Journal of Constructional Steel Research 99 (2014) 140–148

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Effective stiffness of composite shear wall with double plates and filled concrete

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ARTICLE INFO

Article history:
Received 22 September 2013
Accepted 1 April 2014
Available online xxxx

Keywords:
Composite shear wall
Double steel plates
Filled concrete
Plane combination truss model
Effective stiffness

ABSTRACT

Shear walls are the primary lateral load-carrying elements in tall buildings. The composite shear walls with double steel plates and filled concrete are composed of two steel plates with studs inside, side columns made of steel tubing, and an infill of concrete. They were developed to enlarge the building space, and to delay the appearance of cracks by using the steel plates as formwork. This paper focuses on the effective stiffness of the composite shear walls. Despite many design practices addressing the shear stiffness by employing a stiffness reduction factor, a model named as plane combination truss model (PCTM) for the effective shear stiffness of the composite wall is proposed based on the theory of the fixed angle truss model in this paper. The formula for calculating the effective shear stiffness of the composite shear wall is derived based on this model. The total effective stiffness is obtained by combining the effective shear stiffness and the effective flexural stiffness, in which the flexural stiffness can be obtained by the fibre model. The predictions for the effective stiffness correlate well with the results of a series of tests on composite shear walls.

1. Introduction

Shear walls have always been playing a crucial role in the energy dissipation and seismic performance of tall buildings. The composite shear walls have advantages in their mechanical properties by combining the effect of two types of materials. As shown in Fig. 1, the steel plates can be used as the formworks for the concrete filler during construction and they can also delay the appearance of concrete cracks. The concrete in the composite wall can prevent early buckling of the steel plates and the steel tubes. With these advantages, the composite walls will be thinner than RC walls and they can be rapidly constructed due to their simple details.

Over the last two decades, many studies have been carried out on different proposed composite structures. Wright et al. [1,2] tested double-skin composite columns and beams and he also proposed related design methods. The double-skin-profiled composite shear wall system was developed in 1995 by Wright [3]. Link [4] used the composite shear resistant structures to resist offshore loads, and the results indicated that the walls were able to sustain a considerable post-peak residual strength for notably large deflections. The strength of the steel plates in the composite walls has been studied by Wright [3], Pryer [5], Liang [6] Xie [7], and experiments were conducted by Eom [8] and Rahai [9]. Previous researches have demonstrated the outstanding seismic performance of the composite shear wall. These studies mainly focused on the strength of the composite structures, whereas the stiffness has not yet been studied systematically. The shear behaviour is a key factor for shear walls. Since the year 1899, many researchers have proposed various shear models for concrete elements. Ritter [10] showed that a concrete beam could be simplified as truss elements with compression diagonals inclined at 45 degrees with respect to the longitudinal axis of the concrete beam. Mörsch [11] calculated the torsion reaction of the beam with truss models neglecting the concrete in tension. Following this breakthrough, many researchers put forth further efforts on truss models which can predict the shear force–deflection curves. Kupfer [12] proved that the inclination angle proposed by Mörsch is 15% to 25% larger than the results obtained with linear elastic model. Collins [13], Vecchio [14], Hsu [15] and Pang [16] proposed different truss models to predict the shear behaviour of RC panels. The models were known as the compression field theory (CFT), modified compression field theory (MCFT), the rotating angle softened truss model (RA-STM) and the fixed angle softened truss model (FA-STM), respectively. Furthermore, Bentz, Vecchio and Collins [17] reported a simplified method for MCFT based on a number of test results. Kim and Mander [18] proposed a method for calculating the stiffness of RC panels based on the principle of virtual work. Another method for calculating the effective stiffness of RC panels was proposed by Li and Xiang [19], which was verified by a number of tests. These shear theories mainly focus on RC components in which the steel bars are smeared as orthotropic materials subjected to shear forces. However, the properties of the steel plate in the composite shear walls are different from steel bars in RC walls because the steel plates behave in a planar stress state as the steel specimens conducted by Brando [20], who proposed proper strategies to

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http://dx.doi.org/10.1016/j.jcsr.2014.04.001
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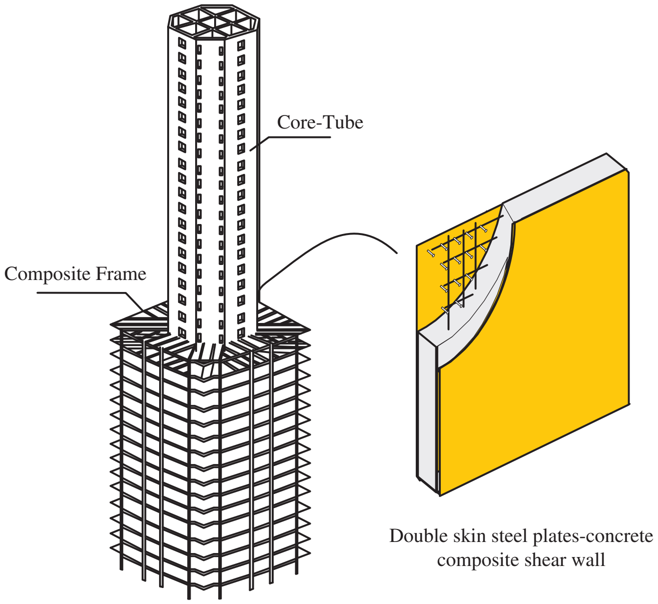

Fig. 1. Research background.

prevent the panels from buckling. Thus the models should be revised to account for this particular stress state, and the shear stiffness should be further studied for the composite walls.

In the present study, a plane combination truss model is proposed for calculating the effective shear stiffness of the composite shear walls based on the fixed angle truss theory. In this model, the planar stress state of the steel plates is considered, and the concrete is assumed to be smeared into struts after cracking. The formula for the effective shear stiffness is derived based on the truss model. A fibre element model is also suggested for calculating the flexural behaviour of the composite shear wall. Simplified formulas for calculating the effective flexural stiffness of the shear wall are obtained by data fitting. The effective stiffness of the composite wall is obtained by combining the effective shear stiffness and the effective flexural stiffness with the results verified by a series of tests.

2. Model for the effective shear stiffness

2.1. Plane combination truss model (PCTM)

Fig. 2a shows the stress state of cracked concrete elements based on the fixed angle theory. The horizontal and vertical coordinates are designated as an x–y coordinate system, which represents the coordinate system of the applied stress. The x'–y' coordinate system represents the direction of cracks and the direction normal to the cracks in concrete, respectively. The angle between the direction of cracks (y' axis) and the direction of the vertical coordinate (y axis) is defined as a fixed angle θ_c based on the fixed angle truss model theory. After cracking, the concrete is assumed to form smeared compression struts in the y' axis. The direction of the principal stress in concrete can be obtained via stress analysis, which is defined as the p–q coordinate system. The angle between the angle θ_c and the inclination θ_p of the principal compressive stress in concrete is defined as β. The fixed angle truss model assumes that β is close to zero when little difference exists between the longitudinal steel ratio and the transverse steel ratio, whereas β increases as the difference between the longitudinal steel ratio and the transverse steel ratio increases based on the experimental research by Pang and Hsu [16]. In this paper, β is set to zero because the longitudinal steel ratio is almost the same as the transverse steel ratio. When β is equal to zero, the principal stresses of the concrete in the p–q coordinate system are the same as those in the x'–y' coordinate system.

Fig. 3 shows the stress circle of concrete, from which the relationships between stress values are obtained in different coordinates. In the PCTM, the principal tensile stress of cracked concrete σ_t is assumed to be zero. The relationships between the stress values in different coordinates can be expressed as follows:

$$\begin{cases} \tau_{cx} = \dfrac{-\sigma_c \sin 2\theta_c}{2} \\ \sigma_{cx} = \sigma_c \sin^2\theta_c \\ \sigma_{cy} = \sigma_c \cos^2\theta_c \end{cases} \tag{1}$$

where σ_{cx} is the normal stress in the x-direction, σ_{cy} is the normal stress in the y-direction, τ_{cx} is the shear stress of concrete, and θ_c represents the inclination angle of cracking in the global coordinate system of x–y.

Although the local steel strains may be higher than the average steel strains, the proposed model assumes the conditions only in terms of average strains and stresses, as shown in Fig. 2b. The stress state of a steel plate element in the x–y coordinate system can be represented by a set of stress arrays: σ_{sx}, σ_{sy}, and τ_s. In the x'– y' coordinate system, the stress state of the steel plate element can be represented by the array $\sigma_{sx'}$, $\sigma_{sy'}$, $\tau_{s'}$, which have the similar meanings as those in the x–y coordinate system. The transfer equations are expressed as follows using the basic stress transformation techniques.

$$\begin{cases} \sigma_{sx'} = \sigma_{sx}\cos^2\theta_c + \sigma_{sy}\sin^2\theta_c - 2\tau_s\cos\theta_c\sin\theta_c \\ \sigma_{sy'} = \sigma_{sy}\cos^2\theta_c + \sigma_{sx}\sin^2\theta_c + 2\tau_s\cos\theta_c\sin\theta_c \\ \tau_{s'} = \left(\sigma_{sy} - \sigma_{sx}\right)\cos\theta_c\sin\theta_c + \tau_s\left(\cos^2\theta_c - \sin^2\theta_c\right) \end{cases} \tag{2}$$

2.2. Derivation of effective shear stiffness by PCTM

As shown in Fig. 4, the shear deformation includes two parts: the shortening of the concrete struts and the elongation of the steel plate

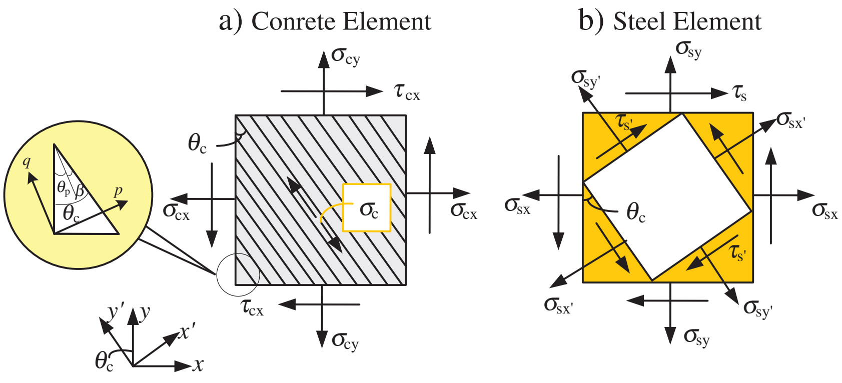
a) Conrete Element
b) Steel Element

Fig. 2. Stress state of the composite element.