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Punching behavior of biaxial hollow slabs

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Abstract

The invention of a new kind of hollow slab with plastic balls as hollow bodies entailed the necessity to investigate its structural behavior. Because of its main field of application as a flat slab, the punching shear capacity is one of the most interesting properties of this slab. To investigate the influence of the cavities on the punching behavior, tests were carried out at the Institute for Concrete Structures in Darmstadt. In addition to these tests nonlinear computations using the Finite Element Method were performed. The computations allowed parametric studies to get a better understanding of the structural behavior without doing further expensive tests. Finally, necessary modifications of existing design recommendations according to the German design code DIN 1045 [1] were developed.

Keywords: Punching behavior; Biaxial hollow slab; BubbleDeck; 3D FE-analysis

1. Introduction

In 1998 tests were conducted with biaxial hollow slabs, the so-called BubbleDeck. The aim of these tests was to investigate the structural behavior of this new kind of monolithic flat slab and to check the validity of the German design code DIN 1045 [1].

The BubbleDeck combines the advantages of material-saving and extreme load-carrying capacity because of its optimized cross-section. The reduction of the dead load is about 30%. It is also called a biaxial hollow slab because the applied loads can be carried in any direction. The principle of this slab is to connect hollow plastic balls (bubbles) with reinforcing elements in an industrial prefabrication phase, which leads to a more efficient method of construction. In Fig. 1 the principle and an example of a plain module is visualized.

The main field of application is large flat slabs. So among properties such as the shear resistance, the bending capacity and the deflection behavior, one of the most important properties of biaxial hollow slabs is its punching shear capacity [7].

To investigate this property a research project has been started, containing the following steps:

Step 1: Punching tests with representative slab dimensions.

Step 2: Numerical simulations using nonlinear finite element method for further investigations of the structural behavior (studies of parameters).

Step 3: Check of the compliance of existing design codes and preparation of required modifications.

Besides the importance of the knowledge of the maximum punching shear capacity as an absolute value, one of the main questions before starting the tests was, whether the punching behavior and the mode of failure of the BubbleDeck would be similar to a solid slab or not. If there would be a completely different failure mechanism, all the research done in the field of punching shear capacity of reinforced concrete slabs would not be transferable. Otherwise if there would be a kind of similarity in the failure mechanism, it would be much easier to work out necessary modifications of the design concepts concerning the extraordinary geometry of the cross-section.

2. Punching tests

2.1. Test specimen

To investigate the punching shear capacity of the biaxial hollow slabs, three specimens with a thickness of

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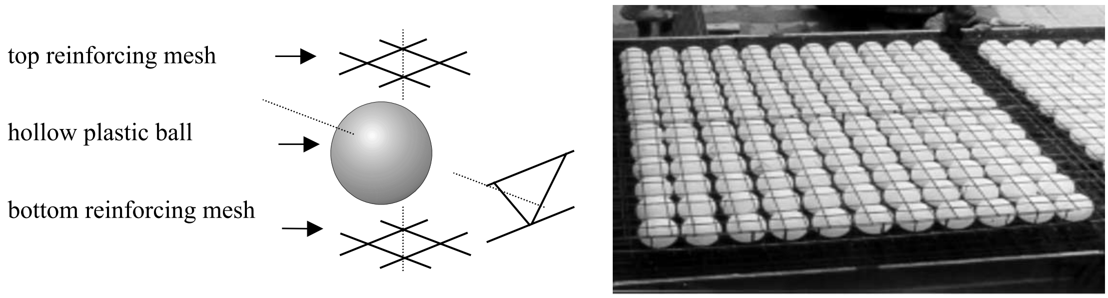

Fig. 1. Principle and example of a precast plain module.

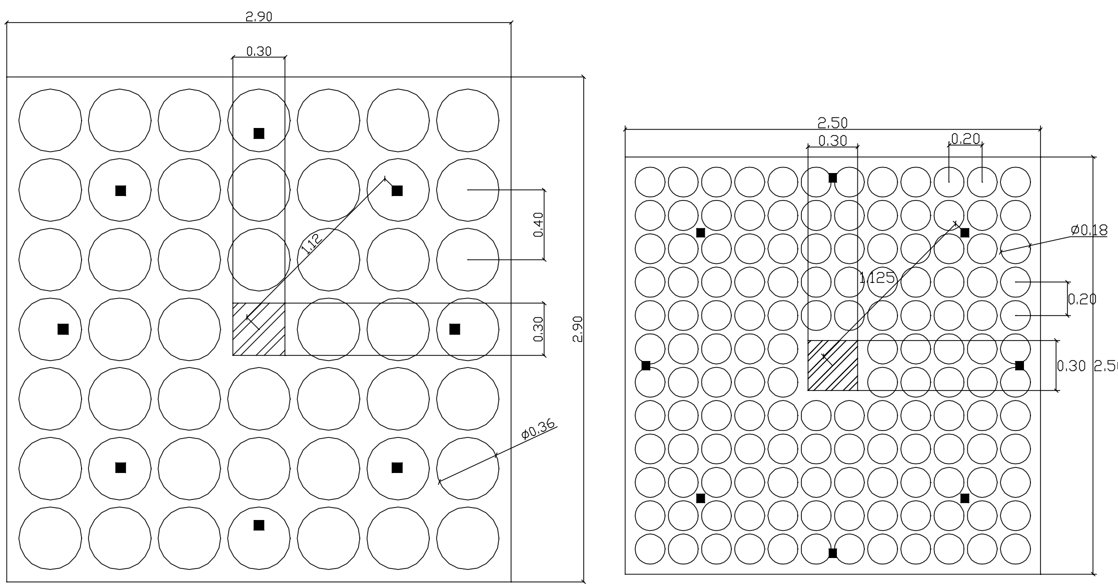

Fig. 2. Top view of the specimens.

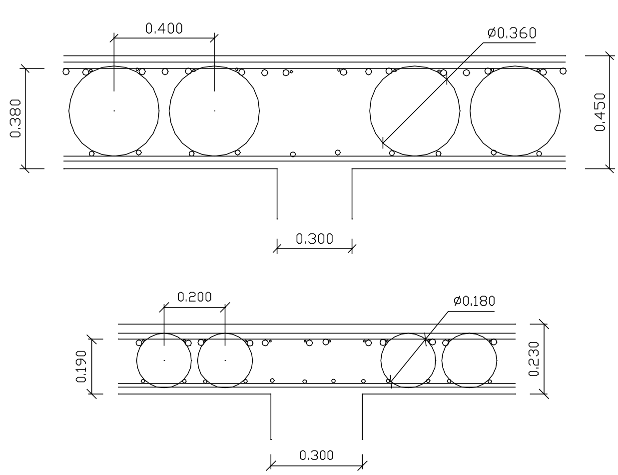

Fig. 3. Cross-section of the specimens.

24 cm and three specimens with a thickness of 45 cm were produced and tested. By choosing these two values of thickness, which represent practicable values, the influence of a possible size effect could be studied.

The slabs were produced with B25 concrete (nominal compressive strength: 25 N/mm^2, average compression strength: 30 N/mm^2) and B35 concrete (nominal compressive strength: 35 N/mm^2, average compression strength: 40 N/mm^2), respectively, and a maximum aggregate size of 16 mm. Each specimen included the slab and a short column to simulate a realistic punching situation. Besides the reinforcement of the plain module an additional upper reinforcement was provided, to make sure that the failure of the specimen will be a punching failure. The dimensions of the tested slabs are shown in Figs. 2 and 3. The material properties and the test results are summarized in Table 1.

2.2. Test setup

During the tests each specimen was fixed in eight points arranged in a circle with a radius of 1125 mm.

Table 1
Measurements, material properties and ultimate punching loads

Name	Thickness (cm)	Hollow body	$A_{s\text{-up}}$ (cm²/m)	$A_{s\text{-down}}$ (cm²/m)	$f_{c,150}$ (N/mm²)	$f_{c,t}$ (N/mm²)	Ultimate load BubbleDeck (test) (kN)	Ultimate load massive slab (calculated[a]) (kN)
D1-24	24	Yes	34.25	11.31	44.4	2.8	520	840
D2-24	24	Yes	34.25	11.31	50.8	2.5	580	945
D3-24	24	Yes	34.25	11.31	46.7	2.9	525	893
D4-45	45	Yes	40.29	15.71	29.6	2.9	935	1503
D5-45	45	Yes	40.29	15.71	37.9	2.1	990	1701
D6-45	45	Yes	40.29	15.71	40.5	3.0	1180	1795

[a] According to DIN 1045.

The load was applied by a hydraulic jack situated beneath the column. The test setup (Fig. 4) enabled a good observation of the crack initiation and the punching failure. Several extensometers, strain gauges and deflection gauges were installed to control the reactions of the steel and concrete under the applied load until the failure appeared.

2.3. Test results

The first observation of the cracks led to the opinion that the failure is different from the failure of a solid slab. The punching circle seemed to be smaller, influenced by the existence of the bubbles (Fig. 5). A close look at the cross-section after the slabs have been sawn in the middle axis could disprove this first impression (Fig. 6). The hollow bodies did not influence the crack pattern compared to that of a solid slab. The angle between the horizontal and the internal crack was in between 30° and 40°. As expected the value of the punching resistance is smaller than the one of a solid slab. Taking into consideration the crack pattern, it can be realized that this value must be related closely to the number of hollow plastic balls crossing the punching cracks.

3. Numerical simulation using nonlinear finite element methods

To verify the test results, to study different parameters and to get the possibility to investigate the failure mechanism without further expensive tests, numerical simulations using nonlinear Finite Element Methods are ongoing. Today the computational modeling is already an effective tool to simulate the behavior of materials and structures. In the literature a large amount of reports can be found. Some examples of use are summarized e.g., in [3–5].

In the case of the biaxial hollow slab the situation is additionally complicated because of the extraordinary geometry. The only way to simulate the structural behavior of such a slab is to use a three-dimensional reproduction. Instead of using axisymmetric elements, normally used to investigate punching behavior, the use of solid elements is required. Because of the three-dimensional stress situation adequate constitutive material-models are necessary to get realistic results.

For the computation of the biaxial hollow slab the nonlinear finite element program *DIANA* is used. First of all the simulations of the tests serve to check the capacity of the program and the FE-model. If this test leads to satisfactory results, the computations can be used to investigate the influence of different material properties and various dimensions of the slab.

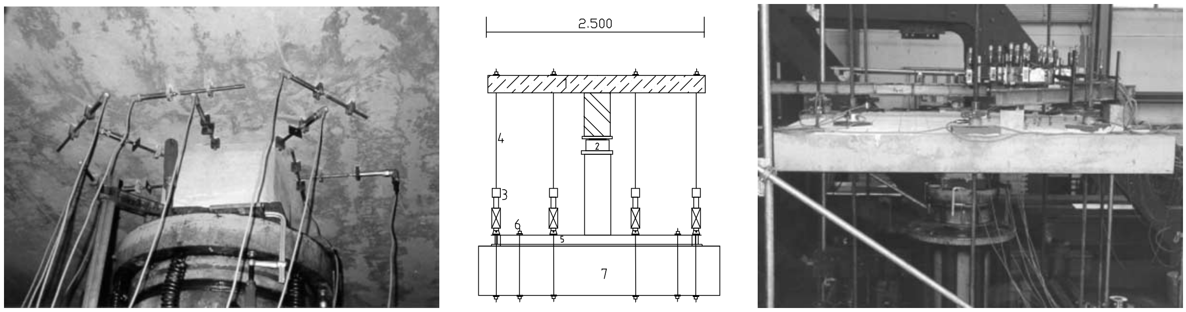

Fig. 4. Test setup.

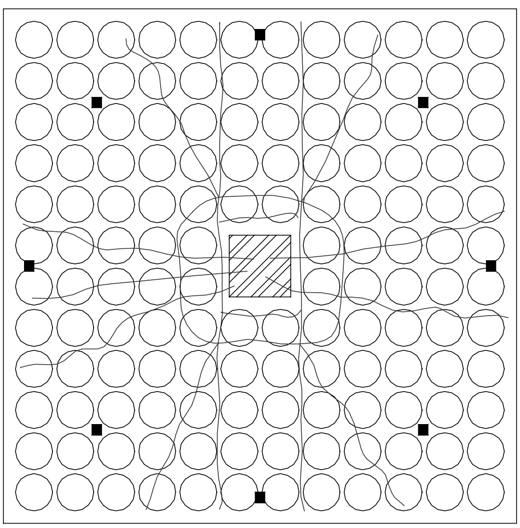

Fig. 5. Crack pattern (top view).

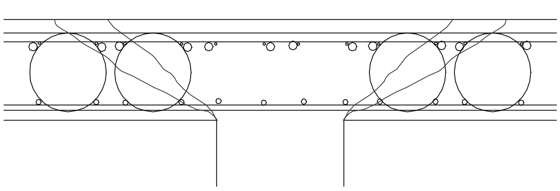

Fig. 6. Crack pattern (cross-section).

To generate a finite element mesh of the slab including the cavities in form of the balls, four-node, isoparametric solid pyramid elements are used. Although the symmetry of the system has been taken into account, the computation time is very high. Another mesh with less elements was not able to reproduce the geometry of the bubbles in a satisfying manner. The use of smaller elements and of elements with an advanced order did not change the results significantly, but led to an increased computation time. In Fig. 7 the mesh is visualized.

The steel has been added as embedded reinforcement that assumes a perfect bond between the reinforcement and the concrete. For the steel a bilinear stress–strain diagram is used. For the concrete the Total-Strain-Concept, developed along the lines of the Modified Compression Field Theory, originally proposed by Vecchio and Collins [8,9], is used. For the compressive regime a parabolic stress–strain diagram and for the tensile regime a softening curve according to Hordijk [6], is taken into account. Influences on the compressive behavior like lateral cracking and lateral confinement are considered additionally.

The diagram in Fig. 8 shows a comparison of the load–deflection curve of the test and the computation. A quite good conformance is observed. The diagram in Fig. 9 gives an impression of the influence of the mate-

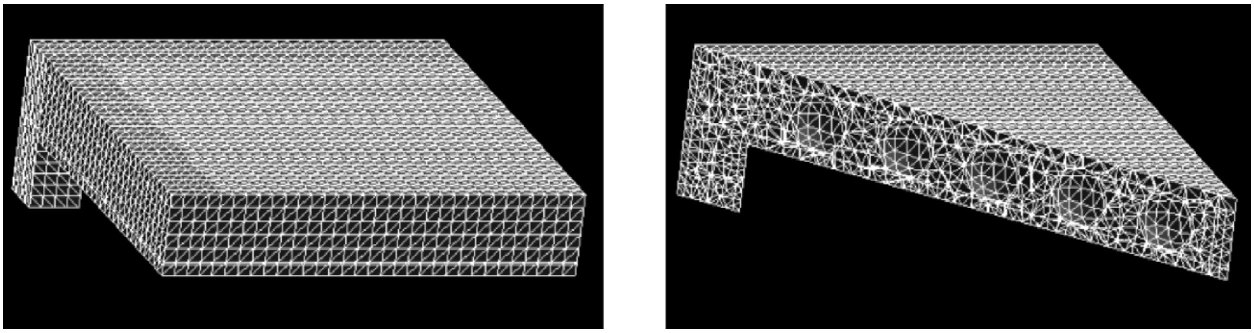

Fig. 7. Finite element mesh (front view and view of the cross-section).

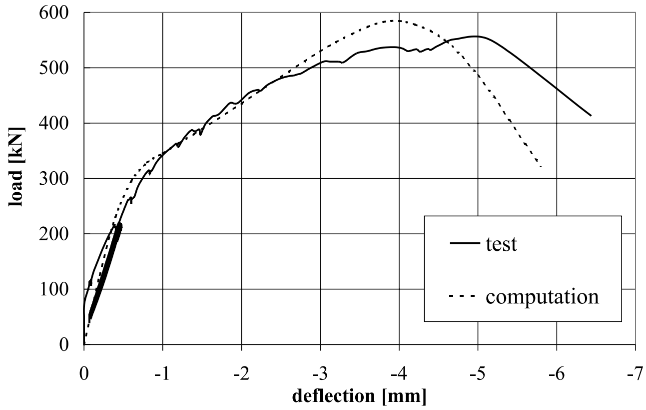

Fig. 8. Load–deflection diagram of a computation and test.

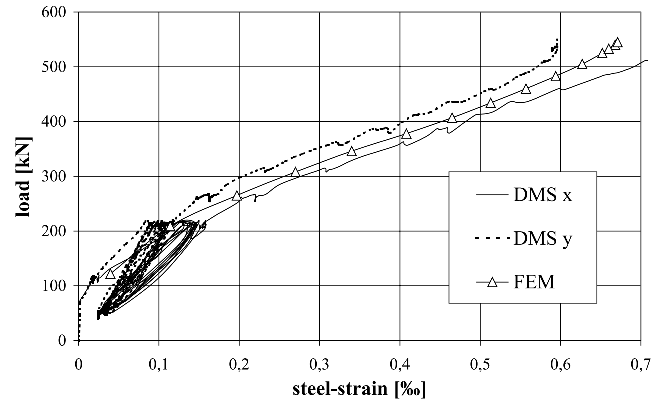

Fig. 10. Comparison of steel-strains on top of the column in test and in computation.

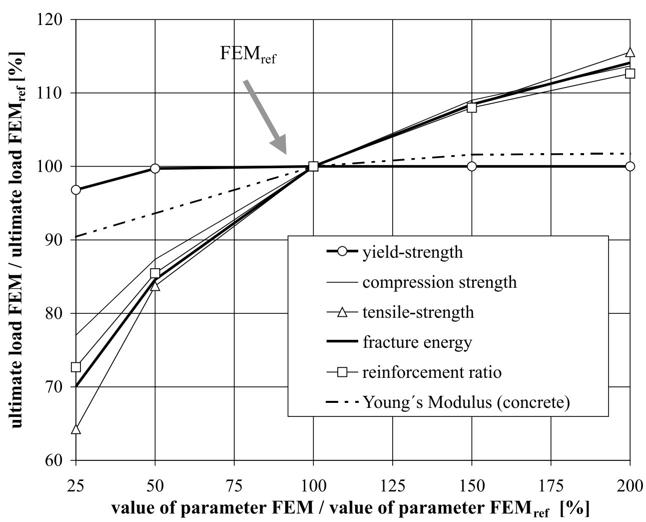

Fig. 9. Influence of material parameters to the ultimate punching load.

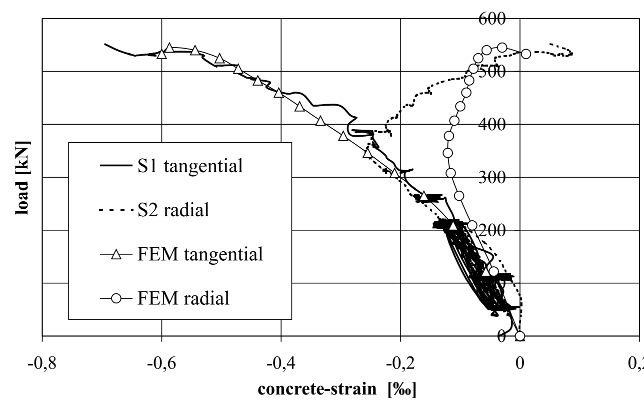

Fig. 11. Comparison of concrete-strains in the near of the column in test and in computation.

rial properties to the ultimate punching load, by changing each parameter in different computations from 25% to 200%. As an important point it should be remarked that the tensile strength and the fracture energy have the biggest influence on the ultimate load.

To be sure that the computations lead to realistic results, besides the comparison of the load–deflection diagrams, it is important to compare the computed stresses and strains with the test results as well as to compare the observed crack pattern. Examples of such confrontations are given in Figs. 10–12. The diagrams and pictures also confirm a good conformance.

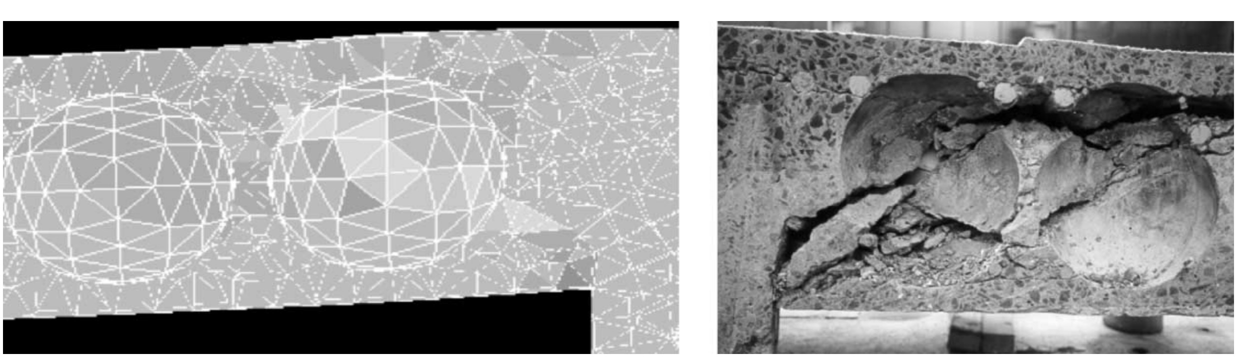

Fig. 12. Comparison of the internal crack pattern in computation and in test.

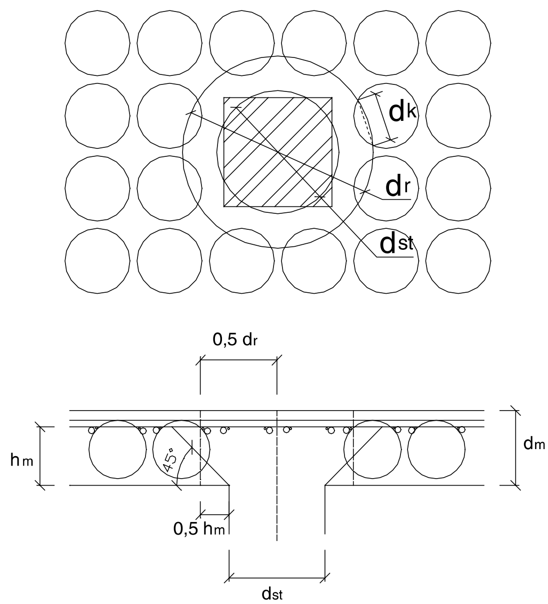

Fig. 13. Reduction of the shear area.

4. Design recommendations

In many design codes punching resistance is treated as a shear resistance that acts at a section, the so-called control perimeter. This control perimeter does not have any physical meaning [2]. In fact this empirical approach gives a close approximation to the resistance obtained by mechanical models of punching behavior. In the case of a biaxial hollow slab this design concept can be used with a simple modification. If any of the bubbles are situated in between the control perimeter and the border of the column, it is necessary to reduce the shear area by the area A of the intersection of the control perimeter with the bubbles (Eq. (1), Fig. 13).

$$A = uh_m - \sum \left(d_k^2 \pi/4\right). \tag{1}$$

If there is no bubble in this area the design rules of a solid slab for punching can be applied to the biaxial hollow deck without modification. It should be remarked that the bubbles must not intersect the column. In Table 1 the calculated ultimate load (by using DIN 1045 and by taking Eq. (1) into regard) is compared with the ultimate load of the tests.

5. Conclusions

The previous investigations showed that the mode of failure of biaxial hollow slabs is similar to the one of solid slabs. To specify the punching shear capacity a proposal of a modification of available design rules has been made. With the described nonlinear finite element computations it is possible to make further investigations of the structural behavior of this slab. Parametric studies with different material properties, different dimensions, and different geometrical proportions will be performed. In the future investigations on the punching shear resistance of biaxial hollow slabs with shear reinforcement and investigations of slab-edge column connections and slab-corner column connections will be performed.

Acknowledgements

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