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Design shear resistance of headed studs embedded in solid slabs and encasements

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ABSTRACT

This paper presents the results from reliability analyses on the design resistance of headed stud connectors embedded in solid concrete slabs and encasements. The present study substantially extends the earlier reliability work for Eurocode 4 by considering a database of 242 push tests, which permits the results presented to be considered valid over a wide range of characteristic compressive concrete strengths ($8 \le f_{ck} \le 90$ MPa) and stud diameters ($12.7 \le d \le 31.75$ mm). As well as considering the performance of the existing Eurocode 4 design model, two alternative design models were also studied. Although the design models for steel failure performed well, it was found that the current target value of $\gamma_V = 1.25$ was not justified in the design models for concrete failure. In response to this finding, the design models were modified to ensure that the target value was delivered. In the interests of harmonization between the Eurocodes, further improvements were made to enable design equations to be proposed that deliver a uniform value for the partial factors, which may be considered worthy for inclusion within the second generation of Eurocode 4. Finally, from the significant number of tests considered in this paper, a revised procedure is presented for evaluating the characteristic resistance of stud connectors from small numbers of nominally identical push tests.

1. Introduction

Shear connectors embedded in solid concrete slabs or encasements are critical in transferring the longitudinal shear forces within composite steel and concrete structures. The load-slip performance of shear connectors have been established from push test specimens, which were first devised in Switzerland in the early 1930s [1]. Following the development of the electric drawn arc stud welding apparatus in the early 1950s, the headed stud connector became one of the most popular shear connector type; this was accompanied by extensive push test investigations in North America between 1956 and 1959 at the University of Illinois [2] and Lehigh University [3]. From considering push test data on headed stud connectors, empirical design equations were developed to describe their resistance, which have continuously been updated and improved as further test data became available.

For the 1985 draft of Eurocode 4 [4], the key reliability studies that considered the design resistance of stud connectors were undertaken by Roik et al. [5], followed by Stark and van Hove [6], using a procedure [7,8] that was later updated and implemented within EN 1990 [9]. From considering the results of 75 push tests, these studies demonstrated that a partial factor of $\gamma_V = 1.25$ was appropriate for stud diameters of between 15.9 and 22 mm and mean compressive cylinder strengths f_{cm} of between 16.6 and 59 MPa, which broadly correspond to the concrete strength classes given in the draft Eurocode 4 and Eurocode 2 [10] at the time of C12/15 and C50/60. (N.B. Strength classes are defined as Cx/y for normal weight concrete, where x and y are the characteristic cylinder f_{ck} and cube $f_{ck,cube}$ compressive strengths, respectively). However, the final published version of Eurocode 4 [11,12] covers a wider range of concrete strength classes of between C20/25 and C60/75 (cf. the final version of Eurocode 2 [13], which permits classes between C12/15 and C90/105), as well as stud diameters between 16 and 25 mm. When these reliability studies were undertaken, not all of the product standards had been published so that the geometrical tolerances used were based on values that had historically been used to calibrate other national design standards.

Recently, Pallarés and Hajjar [14] conducted a reliability study on the shear resistance of headed studs embedded in concrete to justify the resistance factor ϕ in the 2005 AISC Specification [15] (N.B. $1/\gamma_V \equiv \phi$). However, the results from this work cannot be used directly in Eurocode 4 because, in the database of 391 results that was considered: some of the reported test data had previously been deemed to be incomplete to enable calculations to be undertaken [5,6]; tests on small-scale specimens were included [16], which were discarded in the earlier studies because of concerns that the performance may differ from normal scale behaviour [6]; and 134 of the tests were on special specimens that didn't satisfy the rules for the standard push test specimen in Eurocode 4.

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Push test investigations on headed studs have recently been undertaken with higher strength concrete and larger diameter studs than was considered in the original Eurocode 4 reliability studies, or by Pallarés and Hajjar. Moreover, work has commenced on the second generation of Eurocodes following the publication of mandate M/515 by the European Commission [17]. The mandate, inter alia, requires: a reduction in the number of National Determined Parameters (values of partial factors), thereby leading to an alignment of safety levels; harmonization between the Eurocodes; and assessment of discrepancies between calculation approaches within the Eurocodes and performance requirements in product standards. Given these recent developments, this paper presents the results from a new structural reliability study on the resistance of headed stud connectors, which extends the scope of the earlier Eurocode 4 studies to include 242 push tests. The expanded database of tests covers the full range of strength classes currently permitted by Eurocode 2 and considers a wider range of stud diameters (from 12.7 to 31.75 mm). As well as evaluating the partial factors for the current design equations, the performance of other design models are also studied, which may be considered as worthy candidates for inclusion within the second generation of Eurocode 4.

2. Design resistance of headed studs embedded in solid concrete slabs and encasements

An overview of the different design models considered in this paper is given in the following sub-sections. To facilitate comparisons, a graphical representation of the design models is presented in Fig. 1 in terms of the design resistance P_{Rd} of a headed stud connector versus the characteristic compressive cylinder strength f_{ck}. The data points in Fig. 1 correspond to the concrete strength classes given in EN 206 [18]. The solid lines shown in Fig. 1 indicate the range of concrete strengths where previous reliability studies have shown that a partial factor $\gamma_V = 1.25$ is justified for the respective design model. Conversely, the dotted lines indicate how far the design models could theoretically be extended, if justified by test evidence.

2.1. Basis for design model in Eurocode 4

A summary of the development of the empirical equations for the North American design standards is given by Pallarés and Hajjar [14]. The European design rules were strongly influenced by this North American work, and the ECCS Model Code for composite structures [19] gave the following equations for calculating the resistance of stud connectors:

$$P_{Rd} = \frac{0.36d^2\sqrt{f_{ck}E_{cm}}}{\gamma_c} \le \frac{0.7 f_y \pi d^2/4}{\gamma_a} \qquad \text{for } \frac{h_{sc}}{d} \ge 4.2 \tag{1}$$

$$P_{Rd} = \frac{0.28d^2\sqrt{f_{ck}E_{cm}}}{\gamma_c} \le \frac{0.7 f_y \pi d^2/4}{\gamma_a} \qquad \text{for } \frac{h_{sc}}{d} = 3.0 \tag{2}$$

For $3.0 \le h_{sc}/d < 4.2$, linear interpolation between Eqs. (1) and (2) is permitted.

where d is the diameter of the stud shank, f_{ck} is the characteristic compressive cylinder strength of the concrete, E_{cm} is the secant modulus of elasticity of the concrete, f_y is the yield strength of the stud material (but not $>0.8\, f_u$), f_u is the specified ultimate tensile strength of the stud material, h is the overall height of the stud, γ_c is the partial factor on concrete strength (taken as $\gamma_c = 1.50$) and γ_a is the partial factor on steel strength (taken as $\gamma_a = 1.0$).

Eq. (1) and (2) are essentially based on the work of Ollgaard et al. [20]. Whilst the reduction in stud resistance between $3.0 \le h_{sc}/d < 4.2$ is based on a relationship developed by Driscoll and Slutter [21].

The Eurocode 4 design equations have combined Eq. (1) and (2), but with the h_{sc}/d limit rounded down to 4.0. The resistance of headed stud connectors embedded in concrete is taken to be the smaller of the following two equations:

$$P_{Rd} = \frac{k_1 \alpha d^2\sqrt{f_{ck}E_{cm}}}{\gamma_V} \left(\text{`concrete failure'}\right) \tag{3}$$

$$P_{Rd} = \frac{k_2 f_u \pi d^2/4}{\gamma_V} \left(\text{`steel failure'}\right) \tag{4}$$

with

$$\alpha = 0.2\left(\frac{h_{sc}}{d} + 1\right) \qquad \text{for } 3 \le h_{sc}/d \le 4 \tag{5}$$

$$\alpha = 1 \qquad \text{for } h_{sc}/d > 4 \tag{6}$$

where k_1 and k_2 are coefficients for concrete and steel, respectively (see Table 1) and γ_V is the partial factor for the design shear resistance of a

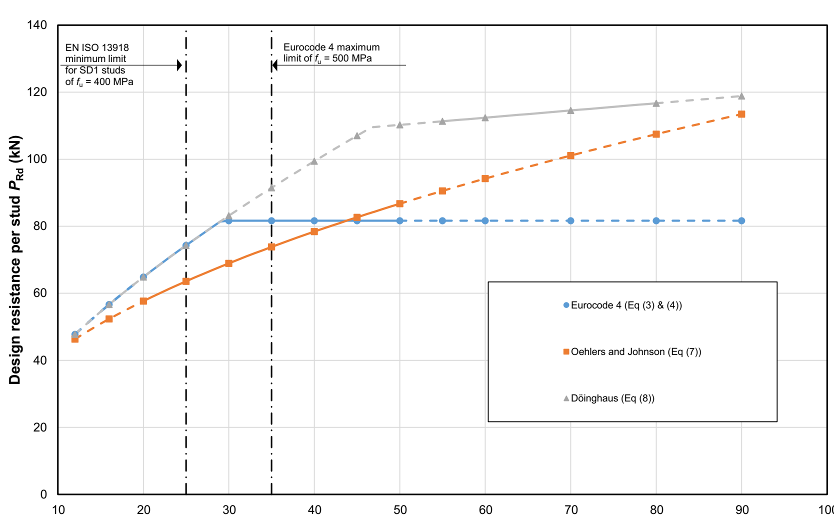

Fig. 1. Design resistance of headed stud connectors versus characteristic compressive cylinder strength of concrete with $d = 19$ mm, $f_u = 450$ MPa, $h_{sc}/d > 4$ and $\gamma_V = 1.25$ for design model according to: Eurocode 4 ($k_1 = 0.29$ and $k_2 = 0.8$); Oehlers and Johnson ($k = 3.66$); and Döinghaus ($k_2 = 0.92$ and $\eta_c = 1.84$).