PRESTRESSED FIBRE REINFORCED POLYMER (FRP) LAMINATES FOR THE STRENGTHENING OF REINFORCED CONCRETE STRUCTURES

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Abstract. Recent development in the field of strengthening has seen the application of prestressing of FRP laminate prior to bonding in order to exploit its high tensile strength. The method of prestressing the laminate induces an initial tensile strain in the concrete beams upmost fibre, thus reducing the deflection of the beam throughout the design loads. This alteration of the beams structural characteristics provides advantages in beam serviceability requirements. Structurally the beam can withstand greater ultimate loads, while yielding of internal reinforcement and cracking moments are delayed substantially, compared to unlaminated beams. Extensive experimental investigations have been undertaken by many researchers with variables ranging from anchorage type, number of laminates applied to beam, tensile reinforcement ratio and the initial prestress level of laminates before bonding. Despite the large amount of experimental data in the field, current analytical models generally employ elementary procedures in predicting beam behaviour and as a result the analytical results exhibit poor correlation with the experimental results. This implies the necessity for the development of a generic model that can accurately predict beam behaviour that will be the basis of the present study. The focus of this paper is the development of a new analytical model that can accurately predict the behaviour of an RC beam strengthened with an externally bonded (EB) prestressed fibre reinforced polymer (FRP) laminate. The model will be critically compared to an experimental database for calibration purposes then applied in a parametric study.

1. Introduction

As many reinforced concrete (RC) structures meet the end of their service life due to deterioration or the need to increase service loads, the development of alternatives to replacement are been found. Such an alternative is that of retrofitting the concrete structure with externally bonded fibre reinforced polymer (FRP) laminates. This technique suffers from many shortcomings including premature debonding; primarily intermediate crack debonding which affects flexural strength and ductility of the beam (Oehlers and Sercacino 2004). As the laminate debonds prematurely the full tensile strength of the laminate, in excess of 3700MPa is not achieved and therefore the method becomes inefficient. Recent development in this field has seen the application of prestressing of FRP laminate prior to bonding in order to exploit its high tensile strength. The method of prestressing the laminate induces an initial tensile strain in the concrete beams upmost fibre, thus reducing the deflection of the beam throughout the design loads (Yu et al. 2008). This alteration of the beams structural characteristics provides advantages in beam serviceability requirements. Structurally the beam can withstand greater ultimate loads, while yielding of internal reinforcement and cracking moments are delayed substantially, compared to unlaminated beams (Yang et al. 2008).

Extensive experimental investigations have been undertaken by many researchers with variables ranging from anchorage type, number of laminates applied to beam, tensile reinforcement ratio and the initial prestress level of laminates before bonding (Xue et al. 2008; Yang et al. 2008). Despite the large amount of experimental data in the field, current analytical models generally employ elementary procedures in predicting beam behaviour and as a result the analytical results exhibit poor correlation with the experimental results (Yu et al. 2008). This implies the necessity for the development of a generic model that can accurately predict beam behaviour; that will be the basis of the present study.

2. Moment-Rotation model

After cracking occurs in an RC beam the full interaction(i.e. there is no slip occurs between the reinforcement and surrounding concrete) approach becomes inaccurate and therefore using a partial interaction, moment- rotation approach is necessary. This approach has been developed at the University of Adelaide in the past few years and is most recently presented in Mohamed Ali et al.

(2009) and Haskett et al. (2009). Both approaches assume a single crack at mid-span about which the beam rotates, refer to Fig 1. This rigid body rotation can be idealised, as shown in Fig 3 (Haskett et al. 2009).

Concrete compression zone: In the analysis of the RC beam the concrete compression zone can be split into two regions; the concrete softening region and the concrete ascending region, refer to Fig 2. Equations have been derived to determine the force in each of these regions and are presented in Haskett et al. (2009) and Mohamed Ali et al. (2009), shown in Eqs.1&2. When developing the new model in this research, the two different cases will need to be taken into account for the compression region as presented in Mohamed Ali et al. (2009). Initially in the case where the maximum strain, $\varepsilon_{c,max}$, in the concrete is less than the peak strain, ε_{pk}, (Fig 2) then there will be no concrete softening i.e. no wedge forms. In this case a linear strain profile is assumed in the compression zone and therefore the force in the concrete can be found using the stress-strain relationship for concrete under uniaxial compression, as shown in Fig. 2 and Eq. 2. The second case is when the compressive strain reaches peak strain and therefore there will be a softening region with depth, d_{soft}, and length, L_{soft}, (Fig 1). Shear friction theory has been used to find the force in the softening region and this force can be found through knowing the stress at softening, σ_{soft}, which is dependent on the lateral confinement σ_{lat} of the concrete and the shear friction material properties, m and c, refer Fig 2 and Eq 2.

For $\varepsilon_{c,max} < \varepsilon_{pk}$ $$P_{cc} = \frac{f_c b \varepsilon_{c,max}}{\varepsilon_{pk}}\left[1 - \frac{\varepsilon_{c,max}}{3\varepsilon_{pk}}\right]\left[\frac{\varepsilon_{c,max} d_{asc}}{(\varepsilon_{c,max}+\varepsilon_r)}\right] \quad (1)$$

For $\varepsilon_{c,max} \geq \varepsilon_{pk}$ $$P_{cc} = P_{asc} + P_{soft}, \quad P_{asc} = \frac{2}{3} f_c b d_{asc} \quad (2)$$

$$\& \quad P_{soft} = w_b d_{soft}\left[\frac{c + \sigma_{lat}\cos\alpha(\sin\alpha + m\cos\alpha)}{\sin\alpha(\cos\alpha - m\sin\alpha)}\right]$$

Where: f_c is the concrete compressive strength; b is the width of the beam; d_{asc} is the depth of the ascending region; ε_r is the strain in the reinforcement; d_{soft} is the depth of the softening region and α is the angle of inclination of the concrete wedge.

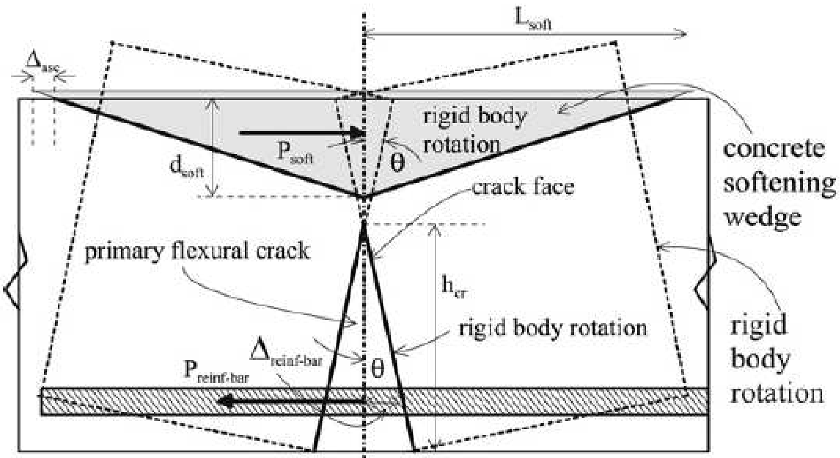

Fig.1 Idealised rigid body rotation

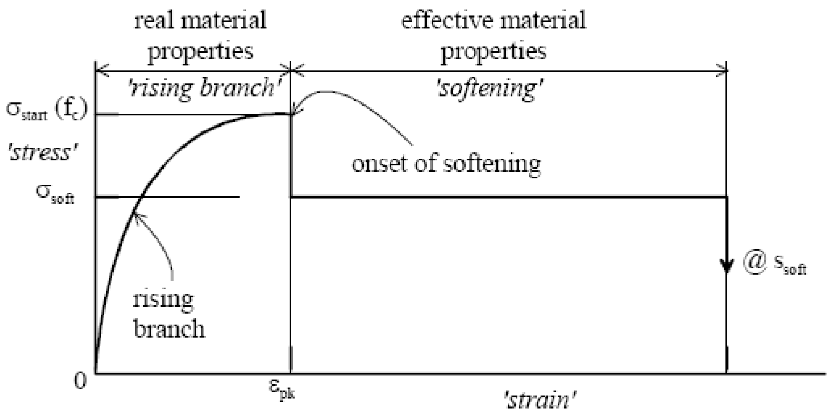

Fig.2 Stress strain relationship of concrete under compression

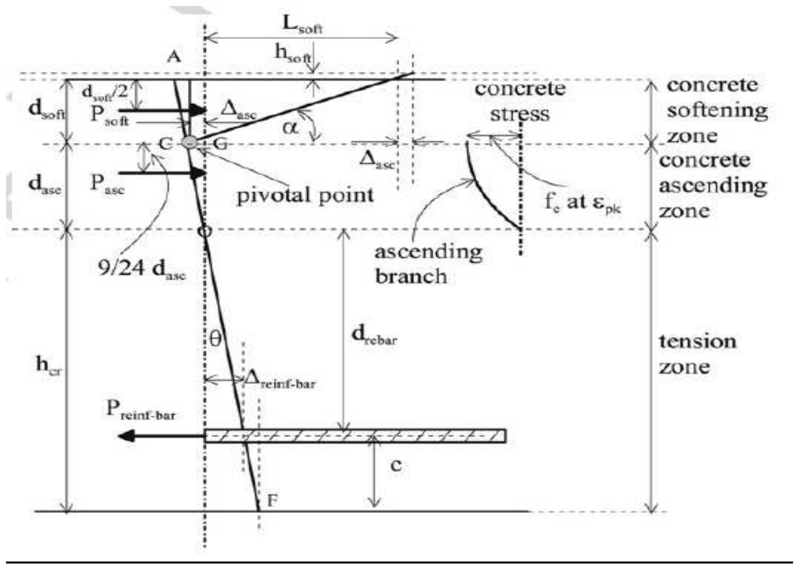

Fig.3 Moment-rotation analysis

Reinforcement force- slip relationship: The reinforcement force – slip relationship is critical in this approach as for a given slip (Fig 3), the corresponding crack width (twice the slip) and the force in the steel reinforcement can be found using derived equations. This force - slip relationship is dependent on the bond-slip characteristics between the reinforcement and the concrete. These characteristics, control the interface slip and hence the crack width and the rotation. Four typical idealized bond slip relationships are shown in Fig.4. For the model to be developed in this study, the uni-linear-descending relationship, line A-C, will be used as Eqs. 3-7, have been developed by Haskett et al. (2009) and Mohamed Ali et al. (2009), based on this relationship. These equations are presented below and will be crucial when developing our model. Two equations are shown for the force in the steel reinforcement as the force will vary depending on when the steel yields. For our model the equation for the force in the FRP reinforcement will need to be modified to incorporate the additional force due to the FRP laminate being prestressed. This additional force can be calculated through knowing the additional strain in the laminate due to prestressing as presented in Xue et al. (2009). The slip at yield can be determined by:

$$\Delta_{yield} = \delta_{max}(1 - \cos(\lambda_{el}\alpha_{el})) \qquad (3)$$

Where $$\alpha_{el} = \frac{\arcsin\left[\frac{A f_y \lambda_{el}}{L_{per}\tau_{max}}\right]}{\lambda_{el}} \qquad (4)$$

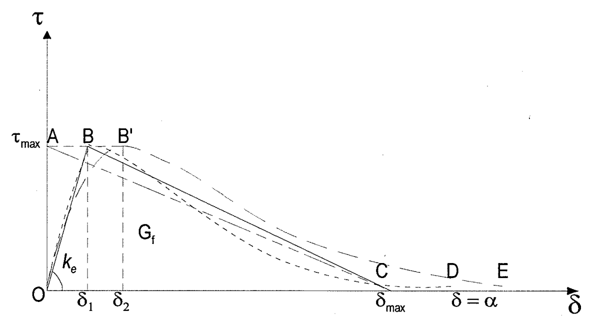

Fig.4 various interface bond characteristics

Equations for the force in reinforcing laminate and in reinforcing bar prior to yielding are:

$$P_{reinf-plate} = \frac{\tau_{max} L_{per}}{\lambda_{el}} sin\left\{arccos\left\{\frac{\Delta_{reinf-plate}}{\delta_{max}}\right\}\right\} \quad (5)$$

$$P_{reinf-bar} = \frac{\tau_{max} L_{per}}{\lambda_{el}} sin\left\{arccos\left\{\frac{\Delta_{reinf-bar}}{\delta_{max}}\right\}\right\} \quad (6)$$

$$P_{reinf-bar} = \frac{\tau_{max} L_{per}}{\lambda_{sh}} sin\left\{arccos\left\{\frac{\Delta_{reinf-bar} - \Delta_{yield}}{\delta_{max}}\right\}\right\} + A_r \sigma_y \quad (7)$$

Where $$\lambda_{el} = \sqrt{\frac{L_{per}\tau_{max}}{\delta_{max} E_s A}} \text{ and } \lambda_{sh} = \sqrt{\frac{L_{per}\tau_{max}}{\delta_{max} E_{sh} A}}$$

Where: τ_{max} is the interface bond-slip shear capacity (Fig 4); L_{per} and A are the perimeter and cross sectional area of the reinforcement respectively; δ_{max} is the bond slip capacity of the reinforcing ; E_s is the elastic modulus of the reinforcing material; E_{sh} is the strain hardening modulus of steel and $\Delta_{reinf-plate}$, $\Delta_{reinf-bar}$, Δ_{yield} are the slips at the reinforcing laminate, the reinforcing bar and at bar yield, respectively.

Through using the methods discussed above for finding the forces in the beam, an iterative approach can be used to allow for a moment-rotation relationship to be derived. Many pivoting points may be used when using an iterative approach; for the model in this research for ease of use, a depth of the softening region, d_{soft} will be initially assumed. Through knowing d_{soft} the slip of wedge can be found geometrically, which can then be used as the pivotal point in the analysis, i.e. change the rotation whilst keeping the slip in the wedge constant, until the force equilibrium is satisfied. Once the equilibrium is satisfied the moment for the given rotation can be found. This partial interaction, moment-rotation approach will be used for the analysis throughout loading. At every stage of the analysis, the limits on rotation will need to be checked. These limits are reinforcement debonding or fracture and concrete wedge sliding. The slip to cause FRP fracture, $\Delta_{fracture}$ (mm), and debonding, $\Delta_{debonding}$ (mm), are given as:

$$\Delta_{fracture} = \delta_{max}(1 - \cos(\lambda_{el}\alpha_{el})) \quad (8)$$

Where $$\alpha_{el} = \frac{\arcsin\left[\frac{A f_{fract} \lambda_{el}}{L_{per}\tau_{max}}\right]}{\lambda_{el}}$$

$$\Delta_{debonding} = \delta_{max} + \frac{\varepsilon_{\delta max} d}{2} \quad (9)$$

Where $\varepsilon_{\delta max}$ is the strain in the FRP laminate at debonding and *d* is the effective depth of the flexural member. The slip at which sliding failure, s_{slide} (mm), occurs is given by Haskett et al. (2009) as:

$$s_{slide} = 2.51\frac{\sigma_{lat}}{f_c} + 0.42 \qquad (10)$$

Where σ_{lat} is the confinement provided by stirrups, therefore if there are no stirrups then $\sigma_{lat} = 0$.

3. Typical results

A parametric study has been undertaken on beam to find the changes in strength at serviceability due to the increase of application of a prestressed FRP laminate with varying prestress level using the above model. The prestress level in this paper is referred to as the percentage axial strain applied compared to that of the ultimate axial strain of the FRP laminate. A small size beam is used with prestress level varying from 25 – 50% of the axial strength of the FRP laminate and is compared to that of a virgin beam with the same material properties. Fig.5 shows an increase in ultimate load as much as 230% is achieved with the application of a 50% prestressed laminate on the RC beam, in comparison with the unplated beam. Furthermore a decrease in ductility of 46% is achieved with the application of the 50% prestressed laminate. Despite the increase in ultimate load of over 2 times the virgin beam, it should be noted that the act of increasing the prestress level from 25% to 35% and 35% to 50% only increases the ultimate load by 10% and 11% respectively, which poses the question if the extra amount of prestressing is worth the gain in ultimate beam strength.

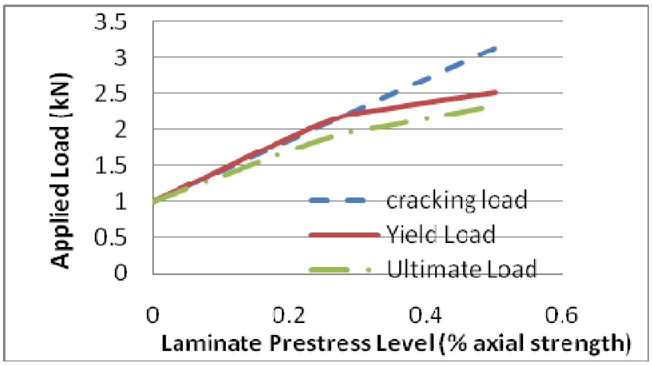

Fig.5 *Normalized-Load Milestones Vs. Laminate prestress levels*

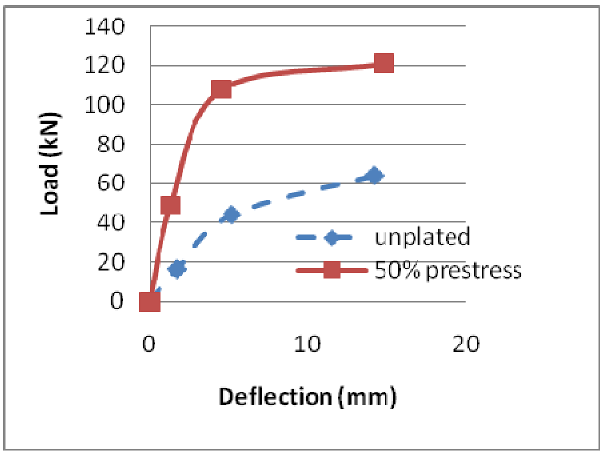

Fig.6 *Load Vs beam deflection*

The affects of cracking load on the beam due to prestress is similar to that of the changes in ultimate strength with an increase of over 300% been achieved due to the application of a 50% prestressed

FRP laminate. An increase in prestress level from 25% to 35% and 35% to 50% results in and increase in cracking load of 17% and 20%, respectively. These results and other findings suggest the preliminary conclusion that the ‘optimal’ prestress level lies somewhere between 25-45% of the axial strength of the laminate. From a serviceability perspective, the application of a prestressed FRP laminate greatly reduces the deflection of the beam throughout the design loads and up until ultimate failure. In reference to Fig.6**,** it can be seen that the presence of a prestressed laminate shifts the load-deflection curve in a vertical manner. The 3-points represented on from left to right are cracking, yield and ultimate, respectively. For example it can be seen that the load at 5mm deflection is increased by in excess of 200%.It can then be concluded that if the optimal prestress level does lie within the 25-45% region, then increases in prestress level of the laminate do not increase the ultimate load

ABSTRACT: The roof slab of a portion of a government public utility building situated in Colombo, Sri Lanka, comprises of precast – prestressed ‘T’ beams. There was a huge fire in this building and during the subsequent refurbishment of the building it was noted that the majority of the ‘T’ beams at this area were exhibiting distresses in the form of cracks. A thorough investigation conducted by the concerned authorities in conjunction with the University of Moratuwa concluded that the structural distress was due to event overloading onto the roof slab during the fire fighting operations. It was also concluded that a requirement of certain remediation and retrofit measures to the distressed elements were necessary to bring the ‘T’ beams back to their intended service performance level. This paper describes in detail the site case study of the repairs and retrofit that was carried out to achieve the desired design objective. Repairs to cracks were carried out using multi-port, low pressure resin injection, the retrofit was carried out using the Carbon Fibre Reinforced Polymer (CFRP) system, thus resulting in a quick, discreet and cost effective way to meet the design objective.

withstood, rather it will decrease the beams deflection.

4. Concluding Remarks

In this paper, a novel analytical model for estimating the rotation and deflection in RC beams bonded with prestressed FRP plate based on the rigid body displacement model at the University of Adelaide and the study is under progress and the model shows promise in estimating the optimal prestressing level for a given RC beam and FRP parameters.

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