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Torsional responses of steel fiber-reinforced concrete members

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ABSTRACT

This study introduces two analytical approaches to estimate the torsional behavior of steel fiber reinforced concrete (SFRC) members. The first approach utilized the tensile constitutive relationship of SFRC in tension derived from SFRC panel test results, and the second approach adopted the direct tension force transfer model, which were applied to the smeared-truss model. In addition, three torsional members including two SFRC specimens with large amounts of transverse reinforcement were tested, and twenty-three SFRC torsional specimens were collected from literature to verify the proposed models. From this study, it appears that the proposed approaches provide enhanced analysis accuracy in estimating the torsional capacities of SFRC members, and closely capture their overall torsional responses compared to other models examined in this study.

1. Introduction

Steel fiber-reinforced concrete (SFRC) is a type of advanced composite material, in which conventional concrete is mixed with steel fibers having short length and diameter. SFRC is considered, in modern civil engineering and material science field, an alternative material to improve the brittle material characteristics of conventional concrete [1]. Many studies have been conducted since the 1960s on the tensile, flexural, and shear behavior of SFRC [1,2] members, and the superiority of its structural performance has been repeatedly substantiated. On this basis, it is expected that there will be growing demand for SFRC as a high-performance composite material in the construction market in the future. While the existing researches on SFRC, however, focused mostly on its tensile [3–6], shear [7–10], and flexural behavior [11,12], the number of studies on the torsional behavior of SFRC is still limited. It becomes now more important to consider torsional actions in design office than before, because modern buildings and civil infrastructures often include complex asymmetric structures or even free-form shapes.

Comprehensive understanding of the behavioral mechanisms of a SFRC member subjected to torsion is also becoming an important issue as its application increases [13]. However, torsional behavior of SFRC is not simple or easy to estimate accurately, due to complex inter-related mechanisms among the aggregate interlocking at crack surface [14], the dowel action of reinforcement [2,15,16], and in addition, the directionality [11] and bond performance of the steel fibers at crack interface. Also, force equilibrium and deformation compatibility in the three-dimensional body considering the effect of the strain gradient developed in the shear flow zone should be properly considered in the torsional analysis [17–19]. Some investigations were conducted on the torsional strength and behavior of SFRC members, but most such research focused on providing an empirical or semi-empirical design expression based on limited experiment results [20–22].

Since 1980s experimental and theoretical studies on torsion of SFRC members have been conducted by many researchers, and it is known that the addition of steel fibers into conventional concrete can enhance the stiffness, ultimate strength, rotational capacity and ductility, and crack control performance of torsional members [20–23]. Mansur and Paramasivam [24] and Craig et al. [22] simply adopted the tensile strength of SFRC for their torsional strength models, under the assumption that SFRC is a completely composite material made of steel fibers and concrete. This simple method, however, generally requires excessive experimental efforts through the various ranges of key influential factors. Narayanan and Kareem-Palanjian [20] proposed a torsional strength model by summing the torsional contributions of plain concrete (T_p), reinforcing steel (T_r), and steel fiber (T_f), which

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Notations

A_0	area enclosed by the centerline of shear flow, taken as $(A_c - (0.5)p_c t_d + t_d^2)$
A_c	cross-sectional area bounded by the outer perimeter of the concrete
A_l	cross-sectional area of longitudinal steels
A_t	cross-sectional area of one leg of stirrups
B	cross sectional width of member
$c_{\tau,pull}$	curve-fitting coefficient
d_f	diameter of fiber
E_c	elastic modulus of concrete
E_s	elastic modulus of the steel bars
E_{sf}	elastic modulus of the steel fiber
F	fiber factor
f'_c	specified compressive strength of concrete
f_{cr}	stress in concrete at cracking
$f_{cr,f}$	stress in concrete or SFRC at cracking
f_{ct}	direct tensile strength of material
f_l	stress of steel used in longitudinal directions
f_{ly}	yield stress of steel used in longitudinal directions
f_n	average yield stress of the embedded steel bars
f_r	modulus of rupture
f_s	average stress of steel bars
f_{sp}	splitting tensile strength of concrete
f_{ty}	yield stress of steel used in stirrups
f_t	stress of steel used in transverse directions
f_y	yield stress of bare steel bars
H	cross sectional height of member
k_c	ratio of the average compressive stress to the peak compressive stress in the concrete strut
k_{sf}	ratio of the average tensile stress to the maximum tensile stress of the steel fibers on the SFRC crack surface
k_t	ratio of the average tensile stress to the tensile cracking stress in the concrete sruts
l_f	length of fiber
p_0	perimeter of the centerline of shear flow, taken as $(p_c - 4t_d)$
p_h	perimeter of the centerline of closed stirrup, taken as $(2(x_0 + y_0))$
p_c	perimeter of the outer concrete cross section
q_{cr}	crack spacing control factor
q	shear flow
r	ratio of fiber cross section to its perimeter
s	spacing of transverse hoop bars(stirrups)
T	torsional moment
T_c	the strength attributable to concrete
T_d	the torque capacity contribution due to dowel action
T_f	the contribution of fibers to the ultimate torsional capacity
T_n	nominal torsional strength of SFRC
T_p	torsional moment of plain concrete
T_r	contribution of conventional reinforcement to ultimate torque
t_d	shear flow zone
V_f	volume fraction of steel fiber
x, y	smaller and larger sides of rectangular cross section
x_1, y_1	smaller and larger center-to-center dimensions of stirrup
x_0, y_0	smaller and larger center-to-center dimensions of stirrup in model
w_d	crack width of SFRC at the onset of decay
w_{sfrc}	crack width of SFRC member
α_2	angle of applied principal compressive stress with respect to l axis
β	deviation angle $(\alpha_2 - \alpha)$
γ_{21}	average shear strain in the 2–1 coordinate
γ_{lt}	average shear strain in the $l - t$ coordinate
δ_{sf}	the amount of fiber pullout $(w_{sfrc} - w_d)$
ε_o	strain at specified compressive strength of concrete
ε_1	average strain in the 1-direction
ε_2	average strain in the 2-direction
ε_{1s}	average surface strain in the 1-direction
ε_{2s}	average surface strain in the 2-direction
ε_{cr}	cracking strain
ε_d	average principal compressive strain
ε_{ds}	maximum principal compressive strain
ε_l	average strain in the l -direction
ε_n	average yield strain of the embedded steel bars
ε_r	average principal tensile strain
ε_{rs}	maximum principal tensile strain
ε_s	average strain of the steel bars
$\varepsilon_{sf,a}$	average tensil strain in crack surface when steel fibers reach at average ultimate bond strength
$\varepsilon_{sf,b}$	average tensil strain in crack surface when crack width is w_d
ε_t	average strain in the t -direction
ε_y	yield strain of the bare steel bars
ζ	softened coefficient of concrete in compression
η	reinforcement index, taken as $(A_t f_{ty} p_h)/(A_l f_{ly} s)$
η_0	length difficiency factor
η_l	orientation factor for fiber
θ	angle of twist per unit length
θ_u	ultimate angle of twist per unit length
ρ	steel ratio
ρ_f	bond factor that accounts for differing bond characteristics of the fiber
ρ_l	volume fraction of longitudinal steel used
ρ_t	volume fraction of transverse steel(stirrups) used
σ_1^c	average normal stresses of concrete or SFRC in the 1-direction
σ_1^{sf}	average normal stresses of steel fibers in the 1-direction
σ_2^c	average normal stresses of concrete in the 2-direction
σ_d^c	average principal compressive stress in conrete
$\sigma_{\max}^{sf}$	average maximum bond strength of steel fiber
σ_r^c	average principal tensile stress in concrete
σ_r^f	average principal tensile stress in SFRC
σ_l	applied normal stresses in the l-direction
σ_t	applied normal stresses in the t-direction
σ_{tu}	composite ultimate postcracking tensile strength
τ_{21}^c	applied shear stresses in the 2–1 coordinate
τ_{lt}	applied shear stresses in the $l - t$ coordinate
τ_u	ultimate bond strength of fiber
τ_{uf}	ultimate bond stress of steel fiber
$\tau_{u,pull}$	maximum interfacial shear strength during pullout
ψ_c	curvature of the concrete struts along the 2-direction
ψ_t	curvature of the concrete struts along the 1-direction

was determined from the space truss model [25]. In this model, it is assumed that concrete and steel fibers behave independently, and the torsional strength contribution of steel fibers is simply added into the torsional strength of a conventional reinforced concrete member. El-Niema [21] also proposed a torsional strength equation for a SFRC beam by adding the torsional contribution of steel fibers (T_f) to the torsional strength presented by ACI318-83 [26] code. In particular, for the torsional members with no