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Autor(en): **Johnson, Roger P. / Yuan, Hui**

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Shear Resistance of Stud Connectors with Profiled Sheeting

Roger P. JOHNSON
Professor of Civil Eng.
University of Warwick
Coventry, Great Britain

Hui YUAN
Research Student
University of Warwick
Coventry, Great Britain

Summary

The static resistance to shear of stud connectors welded through profiled steel sheeting is a complex function of over 20 parameters. Study of the results of 269 push tests shows that none of three recent sets of design rules is valid over the full range of parameters. All can give errors around ± 30 %. Results are given of 34 new push tests, in accordance with Eurocode 4. Models are developed for 7 modes of failure. They lead to rules that predict all relevant test results (172) with a mean error of 2% and a coefficient of variation of 9.5%.

1. Introduction

Profiled steel sheeting is widely used as permanent formwork for composite floor slabs in buildings. Stud shear connectors for composite beams are placed in troughs in the sheeting, the span of which is normally either transverse to or parallel with the span of the beams. Predictions of the static shear resistance per stud, P_r, are based on resistances P_e found in push tests, and are often presented, as in draft Eurocode 4:Part 1.1 [1], in the form $P_r = kP_{rs}$, with $k \leq 1$, where P_{rs} is the resistance of a stud in a solid slab of the same concrete, and k is a reduction factor.

For many re-entrant profiles (e.g., Holorib, Bondek II), studs can be so located that $k \approx 1$. The many trapezoidal profiles in use give lighter composite slabs; but the studs may be less efficient ($k < 1$), especially where there are two per trough with one placed on the 'unfavourable' side (denoted U here) of a central rib (e.g., as in Fig. 1). In such situations, all recent design methods known to the authors have errors of prediction exceeding ± 30%. They do not identify which of the many failure modes is critical, and do not include all relevant parameters.

This paper is a summary of an extensive search for better design methods [2], more fully reported elsewhere [3]. It was found that the resistance P_r can be influenced by over 20 independent parameters. They are now listed, with relevant notation:

- the eight dimensions shown in Fig. 1, and the strength f_{yp} of the sheeting;
- the cylinder strength f_c, density ρ, and stiffness E_{cm} of the concrete;
- the ultimate strength f_u of the studs, and their number N_r per concrete rib;
- the spacings and positions of the studs relative to the sheeting: single studs in Unfavourable, Central, or Favourable positions in a trough of the sheeting, and pairs of studs loaded in Series, in Parallel, or in a Diagonal arrangement. (The upper case letters U, C, etc., are used below to refer to these layouts);

- the use of through-deck or through-hole welding;
- the use of non-standard push tests, especially with studs at only one level in each slab, or with the slabs 'on end' when cast;
- the size, spacing, and level in the slab of reinforcement, if any.

Most publications of push-test results fail to give data on all these parameters, and few describe modes of failure. This led to the exclusion of many reported results from this work, the stages of which are now listed.

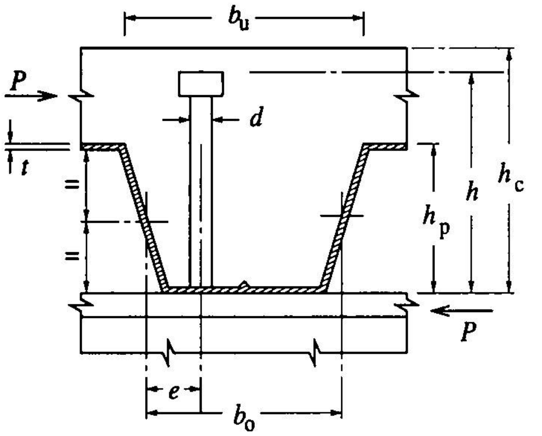

Fig. 1 Shear connector in a composite slab

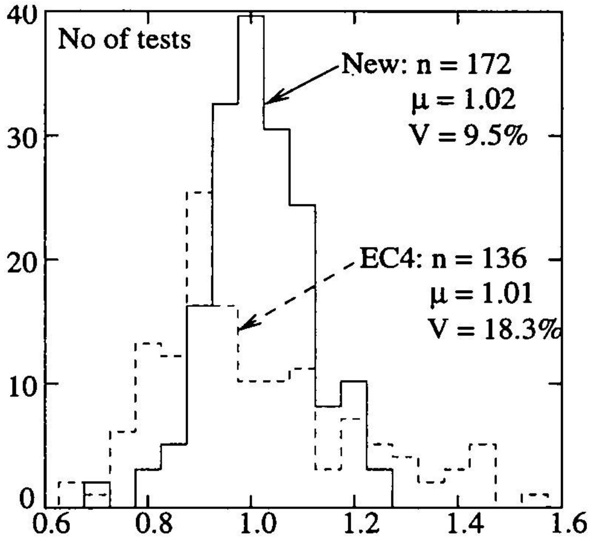

Fig. 2 Histograms of P_e/P_r for 172 push tests

2. Method, and principal conclusions

(1) All available push-test results (269) were studied, and 66 that lacked data were rejected. This left only 20 with parallel sheeting, so that statistical work was done for transverse sheeting only. The 183 other results were placed in 8 groups, according to the method of welding, the number N_t of troughs per slab, and N_r. It was found using the statistical t and F tests and the design rules of Eurocode 4 that, with 95% probability, these data were samples from seven different populations. The 14 through-hole results were about 20% weaker than the others, so they were excluded from further study. This left five groups, with $8 \leq n \leq 66$, where n is the number of samples (tests) per group.

Table 1. Ranges of ratios P_e/P_r, with P_r given by three methods, after mean-value correction, for five layouts of studs

Range of:	1, central	1, unf.	1, fav.	2, parallel	2, series
b_o/h_p	0.7 - 2.6	2.4 - 3.2	2.0 - 3.2	1.3 -3.1	2.0 - 3.2
δ_{EC}	0.7 - 1.3*	0.7 - 1.1	0.9 - 1.4	0.6 -1.4*	0.7 - 1.4
δ_L	0.7 - 1.3*	0.8 - 1.4	0.8 - 1.2	0.6 - 1.2*	0.7 - 1.2
δ_H	0.8 - 1.3			0.7 - 1.3	

*excluding one very high result

(2) Three design methods were studied, denoted by subscripts EC, for Eurocode 4; L, for a proposal by Lawson [4], and H, for work by Hanswille [5]. For each test and design method, the ratio b_i (= P_e/P_r) was found, and the mean value μ_b calculated for each group and design method. Values δ, given by $\delta = P_e/\mu_b P_r$, were then found. Their ranges are given in Table 1 for each group and design method. It is evident that, even with mean-value correction, each method has errors of at least ± 30%, and for more than one group. The most important independent variable is probably the breadth/depth ratio of each trough, b_0/h_p, so the ranges of values present in these data are also given.

(3) The widest gaps in the data were narrowed by doing 34 new push tests, as specified in Eurocode 4. There were 17 matched pairs, which included 6 different profiles, with ratios b_0/h_p (Fig. 1) ranging from 1.75 to 3.2; three sheet thicknesses; three concrete densities; single studs in U, C, and F positions; and pairs of studs in S, P, and D arrangements. In most specimens the slab reinforcement, a light mesh, was at or above the heads of the studs. Its influence, if any, was neglected in subsequent work. The load-slip curves are on record [2]. The slip capacities, defined as the slip at which the load first fell to 80% of its peak value, ranged from 2 mm to 16 mm, based on the lower of the results from a pair of tests. The 17 pairs of failure loads per stud differed, on average, by only 3%, which is exceptionally low for push tests.

The observed failure modes are denoted:

- CPT, concrete pull-out; SS, shank shear; RP, rib punching; and combinations of these, for transverse sheeting;
- CPP, concrete pull-out; and SP, splitting, for parallel sheeting.

(4) Theoretical models for the prediction of the failure mode and the resistance P_r were developed for each of the five modes for transverse sheeting and two for parallel sheeting. The introduction of new parameters, such as the thickness of the sheeting, reduced the number of existing tests with sufficient known data from 203 to 138, plus the 34 new ones. These results were used to determine certain coefficients in the expressions for P_r so that, as expected, the mean of the 172 values was, at 1.02, close to 1.0. The significant result is evident in the histogram of P_e/P_r for the new methods (Fig. 2), for which the coefficent of variation is only 9.5%, less than half that previously achieved. For example, the histogram for tests with transverse sheeting given by the methods of Eurocode 4, Fig. 2, has V = 18.3%, and that for parallel sheeting (36 tests) has $\mu = 1.66$, V = 35%.The failure mode was predicted correctly for all the tests except 9, where CP failure was predicted, and SS failure occurred, at a higher load.

(5) The new expressions for prediction, outlined in the next Section, are rather complex; but their use does not involve trial and error. If they are applied to studs and sheeting of given properties, with a given layout of studs, the properties of the concrete are the only independent variables.

Advantage was taken [2] of the implicit inter-relationships that exist between the combinations of the parameters that occur in practice, to develop simpler but empirical resistance functions for studs in transverse sheeting, as described elsewhere [3]. They give a histogram of 136 values of P_e/P_r with $\mu = 1.03$, $V = 10.5\%$. Thus, the simplified rules are almost as good as the more complex ones; but they are not based on mechanical models, and should not be used outside their defined scope.

(6) Both the general and the simplified methods give predictions for the mean value of the resistance P_r. The characteristic value P_{rk} and the partial safety factor γ_M ($= P_{rk}/P_{rd}$, where P_{rd} is the design value) should be based on statistical analyses. The number of sets of data, n, exceed 20 for only one group of the data, tests on transverse sheeting with one stud per trough and two troughs per slab, for which $n = 51$. Analysis of this group led to: $P_d = 0.75\, k\, P_{rs}/\gamma_M$, with $\gamma_M = 1.25$, the value given in Eurocode 4. There are many reasons [3] why the authors consider that the coefficient 0.75 is too low. It should probably be increased to between 0.9 and 0.95; but that still leaves a step, when $k \approx 1$, of between 5% and 10% between the new method and that of Eurocode 4, because in that code, the 0.75 factor is 1.0.

Test data are not yet sufficient to show clearly how best to bridge this gap, so the main basis for the safety level of design rules will continue to be experience rather than theory. However, it is clear that the new models and rules provide more accurate predictions of both modes and mean resistances than do any others known to the authors.

The areas most in need of new test data are parallel sheeting; lightweight concrete; transverse sheeting with two studs per trough; minimum spacings of pairs of studs; and the influence of transverse reinforcement, especially on slip capacity.

3. Theoretical models, for both normal-density and lightweight concrete

3.1. Shank shearing, SS, for transverse sheeting

This is the expected mode of failure of a stud in a well-reinforced solid slab. The resistance was assumed to be as given in Eurocode 4 [1], and to be the upper limit for failures by other modes:

$$P_{rs} = 0.37\, A_s\, (f_c\, E_{cm})^{0.5} \leq 0.2\, \pi\, d^2 f_u. \qquad (1)$$

The limit set by the strength f_u of the stud material did not govern, in the present work. For the other modes of failure, $P_r = k_t\, P_{rs}$, with $k_t \leq 1$.

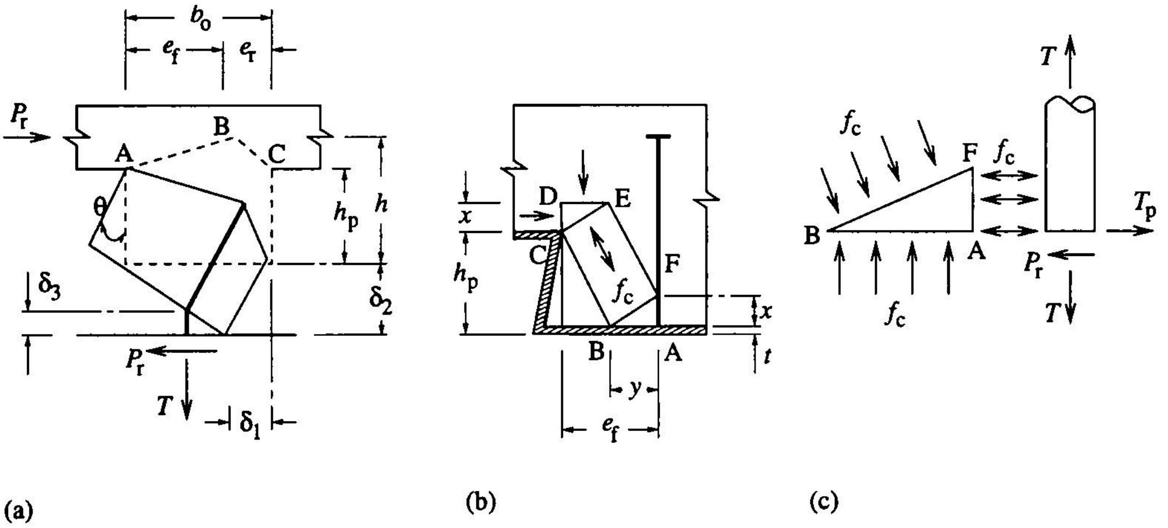

Fig. 3 Models for failure modes CP and RP, for transverse sheeting

3.2. *Concrete pull-out, CP, for transverse sheeting*

This mode is shown in Fig. 3(a). The slab is assumed to be free to separate from the steel beam. Torsional shear failure occurs at each end of a prism of concrete that includes the stud. Using a von Mises-type yield criterion for the stud and a rigid-plastic model for the concrete leads to

$$k = [\eta + \lambda(1 + \lambda^2 - \eta^2)^{0.5}] / (1 + \lambda^2) \tag{2}$$

where $\eta = 0.45 f_c^{0.5} h^2 (b_o - h/4) / (h_p N_r P_{rs})$, with $h \leq 2h_p$ (3)

$\lambda = e_r T_y / (h_p P_{rs})$ (4)

and $T_y = 0.2\,\pi\, d^2 f_u$ (5)

with notation as in Figs 1 and 3. The model is applicable where the number of studs per rib, N_r, is 1 or 2, and they are in locations C or F. If equation (3) gives $\eta > 1$, $\eta = 1$ is assumed. Equation (2) then gives $k = 1$, and shank failure is predicted.

3.3. *Rib punching, RP, for transverse sheeting*

This mode, shown in Figs 3(b) and (c), governs for studs in 'unfavourable' positions (i.e., $e_f < b_o/2$). At failure, a prism of concrete, of cross-section ABCDEF and length b_c, is assumed to be at uniform stress f_c. The force $b_c f_c y$ that it applies across surface AB is assumed to be equal to the tension T in the stud. The shear force P_r applied to the stud is resisted by the reaction $b_c f_c x$ from the concrete and force T_p arising from yielding of the sheeting in tension over a length b_p, normal to the cross-section shown. Analysis of this model and use of the test results leads [3] to equation (2) for k, with

$$\eta = 1.8\,(e_f + h - h_p)\, t f_{yp} / P_{rs} \tag{6}$$

$$\lambda = e_f T_y / (2\, h_p P_{rs}). \tag{7}$$

Where a pair of studs is placed with one near each side of a rib, one fails in mode RP and the other in mode CP.

3.4. *Splitting failure and concrete pull-out failure, for parallel sheeting*

The derivation of the following expressions is given elsewhere [3]. The model for splitting failure is based on extensive work by Oehlers [6]. Splitting of a long prism, with cross-section EHLI in Fig. 4, is caused by a patch load P_r on area FGKJ. The result is

$$P_r = 2.4\,\pi f_c^{0.5}\,[e^3 h_{es} / (2e - d)^2 + h_c^3 d / (2h_c - h_{es})^2] \tag{8}$$

with h_{es} given by $(h_{es} - h_p) / (h - h_p) = 0.56\,[2.4 - 2e / h_p], \leq 0.5.$ (9)

Concrete pull-out failure occurs when the mean tensile stress on a pyramidal surface of area A_c, enclosing the stud(s), reaches the tesile strength of concrete. The total tensile force is deduced from the splitting theory, and expressions for area A_c are easily obtained for any layout of studs within the trough. The final result for a single stud is

$$P_r = 0.6 f_c^{0.5}\,[\,4\,\pi\, e^3 h_{ep} / (2e - d)^2 + A_c\,] \tag{10}$$

where $h_{ep} = 2\, h_c\,[1 - (\pi d h_c / A_c)^{0.5}].$ (11)

Height h_{ep} is equivalent to h_{es} in Fig. 4, and this mode governs where $h_{ep} < h_{es}$.

4. Conclusions

(1) These conclusions relate to the static shear resistance P_r of stud shear connectors with $f_u \geq 400$ N/mm^2 welded through steel sheeting of trapezoidal profile with $0.8 \leq b_0/h_p \leq 3.2$ (see Fig. 1), in concrete with $20 \leq f_c \leq 35$ N/mm^2, and projecting at least 35 mm above the sheeting. Restrictions on stud spacing, data on slip capacity, and more detailed results are given elsewhere [2,3]. The many conclusions given in Section 2 above are not repeated here.

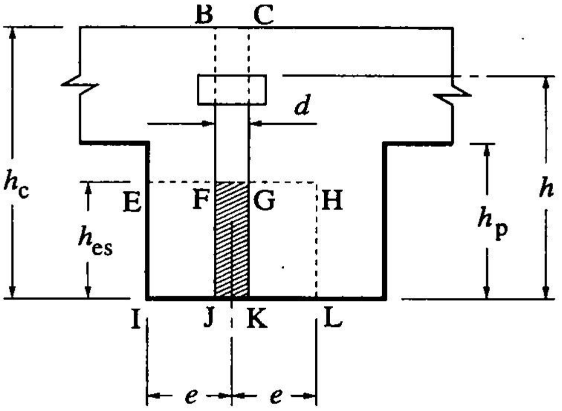

Fig. 4 Patch load for splitting failure

(2) Regions with sparse test data were explored in 34 new push tests, in accordance with Eurocode 4 [1]. The resistances P_e found in these tests and in 169 others show that predictions by all of three recent design methods include errors of at least ± 30% (Table 1).

(3) Seven failure modes have been identified, and methods developed for predicting the critical mode and the failure load, P_r. A histogram of 172 ratios P_e/P_r that includes all the failure modes (Fig. 2) shows a mean ratio $\mu = 1.02$, with coefficient of variation $V = 9.5\%$, much better than for the predictions of Eurocode 4 for transverse sheeting only. Its predictions for parallel sheeting give ratios that range from 0.76 to 2.9.

(4) Simpler design equations, not based on mechanical models, have been developed [3]. Their predictions for the same 136 tests with transverse sheeting give $\mu = 1.03$, $V = 10.5\%$.

(5) The results are for mean resistances, from push specimens with at least four studs. Test data from beams are so sparse and insensitive to the resistance of small groups of studs that the codification of design values must continue to be based as much on experience as on testing. The present work enables current rules to be improved.

5. References

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