DEVELOPMENT OF A NEW PUSH TEST FOR EUROCODE 4

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ABSTRACT

The standard push test specimen in the current version of Eurocode 4 does not provide any information on what modifications should be made when profiled steel sheeting is introduced. Whilst the lack of information was intended to encourage innovation, this has sometimes lead to test results implying that stud connectors possess a lower resistance and ductility than assumed in current Standards. From full-scale beam and companion push tests in Europe, it has been shown that modifying the push test through the introduction of a normal force to the face of the test slabs provides comparable load-slip performance to that encountered within a beam. Within the work programme for developing the second generation of Eurocodes, this paper presents part of the background to Sub-task 1 of SC4.T3, whose aim is to develop an improved push test for Eurocode 4 when stud connectors are welded within profiled steel sheeting.

INTRODUCTION

STANDARD PUSH TEST

The forces that occur in the concrete flange of a composite beam are shown schematically in Fig. 1(a). Should a distributed load q be introduced, the vertical shear forces are affected such that $\Delta V = V_l - V_r = q \times \Delta_l$. If the distributed load q acts on the concrete flange, as well as the longitudinal shear force F_ℓ, a compression force $q \times \Delta_l$ exists at the interface between the concrete and the top flange of the steel beam.

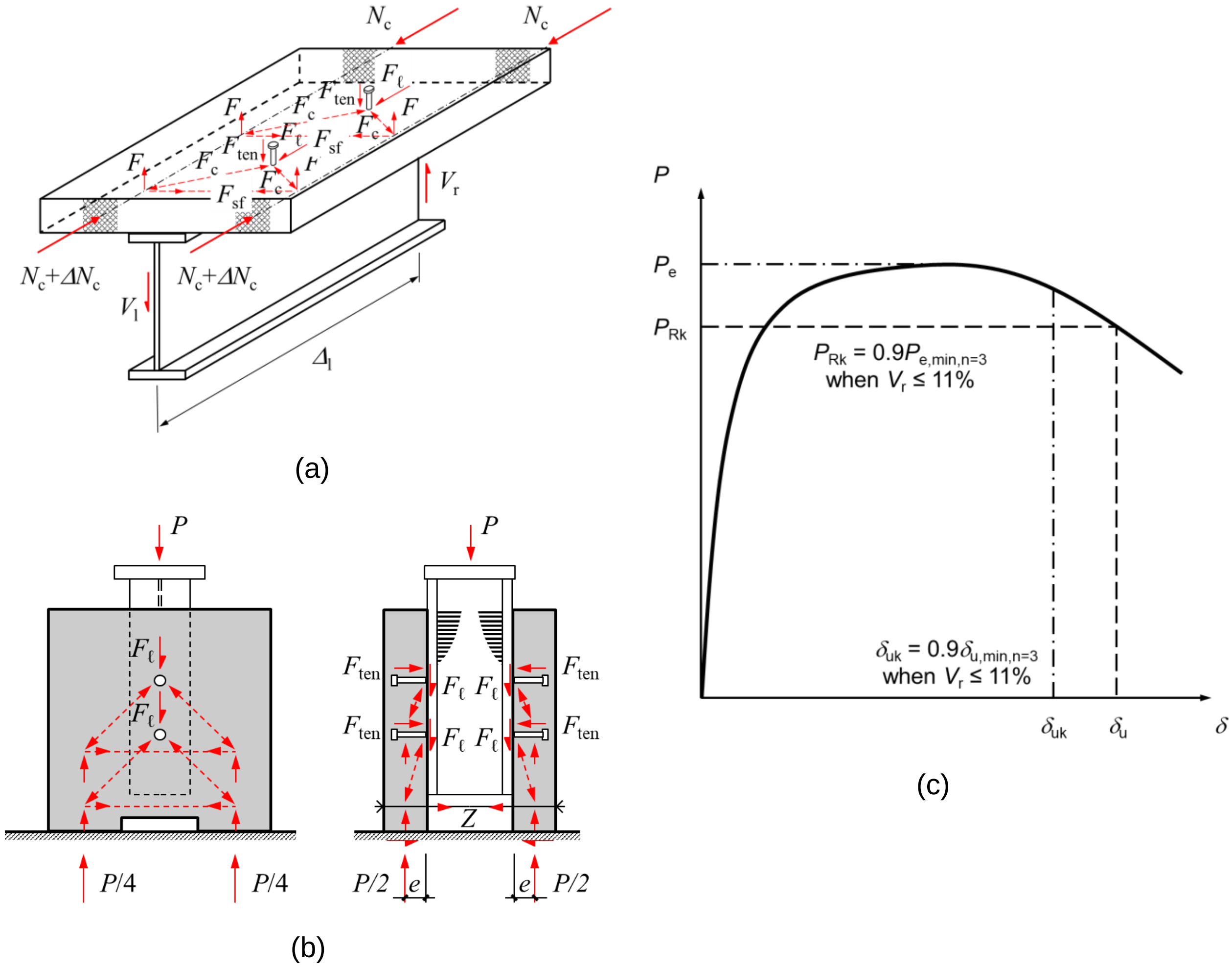


Fig. 1 - (a) Internal forces within: a composite beam; (b) a push test (Roik and Hanswille, 1987); and (c) determination of characteristic resistance and slip capacity from push test load-slip curve according to Eurocode 4.

The load-slip performance of shear connectors has been historically established from small-scale push specimens of the type shown in Fig. 1(b). By applying a load to the top end of the steel-section, the load-slip behaviour of the connectors can be determined. This type of specimen is known as a ‘push test specimen’ in Eurocode 4 (EN 1994-1-1, 2004) and, apart from slight variations in its geometry, has hardly changed since its inception in the early 1930’s (Roš, 1934). The internal forces in the push specimen are shown in Fig. 1(b) to enable direct comparisons to be made with those in a composite beam. The forces F_ℓ are transferred through the concrete in a similar way as a composite beam (N.B. the recess at the bottom of the slab is optional in the standard test in Eurocode 4). The moment $P \times e$, resulting from the eccentric load introduction, causes tension in the studs and compression at the interface between the concrete and the flange of the steel section. In the Eurocode 4 standard test, the magnitude of the tension forces in the studs F_{ten} is therefore affected by frictional forces developing at the interface between the test slabs and the strong floor $\mu \times P$ (where μ is the friction coefficient); if these frictional forces are eliminated, F_{ten} increases, which has been shown to reduce the shear resistance of the studs by approximately 30% (Hicks and McConnel, 1997).

EVALUATION OF THE RESULTS FROM PUSH TESTS

Characteristic resistance P_{Rk}

According to current requirements of Eurocode 4, if 3 nominally identical push tests are carried out, and the deviation of any individual result from the mean value does not exceed 10%, the characteristic resistance of a shear connector P_{Rk} is defined as 0.9 times the minimum failure load per stud (see Fig. 1(c)). Letting $P_{e,m}$ be the mean measured resistance per connector from three nominally identical push tests, and $P_{e,min,n=3}$ be the lowest of the three measured resistances per connector, this requirement can be written as follows:

$$P_{Rk} = 0.9P_{e,\min,n=3} \text{ provided that } \left|P_{e,e} - P_{e,m}\right| \leq 0.1P_{e,m} \qquad (1)$$

where $P_{e,e}$ is each extreme (maximum or minimum) measured resistance.

If the scatter of results exceeds the 10% limit (i.e. $\left|P_{e,e} - P_{e,m}\right| > 0.1P_{e,m}$), the test evaluation should be carried out according to EN 1990, Annex D (2005).

Equation (1) is effectively based on the EN 1990 provisions for the evaluation of a characteristic value from a small number of test results, when the coefficient of variation V_r is known from a significant number of previous tests (i.e. 'V_X known'). Although there may be some debate on the exact value for the coefficient of variation from historical push tests, it can be deduced from EN 1990 that, for a set of three results with extreme measured resistances $P_{e,e}$ less than 10% of the mean value $P_{e,m}$, the method in Eurocode 4 implies that V_r = 11% (Johnson, 2012).

It would be unwise to assume that V_r = 11% is always satisfied since, from a recent investigation undertaken in the UK (Smith and Couchman, 2010), 3 of the 9 groups of nominally identical push tests did not satisfy the 10% limit for the scatter of results. Furthermore, if three nominally identical tests are not undertaken, it would be impossible to verify the Eurocode 4 requirement for the scatter of the results. Therefore, hypothetically, if only one push test was undertaken, the characteristic resistance could be at least 20% lower than expected.

Characteristic slip capacity δ_{uk}

The ductility of a shear connector is measured by the slip capacity δ_u, which is defined in Eurocode 4, B.2.5 as the slip corresponding to the point where the characteristic resistance of the connector intersects the falling branch of the load-slip curve (see Fig. 1(c)). The characteristic slip capacity δ_{uk} is taken as 0.9 times the minimum test value of $\delta_{u,min}$, such that $\delta_{uk} = 0.9\delta_{u,\min,n=3}$. Alternatively, the characteristic properties of a shear connector can be determined by a statistical evaluation of all of the results according to EN 1990. It is therefore implied by Eurocode 4, that the coefficient of variation for the slip capacity is V_r = 11% when $\delta_{uk} = 0.9\delta_{u\,\min,n=3}$, but no information is given to the designer on when it is appropriate to use EN 1990.

PUSH TESTS ON HEADED STUDS WELDED WITHIN TRAPEZOIDAL PROFILED STEEL SHEETING TRANSVERSE TO A BEAM

Questions have arisen on the appropriateness of using the reduction factors contained within Eurocode 4, owing to the fact that the failure mechanisms of studs in trapezoidal profiled steel sheeting are quite different to those experienced in solid slabs. For example, when push tests are conducted on studs welded favourably or centrally within the ribs of a sheet (see Fig. 2), a typical failure mode known as concrete cone pull-out occurs (Hawkins and Mitchell,1984; Lloyd and Wright, 1990). In this case, the whole cone together with stud rotates and is pulled out of the slab, carrying with it a wedged-shaped pyramidal portion of concrete (see Fig. 2(d)); in these cases the axial tension in the stud can be significant, which has been measured in some special test specimens to be in the order of 30% of the longitudinal shear resistance (van der Sanden, 1996). Due to the tension and rotation of the stud, the concrete slab can separate from the profiled steel sheeting relatively early in push tests, which brings into question whether it is entirely appropriate to neglect the compression at the interface between the concrete and the steel section that would occur in a composite beam subjected to a uniformly distributed load together with its self-weight (see Fig. 1(a)).

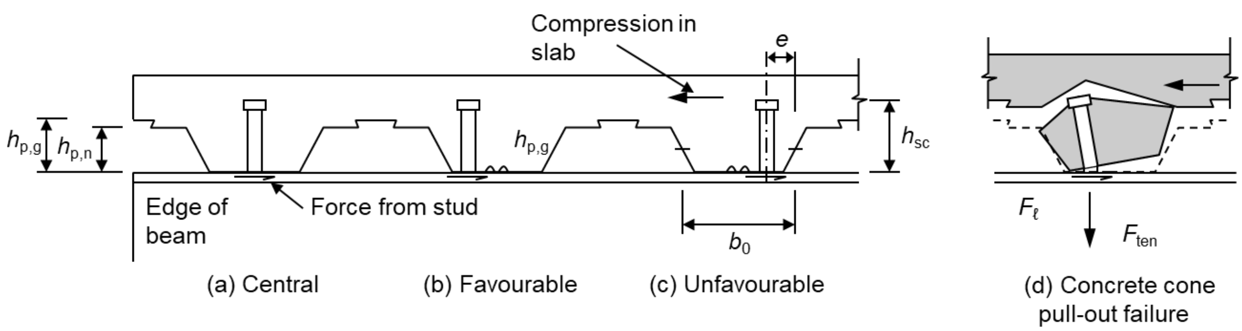
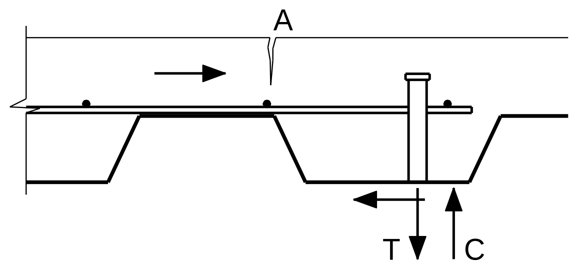


Fig. 2 - Dimensions of profiled steel sheeting and studs in the (a) Central (b) Favourable (c) Unfavourable position

The Eurocode 4 rules for partial shear connection are based on two independent studies (Johnson and Molenstra, 1991; Aribert, 1990). These studies assumed that, in solid concrete slabs and composite slabs using profiled steel sheets prevalent in the 1980's, the characteristic slip capacity of 19 mm diameter studs was approximately δ_{uk} = 6 mm (see Fig. 1(c)). The rules for partial shear connection in Eurocode 4 were limited to situations where the required slip did not exceed 6 mm. Studs were deemed to be 'ductile' in those situations.

Push tests in Australia (Patrick, 2004) suggested that studs welded within the ribs of modern trapezoidal profiled steel sheeting possess lower resistance and ductility than assumed in Eurocode 4. To investigate whether the claims were affected by the thinner (0.75 mm), high strength steel decking (550 MPa) that is common in Australasia, 24 push tests with trapezoidal decking were undertaken at Imperial College London in 2003 (Hicks, 2007a). Each test slab had three concrete ribs with studs through-deck welded in the two ribs to the top of the specimens. However, it was found that the specimens with two studs per rib in the favourable position (n_r = 2F) gave consistently lower resistances than those with one stud per rib (n_r = 1F), irrespective of the stud layout. From an inspection of the specimens it was clear that the results had been affected by an artificial 'back-breaking' failure mode, which was characterised by the last studded rib at the top of the specimen rotating, causing a horizontal crack to appear across the full width of the test slab (see Fig. 3(a)). It was believed that this failure was caused by the couple of internal forces in the last studded rib at the top of the specimen (see Fig. 3(b)). To remedy this situation, it appeared that the provision of an unstudded rib at the top of specimen eliminated this artificial back-breaking failure mode.

(a)

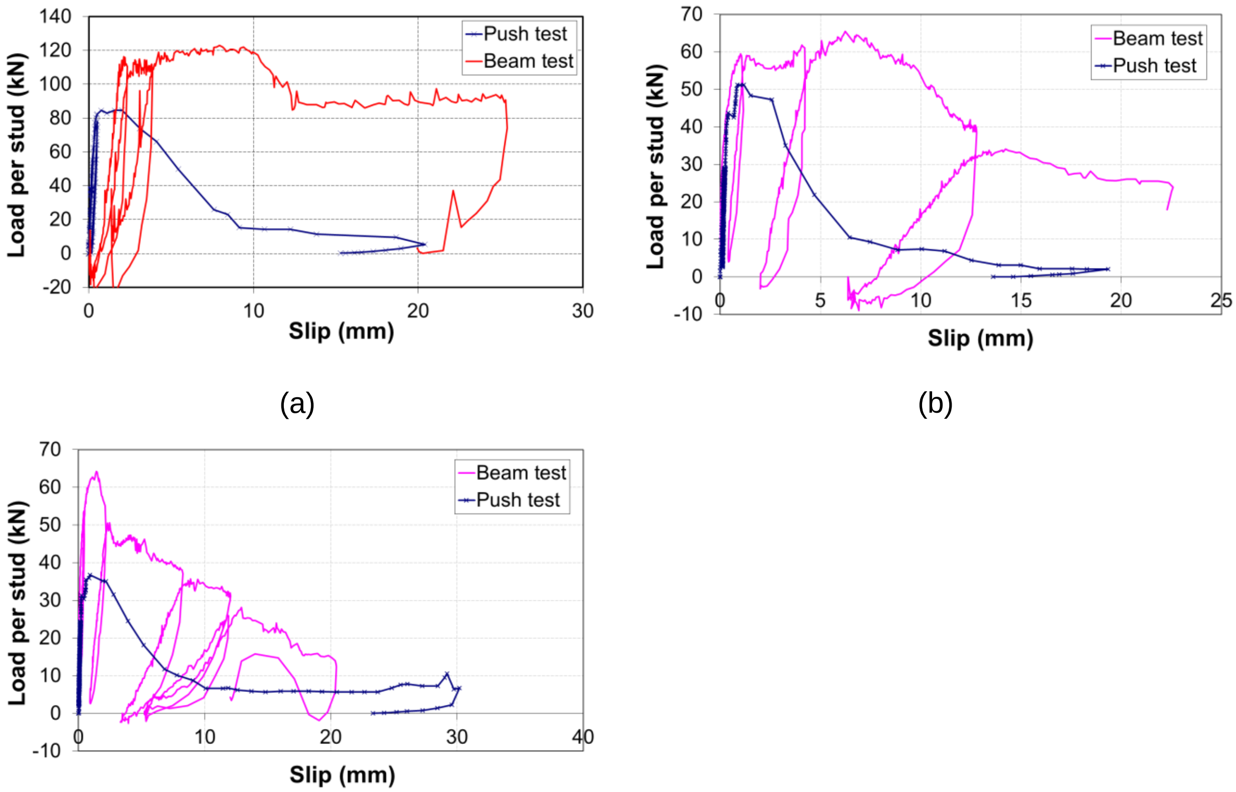


(b)

Fig. 3 - (a) Back-breaking failure experienced in Imperial College London tests (b) Internal forces causing rotation of the last studded rib at the top of the specimen

An obvious question regarding stud connectors in push specimens is whether their behaviour is comparable to that which would occur in a full-scale beam. In an attempt to address this question, tests on a 10.0, 5.0 and 11.4 m span composite beam, together with 12 companion push tests were undertaken in the UK between 2004 and 2008 (Hicks, 2007b; Hicks and Smith, 2014). To enable the internal forces to be evaluated, the steel beams were instrumented with strain gauges on the top and bottom flange at cross-sections corresponding to the shear connector positions. As well as determining the build-up of axial force, the internal bending moments were evaluated to check the reliability of the strain gauge readings. The slip distribution at the shear connection was established from horizontally mounted transducers, which monitored the relative displacement between bars cast in the concrete behind the shear connector positions and the top flange of the beam. The internal load–slip curves for the shear connectors were therefore evaluated by plotting the change in axial force at each cross-section against the corresponding slip.

The load-slip curves for studs with the lowest failure load in the beam tests are compared to their companion push tests in Fig. 4. As can be seen from these plots, there is no similarity in performance of studs for these two types of specimen. In Fig. 4, the slips measured in the push tests are well below the levels achieved in the beam and, if considered in isolation, would suggest that the studs should not be taken to be ‘ductile’ (which has adverse implications for partial shear connection design). Furthermore, the tests showed that the resistance per stud for n_r = 3F was no better than n_r = 2F, thereby indicating that the design equations in BS 5950-3.1 (1990) and ANSI/AISC 360-16 (2016) were unconservative by up to 45%. As a direct result of this work, an amendment was made to BS 5950-3.1 (2010).



(a) (b)

(c)

Fig. 4 – Load-slip curve for through-deck welded studs in beam test compared to standard push test for: (a) one stud per rib n_r = 1F; (b) two studs per rib n_r = 2F; and (c) n_r = 3F three studs per rib in the favourable position, respectively.

DEVELOPMENT OF AN IMPROVED PUSH TEST FOR HEADED STUDS WELDED WITHIN TRAPEZOIDAL PROFILED SHEETING

NORTH AMERICAN INVESTIGATIONS

It was considered that the reason for the poor performance of studs welded within trapezoidal sheeting in push tests was due to the absence of the compression force at the interface between the concrete and the flange of the steel section, which exists in real composite beams from the floor loading (see Fig. 1(a)). Easterling *et al.* (1993) can be credited for attempting to remedy the problem of poor load-slip performance by modifying the standard push test through the introduction of a normal force to the face of the test slabs. In these North American investigations normal forces equivalent to between 0 and 20% of the vertical load, were applied directly over the centre-line of the steel section. In total, 234 push tests and 4 full-scale composite beam tests were undertaken. It was concluded that “only a 5% normal load in the push test causes a lot of variability in stud strength” (Rambo-Roddenberry, 1994). It was also deemed that the results from push tests with a normal force equivalent to 10% of the vertical load compared favourably with the performance of the four 9.0 m span companion beam tests.

AUSTRALIAN INVESTIGATIONS

Bradford *et al.* (2006) found that the standard push test shown in Fig. 1(b) was inappropriate for composite slabs using trapezoidal decking. It was found that the specimen tended to twist (similar to the 'back-breaking failure' shown in Fig. 3), and fail in a brittle and premature way. The standard push test was modified to a single-sided arrangement and tested in the horizontal position. A total of 10 push specimens were tested, where normal forces equivalent to between 0 and 10% of the longitudinal load was applied along the edges of the specimen at an eccentricity of 600 mm, thereby applying a hogging moment over the centre-line of the steel section. The eccentric loading was chosen to introduce the beneficial effect on the stud connector resistance from the presence of this hogging moment (from a compression force being applied to the base of the stud), and to reflect the loading conditions on two 8.05 m span companion composite beam tests (Ranzi *et al*., 2009).

EUROPEAN INVESTIGATIONS

Taking inspiration from the earlier North American and Australian modifications a new test was devised in the UK, which was thought to better reflect the conditions that exist in a real beam. As good quality *in situ* load-slip data existed from three full-scale composite beam tests, the new test could be calibrated against this performance (Hicks, 2007b; Hicks and Smith, 2014). Also, rather than developing a completely new specimen, it was proposed to modify the standard specimen given in Eurocode 4, in the interests of developing a relationship with historical push test resistances. Due to the possibility of different friction coefficients at the base of the test slabs affecting the repeatability of the tests, it was decided to develop a self-contained rig that could be disassembled and erected in different locations without the need of a strong floor.

The improved push rig is shown in Fig. 5(a). The loading system consists of vertical jacks applying the longitudinal shear force, accompanied with horizontal jacks applying a uniform normal force to the face of the test slabs. From testing a total of 14 nominally identical specimens that had been constructed from a single concrete mix using the same details that had been provided in the companion beam tests (with n_r = 1F and n_r = 2F), the following levels of normal force were applied (taken as a proportion of the longitudinal force): 0; 4%; 8%; 12%; and 16%. The load-slip curves for these tests are presented in Fig. 5(b) and Fig. 5(c), which are compared with those measured in the beam tests. It was considered that the results with a 12% lateral load provided the closest match with the load-slip behaviour from the beam tests.

A further two tests with a lateral load of 12% were conducted to evaluate the characteristic values for n_r = 1F and n_r = 2F. By employing the test evaluation procedure given in Eurocode 4, the improved push rig delivered characteristic resistance and slip capacity values that were comparable to those achieved in the companion the beam tests (Hicks and Smith, 2014). The improved push rig was subsequently used to investigate the effect of a number of key variables on the load-slip arrangement of headed stud connectors by Smith and Couchman (2010) whom undertook 27 push tests.

The development work described above was extended through the major RFCS DISCCO research project (Aggelopoulos *et al*., 2016), which included both beam and push tests. A total of 64 push specimens were tested, where normal forces equivalent to between 0 and 16% of the longitudinal load were applied directly over the steel beam (concentrically) or through the slab at different eccentricities to the steel beam. The eccentric loading was chosen to introduce the beneficial effect on the headed stud connector resistance from the presence of this hogging moment and to reflect the loading conditions in composite floors. Also, as well as considering that the normal force increased in proportion to the applied longitudinal shear force (as would occur in a beam), the maximum required normal force was established and fixed before the longitudinal shear force was applied (i.e. a constant normal force).

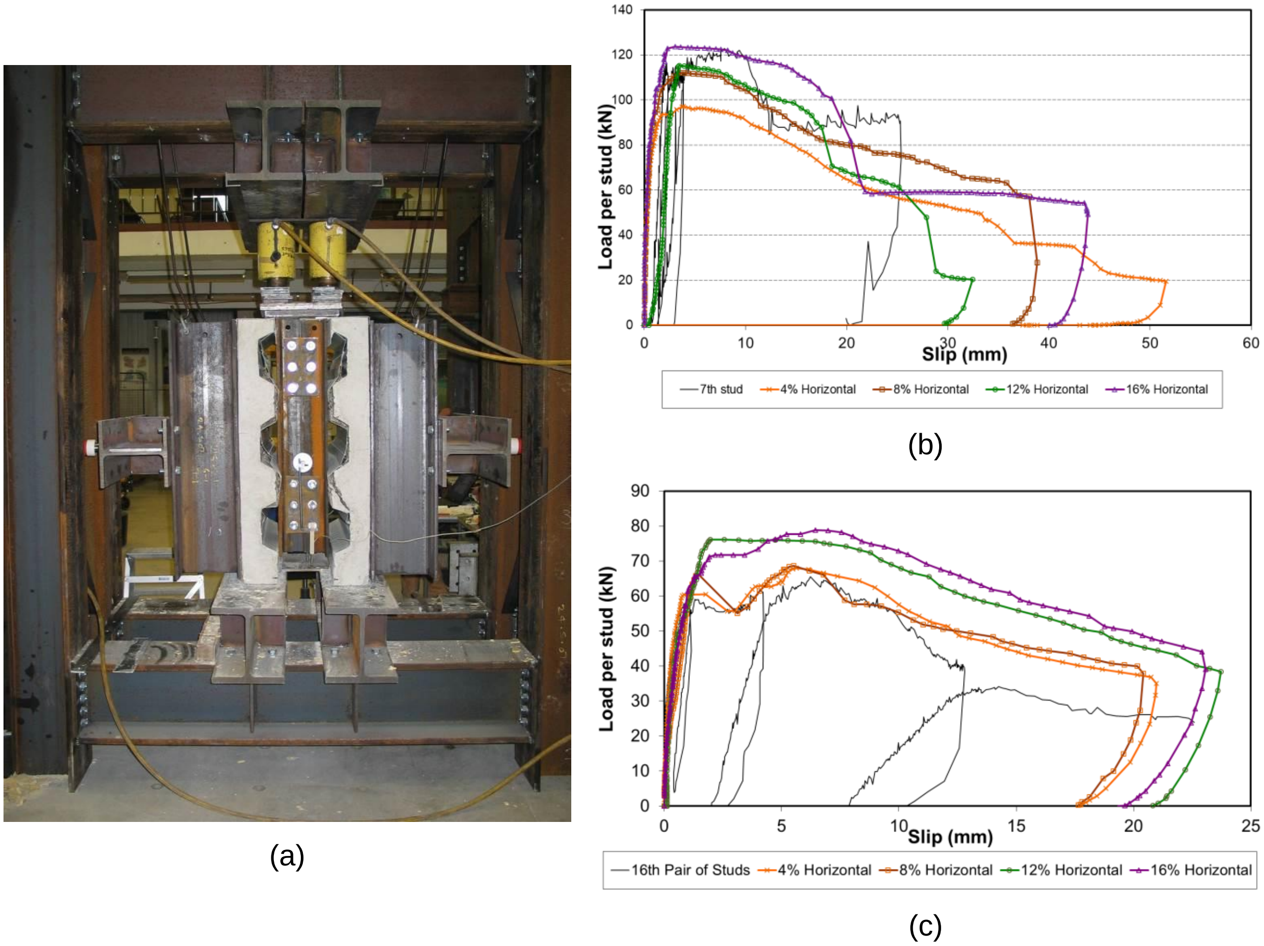
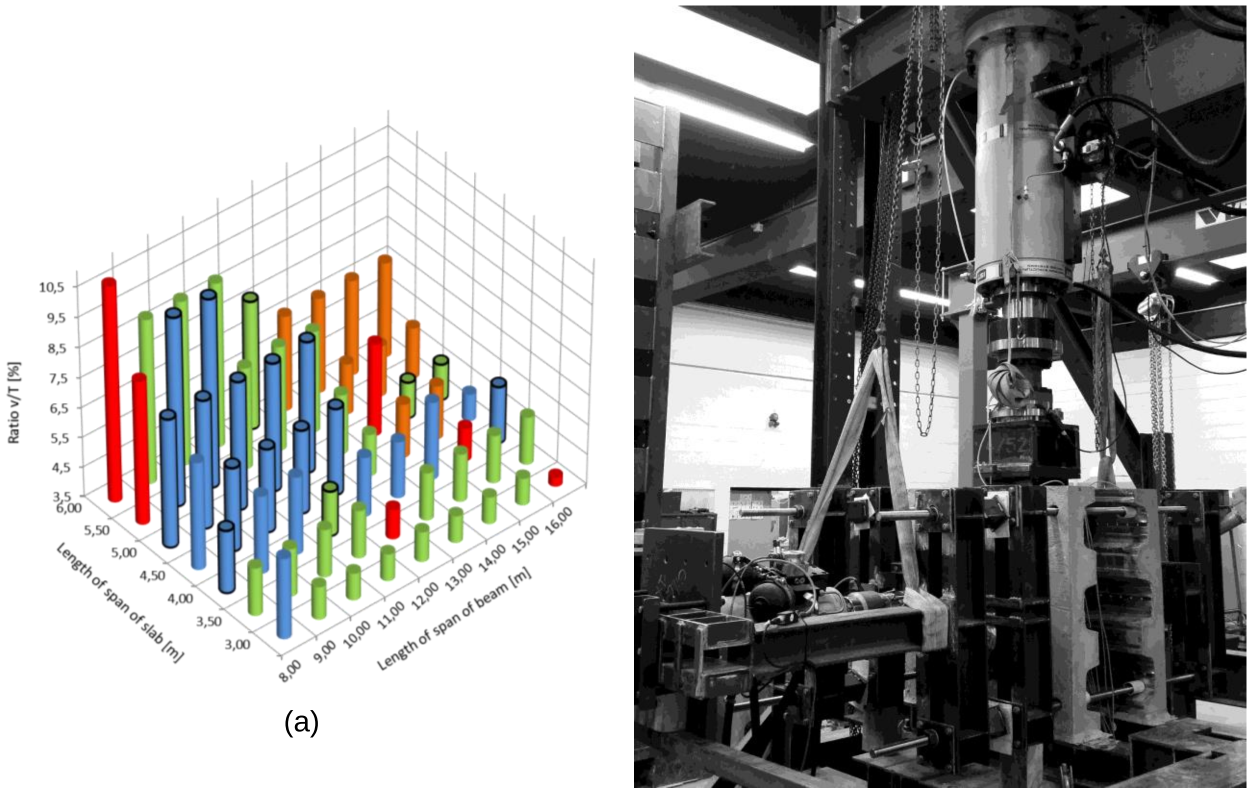


Fig. 5 - (a) Improved push test rig developed in the UK; Comparison of load-slip behaviour for the new improved test with that measured in beam tests for: (b) n_r = 1F; and (c) n_r = 2F)

In order to define reasonable values for the normal force, a typical floor bay within a building was considered (Nellinger *et al*., 2017), which consisted of an internal simply-supported composite beam which, in turn, supported a double-span composite slab. To reflect current practice, steel grades of S235 and S355 were considered, together with a concrete grade of C30/37. Furthermore, two different composite slabs with a deck height of 58 and 80 mm were considered in the study. An imposed load of q_k= 3,5 kN/m² was considered in all cases. Using the current Eurocode 4 design provisions (i.e. rigid-plastic material was considered), the spans of the beams and slab were varied to determine the range of normal forces v versus longitudinal shear forces T that would be expected in practice. The results from this study are presented graphically in Fig. 6(a), which showed that the degree of transverse loading v/T ranged from 5 to 10%.



(a)

(b)

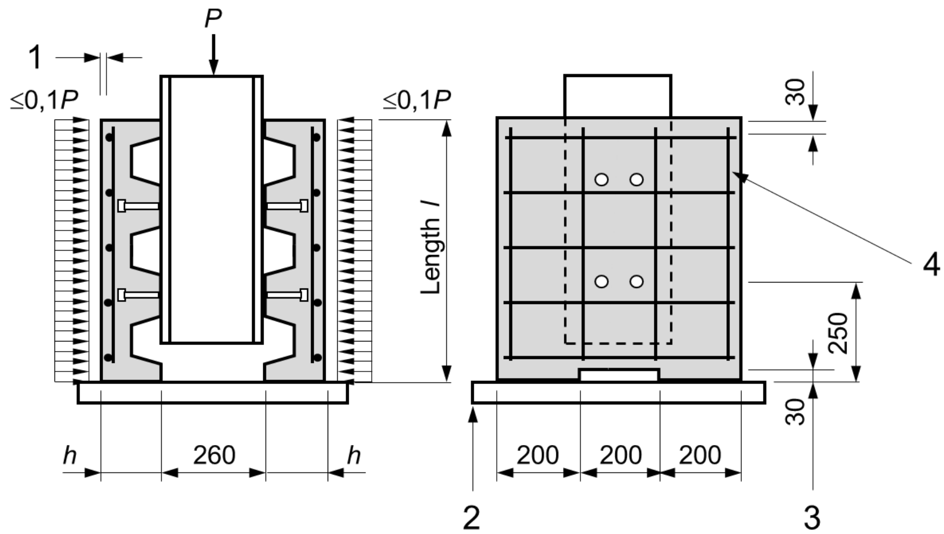
Fig. 6 - (a) Degree of transverse loading v/T (b) Improved push test developed within the RFCS DISCCO project

In some of the subsequent push tests where no normal force was applied to the face of the test slabs, a 'torsional failure mode' was reported which was characterised by the last studded rib at the top of the specimen rotating, causing a horizontal crack to appear across the full width of the test slab (see Fig. 3). In subsequent push tests that were carried out in the DISCCO project, it was considered important to include a normal force in the push tests, in order to suppress this artificial failure mode.

Through the comprehensive test programme within the DISCCO project, similar findings to that reported in the earlier investigations were made, in that the resistance and ductility of stud connectors welded within the ribs of trapezoidal profiled steel sheeting were strongly affected by the magnitude of the normal force applied to the face of the test slabs (Nellinger *et al.*, 2017). The improved push test arrangement that was developed by the University of Luxembourg within this RFCS project is shown in Fig. 6(b).

DEVELOPMENT OF A NEW STANDARD PUSH TEST FOR THE SECOND GENERATION OF EUROCODE 4

Due to the favourable comparisons with full-scale composite beam tests, as well as similar levels of lateral force being found to be appropriate in the earlier North American and Australian research programmes, it is recommended that besides the standard push test procedure for shear connectors, a distinct push test should be used for stud connectors welded within the ribs of trapezoidal profiled steel sheeting to ensure that this popular form of construction is supported by Eurocode 4. The proposed test arrangement that is currently being considered is presented in Fig. 7.



1 cover 15 mm

2 bedded in mortar, gypsum or similar

3 recess optional

4 reinforcement:
ribbed bars with $450 \leq f_{sk} \leq 550$ MPa

steel section: HE 260 B or 254 x 254 x 89 kg. UC

Fig. 7 – Proposed test specimen for headed stud connectors welded within trapezoidal profiled sheeting

To avoid the premature back-breaking failure mode observed previously (see Fig. 3), and provide comparable load-slip performance of shear connectors in full-scale beams, it is proposed to provide a lateral force normal to the face of the test slabs. From the above review of previous international push tests, the value of the lateral force has ranged between 5 to 12% of the longitudinal shear force. As a compromise, it is currently proposed that a normal force not greater than 10% of the longitudinal shear force should be applied in the improved push test. This upper value is consistent with that used in the North American test programme whose results were used to form the basis of the design rules for stud connectors in the AISC Specification (ANSI/AISC 360-16, 2016).

CONCLUSIONS

From the considerable variations that have been observed in the behaviour of stud connectors in terms of resistance and ductility, it would appear that a clear case exists for the need to standardize the push specimen test regime when trapezoidal profiled steel sheeting is employed. From a review of international experiments (comprising 12 full-scale composite beams and 361 push tests), it was found that the application of a normal force to the face of the slabs in push specimens eliminated an unrealistic premature back-breaking failure mode. Moreover, the application of a normal force also provided comparable characteristic resistances and slip capacities to that achieved in companion full-scale beams. From a consideration of this wealth of international data, a push test specimen for headed stud connectors welded within trapezoidal profiled sheeting is proposed for the second generation of Eurocode 4. Given that the value of the maximum normal force proposed is similar to that used to form the basis for the provisions in the 2016 AISC Specification, it is hoped that the new Eurocode 4 test will encourage international harmonization for push tests, which will lead to more consistent experimental data and improved design equations in the future.

ACKNOWLEDGMENTS

Whilst the present authors are members of the Eurocode 4 Project Team SC4.T3 ‘Revised rules for shear connection in the presence of modern forms of profiled sheeting’, any views expressed in this paper do not necessarily reflect those of the entire Project Team. The draft revisions to Eurocode 4 are still at a draft stage and may be subject to change. Any views expressed in this paper may not necessarily reflect those of sub-committee responsible for Eurocode 4 (CEN/TC250/SC4).

REFERENCES

Aggelopoulos E.S., Lawson, R.M, Kuhlmann, U., Eggert, F., Odenbreit, C., Nellinger, S., Lam, D., Dai, X, Sheehan, T. and Obiala, R. (2016). “Development of Improved Shear Connection Rules in Composite Beams (DISCCo)”, Draft Final Report, RFSR CT 2012-00030.

ANSI/AISC 360-16. (2016) Specification for Structural Steel Buildings. American Institute of Steel Construction, Chicago, IL.

Aribert J-M. (1990). “Dimensionnement de poutres mixtes en connection partielle”. Mixed Structures Including New Materials. IABSE Symposium, Brussels, International Association for Bridge and Structural Engineering. 60. pp. 215–220

Bradford, M.A., Filonov, A., Hogan, T.J., Ranzi, G. and Uy, B. (2006). “Strength and ductility of shear connection in composite T-beams”. 8th International Conference on Steel, Space & Composite Structures, Kuala Lumpar, Malaysia, 15-17 May, pp. 15-26

BS 5950-3.1 (1990). Structural use of steelwork in buildings: Part 3: Section 3.1: Code of practice for design of simple and continuous composite beams, British Standards Institution, London.

BS 5950-3.1+A1 (2010) Structural use of steelwork in buildings: Part 3: Section 3.1: Code of practice for design of simple and continuous composite beams, British Standards Institution, London.

Smith, A.L. and Couchman, G.H. (2010). “Strength and ductility of headed stud connectors in profiled steel sheeting”. Journal of Constructional Steel Research, 66. pp. 748-754

Easterling, W.S., Gibbings, D.R. and Murray, T.M. (1993). “Strength of Shear Studs in Steel Deck on Composite Beams and Joists” Engineering Journal, American Institute of Steel Construction, Second Quarter. pp. 44-55

EN 1990 (2005). Eurocode: Basis of structural design. European Committee for Standardization, Brussels

EN 1994-1-1 (2004). Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings, European Committee for Standardization, Brussels.

Hawkins, N. M. and Mitchell, D. (1984). “Seismic response of composite shear connections”. J. Struct. Eng. 110, 9. pp. 2120–2136.

Hicks, S.J. and McConnel, R.E. (1997) “The shear resistance of headed studs used with profiled steel sheeting”. In Composite Construction in Steel and Concrete III, Buckner, C.D., Shahrooz, B.M, ASCE: New York. pp. 325-338

Hicks S. (2007a) “Resistance and ductility of shear connection: full-scale beam and push tests”. Sixth International Conference on Steel and Aluminium Structures (ICSAS ‘07), Beale, RG (ed). Oxford Brookes University, UK, pp. 613-620

Hicks, S. (2007b) “Strength and ductility of headed stud connectors welded in modern profiled steel sheeting”. Structural Engineer. 85(10). pp. 32-38.

Hicks, S.J. and Smith, A.L. (2014). “Stud Shear Connectors in Composite Beams that Support Slabs with Profiled Steel Sheeting”. Structural Engineering International. 24(2). pp. 246-253

Johnson, R.P. (2012). Designers’ Guide to Eurocode 4: Design of Composite Steel and Concrete Structures EN 1994-1-1 (Second Edition), London, Thomas Telford.

Johnson, R.P. and Molenstra N. (1991) “Partial shear connection in composite beams for buildings”. Proc. Inst. Civ. Eng. 91(Part 2). pp. 679–704.

Lloyd, R. M. and Wright, H. D. (1990). “Shear connection between composite slabs and steel beams”. Journal of Constructional Steel Research. 15. pp. 255–285.

Nellinger, S., Odenbreit, C., Renata Obiala, R. and Lawson, R.M. (2017). “Influence of transverse loading onto push-out tests with deep steel decking”, Journal of Constructional Steel Research, 128. pp. 335-353

Patrick, M. (2004). Composite beam shear connection design and detailing practices for Australian steel decks, University of Western Sydney, Report CCTR-CBSC-001-04, Sydney.

Rambo-Roddenberry, M. (1994). “Behavior and Strength of Welded Stud Shear Connectors”, PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Ranzi, G, Bradford, M.A., Ansouriana, P., Filonov, A., Rasmussen, K.J.R., Hogan, T.J., Uy, B. (2009). “Full-scale tests on composite steel–concrete beams with steel trapezoidal decking”. Journal of Constructional Steel Research, 65(7). pp. 1490-1506

Roik, K. and Hanswille, G. (1987) “Zur Dauerfestigkeit von Kopfbolzendübeln bei Verbundträgern”. Der Bauingenieur. 62. pp. 273–285.

Roš, M. (1934) “Les constructions acier-béton système «Alpha»”. L’Ossature Métallique. 3(4). pp. 195-208

Smith, A.L. and Couchman, G.H. (2010). “Strength and ductility of headed stud connectors in profiled steel sheeting”. Journal of Constructional Steel Research. 66. pp. 748-754.

van der Sanden, P.G.F.J. (1996). The behaviour of a headed stud connection in a ‘new’ push test including a ribbed slab, Tests: Main report. BKO Report 95-15, Eindhoven.