Title

High-strength reinforcement in reinforced concrete construction – identification of potential fields of application, development of design principles and determination of potential economic savings

Purpose/ basis

Within the scope of this research project, possibilities for saving reinforcement steel by installing high-strength reinforcing bars in structural members subjected to bending load were examined. In addition to its high grade, S 670 high-strength reinforcement features an increased relative rib area. For its practical application, information on bond behaviour, crack width verification as well as other static and structural verifications is required.

Steel grades examined

In addition to S 670 high-strength reinforcement, S 600 and B 500 reinforcing bars were examined as well, to serve as reference. The examined high-strength steel has already been successfully used in various projects for structural members subjected predominantly to compressive stress. Other potential application fields are structural members subjected to bending stress in particular if these structural members have high reinforcement ratios. These include e.g. foundation members, underpinning girders and frame corners.

B 500

S 600

S 670

Fig. 1: Examined steel grades

To examine the bond behaviour of high strengt reinforcement, 66 pull-out tests were carried out at the Institute of Structural Concrete (IMB) of the RWTH Aachen. In these tests, the influence of the relative rib area, concrete strength, bar diameter, rib alignment and confinement due to a concrete cover and stirrup reinforcement on the bond strength and stiffness were examined. To determine the bond stress-slip curves, the slip of the reinforcing bar relative to the concrete surface was recorded during loading.

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Fig. 2: Pull out test

The increased relative rib area affected the bond strength only when the slip values were low. A doubling of the concrete cover from 1·Ø to 2·Ø significantly increased the bond strength, whereas the stirrup reinforcement only affected the post-cracking behaviour of the test specimen.

The crack behaviour of tensile elements with S 670 reinforcement was examined by carrying out 14 tensile tests. The tests served to examine the influence of the relative rib area, concrete strength, bar diameter, alignment of the stirrup reinforcement and reinforcement percentage on the crack pattern.

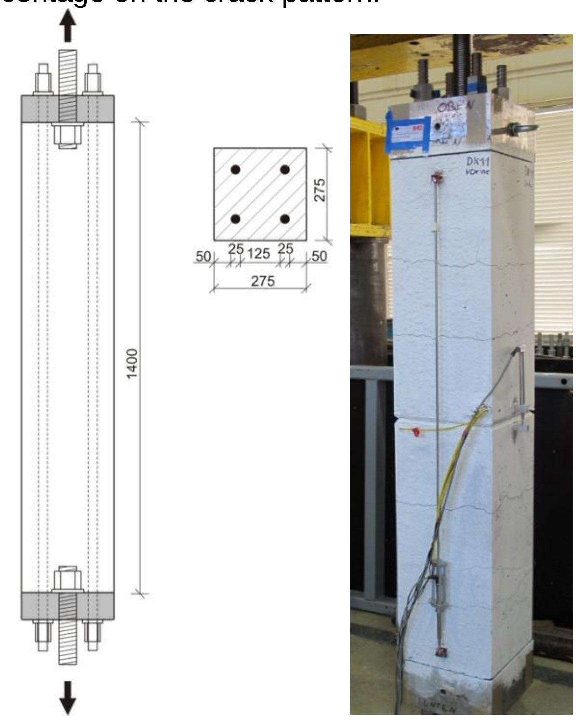

Fig. 3 Tensile test

While an increased concrete cover and bar diameter results in larger crack widths, a higher reinforcement percentage leads to smaller crack widths.

Based on the results of the pull out and tensile tests, the crack theory used in EN 1992-1-1 (EC 2) as the basis for determining crack widths was adapted for the high-strength reinforcement. For this, first, a bond stress-slip law was deduced from the pull out tests and was then used to determine the theoretical crack spacing as well as the steel and concrete stress-strain curve between the cracks. From this basis, the parameters required to determine the crack width were deduced.

In addition to the crack determination in the tensile tests, 4 bending tests were carried out as well. Based on the bending tests, the influence of the reinforcement percentage, compressive strength of concrete and relative rib area on the crack and load-bearing behaviour of the girders was examined.

Fig. 4: Four-point bending test

Also in this test series, a reduction in the crack widths could be observed with increasing reinforcement percentages. At identical absolute stresses, the crack widths of the S 670-reinforced girders subjected to bending were smaller than those reinforced with B 500. At identical stresses relative to the yield strength, both girders showed the same crack widths.

The bond tests as well as the tests carried out to determine the crack widths were numerically represented and calculated using the finite element method. For the bending tests, a parameter study was performed. Since the simulation of the bond area between steel and concrete is very complex, the reinforcing bars were firmly connected with the reinforcement in the numerical model in the tensile and bending tests carried out within the scope of this research project. The finite element programmes do not yield any crack widths, therefore the crack widths were determined based on the elongation of the finite elements.

For the practical application of high-strength reinforcement, design rules are required as well, since EC 2 only covers reinforcing grades up to S 600. The most important design rules of EC 2 (determination of the stress-strain curve for S 670, ULS determination for bending, SLS design – stress, crack width and deflection verification) were summarized and relevant design recommendations specified. This should facilitate its application and thus increase the acceptance of the new construction material in practice.

Conclusion

The bond properties of high-strength steel with a larger relative rib area as compared to B 500 were determined within the scope of the research project. Pull out tests were carried out to empirically determine the bond stress-slip curves. Based on these, a bond law for steels with increased relative rib areas and higher steel stresses was deduced and used to modify calculation of the crack width according to EC 2. The deduced bond law leads to a slight change in the model limiting the crack widths according to EC 2. The magnitude of the bond strength was chosen dependent on the concrete cover, in order to transfer the bond forces and limit splitting cracks.