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Resistance of headed studs subjected to fatigue loading Part II: Analytical study

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Abstract

Most design codes consider the static and fatigue resistance of composite steel–concrete structures with separate verifications for ultimate limit state and the limit state of fatigue. For headed shear studs both verifications are based on worldwide performed experimental investigations with push-out specimens. The determination of the fatigue life of headed shear studs in recent European codes is based on the S–N curve developed from the statistical analysis of a great number of cyclic push-out tests. The S–N curve considers the shear stress range as the only loading parameter. In addition, the maximum shear force is limited at serviceability limit states in order to avoid significant inelastic behaviour. However, recent researches showed that beside the shear stress range, also the peak load and the static strength of the shear studs influence the fatigue life. Based on the results of the 71 push-out tests presented in the earlier companion paper, international push-out tests to determine the fatigue life of headed shear studs in solid concrete slabs are sorted and reanalyzed and analytical expressions are developed to predict the fatigue life and the reduced static strength after high cycle preloading. Furthermore, the linear damage accumulation hypothesis according to Palmgren and Miner is modified and improved to consider load sequence effects and non-linear behaviour.

Keywords: Fatigue life; Push-out test; Steel; Concrete; Composite; Headed shear studs; Unidirectional cyclic loading; Reduced static strength; Damage accumulation

1. Introduction

In several national and international codes for composite structures, the determination of the ultimate strength and fatigue life of headed studs is considered with two separate and independent verifications at the ultimate limit state and at the limit state of fatigue. This presumes that the structure maintains its full static strength until fatigue failure occurs. In this case, in the concepts for steel structures, the first crack defines the theoretical fatigue life. However, the fatigue resistance of headed shear studs in composite beams is determined from the fatigue strength curves (also known as S–N curve) which are developed from statistical analysis of cyclic push-out tests, where a complete failure after a significant increase of deformation with increasing number of cycles could be observed. In this case, the assumptions for two independent limit states are not valid because the design life is characterized by a significant predamage stage. Early investigations [1] and the systematic experimental investigations reported in the earlier companion paper have shown that the fatigue loading causes a reduction of the static strength of the shear studs within its fatigue life. Furthermore, it has to be considered that the fatigue life of the push-out specimen is influenced, beside the shear stress range, also by the peak load of the cyclic loading.

In the light of information gained from the results of push-out tests presented in the companion paper international fatigue tests on push-out specimen [2–14] subjected to unidirectional cyclic loading are sorted and reanalyzed to develop analytical expressions to predict the lifetime of headed shear studs in solid slabs. Further, an improved modified non-linear damage accumulation method concerning the load sequence effects and an empirical formula to predict the reduced static strength within the lifetime are presented.

2. International fatigue tests on shear stud connectors

Evaluation of the results presented in the companion paper showed that the determination of the fatigue life of headed shear studs may not be decoupled from its static strength and

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Notation

A_D	fatigue fracture area of the shear stud
A_G	forced fracture area of the shear stud
E_{cm}	secant modulus of elasticity of concrete
N	number of load cycles
N_f	fatigue life
P_{max}	peak of cyclic loading
P_{mean}	mean value of the cyclic loading
$P_{u,0}$	ultimate static strength of the shear stud
$P_{u,N}$	reduced static strength of the shear stud after N load cycles
V_x	coefficient of variation
d	diameter of the shank of the shear studs
f_c	compressive cylinder strength of concrete
f_u	tensile strength of the shear stud
N_i	number of cycles corresponding to the ith block of constant loading in a loading sequence
$\Delta n_{f,i}$	additional damage term corresponding to the ith block of constant loading in a loading sequence
ΔP	range of the cyclic loading
δ_i	inelastic displacement at ith load cycles
δ_1	plastic slip at the first cycle

in addition to the loading range also the peak load must be considered. Considering this information a literature survey concerning the cyclic push-out tests on headed shear studs is undertaken.

2.1. Selection criteria

Since the 1960s, various researchers have conducted a great number of fatigue tests on push-out test specimens. Because of different sizes and shapes of the composite components, because of number and position of studs, because of various restraints the results from international tests vary widely. Thus to achieve comparable results as the first step the following criteria are applied:

- The specimen must consist of two concrete slabs and a steel beam with headed shear studs as shear connectors in accordance with EC4 [15].
- The concrete slabs must be cast in a horizontal position.
- The studs must be welded with an adequate welding procedure ensuring the formation of a weld collar in accordance with EN13918 [16] and EN14555 [17].
- Tests must be made with sufficient transverse reinforcement.
- Only tests with unidirectional loading are considered.
- Only headed shear studs in solid slabs are considered.

2.2. Procedure for the comparison of test results

The static as well as the fatigue behaviour of headed shear studs embedded in concrete is affected by the material properties of both components, concrete and steel (stud), at the same time. Therefore it will not be correct to compare the absolute values of loading parameters or stresses. The fatigue behaviour of the push-out specimen is directly influenced by its static strength. Thus, to include various effects from specimen geometry and material properties, the loading parameters in each test program are considered as relative values with the static strength as the reference parameter. As the effect of the static strength on the fatigue life was not considered, in most previous works except in tests of Oehlers [7], Hanswille et al. [14] and Veljcovic, Johansson [13] short time static tests do not exist. In such cases the static resistance of the headed shear studs is calculated with the model given in Eurocode 4. In EC4 the static strength is defined by the minimum of the two equations given in (1) and (2), where the first one corresponds to the case "steel failure" and the second one to the case "concrete failure".

$$P_{ts} = k_{sm} \frac{\pi d^2}{4} f_u \tag{1}$$

$$P_{tc} = k_{cm} d^2 \sqrt{E_{cm} f_c} \tag{2}$$

The calculation model contains as the material coefficients the cylinder strength and the modulus of elasticity of concrete, as well as the tensile strength of the stud material. In EC4 and EC2 [18] the determination of the cylinder strength takes place on cylinders 150 × 300, which are stored under water at a temperature of 20 ± 2 °C. The cylinder strengths given in the literature [3–5,7,11–14] were determined on specimens with different geometries and climatic conditions. To accomplish comparable test results, all material coefficients were converted according to EC4 with the Eq. (3) using correction factors given in [19]. The correlation factor δ_{LR} takes into account the above mentioned effects.

$$f_c(\text{EC4}) = \delta_{LR} \cdot f_R \tag{3}$$

In most of the tests the modulus of elasticity of concrete was not determined experimentally so this is determined on the basis of the relations given EC2 with the Eq. (4).

$$E_{cm} = 9500 \cdot (f_{cm})^{1/3} \tag{4}$$

In the tests, headed shear studs with different material properties were used, thus making the tests comparable, and the tensile strength of the pure stud material was considered. Influences from the welding procedure on the material properties in the heat affected zone are neglected.

2.3. Selected tests

Tests fulfilling the above selection criteria are listed in the Table 1 chronologically with the range of material properties.

Investigation of 65 fatigue tests revealed that the use of experimental (or theoretical) static strength of the shear stud $P_{u,0}$ as reference parameter for the loading parameters P_{max}, P_{min} and ΔP makes it possible to include effects from different material properties, size and shapes of components. However, effects from different number and position of studs and different restraints of concrete slabs lead to incomparable results. In cases of shear studs with fewer than four on one side of the steel beam due to absence of redistribution possibilities of forces,