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Analytical and numerical study of the shear stiffness of rubber-sleeved stud

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ABSTRACT

In some cases of designing headed stud, the shear stiffness of headed stud is much higher than needed, which will result in large stress in the some studs and concrete. However, the shear stiffness of ordinary stud is directly related to the shear strength and cannot be changed. Rubber-sleeved stud, which is a composite of ordinary stud and rubber sleeve, is a promising solution. Its shear stiffness decreases significantly with rubber sleeve height. Therefore, its shear stiffness can be controlled and designed by changing the rubber sleeve height. To calculate the shear stiffness of rubber-sleeved stud, an analytical model based on 'beam on elastic foundation' theory was established, and calculation method was developed taking into account the lower limit of shear stiffness. The ratio of rubber sleeve height to stud diameter was found to be the predominant factor. Compared to the push-out test results by other researchers, the calculation method slightly underestimates the value of shear stiffness. Moreover, finite element models were developed considering weld collar, residual stress, cyclic load and the nonlinear behavior of concrete under local loading. The results show that weld collar increases the shear stiffness while residual stress has negligible influence on it.

1. Introduction

The overall behavior of steel and concrete composite structures largely depends on the type of shear connector used to transfer shear forces at the interface between steel and concrete members. Though many new kinds of shear connectors have been proposed, headed stud is the most commonly used type of shear connector [1].

Headed stud has been investigated by numerous researchers worldwide. The static behavior of headed stud can be represented by shear stiffness in an elastic region, shear strength and shear load-slip curve. Shear strength of headed stud is the focus of most researches. The earliest research extends back to the 1950s. Viest [2] performed 12 push-out tests with varying ratios of effective depth-to-stud diameter, H_{ef}/D_s, where H_{ef} is the stud height from its base to the underside of the stud head and D_s is the stud diameter. Furthermore, Viest proposed one of the first formulas to assess the shear strength of headed stud as a function of concrete compressive strength and stud diameter. After that, plenty of push-out tests [3–5] were conducted on headed studs to consider the effects of concrete material property and stud diameter on the shear strength. Current design codes like Eurocode 4 [6] and ANSI/AISC 360-05 [7] are based on these results.

As for the shear stiffness of headed stud, Oehlers and Coughlan [8] analyzed 116 push-out tests and suggested the empirical equation of the shear stiffness as Eq. (1).

$$K_s = \frac{P_{\max}}{D_s(0.16 - 0.0017f'_c)} \tag{1}$$

where K_s is the shear stiffness equal to the tangent stiffness at the load of $0.5P_{\max}$; $P_{\max}$ represents the shear strength of headed stud. Lin et al. [9] conducted 40 push-out tests and proposed a formula as Eq. (2) for calculating the shear stiffness of headed stud which is defined as the secant slope of shear load-slip curves at the slip of 0.2 mm

$$K_s = 0.32 D_s E_s^{1/4} E_c^{3/4} \tag{2}$$

where E_s and E_c are the elastic modulus of steel and concrete respectively. Though the definitions of shear stiffness are different, both studies show that concrete material property and stud diameter have a significant influence on the shear stiffness of headed stud and there is a positive correlation between shear strength and shear stiffness of headed stud. That means that once concrete material property and stud diameter are decided under the design requirement of shear strength, the shear stiffness is determined indirectly. In other words, the shear stiffness of headed stud cannot be designed.

This characteristic of headed stud may bring some design problems when the shear stiffness is much larger than needed. Especially, in the

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case that a large number of headed studs are applied, the stiffness at the interface between steel and concrete members becomes so large that some headed studs suffer high shear forces. The study by Xue et al. [10] on the mechanical properties of headed studs in composite truss joint reported that the shear forces in the first few rows of headed studs are greater than others on the gusset plate. Machacek and Cudejko [11,12] studied on the shear connector arrangement of a simple truss and showed that the nonlinear distribution of the longitudinal shear forces depends on shear stiffness of the shear connector. Xu et al. [13] studied the design method of orthotropic steel deck composited with concrete slab by headed studs for railway through truss bridges. In such bridge decks, plenty of headed studs are used in order to decrease shear forces in headed studs, and the shear stiffness at the interface becomes very large. As a result, the concrete slab will be deformed with the bottom chord and steel deck, thus under high tensile stress.

These cases show that the shear stiffness of headed stud should be designable as the shear strength. Fig. 1 shows a kind of shear connector which is a composite of ordinary stud and rubber sleeve, named "rubber-sleeved stud". Push-out tests and numerical simulation show that its shear stiffness is significantly affected by the height of rubber sleeve [14,15]. So we can take advantage of the characteristic of rubber-sleeved stud to have a designable shear stiffness and overcome the problem of traditional stud. However, up to now the effect of rubber sleeve on the shear stiffness is studied mostly through empirical analysis, and the design method for this kind of stud is not established. Therefore, more theoretical study should be conducted.

In this study, an analytical model was established based on 'beam on elastic foundation' theory to evaluate the effect of rubber sleeve on the shear stiffness of headed stud. A formula verified by the experiment results was proposed to design the shear stiffness which is defined as the secant slope of shear load-slip curve at the slip of 0.2 mm. Additionally, considering the limit of 'beam on elastic foundation' theory, nonlinear finite element models have been developed. The effects of weld collar, residual stress and cyclic load on shear stiffness were evaluated. And the ratios of shear versus moment and shear versus axial force at the stud root were calculated.

2. Rubber-sleeved stud

Rubber-sleeved stud as shown in Fig. 1 is a kind of shear connector which is a composite of ordinary stud and rubber sleeve. Its shear stiffness can be controlled conveniently by changing the dimension of rubber sleeve. Xu et al. [15] fabricated and tested eighteen push-out test specimens according to Eurocode 4 [6]. 19 mm diameter and 100 mm height headed studs with different dimensions of the rubber sleeves were used. Fig. 2 shows the shear load–slip curves under monotonic loading for the studs with rubber sleeve height ranging from 0 mm to 75 mm. At low loading stage, the load increases almost linearly with the slip as a result of small deformation of the concrete and headed stud, and the load-slip curves are steep. Compared with ordinary stud, the variation of shear strength for rubber-sleeved stud is negligible, but the stiffness significantly decreases with the rubber sleeve height.

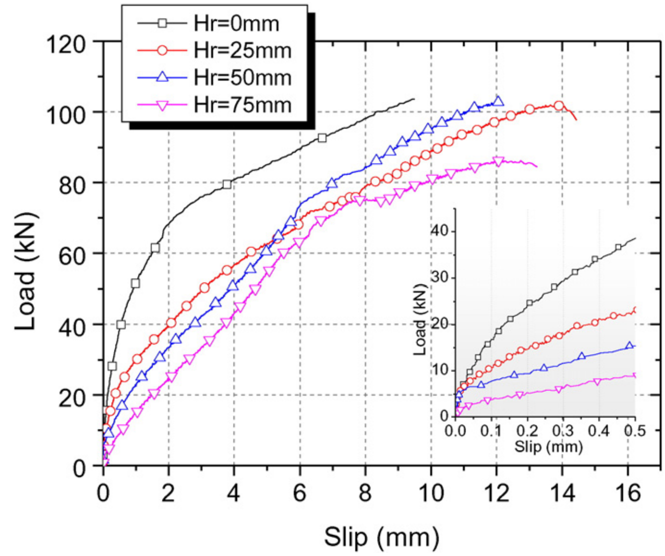

Fig. 2. Shear load-slip curves of shear connectors with different rubber sleeve heights [15].

Fig. 3 shows the failure modes of two kinds of studs, and the shear transfer mechanisms are illustrated in an idealized and simplified form. The root part of the stud bends, while the rest of the stud is almost fixed, especially the head of the stud. The length of bending part of rubber-sleeved stud is approximately equal to the rubber sleeve height H_r. The shear force P applied in headed stud is in vertical equilibrium with the reaction forces from rubber sleeve and concrete. Since the modulus of elasticity of rubber is much smaller than concrete, the stress in rubber sleeve is much smaller than that in concrete even though large compressive deformation occurs. Thus, q_{rubber} only has a small contribution to resist shear load. In order to maintain rotation equilibrium, moments at the root and head of the headed stud are induced. At the same time, since the concrete slab has a tendency of splitting from the steel member, an axial fore N at the root of headed stud is induced. This axial fore is resisted by the friction force along the stud and the horizontal reaction in head of the stud.

3. Analytical study

3.1. Shear stiffness of ordinary stud

The failure process of headed stud is a complicated nonlinear problem. However, if the shear stiffness at low load stage is considered, deformation is so small that concrete and steel can be taken as elastic material. At the same time, the friction force as well as the axial force along the stud can be neglected. Therefore, based on the shear mechanism of headed stud, the headed stud is analogous to a beam on an elastic foundation as Fig. 4 shows.

Fig. 1. Rubber-sleeved studs with different rubber sleeve heights.