Nonlinear finite element modelling of concrete columns confined with textile reinforced mortar

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Abstract. Textile reinforced mortar (TRM) is an innovative material developed to overcome the limitations of fibre reinforced polymer (FRP). It consists of high strength textile fibre mesh embedded in cementitious binder which is organic in nature and compatible with concrete substrate. This paper presents the development of a finite element model for confinement of concrete columns using TRM. Concrete damaged plasticity model was used to represent the behaviour of TRM. The model accounts for nonlinear material behaviour in concrete core and mortar. The model was validated against experimental result from literature. Maximum divergence between experimental and numerical results was 5%. Following the validation, the developed model was used to carry out parametric studies on circular and square column confinement. The thickness of mortar layer, cross section shape of the core and corner radius of square column were considered in the study to gain a profound knowledge of the confinement and to study its influence on the behaviour of confined concrete column.

Keywords: Finite Element Modelling, Numerical Analysis, Confinement, Textile Reinforced Mortar, Concrete Column

1. Introduction
The upgradation of existing concrete structures through jacketing of columns has become popular in the past few decades. The most widely used method is FRP strengthening. The FRP strengthening has favourable properties such as high strength to weight ratio, corrosion resistance, ease and speed of application and minimal change in geometry which made it superior to other strengthening techniques [1, 2]. Even though FRP strengthening is a widely used technique, it has few drawbacks like incompatibility of resin with substrate, poor behaviour of resin at higher temperatures, high cost of epoxy resin, lack of vapour permeability, difficulty to apply on wet surfaces etc. [2, 3, 4]. The drawbacks of FRP strengthening technique can be minimised by the use of cementitious binder instead of epoxy resin, which led to the development of textile reinforced mortar (TRM). Fibre reinforced cementitious materials like ferrocement jacketing have a long-term record in the field of structural engineering, especially in the development of thin sections. TRM technique utilises the same technology by the usage of high strength textile fibres embedded in cementitious mortar. Extensive
research studies have been conducted on TRM confined concrete columns, but studies are fewer on finite element modelling of TRM confined concrete columns. Numerous studies are available on strengthening of structures using TRM. Seismic retrofitting of RC columns have been studied by Bournas et al. [1]. The effectiveness of TRM jacketing and FRP strengthening was compared in terms of increasing the cyclic deformation capacity of lap spliced columns. John et al.[5] studied the tensile behaviour of TRM using glass textile. TRM exhibits bilinear tensile behaviour by the formation and widening of cracks eventually leading to sudden brittle failure which contributes its bilinear nature. The TRM jacketing was found to be equally effective compared to FRP in increasing strength and deformation capacity. Bournas et al. [6] also conducted experimental studies on stub square columns confined with TRM and compared with that of FRP strengthening. TRM jacketing was found to have practically the same effectiveness compared to that of equal stiffness FRP. Zeng et al.[7] investigated the behaviour of TRM confined columns under axial compression by jacketing cylinders of 150mm diameter and 300 mm height. The TRM jacketing was found to be equally effective compared to FRP strengthening with a strength increase of about 20% and improved ductility. Strength and ductility was found to be increasing based on studies by Colajanni et al. [8] on cylinders and square prisms. Finite element analysis of TRM is complicated due to its composite behaviour. Finite element analysis of RC beams strengthened using TRM was studied by Gopinath et al. [9]. The authors used smeared cracking model to simulate the multiple cracking behaviour of TRM. The reinforcing textile layer was modelled using truss elements embedded in mortar modelled using solid elements. The interaction between textile and mortar can also be modelled using zero thickness bond elements based on the studies by Hartig et al. [10]. The bond slip relations are used as the interaction between the TRM elements. Larrinaga et al.[11] examined the effect of models with bond slip laws and the model with rigid/embedded interface. No significant deviations were found and, in the models, and the authors suggests rigid bond interface between textile fibre mesh and mortar. Kadhim et al.[12] modelled textile fibre in TRM layer of strengthened column using shell elements. Rigid bond interface was assumed between the textile and mortar. The core concrete and cement mortar were modelled using damaged plasticity models which was found to be effective.

This paper reports finite element modelling of plain concrete columns confined with TRM jacketing. The developed model accounts for material nonlinearity in column core and cement mortar, and tensile failure of textile fibres. The model response was validated against experimental study from literature which uses glass fibre textile and cement mortar for TRM. The ultimate load and load-deflection response are validated. Parametric analysis on plain cement concrete columns confined by TRM jackets are carried out using the validated finite element model.

2. Material Modelling
Concrete was modelled using concrete damaged plasticity (CDP) model approach. The constitutive behaviour of concrete in CDP model is given in Fig 1. This model is designed for applications where concrete is subjected to monotonic or cyclic loading under low confining pressures, and can be used to model the behaviour of plain concrete. The model has two failure mechanisms: tensile cracking and compressive crushing. The input parameters used are given in table 1.

| Material  | Parameter                  | Value |
|-----------|----------------------------|-------|
| Concrete  | Young’s modulus (MPa)      | 25000 |
|           | Poisson’s ratio            | 0.2   |
| Mortar    | Young’s modulus (MPa)      | 27500 |
|           | Poisson’s ratio            | 0.2   |

Table 1. Input parameters used
Elastic strain and plastic strains are given as input in both tension and compression. The Young’s modulus decreases as a function of plastic strain as given in figure 1.

![Figure 1](image)

**Figure 1.** Concrete damaged plasticity model; (a) behaviour of concrete under tension (b) behaviour of concrete under compression [13]

Damage evolution takes place through softening of concrete in a CDP model. Plastic strain in both compressive and tensile behaviour was given as input. The parameters used in CDP model is given in table 2.

| Parameter                  | Value |
|----------------------------|-------|
| Dilation angle             | 31    |
| Flow potential eccentricity| 0.1   |
| Viscosity parameter        | 0     |
| $f_{\text{uo}}/f_{\text{co}}$ | 1.16  |
| $K$                        | 0.67  |

The dilation angle is the ratio of volume strain by shear strain ranging from 20 to 40 degrees which affects the ductility, and thus the entire model. As the dilation angle increases, the flexibility of the system increases. In the practical side, increase in internal dilation angle results in increased plastic strain and confining pressure. The flow potential eccentricity is the measure of curvature of flow potential. The ratio $f_{\text{uo}}/f_{\text{co}}$ is the ratio of uniaxial compressive yield stress and initial uniaxial compressive stress. It is determined from Kupfer’s curve for concrete [14]. The shape of deviatoric plane is determined by the parameter $K$, and a value of 0.67 is accepted for it. Viscosity parameter enhances the convergence rate of the model when softening process occurs.

Mortar is also modelled using CDP model with all the relevant parameters described in the above section. Since the mortar layer contains the textile reinforcement, the interaction between them tends to reduce mesh sensitivity. Therefore, a reasonable amount of tension stiffening is introduced in the model. This is dependent on the density of reinforcement, bond between reinforcement and mortar,
and the mesh. For a fairly detailed mesh it is reasonable to assume that the strain softening after failure reduces the stress linearly to zero at a total strain of about 10 times the strain at failure. For concrete/mortar the strain is about 0.0001 at failure, which suggests tension stiffening reduces stress to zero at strain of about 0.001 which is reasonable in the model [13]. Textile was assumed to be linearly elastic until failure. The modulus of elasticity (E), Poisson’s ratio and maximum tensile stress (σᵤ) of the textile was given as the input. The inelastic behaviour of the textile is negligible in the study since the textile fibres used in textile reinforced mortar shows highly brittle nature.

3. Geometrical Modelling
The concrete and mortar layer were modelled using C3D8(Three-dimension continuum with 8 nodes) elements. The solid elements were chosen to model the linear and non-linear analysis. The modelling involves contact elements, plasticity properties and large deformations. The most suitable element for modelling concrete and the mortar layer is solid C3D8 element. Since first order triangular and tetrahedral elements are over stiff and exhibit slow convergence mesh refinement, first order hexahedral elements were chosen. In order to reduce the running time, reduced integration was used to form element stiffness. Both the substrate concrete and the mortar in the textile reinforcement layer are modelled using the same element to avoid incompatibility. The concrete core and mortar layer were divided into eight partitions to avoid distortion elements in the model by creating multiple mesh boundaries. The textile yarns were modelled using T3D2(Three-dimensional truss with 2 nodes) elements for both longitudinal and transverse directions. Truss elements are used for long, slender structural members that supports loading along the axis. A constant stress was assumed for the textile yarns, thus a 2-node truss element, which uses linear interpolation was sufficient. In order to model the yarns, the equivalent diameter of yarns was calculated and a circular profile was assumed. The boundary conditions and loadings were given according to the experimental/practical conditions. Axial loading was applied to the model by displacement method of analysis.

4. Interactions
For modelling the bond between the mortar layer and the substrate concrete, perfect bonding was assumed. Experimental studies show no debonding between the substrate concrete and the strengthening textile reinforced mortar layer. A surface-based tie constraint in which two surfaces can be tied together was used for the perfect bonding. The outer surface of the concrete column was considered as the master surface and the inner surface of the mortar layer as the slave surface. Perfect bonding was also assumed between the textile reinforcement and the mortar layer. The mortar layer acts as the host region and the textile as the embedded region.

5. Validation Studies
Validation studies were carried out on column confined by TRM using carbon textile fibre. Colajanni et al. [8] conducted confinement studies on concrete column confined using TRM. The properties of the material used by the authors were used as the input and the modelling strategy as described above. Validation study was conducted on circular columns of size 200mm diameter and 600mm height and square columns of 200mm side and 600mm height. Equivalent diameter of textile was calculated as input data from the thickness of fibres. The carbon fibres used have a tensile strength of 4800MPa and Young’s modulus of 240Gpa. The compressive strength of concrete substrate was 17MPa. The mortar used has a compressive strength of 31.17Mpa and flexural strength of 9.46Mpa. The results of numerical analysis and the experimental study are given in figure 2.
The present numerical model shows good correlation with the experimental result. From Fig 2, the numerical model shows good correlation in the elastic region and negligible deviation in the inelastic region. The ultimate load, for experimental and numerical study are very close, indicating the suitability of the CDP model in TRM. The percentage error in the model is only about 5%. The present model is used to study different parameters on concrete column confinement using TRM.

6. Parametric studies on concrete column confined by TRM

Finite element modelling of concrete column was carried by considering the parameters cross section shape and thickness of TRM. Two cross section shapes, circular and square was considered in the study. The effect of corner radius of square column was also considered in the study. The properties of the material used are given in Table 1 and is based on the studies by Gopinath et al. [9]. The present finite element model substitutes the smeared cracking approach for mortar by CDP model. The CDP model reduces analysis time and simplifies the finite element model. Mesh convergence studies were conducted on the finite element model to obtain an optimum mesh size. Mesh convergence study is essential to ensure accurate results with less computation time. All the elements in the model was meshed with same mesh seed size to eliminate any compatibility issues in the boundary region of various elements. An optimum mesh size of 10mm was used throughout the model.

The parametric study consists of mainly two specimen types, circular and square cross sections. The circular column considered were cylinders of size 150mm diameter and 300mm height [7]. Square columns were of size 150mm x 150mm x 300mm, maintaining the same aspect ratio as that of circular column. The specimen details are given in table 3.

| Specimen ID | Cross section | Thickness of TRM | Corner radius |
|-------------|---------------|------------------|--------------|
| C0          | Circular      | -                | -            |
| C6          | Circular      | 6mm              | -            |
| C8          | Circular      | 8mm              | -            |
| C10         | Circular      | 10mm             | -            |
| C12         | Circular      | 12mm             | -            |
| S0          | Square        | -                | 0 mm         |
| S10         | Square        | 10mm             | 0 mm         |
| S10CR15     | Square        | 10mm             | 15mm         |
| S10CR25     | Square        | 10mm             | 30mm         |
The first letter in the specimen ID denotes the cross-section shape: circular© and square(S). The next number indicates the thickness of the TRM layer. All the specimen. The specimen S10CR is provided with a corner radius of 15mm and 30mm [8]. The thickness of textile yarn was calculated as the equivalent thickness of 4 layers of glass fibre textile, throughout the study. Circular profile was assumed for the textile yarns. The finite element model is given in figure 3.

![Finite element model of concrete core, mortar and textile fibre](image)

**Figure 3.** Finite element model of concrete core, mortar and textile fibre

### 7. Results and discussion

The ultimate stress and stress-strain behaviour of the confined concrete columns are discussed in this section. The results for ultimate stress and strain are given in table 4.

| Specimen ID | Ultimate stress (MPa) | Ultimate strain | Percentage increase in ultimate stress |
|-------------|-----------------------|-----------------|----------------------------------------|
| C0          | 23.816                | 0.0149          | -                                      |
| C6          | 28.738                | 0.0162          | 20.7                                   |
| C8          | 30.293                | 0.0164          | 27.2                                   |
| C10         | 32.879                | 0.0176          | 38                                     |
| C12         | 33.498                | 0.0175          | 40.6                                   |
| S0          | 23.703                | 0.0132          | -                                      |
| S10         | 26.834                | 0.0135          | 13.2                                   |
| S10CR15     | 28.225                | 0.0142          | 19.1                                   |
| S10CR25     | 29.094                | 0.0149          | 22.7                                   |

The TRM strengthening of concrete columns was found to be very effective from the parametric studies through finite element modelling. The confinement was more effective in circular columns compared to that of square columns. For circular columns, the increasing thickness of TRM layer has significant effect on the ultimate stress up to 10mm thickness. For studies on square column, the
optimum thickness of 10mm was used. The stress strain response of circular and square specimens are given in figure 4.

![Figure 4](image_url)

**Figure 4.** Axial stress vs strain of a) circular and b) square columns

From Fig 4, it is clear that the TRM confinement not only increased the axial capacity of columns, it slightly increases the stiffness of the confined columns under axial compression. The TRM confinement was not much effective in square columns. The provision of corner radius to the specimen reduced the corner stress in the TRM layer, which increased the axial capacity of column. The increasing corner radius has very little effect on increasing the axial capacity of columns. The stress plot of the TRM layer without corner radius is given in figure 5. The increased stress at the corners may have led to the early collapse of the specimens. The axial stress of confined square column increased only by 13.2% whereas it increased by 38% for equal thickness TRM.

![Figure 5](image_url)

**Figure 5.** Corner stresses in TRM layer of confined square column without corner radius

The axial compression in column causes hoop stresses in stub columns. For circular columns the hoop stresses are uniform in nature, and therefore are uniformly distributed to the confining TRM layer also. The uniform stress along the circumference is prevented by the tensile capacity of the textile fibre used. Practically, the TRM layer is designed to have hoop tensile stresses. The stresses in circular column confinement is given in figure 6.
Figure 6. Stress plot of Circular column confined with TRM and textile layer

The stress plot of square column is not uniform along the circumference. The cross-section shape leads to increased corner stresses, which in turn reduces the capacity of the column. Even though, the provision of TRM confinement with a corner radius of 30mm increased the capacity of unconfined column by 22.7% from the studies.

8. Conclusions
A nonlinear finite element model was proposed to simulate the response of concrete column confined by TRM. Considerations are given to material modelling, geometrical modelling and interaction between the components. The finite element model validated the suitability of CDP model for TRM by making comparison between the ultimate load and stress strain response of confined concrete column. The main conclusions arrived from the parametric studies by finite element modelling are:

- The axial capacity of concrete columns increases as the thickness of TRM layer increases. In the present study, the increase in strength was significant up to 10mm thickness of mortar layer.
- TRM confinement was found to be more effective in circular columns compared to that of square columns.
- The provision of corner radius in square column leads to reduced corner stresses and thus more axial load capacity.

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