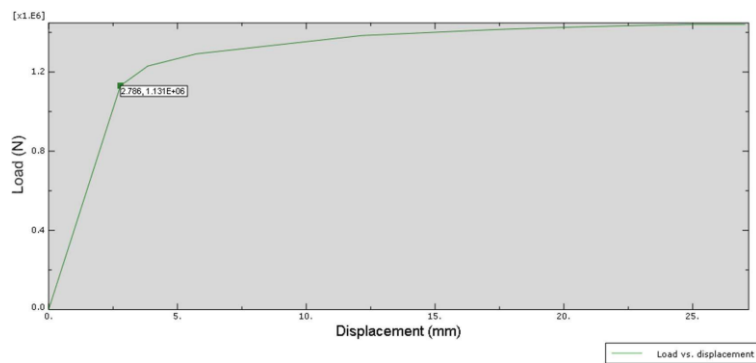


Fig. 10 - Load–displacement curve of the GFRP-wrapped column with rounded corners.

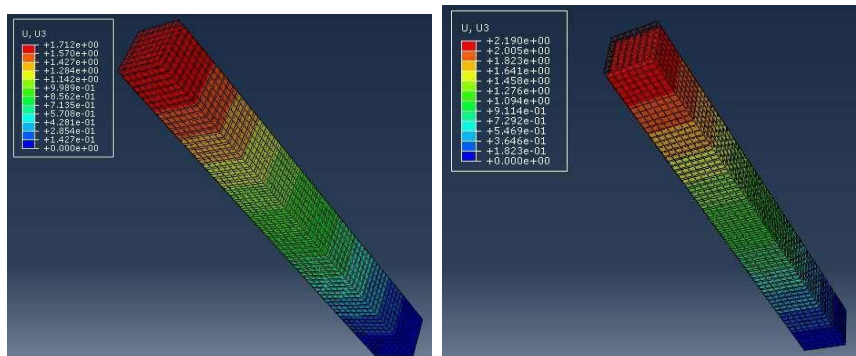


Fig. 11 - Axial displacement (U3) contours of the sharp-cornered column: (a) unwrapped; (b) GFRP-wrapped.

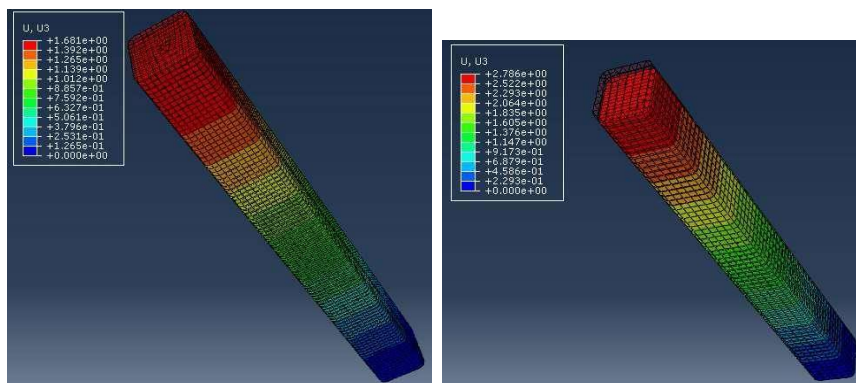


Fig. 12 - Axial displacement (U3) contours of the rounded column: (a) unwrapped; (b) GFRP-wrapped.

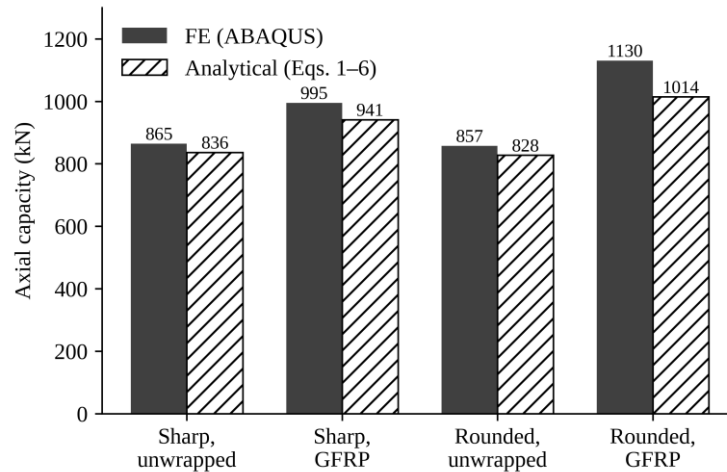


Fig. 13 - Axial capacities from FE analysis and the analytical approach.

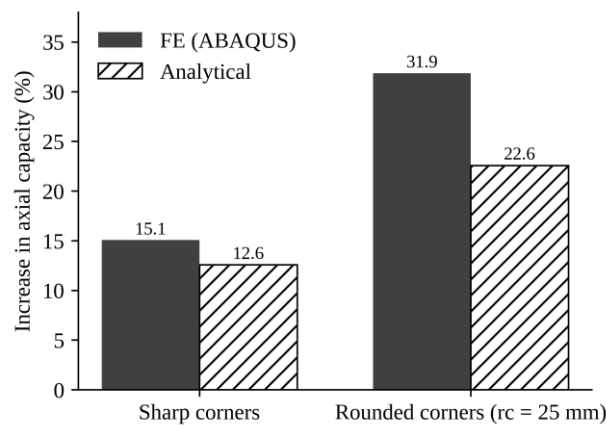


Fig. 14 - Increase in axial capacity due to GFRP wrapping.

## Conclusions

A single layer of GFRP raised the axial capacity of a 200 mm square RC column substantially, and rounding the corners before wrapping roughly doubled that gain. The main findings are:

1. FE analysis showed that GFRP wrapping increased the axial capacity by 15.1% for the column with sharp corners and by 31.9% for the column with 25 mm rounded corners.
2. The code-based analytical procedure gave smaller but consistent increases of 12.6% and 22.6%. FE capacities were 3–11% above the analytical values, so the analytical route is a reasonable and conservative check for design.
3. Rounding the corners lowered the capacity of the unwrapped column by less than 1%, but the wrapped rounded column carried 13.6% more load than the wrapped sharp-cornered column. The confinement effectiveness coefficient nearly doubled, from 0.326 to 0.616.
4. Wrapping increased the axial deformation at capacity by 28% for sharp corners and 66% for rounded corners, which points to better deformation capacity in the confined columns.
5. The jacket material cost was about ₹1,820 per m<sup>2</sup>, or about ₹2,920 for one column. Corner rounding cut the material cost per kN of capacity gained from ₹22.4 to ₹10.7.

Corners of square columns should therefore be rounded before GFRP wrapping. Further work should validate the FE model against test data, use displacement control to capture the post-peak response, and study the effect of corner radius, number of layers, concrete grade, pre-existing damage and cyclic loading.

## Declarations

**Author contributions (CRediT):** Shivendra Kumar Pandey: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. Chandan Kumar: Supervision, Validation, Writing – review & editing.

**Funding:** This research received no specific grant from any funding agency.

**Conflict of interest:** The authors declare no conflict of interest.

**Data availability:** The FE models and data supporting this study are available from the corresponding author on reasonable request.

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