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Non-uniform stress distribution in FRP-wrapped circular concrete columns under uniform axial deformation

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Abstract

The confinement of concrete columns using bonded FRP wraps has become a popular retrofit technique. Through extensive research in the last two decades, many stress-strain models have been developed for concrete in FRP-wrapped circular columns. All these models assume that the stress state is axisymmetric in an FRP-wrapped circular concrete column under concentric axial compression. This implies that the FRP wrap is assumed to be axisymmetric in geometry, but in reality such axisymmetry is not realised due to the existence of an overlapping zone. This paper presents a finite element investigation into the stress state in FRP-wrapped circular concrete columns considering the actual FRP wrap geometry used in laboratory tests and practice. The results show that common FRP wraps with an overlapping zone can lead to significant non-axisymmetric confinement to the concrete and hence a significantly non-uniform stress distribution in the concrete, even when the concrete is under uniform axial shortening.

Keywords

circular, wrapped, frp, distribution, deformation, stress, axial, uniform, non, under, columns, concrete

Disciplines

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NON-UNIFORM STRESS DISTRIBUTION IN FRP-WRAPPED CIRCULAR CONCRETE COLUMNS UNDER UNIFORM AXIAL DEFORMATION

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Abstract

The confinement of concrete columns using bonded FRP wraps has become a popular retrofit technique. Through extensive research in the last two decades, many stress-strain models have been developed for concrete in FRP-wrapped circular columns. All these models assume that the stress state is axisymmetric in an FRP-wrapped circular concrete column under concentric axial compression. This implies that the FRP wrap is assumed to be axisymmetric in geometry, but in reality such axisymmetry is not realised due to the existence of an overlapping zone. This paper presents a finite element investigation into the stress state in FRP-wrapped circular concrete columns considering the actual FRP wrap geometry used in laboratory tests and practice. The results show that common FRP wraps with an overlapping zone can lead to significant non-axisymmetric confinement to the concrete and hence a significantly non-uniform stress distribution in the concrete, even when the concrete is under uniform axial shortening.

Keywords: Concrete column, confinement, FRP, stress distribution

1. Introduction

The confinement of concrete columns using bonded FRP wraps has become a popular retrofit technique [1-4]. Through extensive research in the last two decades, many stress-strain models have been developed for concrete in FRP-wrapped circular columns. All these models assume that the stress state is axisymmetric in an FRP-wrapped circular concrete column (FWCC) under uniform axial compression (i.e. with uniform axial deformation at both ends). This assumption implies that the FRP wrap is assumed to be axisymmetric in geometry, but in reality such axisymmetry is not realised due to the existence of an overlapping zone when the FRP is wrapped on concrete columns. This paper presents a three-dimensional (3D) finite element (FE) investigation into the stress state in FRP-wrapped circular concrete columns considering the actual FRP wrap geometry used in laboratory tests and common practice. Details of the 3D FE model are first presented. It is then used to investigate the non-uniform stress distribution in FRP-wrapped concrete columns following its verification using the existing test data of Lam and Teng [2].

2. FE modelling

An FE model was developed for FWCCs using the multi-purpose FE analysis package ABAQUS [5]. The FE model consisted of one slice of finite elements with the thickness being 1 mm (Fig. 1) subjects to uniform axial shortenings, aiming to provide close predictions of the behaviour of the mid-height section of short FWCCs under axial compression. The constraints at the two ends of a column were assumed to have little effect on the behaviour in the mid-height region of the column. Eight-node solid elements were used to model the FRP, adhesive and concrete. Other details of the FE model are briefly presented below.

2.1 Geometry

A circular concrete column confined with a single continuous FRP wrap comprising N layers/plies was considered. Fig. 1 shows schematically an example column with two layers of FRP. A polar coordinate system is used to describe positions, with the circumferential angular coordinate denoted by θ. The FRP wrap starts at $\theta = 0^{\circ}$ (the inner end) and finishes at $\theta = 360N + \alpha$ (the outer end), giving an overlapping zone of angular length α.

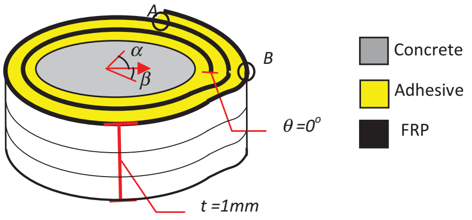


Figure 1. Idealized cross-section of FRP-wrapped concrete column

The change in radius necessary for the outer layer of FRP to overlap the inner layer was assumed to occur within a transition zone of β. The shape of the transition was assumed to be sinusoidal as in Chen et al. [6]. β was assumed to be 30.

In the FE model, it was assumed that there is no slip between the FRP and the adhesive, and between the adhesive and the concrete; therefore, the elements for different materials share the same nodes at the interfaces.

2.2 Materials

2.2.1 Concrete

The concrete was modeled using the modified concrete damaged plasticity model (CDPM) proposed in Yu et al. [7]. The modified CDPM is within the theoretical framework of the CDPM available in ABAQUS [5] and is capable of capturing the distinct characteristics of confined concrete by including a damage variable, a strain-hardening rule, and a flow rule that are all confinement-dependent. In addition, the characteristics of non-uniformly confined concrete are included in this model by defining an effective confining pressure $\sigma_{l,eff}$ as follows [7]:

$$\sigma_{l,eff} = \frac{2(\sigma_2 + 0.039 f'_{co})(\sigma_3 + 0.039 f'_{co})}{(\sigma_2 + \sigma_3 + 0.078 f'_{co})} - 0.039 f'_{co} \tag{1}$$

where σ_2 and σ_3 are the two principal lateral stresses respectively; f_{co}' is the cylinder compressive strength of concrete. More details of this model can be found in Ref. [7].

It should be noted that the analysis-oriented stress-strain model of Teng et al. [8] was used in Yu et al. [7] in deriving the necessary material parameters for the plastic-damage model, while in the present study, Jiang and Teng's [1] model, which provides closer predictions for weakly confined concrete, was used.

2.2.2 Adhesive

An elastic-perfectly plastic model was used to model the adhesive in the present study. While the actual behaviour of adhesive can be much more complex and its appropriate modelling requires further research, such an elastic-perfectly plastic model has been shown to provide reasonably close predictions for similar problems [9]. The Poisson's ratio of the adhesive was assumed to be 0.35 [10]. The elastic modulus and the strength used in the model were 3GPa and 31.5MPa, respectively, based on the properties provided by the manufacturer, as reported by Lam and Teng [2]. The thickness of all the adhesive layers (Fig. 1) was assumed to be 0.1 mm which is similar to measured values in wet lay-up laboratory specimens [11]. Li et al. [9] has also shown that this thickness has very limited effect on the predictions.

2.2.3 FRP

It has been shown in Chen et al. [12] that the use of the actual thickness of the FRP (instead of the nominal thickness) is more appropriate in an FE model. In the present study, the actual thickness of the FRP measured in flat coupon tests of the same FRP material was used, as reported in Lam and Teng [2]. The mechanical properties of FRP based on the actual thickness were obtained from those based on the nominal thickness, making use of the rule of mixtures [13]. The fibre volume ratio was calculated based on the nominal and the actual thicknesses. FRP rupture is assumed to occur when the predicted maximum FRP hoop strain over the circumference reaches the ultimate tensile strain of the FRP obtained from flat coupon tests. In the present study, the maximum hoop strain was found to always occur near Location A (Fig. 1), due to the geometrical discontinuities at this location (see [6, 14]).

3. FE results and discussions

3.1 Lam and Teng's [2] tests

Results from ten FWCC specimens reported in Lam and Teng [2] were used to verify the FE model. The ten specimens covered two types of FRP composites; the mechanical properties of

FRP reported in Lam and Teng [2] and those used in the FE model are summarized in Table 1. All the specimens had a diameter of 152 mm, a height of 305 mm, and an FRP overlapping length of 150 mm. The unconfined strength of concrete was 35.9 MPa for CFRP wrapped specimens and one-layer GFRP wrapped specimens; it was 38.5 MPa for two-layer GFRP wrapped specimens. Other key properties of the FRP are also listed in Table 1 while more details of the tests are available in Lam and Teng [2].

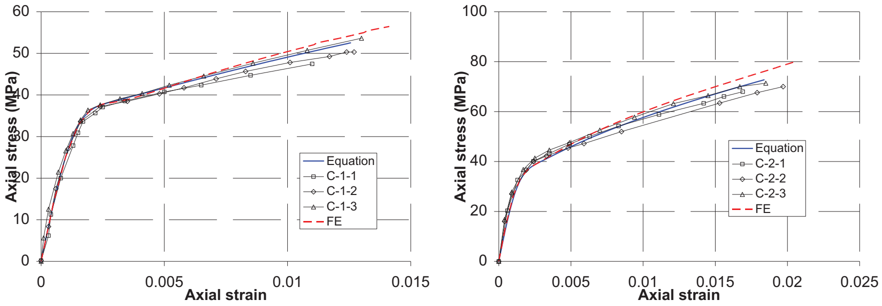
Table 1 Properties of FRP constituents and composites

FRP type	Fibre properties		Fibre volume ratio	Derived properties of FRP composites				
	E_f (GPa)	v_f		E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	$v_{12}=v_{13}=v_{23}$
CFRP	243.1	0.2	16.0%	41.5	3.82	1.45	1.53	0.33
GFRP	22.12	0.2	90.1%	20.2	8.14	3.80	3.36	0.26

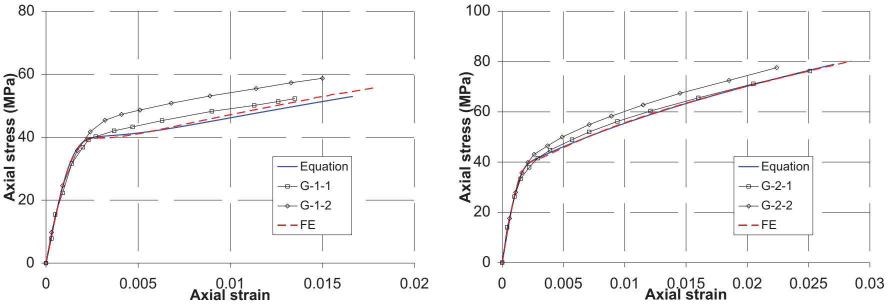
Note:
(a) Direction 1 is the fibre direction, directions 2 and 3 are perpendicular to the fibre direction;
(b) Other Poisson's ratios can be obtained from $E_{ii}/E_{jj}= v_{ij}/v_{ji}$, where $i, j = 1, 2, 3$.

3.2 Axial stress-strain behaviour

The axial stress-strain curves from FE analysis and tests are compared in Fig. 2, where Fig. 2a and 2b are for CFRP-wrapped concrete columns, while Fig. 2c and 2d are for GFRP-wrapped concrete columns. In addition, predictions from Jiang and Teng's [1] analysis-oriented model are also shown (labelled as "Equation"). In Fig. 2, the axial stress is defined as the load carried by the concrete section divided by its cross-sectional area.



(a) One-layer CFRP-wrapped concrete columns (b) Two-layer CFRP-wrapped concrete columns



(c) One-layer GFRP-wrapped concrete columns (d) Two-layer GFRP-wrapped concrete columns

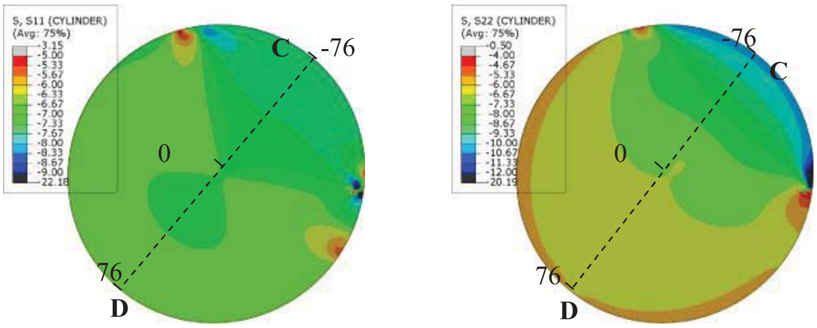
Figure 2. Axial stress-strain curves of FRP-wrapped concrete columns

It is evident from Fig. 2 that both Jiang and Teng's [1] model and the FE model provide close predictions of the test results, with the latter predicting slightly higher stress-strain curves than the former. This slight difference in the overall axial stress-strain curve is due to the existence of an overlapping zone which was considered in the FE model but not in the analysis-oriented model.

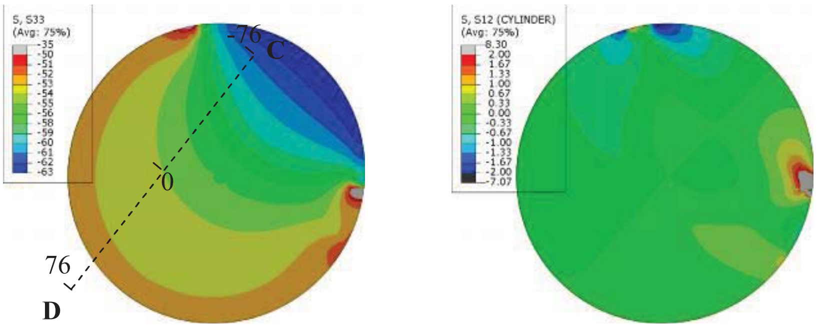
3.3 Concrete stress distribution

Based on the predictions of the FE model, the stress distribution over the concrete cross-section can be examined. Due to the length limit of the paper, only the concrete stress distributions of the CFRP-wrapped specimens are discussed below while those of the GFRP-wrapped specimens are similar.

Figs 3 and 4 show the stress distributions in the concrete at the ultimate state from the FE model (i.e. when the hoop strain at Location A reaches the ultimate FRP tensile strain obtained from flat coupon tests), for one-layer and two-layer CFRP-wrapped concrete columns respectively. The distributions of out-of-plane shear stresses are not shown here, as these stresses are nearly zero over the whole cross-section. These figures clearly show that the stresses are non-uniformly distributed due to the existence of the overlapping zone of the FRP wrap. The maximum concrete stress generally occurs at the middle point of the overlapping zone where the FRP wrap has one more layer than elsewhere.

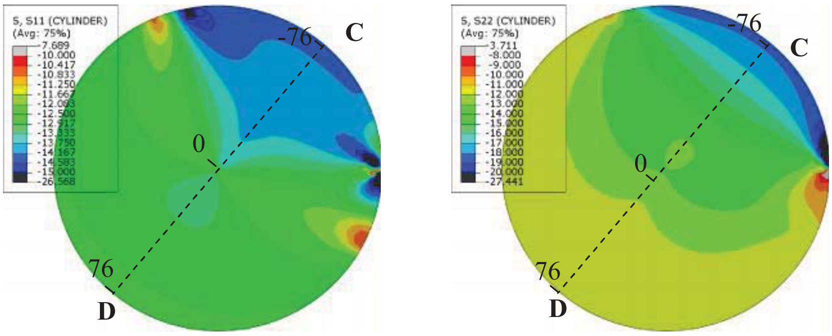


(a) Radial stress **(b) Hoop stress**

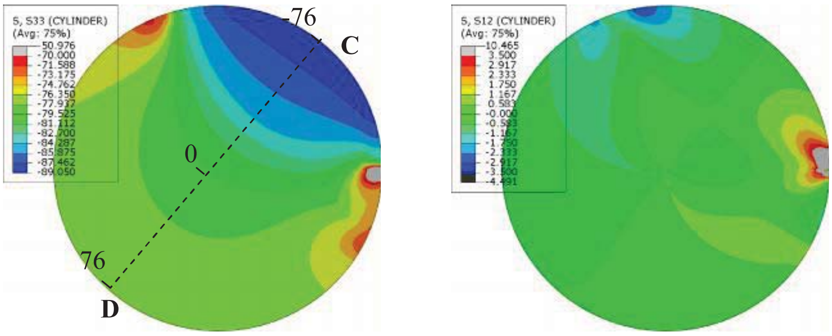


(c) Axial stress **(d) Shear stress $\tau_{r\theta}$**

Figure 3. Stress contours in concrete columns wrapped with one layer of CFRP



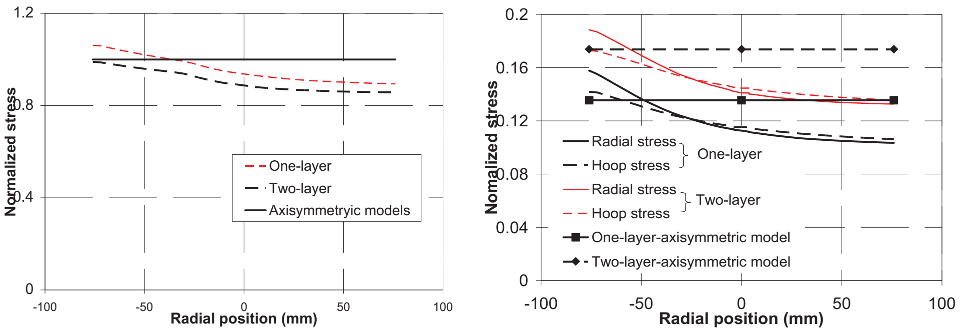
(a) Radial stress **(b) Hoop stress**



(c) Axial stress **(d) Shear stress $\tau_{r\theta}$**

Figure 4. Stress contours in concrete columns wrapped with two layers of CFRP

In order to examine the stress distribution in more detail, the variations of stresses along diametric path C-D through the middle point of the overlapping zone (see Figs 3 and 4) are shown in Fig. 5. In Fig. 5, the stresses are normalized with respect to the corresponding axial stress at the predicted ultimate state in the corresponding axisymmetric model (i.e. without an FRP overlap) so that the stress distributions of different specimens can be compared. The radial positions shown in Fig. 5 can be identified by referring to Figs 3 and 4. Fig. 5 shows that both the axial and confining stresses (i.e. hoop stress and radial stress) reduce from the middle point of the overlapping zone (point C) to its diametrically opposite point D. The maximum axial stresses at point C are approximately 17% and 12% higher than those at point D for the one- and two-layer specimens respectively. The results from the axisymmetric models are also presented in Fig. 5 for comparison. Because the radial stress is equal to the hoop stress in the axisymmetric model, only one of them is shown for each model in Fig. 5b. It is clear that the overlapping zone results in a non-uniform stress distribution in the concrete (Figs 3-5).



(a) Axial stress distribution **(b) Radial and hoop stress distributions**

Figure 5. Stress distributions along path C-D

The ultimate axial strain and strength of the FRP-confined concrete in the axisymmetric model are higher than the ultimate axial strain and average axial stress in the model with an FRP overlap as the stress concentration due to the overlap induces premature rupture of the FRP wrap in the latter. This explains why the average ultimate axial stress of the model with an FRP overlap is smaller than 1.0 when normalised by the ultimate axial stress of the axisymmetric model (Fig. 5a).

Figs 3 and 4 also show that the stresses in the concrete vary significantly near both circumferential ends of the FRP wrap. Both the axial and the confining stresses at these locations are considerably lower than those in their adjacent regions. The lower confinement in turn causes a larger expansion of the concrete, which may amplify the local circumferential bending of the FRP wrap; such local bending has been identified as a major cause for the premature failure of the FRP wrap at these locations [6].

4. Conclusions

This paper has presented a three-dimensional finite element investigation into the stress state in FRP-wrapped circular concrete columns considering the actual FRP wrap geometry used in laboratory tests and practice. The results have shown that FRP wraps with an overlapping zone lead to non-axisymmetric confinement to the concrete and hence a non-uniform stress distribution in the concrete, even when the concrete is under uniform axial shortening. It has also been identified that both the axial and the confining stresses in the concrete are considerably lower near both circumferential ends of the FRP wrap than those in their adjacent regions. The lower confinement in turn causes a larger expansion of the concrete, which may amplify the local circumferential bending of the FRP wrap; leading to premature failure of the FRP wrap at these locations

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