ANALITYCAL STUDY OF THE RADIALLY STRESS DUE TO INITIAL TENSILE FORCE IN MANUFACTURING OF CFRP

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ABSTRAK

Material komposit berserat menerus yang dikenal dengan nama Fiber Reinforced Plastics (FRP) telah dianggap menjadi materil alternatif baru dibidang konstruksi yang dapat digunakan antara lain sebagai tulangan pada konstruksi beton bertulang. Berbagai serat sebagai bahan dasarnya telah dikembangkan seperti serat karbon, serat gelass dan serat aramid. Diantara sekian jenis FRP, salah satu yang memiliki sifat-sifat mekanis yang baik adalah FRP dengan bahan dasar serat karbon yang dikenal dengna nama Carbon Fiber Reinforced Plastics (CFRP). Saat ini ada berbagai jenis CFRP yang telah di produksi. Berdasarkan serangkaian pengujian, kegagalan suatu material CFRP dimulai dari terjadinya kegagalan geser (slip) antara serat dengan bahan plastiknya (bahan polimer) sehingga menimbulkan retakan-retakan mikro yang pada akhirnya menyebabkan konsentrasi tegangan. Untuk meningkatkan kapasitas geser (rekatan), maka telah dikembangkan CFRP yang dalam proses produksinya terlebih dahulu diberi tegangan awal (initial force). Hasil analisa menunjukkan bahwa dengan mentrasfer tegangan awal yang diberikan menyebabkan timbulnya tegangan radial disepanjang batang CFRP yang dapat meningkatkan kapasitas rekatan geser antara serat-serat dengan bahan plastic (resin matriks).

Keywords : *CFRP, Radial stress, Reinforcement, Stress, Concrete Structure*

INTRODUCTION

Fiber reinforced plastics (FRP) composites have been used in automobile, electronics and aerospace engineering for several decades, but their application in concrete engineering as a reinforcing material is relatively recent in origin. Besides the advantages in the field of developments of new fibers, etc., several developments in the construction industry have accelerated the effort to apply FRPs as a reinforcing material in concrete. Most of the reinforcement made of carbon fibers is produced by using the *pultrusion method*. In pultrusion method, the fibers are impregnated into the resin (prepreg) to form a FRP. The traditional motivation for using resin together with fiber to form FRP is to efficiently utilize the extraordinary strength and stiffness properties of small diameter fibers by embedding the fibers in a relatively ductile polymeric binder, or matrix (Figure 1).

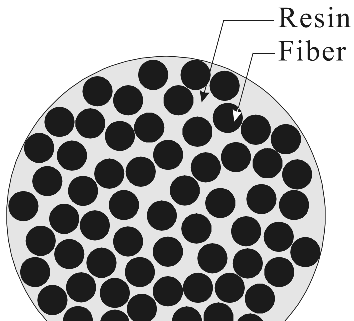

Figure 1. Section area of a FRP

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The basic function of the resin matrix is to hold the fibers together so as to prevent shear between them, to protect the fibers and to give them sufficient dimensional stability over the required range of service temperature.

In order to increase the shear capacity between fibers, a new manufacturing method namely UCAS has been introduced.

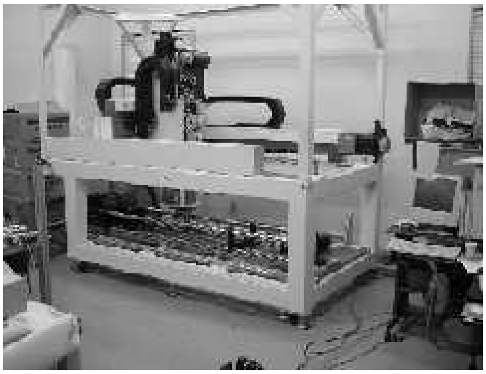

Figure 2. Assembler Robot of UCAS

BRIEFLY ABOUT UCAS METHOD

In UCAS the designated reinforcement system is manufactured by an assembler robot. The photograph of CFRP assembler robot developed for UCAS for manufacturing of prestressed CFRP is presented in Figure 2. To having an initial stress in CFRP as well as to efficiently utilize the extraordinary strength and stiffness properties of small diameter fibers, the unresin continuous carbon fibers (UCCF) are initially tensioned. The introduced initial tension stress is released when the resin matrix has completely hardened. This is an important key of this product in which the releasing of initial tensile stress generates a compressive stress in the rod. The lateral deformation of the section area due to the compressive stress is restrained by the wrapped carbon fiber strands. As the results, the radial stress along the rod length is generated (Figure 3). Detail about the manufacturing method of prestressed CFRP can be found in other author's papers.

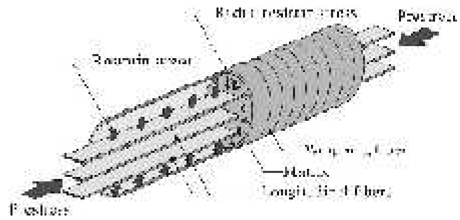

Figure 3. Illustration of Radial Stress

STRESSES OF CFRP

A theoretical approach was carried out in order to investigate the change of the stress in both carbon fibers and matrix due to the release of the tensile stress applied in the longitudinal carbon fiber strands at the manufacturing process. It was assumed that both carbon fibers and matrix undergoing are perfectly elastic, i.e. that they resume their initial form completely after removal of the forces. The matter of an elastic body is homogeneous and continuously distributed over its volume so that the smallest element cut from the body possesses the same specific physical properties as the body. To simplify the discussion it is also be assumed that for the most part the body is isotropic, i.e., that the elastic properties are the same in all directions. The CFRP as a composite material is very far from being homogeneous, but for simulation purposes it is hoped that the solutions of the theory of elasticity based on the assumptions homogeneity and isotropy can show the radial stress of the CFRP.

Linear relations between the component of stress and the components of strain are known generally as Hooke's Law that may be found at many engineering books. The relations between the stress and the strain are defined by two physically constants *E* and *v*. In the case of rod, the stress-strain relationship in the three dimensional polar coordinate illustrated in Figure 4 are:

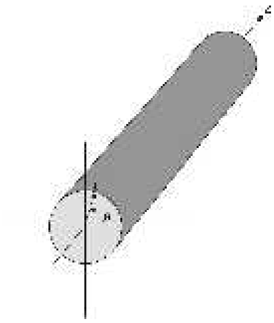

Figure 4. Polar Coordinate of Circular Section

$$\varepsilon_r = \frac{1}{E_p}\{\sigma_r - v(\sigma_\theta + \sigma_x)\} \quad \text{..............} (1)$$

$$\varepsilon_\theta = \frac{1}{E_p}\{\sigma_\theta - v(\sigma_x + \sigma_r)\} \quad \text{..............} (2)$$

$$\varepsilon_x = \frac{1}{E_p}\{\sigma_x - v(\sigma_r + \sigma_\theta)\} \quad \text{..............} (3)$$

where:

σ_r =radial stress (N/mm^2)

σ_θ =circumferential stress (N/mm^2)

σ_x =axial stress (N/mm^2)

E_p = Young's Modulus of resin (N/mm^2)

v = Poisson ratio.

The radial stress σ_r and σ_θ at any point along the rod is perpendicular to longitudinal direction *z*.

Here, it may be assumed that the wrapping strands along the longitudinal strands restrained the radial and circumferential strain. Based on the assumption mentioned, the circumferential strain and radial strain in the Eq.(1) and Eq.(2) could be assumed equal to zero. Under these assumptions, the Eqs. (1), (2), (3) could be simplified as follows

$$\sigma_\theta = v(\sigma_x + \sigma_r) \quad \text{..........................} (4)$$

$$\sigma_r = v(\sigma_\theta + \sigma_x) \quad \text{..........................} (5)$$

$$\sigma_r = \frac{v}{1-v}\sigma_x \quad \text{..................................} (6)$$

$$\sigma_\theta = \frac{\upsilon}{1-\upsilon}\sigma_x \quad \text{....................................} (7)$$

$$\varepsilon_x = \frac{1}{E_P}\frac{1-\upsilon-2\upsilon^2}{1-\upsilon}\sigma_x \quad \text{....................} (8)$$

$$E_P^{'} = E_P\frac{1-\upsilon}{1-\upsilon-2\upsilon^2} \quad \text{......................} (9)$$

$$\varepsilon_x = \frac{1}{E_P^{'}}\sigma_x \quad \text{..................................} (10)$$

Furthermore, if E_{cf}, E_p, A_{cf} and A_p are the Young's Modulus of carbon fiber, Young's Modulus of resin matrix, section area of carbon fiber and section area resin matrix, respectively, the relationship between the longitudinal carbon fibers stress (σ_{cf}) and the resin matrix stress (σ_{pl}) could be determined. Due to the releasing of initial tensile force applied in manufacturing of the longitudinal strands, the compressive stress generated in the rod. The relation between the change stress of the longitudinal carbon fiber and the stress of the matrix could be written as:

$$\frac{\Delta\sigma_{cf}}{E_{cf}} = \frac{\sigma_{pl}}{E_p^{'}} \quad \text{................................} (11)$$

$$P_t = A_{cf}(\sigma_{cf} - \Delta\sigma_{cf}) \quad \text{.........................} (12)$$

$$\sigma_{pl} = \frac{P_t}{A_p} = \frac{A_{cf}}{A_p}\left(\sigma_{cf} - \Delta\sigma_{cf}\right) \quad \text{............ (13)}$$

$$\Delta\varepsilon_{cf} = \frac{\Delta\sigma_{cf}}{E_{cf}} = \frac{1}{E_p^{'}}\frac{A_{cf}}{A_p}\left(\sigma_{cf} - \Delta\sigma_{cf}\right) \quad \text{....... (14)}$$

$$\Delta\sigma_{cf} = \frac{\dfrac{E_{cf}}{E_p^{'}}\dfrac{A_{cf}}{A_p}}{1 + \dfrac{E_{cf}}{E_p^{'}}\dfrac{A_{cf}}{A_p}}\sigma_{cf} \quad \text{...................... (15)}$$

$$n_{cf} = \frac{E_{cf}}{E_p^{'}} \quad \text{...................................... (16)}$$

$$\rho = \frac{A_{cf}}{A_p} \quad \text{.. (17)}$$

$$\Delta\sigma_{cf} = \frac{n_{cf}\rho}{1 + n_{cf}\rho}\sigma_{cf} = \lambda\sigma_{cf} \quad \text{........... (18)}$$

$$\lambda = \frac{n_{cf}\rho}{1 + n_{cf}\rho} \quad \text{................................. (19)}$$

$$\varepsilon_x = \frac{1}{E_P}\frac{1 - \upsilon - 2\upsilon^2}{1 - \upsilon}\sigma_x \quad \text{.................... (20)}$$

$$n_{cf} = \frac{E_{cf}}{E_p^{'}} \quad \text{...................................... (21)}$$

$$\rho = \frac{A_{cf}}{A_p} \quad \text{.. (22)}$$

$$\Delta\sigma_{cf} = \frac{n_{cf}\rho}{1 + n_{cf}\rho}\sigma_{cf} = \lambda\sigma_{cf} \quad \text{............. (23)}$$

$$\lambda = \frac{n_{cf}\rho}{1 + n_{cf}\rho} \quad \text{................................... (24)}$$

NUMERICAL EXAMPLE

By taken an numerical example for the 11 mm diameter rod made of 120 carbon fibers strands with parameters : carbon fiber strand section area=0.46 mm^2, Young's Modulus of carbon fiber = 230 GPa, Young's Modulus of resin matrix = 3.2 GPa, initial tension force applied in manufacturing of longitudinal strands = 1 kN, then the compressive stress at resin matrix due to the releasing of initial tension force is 60 MPa. and by using Eq.(6), the radial stress σ_r is 32 MPa.

CONCLUSIONS

According to an exploratory study presented in this paper, the following conclusions can be made:

(1) A new concept to improve the performance of the CFRP reinforcement was introduced.
(2) In order to increase the shear capacity between resin matrix and fibers, a radial stress along the rod should be introduced.
(3) The compressive stress generated in the rod as an effect of releasing the initial tensile stress in manufacturing process increases the shear capacity between fibers and resin matrix.
(4) Results of the exploratory study on the internal stress of the CFRP indicated that approximately 32 MPa of the radial stress could be expected by applying a tensile force of 1 kN in manufacturing.

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