Journal of Constructional Steel Research 133 (2017) 434–447

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental investigation into stud shear connections under combined shear and tension forces

M.H. Shen *, K.F. Chung

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, SAR, China

ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 13 February 2017
Accepted 16 February 2017
Available online 9 March 2017

Keywords:
Stud shear connections
Shear resistances
Push-out tests
Combined shear and tension forces
Load-slippage curves

ABSTRACT

In order to investigate structural behaviour of stud shear connections with both solid and composite slabs under combined shear and tension forces, a systematic experimental investigation with a total of six test series are conducted. These include 11 standard push-out tests where the shear connections are under shear forces, and 11 modified push-out tests where the shear connections are under combined shear and tension forces. It should be noted that the testing method of the standard push-out tests recommended in EN 1994-1-1 is adopted, and headed shear studs are installed in either "favourable" or "unfavourable" positions of decking troughs. Test results of all the 22 push-out tests are fully presented, and these include typical modes of failure, measured load-slippage curves as well as shear resistances of the test specimens. It is found that the shear resistance of the shear connection should be reduced with a factor of 0.84 for the case of a solid concrete slab, and a factor of 0.75 for the case of a composite slab, provided that the tension force T_n is smaller than or equal to 0.267 Q_m where Q_m is the shear resistance of the shear connection. These data will be adopted in subsequent numerical investigations for calibration of advanced finite element models. These models will then be used to perform parametric studies on stud shear connections with a wide range of geometrical configurations and loading conditions to provide additional data for formulation of design rules.

1. Introduction

In steel-concrete composite structures, effective shear connections are essential in all composite members in order to achieve good structural behaviour in resisting applied loads as well as in deforming consistently within the members. Stud shear connections are widely used in building structures in many parts of the world owing to simple installation. Among a number of different diameters, headed shear studs with a diameter of 19 mm and a height of 100 mm are widely used while the tensile strengths of the stud steel materials at 450 N/mm^2 are commonly specified. Owing to full development of a dowel action in the shear connections with solid concrete slabs, a typical value of the shear resistance at about 110 to 135 kN per stud is readily achieved.

In general, a stud shear connection should be stiff, strong and ductile, and as shown in Fig. 1, the load-slippage curve of such an effective shear connection may be described as follows:

a) In the initial part of the curve, the applied force is equal to at least half of the shear resistance, Q_m, i.e. 0.5 Q_m, at a small slippage, s, equal to 0.5 mm.
b) Along the loading part of the curve, the shear resistance, Q_m, is fully mobilized before or at a slippage of s_m, which is commonly taken as 6 mm.
c) Along the unloading part of the curve, the reduced shear resistance at a slip of s_u, which is commonly taken as 8 mm, should not be smaller than 0.8 Q_m.

Push-out tests have been widely employed to obtain the shear resistances of these stud shear connections. Based on various experimental investigations [7,12–14], the deformation characteristics of stud shear connections are generally considered to depend on:

a) compressive and tensile strengths of the concrete as well as sizes of aggregates;
b) yield and tensile strengths of headed studs as well as their shapes and sizes;
c) yield and tensile strengths of profiled steel deckings as well as their cross-sectional shapes and dimensions, if present;
d) dimensions of longitudinal stiffeners in the troughs of the deckings, if present;
e) number of headed studs per trough as well as their positions and spacings;
f) spanning direction of the decking, if present;
g) welding quality of headed studs, and dimensions of welding collars at stud roots;

* Corresponding author.
E-mail addresses: Stephanie.shen@aecom.com (M.H. Shen), kwok-fai.chung@polyu.edu.hk (K.F. Chung).

http://dx.doi.org/10.1016/j.jcsr.2017.02.021
0143-974X/

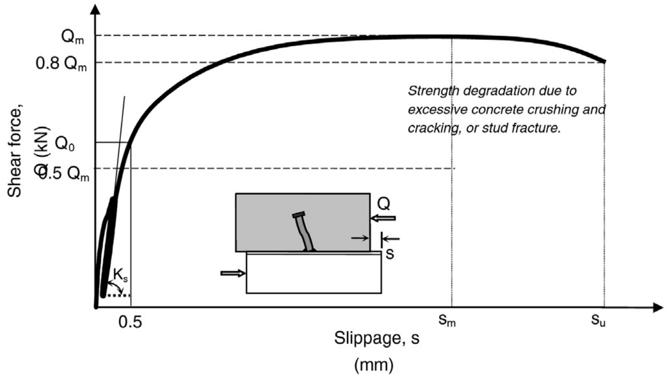

Fig. 1. Typical load-slippage curve of a shear connection with a solid concrete slab.

h) sizes and arrangement of steel reinforcements within the concrete slab in the vicinity of the studs;
i) orientation of steel-concrete interfaces during concreting (for preparation of test specimens);
j) friction along the steel-concrete interfaces, and
k) tilting and initial bedding of the test specimen in a push-out test.

Owing to a large number of factors which may affect deformation characteristics of the stud shear connections, significant variations in the test results obtained from push-out tests are often encountered. Hence, design rules on the shear resistances of these stud shear connections have been developed according to test results of a large number of push-out tests covering a wide range of material specifications and geometrical configurations, in particular for stud shear connections with composite slabs using profiled steel deckings.

1.1. Design rules for shear resistances

a) Stud shear connections under shear forces

According to the literature, a number of design methods for shear resistances of the stud shear connections with solid concrete slabs adopted in many modern design codes are based on the research work carried out by Ollgaard et al. [15]:

$$Q_m = \min\left(c_1 d^2 \sqrt{f_{cy} E_{cm}}, c_2 A_{sc} f_u\right) \quad (1)$$

where

d is the diameter of the stud shank (in mm);
A_{sc} is the cross-sectional area of the headed shear stud (in mm^2);
f_u is the tensile strength of the shear stud (in N/mm^2);
f_{cy} is the cylinder strength of the concrete (in N/mm^2); and
E_{cm} is the mean elastic modulus of the concrete (in N/mm^2).

$$c_1 = 0.29;\ \ c_2 = 0.80 \quad \text{EN 1994} \quad (2a)$$

$$c_1 = 0.29;\ \ c_2 = 0.80 \quad \text{EN 1994} \quad (2b)$$

It should be noted that the first part of Eq. (1) relates to conical concrete failure while the second part of Eq. (1) relates to fracture of a stud shank at its root under shear force. It has been adopted in many design codes, such as EN 1994 and AISC (2005) [2], each with different values of c_1 and c_2 as given in Eq. (2). Both c_1 and c_2 are calibration factors, and their values are based on various reliability analyses of test results reported in the literature. In EN 1994-1-1, c_1 and c_2 are adopted to be 0.29 and 0.80 respectively so that the shear resistance Q_m corresponds to a characteristic shear resistance with a lower 5% fractile among all the relevant test results. However, c_1 and c_2 are adopted to be 0.39 and 1.00 respectively in AISC (2005) [2] instead in order to give an average value of the shear resistance Q_m, i.e. a characteristic resistance with 50% fractile among all the relevant test results.

Pallares and Hajjar [9] reviewed 391 push-out tests with solid concrete slabs. After data analysis, four formulas are proposed to predict the shear resistance of stud shear connections under conical concrete failure while only one formula, i.e. $0.65A_{sc}f_u$, is provided for fracture of stud shank.

In addition, the following design expression is also available in the literature to evaluate the shear resistance of stud shear connections with solid concrete slabs:

$$Q_{m,Oehlers} = 5.0\left(f_{cu}/f_u\right)^{0.35}\left(E_{cm}/E_s\right)^{0.40} A_{sc} f_u \quad (3)$$

Eq. (3) is based on an analysis on 110 push-out tests reported by Oehlers et al. [13], and this is the basis of tabulated shear resistances of stud shear connections given in BS5950-3 [3]. Compared with Eq. (1), this expression reflects the effects of material properties of both the concrete and the stud steel in a rational manner although it is not able to identify explicitly the critical failure modes in the stud shear connections with different material specifications and geometrical configurations.

b) Shape factor for shear connections with composite slabs

According to EN 1994-1-1 [4], a shape factor, k_d, should be applied to the shear resistance of the stud shear connection obtained from Eq. (1) when a composite slab is present instead of a solid concrete slab. Such a reduction is found to be necessary to allow for the presence of the profiled steel decking, or more accurately, to allow for a reduced amount of concrete surrounding headed stud(s) in a decking trough. The shape factor, k_d, is given by:

$$k_d = \frac{0.7}{\sqrt{n_r}}\frac{b_o}{h_p}\left(\frac{h}{h_p}-1\right) \quad (4)$$

where

n_r is the number of headed stud(s) per trough;
h is the height of the headed stud respectively; and
h_p and b_o are the depth and the average width of the decking trough respectively.

However, there is little information on the limits of these dimensions as well as the geometrical configurations of the profiled steel deckings for which Eq. (5) is applicable.

For many modern profiled steel deckings which are designed to span in the range of 3.6 to 4.5 m, there is often a longitudinal central stiffener, with a typical height of 5 to 8 mm, present at the bottom of each of the decking troughs. These stiffeners are provided intentionally to increase the hogging moment resistances of the decking under compression over internal supports. This requires the headed studs to be located off-center. However, no specific guidance on the design using off-centre headed studs is given in EN 1994-1-1 although some detailing rules in BS 5950-3 may be adopted. As shown in Fig. 2, an important dimension, e, is established as the mid-height distance from the centreline of the headed stud to the web of the decking trough. Hence, for any headed stud installed in either the “favourable” or the “unfavourable” position of the decking trough, the value of k_d given by Eq. (2) above should be determined with b_o being taken as 2 e according to BS 5950-3.

c) Stud shear connections under combined shear and tension forces

According to Clause 6.6.3.2 of EN 1994-1-1, the effect of tension forces on stud shear connections with solid concrete slabs may be