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New modifying truss model and numerical simulation of steel fiber reinforced concrete under pure torsion

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ABSTRACT

This paper presents a new strut-and-tie model on steel fiber reinforced concrete (SFRC) members under uniform (Saint Venant) torsion. This truss model is intended to reproduce the structural behavior in ultimate limit state, once concrete is cracked. The proposed model is based on previous formulations developed by other researchers; the main novelty is the use of average value linear interpolation methods. The developed model can be considered for constant section members; can be applied to rectangular, T, L, circular, thin-walled, and single-cell and multi-cell hollow sections, among other shapes. Comparison with experimental and numerical results (developed through accurate finite element analysis) shows that the proposed model is more accurate than the proposed formulations.

1. Introduction

The fiber reinforced concrete technology has developed over 30 years, which has been used in some important cases of engineering applications, such as tunnels, highways and subway segments. It has been proven to be an applicable alternative for the conventional steel reinforcement in construction practices. For example, in Holland and Belgium [1,2], there were the elevated floors constructed by fiber reinforced concrete, which were tested to have higher performance on strength, deflection and ultimate strength than conventional RC members. The most efforts having done are the mechanical behavior in concrete which formed to be the constitutive laws in the main principles of FRC theory. Previous experiments have been focused on the flexibility, prismatic testing under tension, shear capacity and dynamic mechanical behavior [3–5]. Due to demands of structural design of steel fiber reinforced concrete arising, FRC has many potentials on future application. We intended to investigate torsional behavior of FRC, our purpose of this campaign was to find the best estimations of mechanical principles of FRC. Torsion is a common kind of mechanics existing in many structures, and torsional behaviors have always been found to be the combination of flexibility and shear, or the combination of bending and tension [6,7]. Since torsion is an important factor that affects structural safety, it is necessary to find a more suitable model to describe members subjected to torsion, in order to make accurate structural design possible, when fibers are applied in practice. Due to limitations of fiber reinforced concrete theories, none of standard codes on design process of fiber reinforced concrete has been published. Fiber committee has published the guidelines on the FRC structure design process, in order to enhance the probability on using FRC for structure [6]. But in many experiments, existing model fails to accurately predict torsional behavior of SFRC. Thus, we desired to improve accuracy and to modify existing model. Furthermore, in this paper we prepare to compare results of the fiber reinforced concrete subjected to the pure torsion to find out the most suitable methods of evaluating the torsional mechanics and finite element simulation. This new model of steel fiber reinforced concrete members subjected to pure torsion has featured the most suitable model on predicting service limited state and ultimate limited state when members are under pure torsion condition.

2. Torsion of members

2.1. Pre-cracking behavior

The basis of members subjected to torsion is shear flow theory, an assumption that the cross section is enclosed by shear flows when member is subjected to torsion. The Fig. 1 and Fig. 2 are shown as follows:

$$T = \int_A (\tau_x y - \tau_y x) dA$$

$$\frac{d\varphi}{dz} = \varphi' = \frac{T}{GI_t}$$

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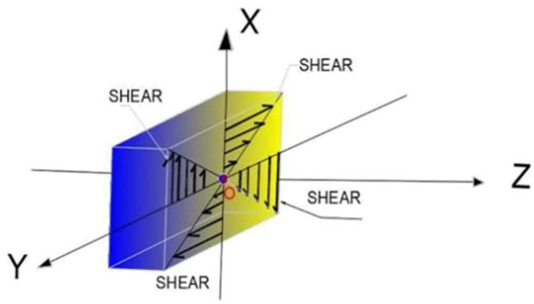

Fig. 1. The coordination of units under torsion.

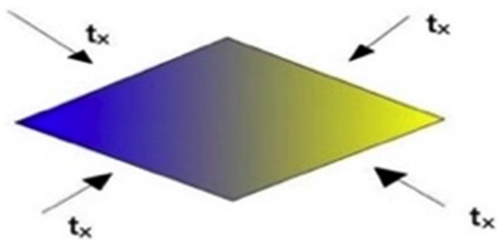

Fig. 2. Shear stress of unit.

$$G = \frac{E}{2(1+\gamma)}$$

where φ is the angles between two sections, *φ′is rate of twist*; a, b are longer and shorter dimensions of cross section, respectively. G, I_t is torsion module and inertial product; γ is poison's ratio. Once the tension strength exceeded ($\tau_x = f_{cm}$), the shear crack appears in the shear unit, seen from Fig. 2. (See Figs. 3 and 4.)

These formulations are used for predicting the torsion and describing of the rate of twist, where T is torque applied on unit; E is elastic module tensor, according to Eq. (1), shear stress is obtained, which is suitable in elastic deformation stage.

$$\tau_m = \frac{T}{\alpha a b^2} \tag{1}$$

Regarding the RC beam under torsion, a theory based on the pre-cracking Saint Venant theory and compression field theory was proposed by Mitchell and Collins (1974) [8]; Then, Vecchio and Collins (1999) proposed simplified theories [9,10] for calculating shear strength, which is based on the development of Truss-Strut model of torsion and thin tube shear resistance calculation. In this theory, he proposed that after cracking, the concrete will not carry tension but torsion will be carried by the field of diagonal compression. Some assumptions and models are shown as follows:

The circulatory shear q acting uniformly along the thickness t_d resists the external torque T. The element A is subjected to a shear stress of equal to q/t_d. The shear flow q enclosed the area $A_{0,}$ then the relationship of torque T and q is obtained from T\2q. The beam is curved under torque and no longer remained plane surface. When torsional strength reaches the cracking strength, diagonal helical cracks are developed near the cross section, after cracking, analogy of truss-strut theory is proposed for predicting torsional behavior resulting from shear stress flow developing around shear stress zone with a thin

Fig. 3. Cracked beam under torsion.

effective width. The diagonal strut curved and the capability, strain and curves related to twist of beam are obtained from Mohr's circle, it is shown as follows:

$$\varphi = \psi.\ Sin2\alpha = \frac{\varepsilon_{ds}}{t_d} \tag{2}$$

Based on such assumption, Hsu et al. (1988) [11] proposed the shear stress equilibrium equations considering the effect of FRP, which were deduced:

$$\begin{aligned} &-\sigma_d Cos^2\alpha = \rho_{sl} f_{sl} + \rho_{fl} f_{fl} \\ &-\sigma_d Sin^2\alpha = \rho_{st} f_{st} + \rho_{ft} f_{ft} \\ &\tau_{lt} = -\sigma_d Sin\alpha Cos\alpha \end{aligned} \tag{3}$$

where σ_d is the principle compressive stress; α is the inclination angle of the diagonal compression struts (crack angle); τ_{lt} is the shear stress; $\rho_{sl.}$ and ρ_{st} are the longitudinal and transverse steel reinforcement ratio, respectively; f_{sl}, f_{st}, f_{fs} and f_{ft} are the stress of steel reinforcement and FRPs in FRP, longitudinal and transverse directions; ρ_{fl} and ρ_{ft} are the ratios of the FRP materials in longitudinal and transverse directions, respectively.

The formulation of members subjected to torsion is based on the linear elastic theory proposed by Saint Venant in early 20th century. The torsional behavior is found normally in the beams or slabs, or beam-slab joints. Some reasons causing torsion are forces produced by the other parts of structures, furthermore, because of the eccentric loads influencing at the slabs or floors which produces twist angles at the ends of beams elements. Tensile strength of concrete is much lower than the maximum compressive strength of plain concrete. In strut-and-tie models, the stress tension and compressive stress form the magnitude 45 degree to axis of member, forming a helix at the 45^0 angles to the axis of beam. Equations are shown as follows:

$$T_e = \alpha.\ b^2 d f_{,t} \tag{4}$$

b is the breadth of beam, d is the depth of beam,α is 0.208 actually influenced by dimensions ratio,f_t is the maximum tensile strength. The result obtained by Eq. (4), denoted SLS1.

The Eq. (4) was tested to be limited in predicting the basic elements subjected to torsion. Then, considering the plastic theory used in equation, it is shown as follows:

$$T_p = \alpha_p.\ x^2.\ y.\ f_t',\ \alpha_p = \left(\frac{1}{2} - \frac{1}{6}\frac{x}{y}\right) \tag{5}$$

where f_t' is the maximum tensile strength, *x*,*y*are dimensions of cross-section, respectively. Results obtained from Eq. (5), denoted SLS2.

The reinforcement in the matrix of member is a significant factor to improve torsional performance. It has been extensively tested in previous research about FRC focusing on fibers improving the ultimate strength of member after post-cracking response, which are described in many literatures [12–18]. Therefore, fiber should be considered to affect the FRC torsional behavior in this paper.

3. Existing truss models for the members subjected to torsion

3.1. Post-cracking behavior

In the post-cracking stage, the concrete is considered to be the significant contributors when it is subjected to the loads. Elastic theory is often used for predicting the cracking strength which means the maximum strength in Serviceability Limit State (SLS). Likewise, the ultimate limit state of fiber reinforced concrete (ULS) is the maximum strength in post-cracking response, in which the stress after post-cracking stage reaches the maximum tensile stress. In this paper, SLS1, SLS2 are denoted as cracking strength by different formulations and names of each formulation as well, respectively; There are some specified formulations proved to be effective in predicting cracking