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Experiments and calculation of U-shaped thin-walled RC members under pure torsion

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ABSTRACT

U-shaped thin-walled RC (Reinforced Concrete) members have been widely applied in construction projects of urban rail viaduct in China. Researches about the torsional response of this kind of structures are extremely limited. Four large U-shaped thin-walled RC beams with both ends restrained were tested to investigate the pure torsional response. The detailed information includes torque–rotation curves, crack patterns, failure mode and steel bar strains. Typical flexural failures at support and mid-span where the warping moment predominates were observed in all four test specimens. And at quarter span, stirrups strain caused by circulatory torsion reached nearly 80% of total stirrup strains at failure stage, due to variable proportion between circulatory torsion and warping torsion after yielding of longitudinal steel bars. Finally, a simple method to calculate ultimate torque of such structures was proposed here. And it agrees well with tested results.

1. Introduction

Because of the advantages of U-shaped thin-walled RC members, namely the lower construction height, noise-isolating and attractive appearance, they are widely applied in urban construction of rail viaduct and the overpass bridges, such as in Shanghai Subway Line 6 and Nanjing Subway Line 2 [1]. However, research on behaviors of this type of structure is lagging behind. The existing studies about the U-shaped thin-walled RC beams are mainly concentrated on bending, but torsion will be an important factor considering transverse wind loads, cars swaying, eccentric loads in multilane and so on. In China, the torsional effect of U-shaped thin-walled members applied in construction is indirectly considered by improving the safety reserve in design of bending and shear capacity, because theoretical analysis and experimental study about U thin-walled members are very sophisticated and very scarce.

Effects of pure torsion depend on cross-section shapes and boundary conditions. Generally, only circulatory torsion is considered in members with closed sections, such as solid or box sections. For thin-walled open sections, if members are not restraint against displacements, there will be only circulatory torsion just like closed sections. This kind of torsion is also called St. Venant's torsion. Shear stresses corresponding to circulatory torsion will form a uniform closed shear flow around cross-section shown in Fig. 1(b), and it is uniform throughout the whole length of the member. However, according to Vlasov's theory [2], if both ends of members with open section are fixed against displacements (see Fig. 1(a)), another kind of torsion, namely warping torsion, appears to be non-ignorable. Referring to Fig. 1(c), shear flows corresponding to warping torsion cannot form a closed circle and it changes in magnitude along with the length of members. These two types of torsion actions appear simultaneously and their proportions depend on their respective stiffness, boundary conditions and length of members. In addition, warping (the effect is called warping moment) causes axial stresses as shown in Fig. 1(d). Warping normal stresses will also be a function to the length of the member reaching the maximum at the fixed ends [2,3].

After a century of exploration, there are lots of achievements in researches aimed at RC members with circulatory torsion. There exist two principal theories: skew bending theory and space truss model, among which the latter is more widely applied [4–12]. Deriving from space truss model, sophisticated theories have been proposed to simulate complex situations in RC members with closed sections, such as members for low loading levels [13], high-strength concrete members [14,15], cyclic loadings [16] and interaction of internal forces [17–19]. These theories have obtained convincing results to compute mechanical properties of members

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Nomenclature

A area of a section
A_s area of tensile steel bars
A_{sw} area of distributing steel bars
A'_s area of compressive steel bars
a cross sectional stiffness ratio
a' distance from center of top steel bars to top surface of concrete
a'' distance from center of bottom steel bars to bottom surface of concrete
b_w width of the cross section of flanges
$C = [ch(a\frac{l}{2}) - 1]/[a \cdot sh(\frac{al}{2})]$ evaluation coefficient for warping moment
E_c elastic modulus of concrete
f'_c crushing strength of concrete as determined from cylinder
f_c crushing strength of concrete as determined from standard prism
G shear modulus
$H_{\omega y}, H_{\omega x}$ sectorial linear static moment
h_{w0} effective height of cross section
$I_{\omega\omega}$ principal sectional moment of inertia
J_ω warping rigidity
K circulatory torsion (Saint Venant torsion) constant
l length of the U-shaped thin-walled member
$M_{fla,r}, M_{fla,left}, M_{bot}$ bending moment of both flanges and bottom slab respectively
M_ω warping moment
T total torque loaded at mid-span
T_c circulatory torsion
$T_{fla,r}, T_{fla,l}, T_{bot}$ ultimate torque calculated from both flanges and bottom slab respectively
T_ω warping torsion
x height of compressive zone
μ_θ ductility coefficient
θ angle of twist
σ_ω warping normal stress
ω principal sectorial area
$\zeta = f_c b_w h_{w0}/f_{yw} A_{sw}$ ratio between forces in concrete and forces in distributing bars

controlled by torsion or shear. But for thin-walled open members under torsion, there exist not only circulatory torsion but also warping torsion and warping moment. Warping action will cause changeable shear stresses and normal stresses when the deformations of both ends of the member are restrained. That is to say, the existing space truss model cannot be directly used to simulate torsional effects of thin-walled open members.

In 1935, Vlasov [2] created the sectorial coordinate system and generated formulas to calculate warping torsion and warping moment for thin-walled open section elastic members, which was called the elastic analysis theory of open thin-walled member. Kollbrunner and Basler [3] summarized elastic torsional effects of circulatory torsion and warping torsion of different torsional structures. Lately, many researches related to elastic torsional property of thin-walled open members were carried out in the following aspect: Influence of shear deformation [20–22], secondary warping effect [23], composite members [24–26], curved members [27,28] and combined actions of torsion, bending and shear [29,30]. Meanwhile, researches into torsional behaviors of thin-walled open members after cracking are rare. In 1968, Zbirohowski-Koscia [31] firstly paid attention to the post cracking behavior of the thin-walled open RC beams especially the effect of the warping moment. In 1981, Collins and Krpan [32] presented methods which were analogy to bending to calculate the elastic and plastic response of the open thin-walled RC beam in pure torsion and got the final ultimate strength through iteration. Experimental tests were conducted by Collins [33] to investigate the torsional response of a U-shaped thin-walled RC member. Although the experiment was terminated by the unexpected anchorage failure of the longitudinal bars, the results verified the rationality of Collins' iteration. Then stiffness matrix method is utilized to analyze prestressed concrete I-beams under combined mixed torsion, flexure and shear [34,35].

U-shaped thin-walled RC beams were implemented in urban rail viaduct more and more widely, but few research achievements in the torsional response are obtained. Torsional behaviors of four large-sized U-shaped thin-walled RC members will be experimentally studied here, to investigate propagation and distribution of cracks, relationship between torque and rotation, steel bars strains and failure mode. And a calculating method of the flexural cracking torque and the ultimate torque based on test results is to be suggested. This work will hopefully provide some helpful references to the design of the U-shaped thin-walled RC torsion members.

2. Experimental plan

2.1. Testing specimens

Referring to the measurement of the members applied in the Nanjing No. 2 rail transit, U-shaped thin-walled members shown in Fig. 2(a), were designed to investigate the torsional response. Its reduced scale is 1:4. Considering the thin-walled feature, thickness of vertical flanges and the bottom slab was designed for 70 mm. The height of vertical flanges and bottom slab are respectively 500 mm and 900 mm, which are almost seven times over the

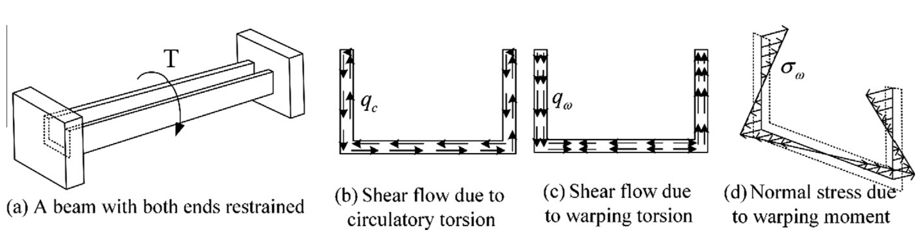

Fig. 1. Stress distribution of circulatory torsion, warping torsion and warping moment of U shaped member.