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Influence of transverse loading onto push-out tests with deep steel decking

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ABSTRACT

This paper presents the results of 20 push-out tests on shear stud connectors, placed centrally in the ribs of 58 mm and 80 mm deep steel decking. The tests were designed to investigate the realistic load–slip behaviour of the shear connectors and the influence of transverse loading. The tests considered two different stud diameters and the effect of concentric and eccentric transverse loading. In addition, the influence of a second layer of reinforcement, the welding procedure and the number of shear connectors in each rib have been considered. The observed influence of these parameters on the load–slip behaviour is presented and explained with regard to material properties and load-bearing models. In addition, the test results are compared with the current analytical approaches, which are shown to be non-conservative in some cases, because the presented deck shapes were not well considered in the development and calibration of EN 1994-1-1.

1. Introduction

The application of composite beams and slabs has many advantages in terms of economic construction of multi-storey buildings due to the increase of stiffness and load-bearing capacity of the structure. Most commonly, composite action and transfer of shear forces between the steel beam and the slab is ensured by use of headed shear studs that are welded to the top flange of the beams. The current rules in EN 1994-1-1 for the analysis of the shear connector resistances are based on the failure modes of studs in solid slabs and do not sufficiently consider the load-bearing behaviour of studs in the ribs of slabs with modern deep steel decking. Also, the push-out testing procedure, described in Annex B of EN 1994-1-1, was originally defined for solid slabs. This setup, when applied to slabs with steel decking, leads to lower resistances and deformation capacity of the shear studs in comparison with beam test results. The paper develops an appropriate push-test method and assesses various test parameters, such as deck shape, shear connector size, reinforcement pattern and concentric and eccentric transverse loading, which have not been studied previously.

1.1. Load-bearing behaviour of shear connectors

The load-bearing behaviour of shear studs in solid slabs is shown in Fig. 1. The shear connectors initially transfer the shear force P by a compression force A acting on the concrete. The compression force A pushes against the weld collar at a shallow angle β. With increasing load, the concrete in front of the stud is damaged and the shear force moves to a higher position into the stud shank. This leads to plastic bending and shear deformations. Because of the fixed support conditions of the head of the stud, a tension force C develops in the stud shank. The tension force C is in equilibrium with a compression cone in the surrounding concrete. The compression struts in the concrete activate friction forces D between the slab and the steel flange. Finally, failure occurs in the stud shank above the weld collar because of combined tension and shear forces.

When the shear stud is placed in the deck rib of a composite slab, the load-bearing behaviour differs from the behaviour of studs in solid slabs, as shown in Fig. 2. The deck rib geometry has a strong influence onto the load-bearing behaviour. In general, two loading stages can be characterised by the two load peaks P_1 and P_2. The first peak load P_1 is reached when the concrete in front of the stud is crushed and two plastic hinges have developed in the stud shank. At higher slips, the support conditions of the head of the stud lead to a back-anchorage effect. Thus, the head of the stud introduces compression forces into the still intact concrete section which are in equilibrium with the tension force C in the stud shank. This effect allows the development of a second peak load P_2. Finally, failure occurs in form of a concrete pullout cone or stud rupture.

The development of this failure mechanism requires a sufficient embedment depth of the head of the stud into the continuous part of the concrete slab topping. If the embedment depth is relatively small, the support reaction of the head of the stud cannot be introduced into the concrete. In these cases, the concrete fails in a brittle form and a failure

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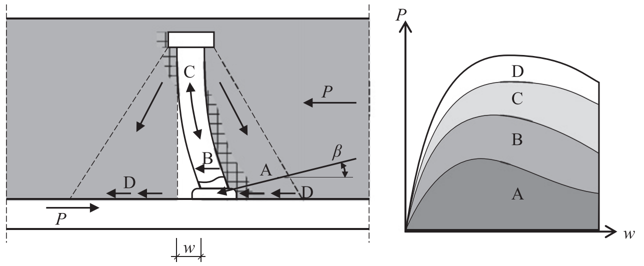

Fig. 1. Load-bearing behaviour of shear studs in solid slabs according to Lungershausen [1].

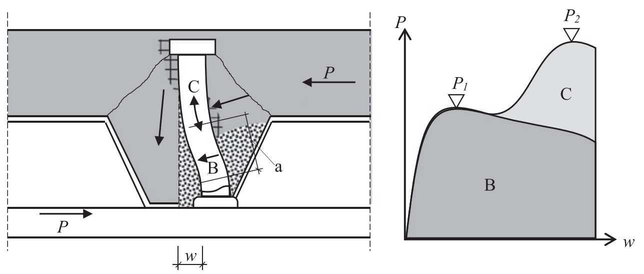

Fig. 2. Load-bearing behaviour of shear studs placed in the ribs of composite slabs according to Lungershausen [1].

mechanism with only one plastic hinge develops (see Fig. 3). Therefore, the behaviour of the shear stud is also influenced by the geometry of the steel decking and the shear stud itself.

In addition to the stresses that are introduced into the concrete directly by the shear stud, additional stresses occur because of the loading of the concrete slab itself. The loading of the slab leads to stresses resulting from vertical loads and bending moments acting on the slab at the line of the shear connectors. These stresses affect the crushing of the concrete in front of the stud, as higher stresses can be reached in multi-dimensional compression. The embedment conditions of the head of the stud may also be influenced by the development of large cracks. These effects are not yet well investigated and so far not considered in the push-out test as proposed in EN 1994-1-1 Annex B [2].

1.2. Test setups to investigate the load–slip behaviour

The push-out test specimen for solid slabs, as given in EN 1994-1-1 Annex B2 [2], is shown in Fig. 4. The distribution of the shear forces according to Roik et al. [3] is suitable to reflect the behaviour in real beams with solid concrete slabs.

However, when deep steel decking is used in concrete slabs, the obtained load–slip behaviour from push-out tests can result in up to 30% lower stud resistances and lower displacement capacities than in composite beam tests using similar configurations [4].

The load–displacement behaviour of a push-out test is strongly dependent on the boundary conditions of the concrete slab. Specimens with sliding bearings may underestimate the real shear resistance, whereas for tests with tension ties or rigid horizontal restraints, the shear resistance may be overestimated [5–7].

The differences of the behaviour of the shear connection in push-out tests and in beam tests led to the development of alternative test setups over recent years, such as the single push-out test [5] (see Fig. 5) and the horizontal push-off test [6,8] (see Fig. 6).

The horizontal push-off test represents a small step towards the consideration of transverse loads because the self-weight of the slab is taken into account. Other research [4,10] explicitly applied transverse loads to normal push-out specimens (see Fig. 7). Typically, concentric loading positions were used. Currently, the degree of transverse loading that should be applied in these tests is under discussion. According to Hicks and Smith [4], who investigated transverse loads of 4% to 16% of the shear load, a value of 12% transverse load was suitable to represent

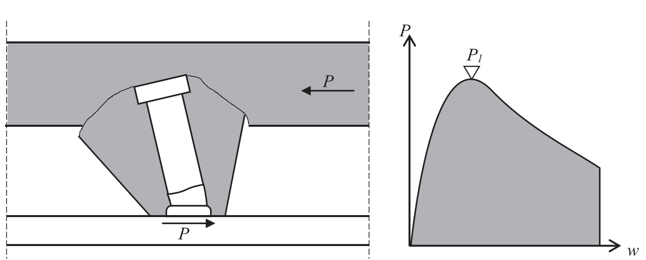

Fig. 3. Failure of ribs because of a too small embedment depth of the stud according to Lungershausen [1].

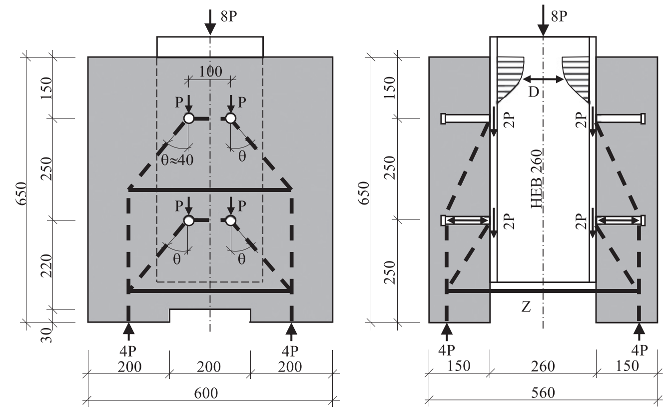

Fig. 4. Dimensions of the push-out test specimen according to EN 1994-1-1 Annex B [2] and force distribution according to Roik et al. [3].

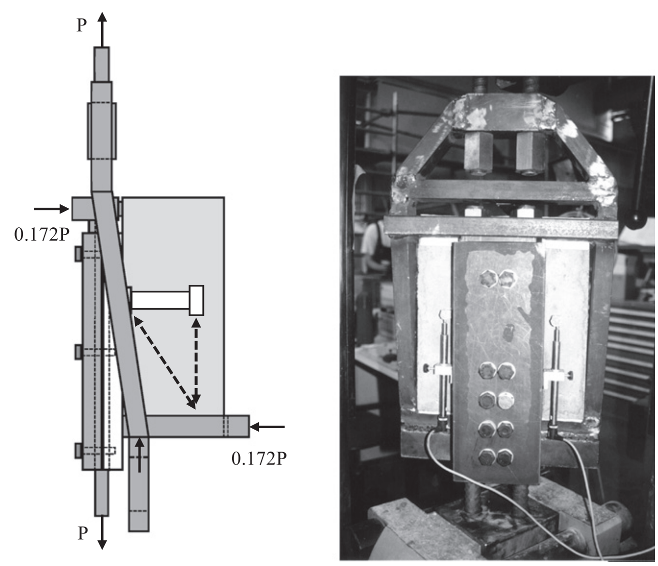

Fig. 5. Single push-out test used by Döinghaus [5].

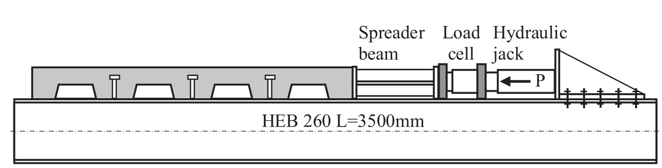

Fig. 6. Horizontal push-off test used by Lam et al. [9].