Computers and Concrete, Vol. 3, No. 2/3 (2006) 91-102

DOI: http://dx.doi.org/10.12989/cac.2006.3.2/3.091

Nonlinear analysis of connectors applied on concrete composite constructions

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(Received November 2, 2005, Accepted April 27, 2006)

Abstract. To place concrete overlays has become a standard application in the strengthening and rehabilitation of concrete structures such as bridges, tunnels, parking decks and industrial buildings. In general, connectors are used to ensure a monolithic behavior of the two concrete layers. Within the framework of the development of a new connector wedge splitting tests and shear tests were performed, in addition nonlinear finite element analyses were applied to investigate the load transfer behavior of the connectors for different prototypes. The numerical simulation results were compared to experimental data. The computed load-displacement curve demonstrates good correspondence with the curves obtained in the experiments, and the experimental crack patterns are reasonably simulated by the computed crack propagation. Both numerical and experimental investigations on the wedge splitting test and on the shear test served as basis for the development of new type of connectors.

Keywords: concrete; composite construction; connector; nonlinear analysis.

1. Introduction

The placing of concrete overlays has gained in importance as a result of the more frequent need to strengthen existing structures. Concrete overlays are mainly used for repairing or strengthening of bridges, tunnels, parking decks and industrial buildings. Therefore, a monolithic behavior of the resultant structure should be insured. Different attempts have been made to achieve this goal, mainly by a special treatment of the old concrete surface. However, experiences made by such methods often result in delamination, which can occur right away or after some time. To remedy this problem connectors served as connection elements between the two layers have been introduced in order to transfer the forces away from the critical interface zone. Different types of connectors were applied in the past, e.g., rebars, rebars with forged heads or threaded rods with plates and nuts. The connectors were fixed in the old concrete like adhesive anchors to be cast in the new concrete layer afterwards. The mechanical behavior of the related interface zone depends on the roughness of the old concrete surface due to cohesion and friction. In addition, the pullout behavior of the connector and the related dowel action play a crucial role for the load transferring capability of the structure (Tsoukantas and Tassios 1989).

Within the framework of the development of a new connector nonlinear finite element analyses were applied to investigate the load transfer behavior of the connectors with different prototypes.

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Therefore, uniaxial wedge splitting tests (Tschegg, *et al.* 2000) and shear tests (Randl 1997) were performed. In the current paper we focuse on (i) the determination of the load carrying behavior of a new connector designed for concrete composite constructions and (ii) the comparison of the obtained results with an existing solution.

2. Material modeling

The development of innovative connectors can only be successful with an in-depth understanding of the physical phenomena including the complete load transfer process. In order to fulfill these requirements Hilti Corporation has been developing own simulation tools for the specific process occurring within its product range. Especially, in the field of fastening technology numerical simulation plays a key role for the development process (Nienstedt and Dietrich 1995 or Nienstedt and Mattner 2001). The main base material of these products is concrete.

Evidently, the simulation of anchoring system requires a realistic modeling of tensile stresses and the cracking process after reaching the tensile strength of the material. An essential part of the material description is the modeling of fracturing that is generally caused by mode I fracture failure. The fracture energy needed for crack propagation must be modeled consequently. A widely distributed approach to describe the mode I crack for brittle material is the so-called smeared crack approach. The utilization of the rotation smeared crack approach is integrated in a uniaxial stress-strain environment. To consider the influence of multi-axiality of the stress state an interaction between the stress state and the stress-strain relationship in the corresponding integration point was introduced, especially necessary in the regions of load transfer into the base material (Nienstedt, *et al.* 1999).

The constitutive model has been proven for several applications with very robust and easy to handle for the development engineers in their daily business for several applications. Comparison between simulated results and the corresponding experimental data shows a very good agreement (Nienstedt, *et al.* 2001).

3. Numerical simulation

In general, connectors are used to ensure a monolithic behavior of the two concrete layers. Concerning the mechanical behavior of the connector different types of loads have to be considered; such as external loads, thermal gradients or shrinkage resulting in normal and shear stresses at the interface surface as well as in the connector. The latter can result in delamination, especially at the edges of a concrete overlay. The related resistance can be subdivided in three different parts: the interlock by means of the roughness of the old concrete surface due to cohesion and friction, the pullout behavior of the connector and the dowel action due to bending and shear force (Fig. 1).

3.1. Uniaxial wedge splitting test

To investigate the pull-out capacity of the different prototypes a uniaxial wedge splitting test was used (Tschegg, *et al.* 2000). A schematic representation of the test is shown in Fig. 2. In the test a cubic specimen is placed on a narrow linear support. In the upper part of the specimen there is a

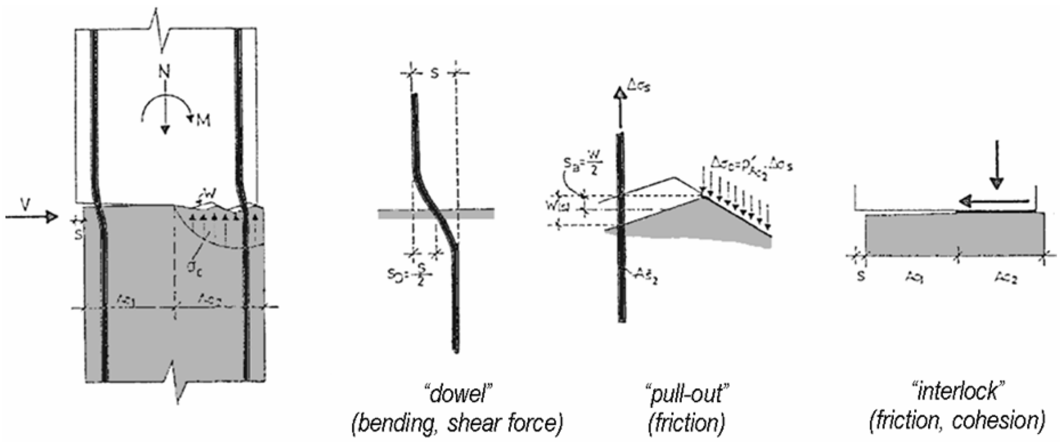

Fig. 1 Transfer of shear across a concrete crack (Tsoukantas and Tassios 1989)

notch ensuring the crack initiation in the central plane of the specimen. The system was loaded by a vertical displacement on the wedge resulting in horizontal forces on the two concrete parts of the specimen. The related load-displacement curves show the influence of the interface by means of the maximum peak load as well as of the behavior of the connector in the post-peak region. Therefore, a reduced decrease of the resistance after reaching the peak load provides an indicator for an optimized static behavior of the connection.

Taking advantage of symmetry only half of the specimen was modeled. The right side of Fig. 3 represents the old existing concrete structure, while the left is the new one cast on top of the other. The connector is fixed in the old concrete part by using an adhesive compound. On the left a

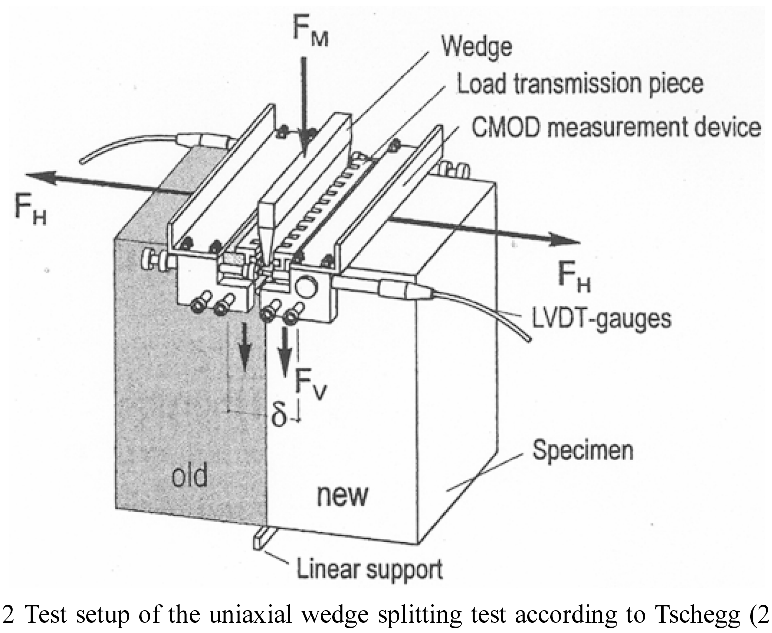

Fig. 2 Test setup of the uniaxial wedge splitting test according to Tschegg (2000)

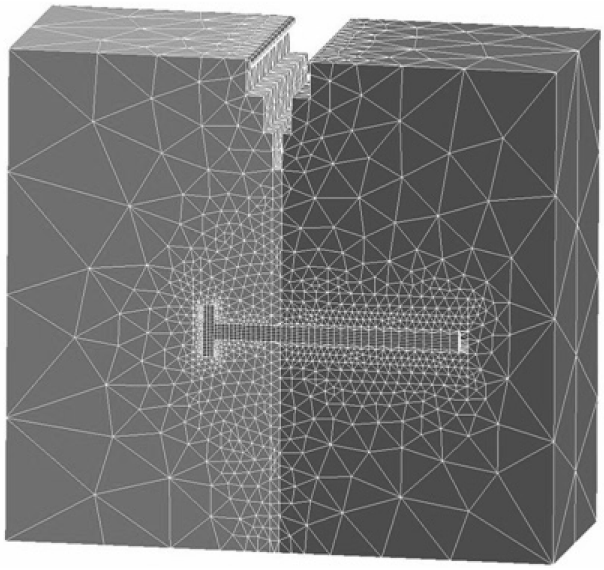

Fig. 3 Finite element mesh for the uniaxial wedge splitting test using a threaded rod with a diameter of 10 mm and a rectangular plate of 28 × 35 × 6 mm

rectangular plate is provided to introduce the load like a headed stud. The specimen was discretised by 28848 elements for modeling the old concrete, 25301 elements for the new concrete, 4524 elements for the interface, 750 elements for the adhesive compound and 667 elements for the connector. Considering experimental results for a threaded rod with a diameter of 10 mm and a rectangular plate of 28 × 35 × 6 mm the first simulation served as a validation of the structural modeling of the system. For the concrete specimen a concrete quality C20/25 according to CEB-FIP (1991) was used. The material parameters for the interface were determined by means of preliminary studies disregarding the load carrying capacity of the connector.

The comparison of the experimental and numerical investigations is made in terms of the related load-displacement curves. Therefore, the experimentally and numerically determined horizontal forces were applied as a function of the crack mouth opening displacement. The respective curves are shown in Fig. 4. The correspondence of the computed and the experimental load-displacement curves is quite good. Two load-additional displacement curves are plotted in Fig. 4, one shows the behavior of the interface and another one is focused on the pull-out capacity of the connector neglecting the tensile load capacity of the interface.

Considering typical applications of concrete composite constructions connectors with a diameter of 12 mm are usually used. Additional simulations concerning a threaded rod with a diameter of 12 mm and a rectangular plate of 40 × 40 × 6 mm were performed. The respective load-displacement curve is shown in Fig. 6. In addition, the load-displacement curve showing the pull-out capacity of the connector disregarding the tensile load capacity of the interface is shown in the same figure.

Based on the presented model further investigations were conducted in order to test different shapes of the head part of the connector. Most of them were prototypes with different inclinations of the surface which introduced the load. The finite element mesh of the resulting prototype for the new Hilti Concrete Connector (HCC) is displayed in Fig. 5. The related load-displacement curve is

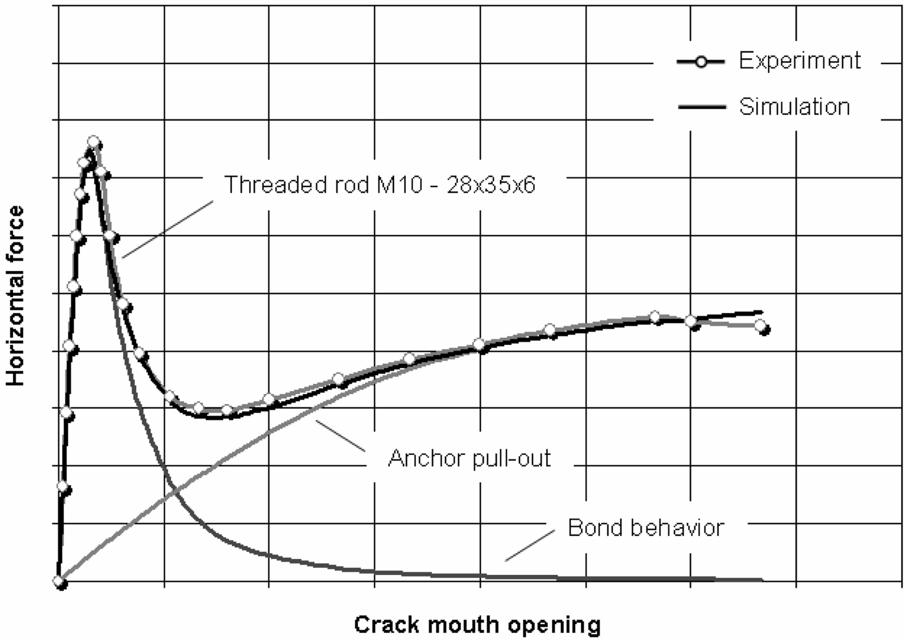

Fig. 4 Load-displacement curves for the uniaxial wedge splitting test using a threaded rod with a diameter of 10 mm and a rectangular plate of 28 × 35 × 6 mm

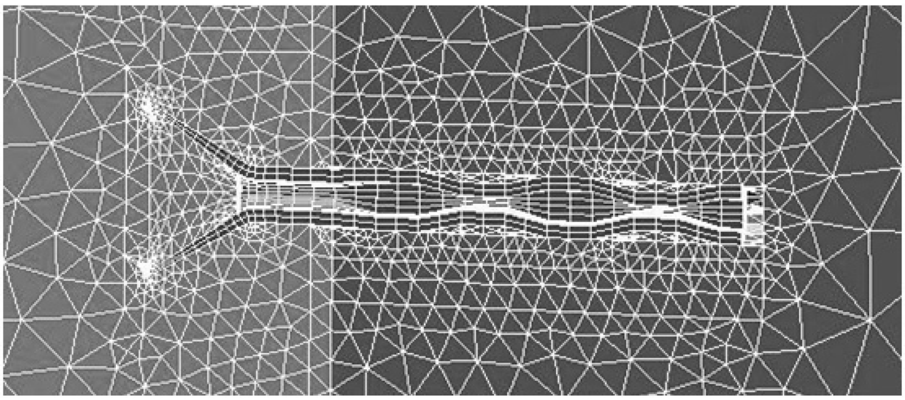

Fig. 5 Finite element mesh of the new HCC element for the uniaxial wedge splitting test

shown in Fig. 6. Additionally, the load-displacement curve showing the pull-out capacity of the new connector neglecting the tensile load capacity of the interface is displayed in Fig. 6 as well. In order to verify the numerical results for new concrete connector experimental investigations were performed. The numerically determined load-displacement demonstrates good correspondence with the curve obtained in the experimental investigations (Fig. 6). Moreover, the experimental crack pattern (Fig. 7) is reasonably simulated by the computed crack propagation as shown in Fig. 8.

According to the comparison between the existing solution of a 12 mm threaded rod with a

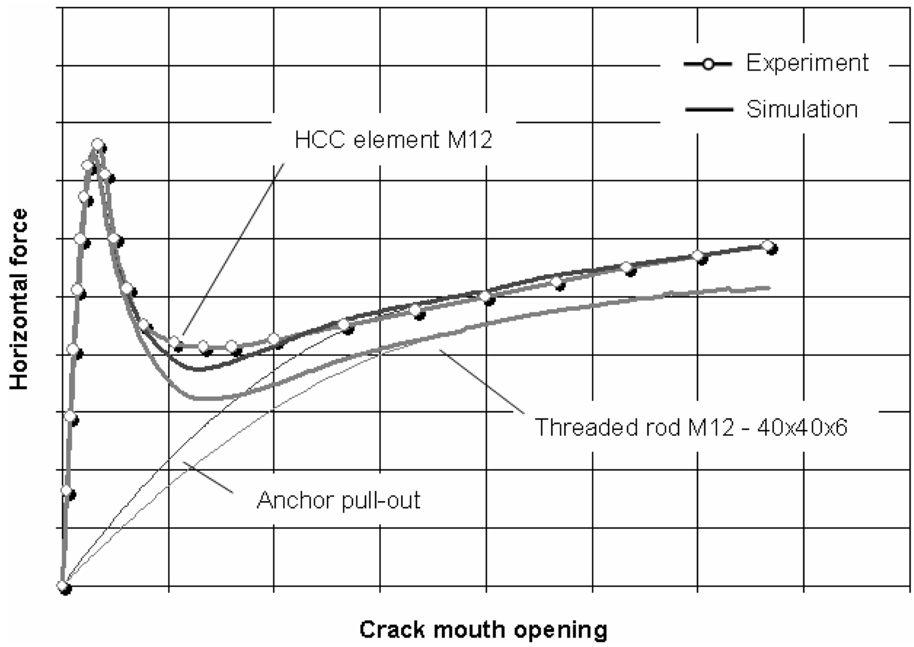

Fig. 6 Load-displacement curves for the uniaxial wedge splitting test using a threaded rod with a diameter of 12 mm and a rectangular plate of $40 \times 40 \times 6$ mm and the new HCC element

Fig. 7 Experimental failure mode for the uniaxial wedge splitting test using the new HCC element

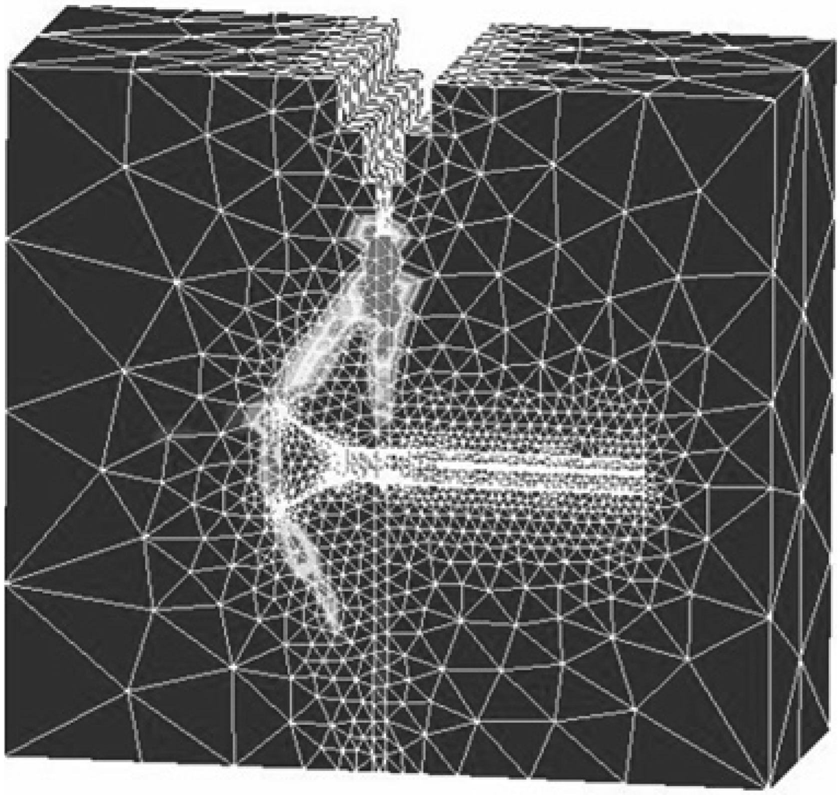

Fig. 8 Numerical crack pattern for the uniaxial wedge splitting test using the new HCC element

rectangular plate and the new HCC connector a less pronounced drop of resistance after reaching the first peak load could be observed. This could be realized by increasing the stiffness of the connector as well as by improving the load introduction into the concrete layer.

3.2. Shear test

In order to verify the improvements of the newly developed connector a shear test was analyzed numerically. The related experimental investigations were carried out at Hilti Corporation to investigate the interrelationships of various degrees of roughness and transferable shear stresses with various degrees of reinforcement. A new concrete overlay was cast on a concrete slab (Fig. 9). The system was loaded by applying a horizontal load at the corner of the surrounding steel frame. The concrete slab was fixed by means of the pistons of the test rig.

The test results confirm the strong influence of the roughness on the shear resistance and shear stiffness. The three components of cohesion, friction and dowel action could be isolated and determined quantitatively. They contribute differently to the overall resistance depending on surface roughness and amount of reinforcement. In Fig. 10 a typical load-displacement curve obtained in these experimental investigations is displayed. At a very small horizontal displacement the peak load is attained. The increase of the displacement leads to a significant decrease of the resistance due to overcoming of the surface interlock. Finally, the resistance increases again due

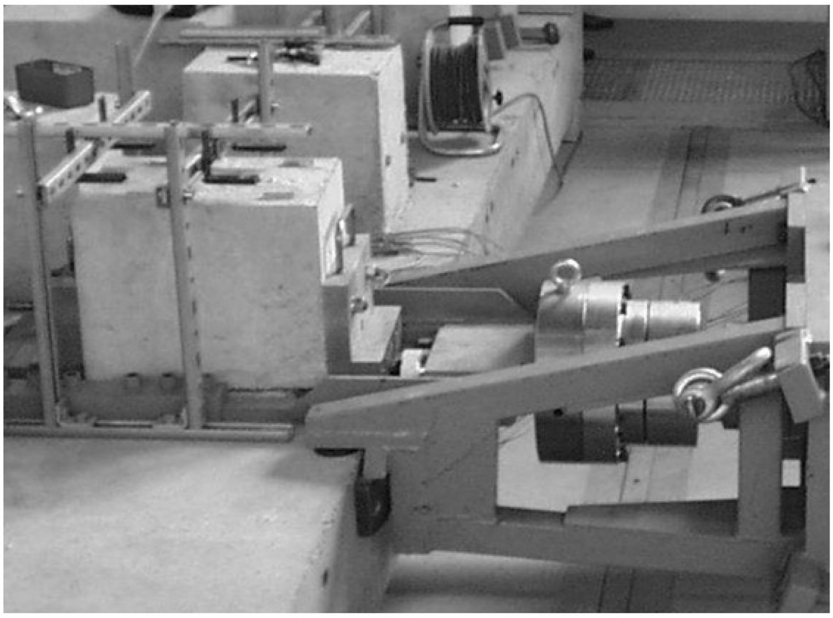

Fig. 9 Test setup of the shear tests performed at Hilti Corporation

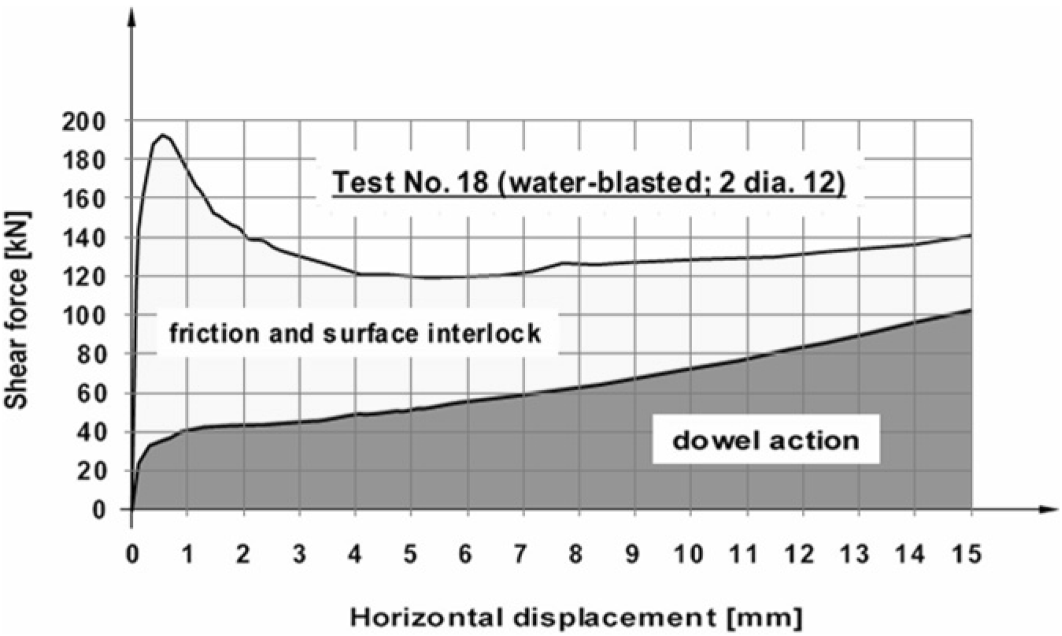

Fig. 10 Load-displacement curve for the shear test in case of a water-blasted surface treatment

to dowel action and the pull-out capacity of the connector. Moreover, this load-displacement curve shows a strong influence of the surface roughness for a water-blasted surface treatment. Concerning a sand-blasted surface treatment the influence out of the surface roughness is

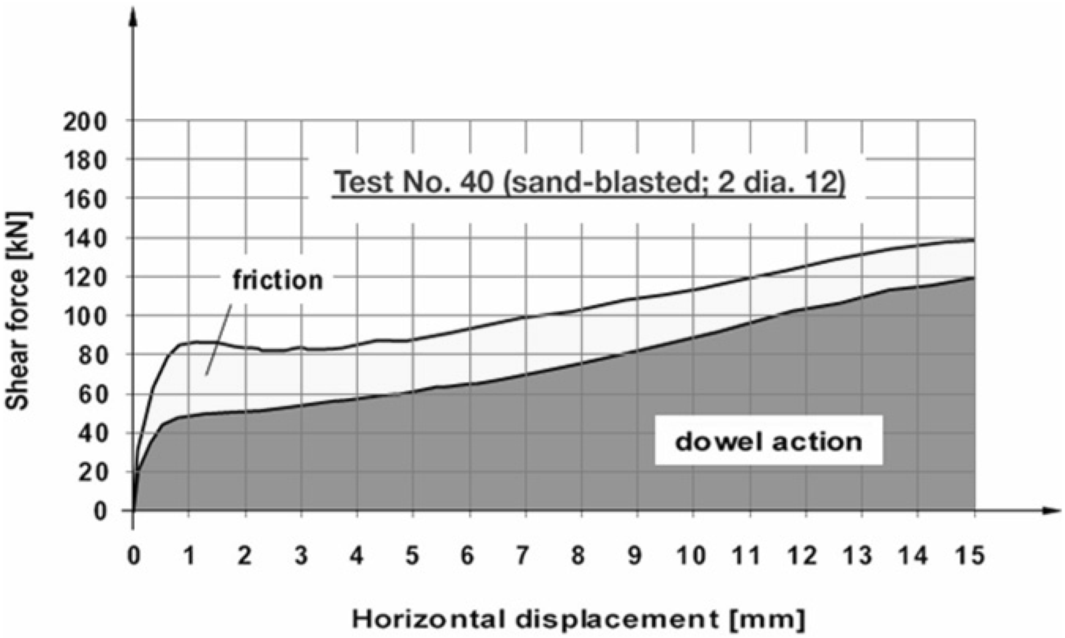

Fig. 11 Load-displacement curve for the shear test in case of a sand-blasted surface treatment

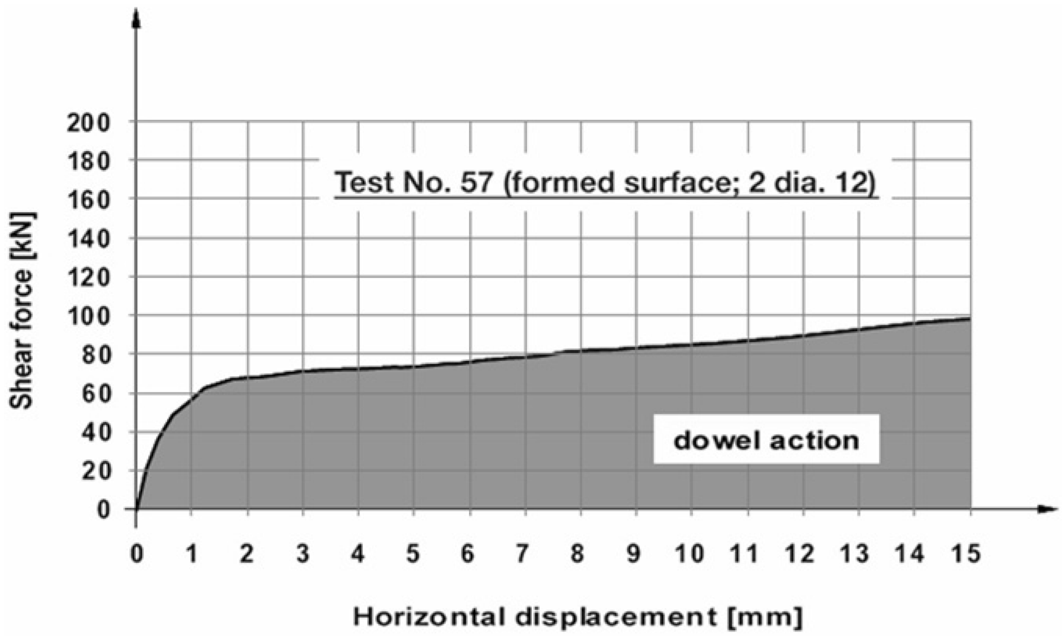

Fig. 12 Load-displacement curve for the shear test in case of a formed surface treatment

significantly smaller (Fig. 11).

Neglecting any roughness of the surface by means of a smooth interface surface the entire resistance of the composite construction is provided only by dowel action (Fig. 12). The measured displacements

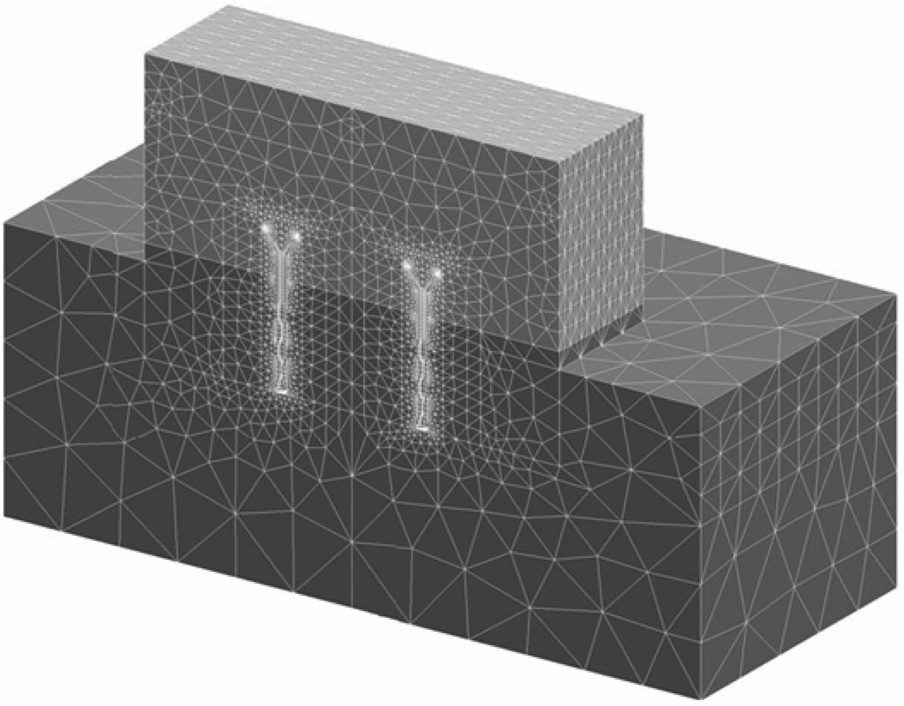

Fig. 13 Finite element mesh for the shear test using two new HCC elements

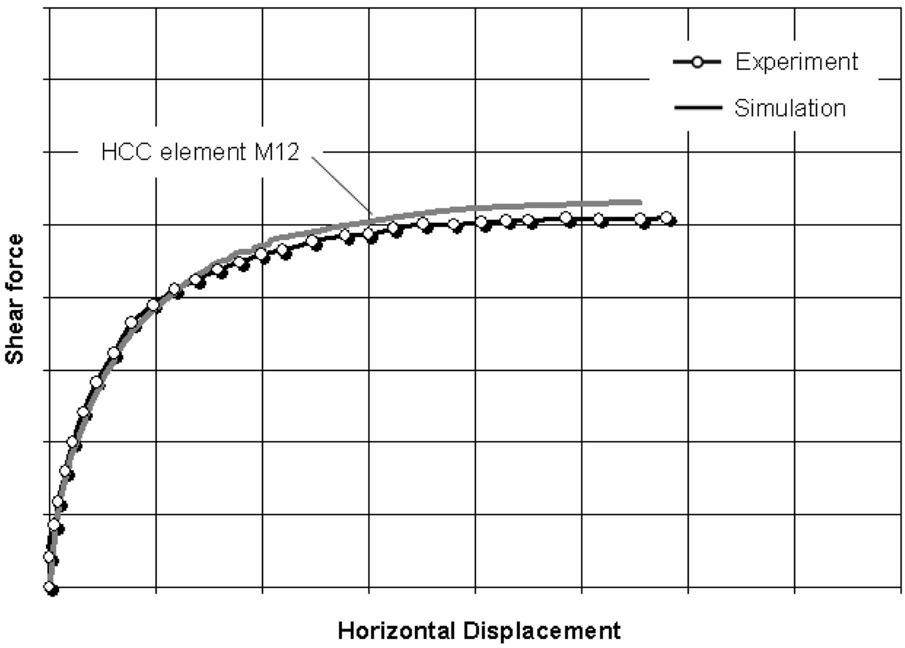

Fig. 14 Load-displacement curves for the shear test with respect to a smooth surface

showed a separation of the interface and, due to the lack of roughness, a loss of contact. This specific test was used in order to investigate the load carrying capacity of the new connector.

Due to symmetry only half of the specimen was modeled. The concrete is subdivided in two parts: the old concrete represented by the base plate and the new concrete indicated by the upper part. Two connectors are used. The specimen was discretised by 34504 elements for modeling the old concrete, 34136 elements for the new concrete, 3866 elements for the adhesive compound and 2304 elements for the connector. The respective finite element mesh is displayed in Fig. 13.

The comparison between the experimental and numerical investigations is made in terms of load-displacement curves. Therefore, the experimentally and numerically determined shear forces were applied as a function of the horizontal displacement. The respective curves are shown in Fig. 14. The computed load-displacement curve demonstrates good correspondence with the curve obtained in the experimental investigation. Moreover, the separation of the interface could be observed in the simulation. The ultimate load of the connection was attained by yielding of the connectors. In addition, the location of the damaged parts in the concrete layer agrees well with the concrete failure observed in the experiments.

4. Conclusions

The aim of this study was to investigate the load carrying behavior of a new connector designed for concrete composite constructions and to compare the results with an existing solution. Therefore, uniaxial wedge splitting tests and shear tests were performed. The comparison of the results between simulation and experiment based on the load-displacement curves and the failure modes demonstrates good correspondence.

Concerning the comparison of the obtained results with an existing solution the new HCC connector showed a significant improvement on the load carrying behavior by means of a less pronounced drop of resistance after reaching the first peak load in the respective load displacement curves. This could be realized by increasing the stiffness of the connector as well as by improving the load introduction into the concrete layer. Moreover, the better design of the HCC connector led to an improved reliability of the system and to an easier and faster setting with respect to existing solutions.

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