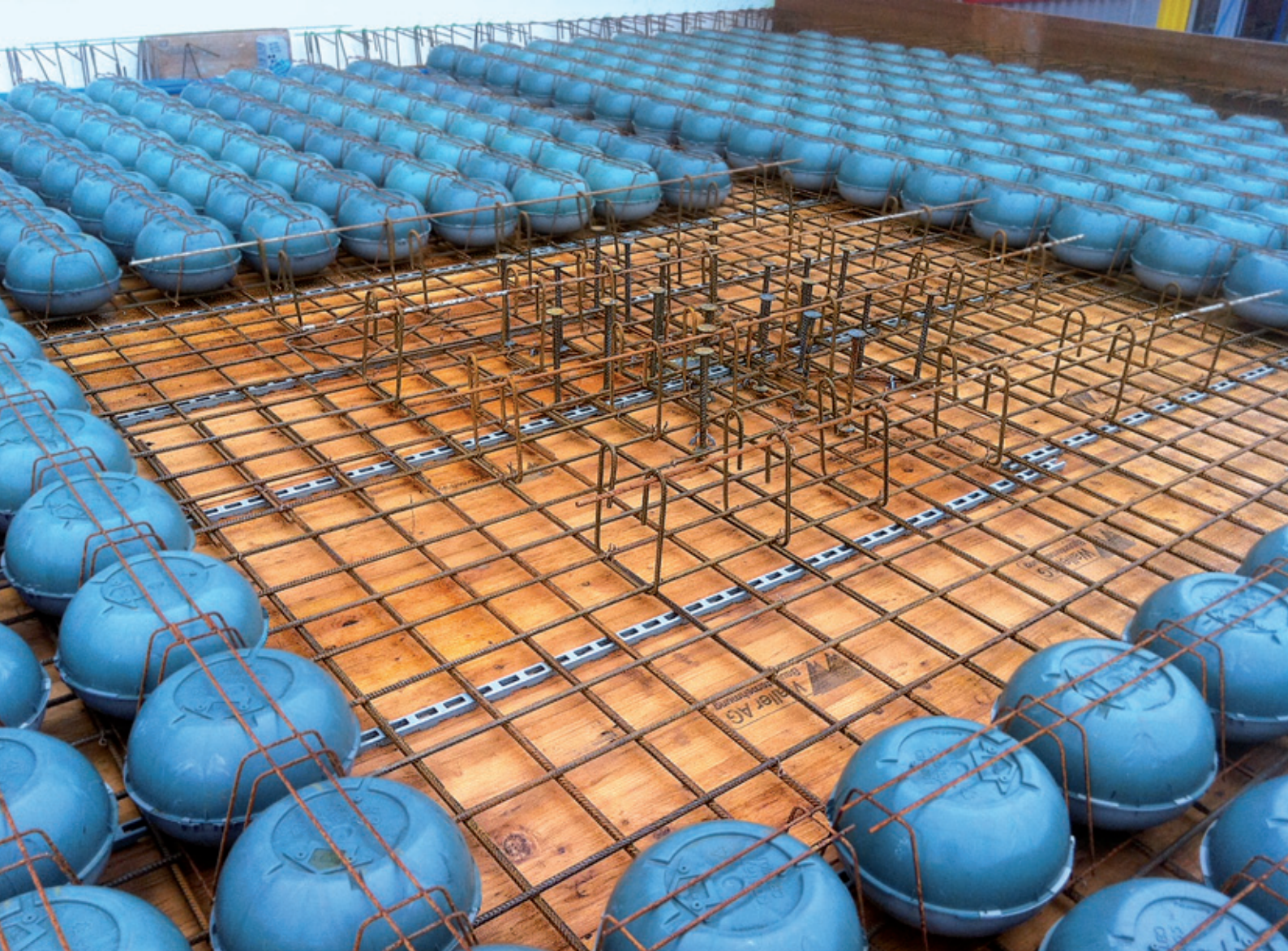


Beton- und Stahlbetonbau



Design and construction of two-way spanning reinforced concrete slabs with flattened rotationally symmetrical void formers

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Hollow body systems are increasingly used for the realization of lightweight, two-way spanning concrete slabs, resulting in economic and resource-efficient constructions. The special structural behaviour of these systems must be considered in the design and construction. Experimental investigations are required in order to establish a safe design model. Numerical investigations can be used to model the tests can be modelled and carry out parametric studies. Simplifications and design tools enable a simple design and construction similar to that of conventional reinforced concrete slabs. The level of safety required by the building authority is met by considering the design and detailing rules of two-way spanning concrete slabs with flattened rotationally symmetrical void formers.

1 Introduction

Voided flat plate slabs enable a type of construction that can be more cost-effective than customary solid slabs due to the reduction in the amount of material used and therefore of the dead load. Reduction of the dead load also means that lower loads have to be introduced into the subsoil which goes is associated with a variety of static advantages.

While one-way spanning voided flat plate slabs with continuous void chambers have already been part of the prior art for some time, in recent years there has also been increasing use of two-way spanning voided flat plate slabs. Due to the bi-axial load transfer, these systems can also be manufactured by the cast-in-place method and as a result can also be used for flexible horizontal plan shapes. Voided flat plate slabs are not included in the current codes and standards. General Technical Approvals can be used in Germany as proof of suitability. So far, the only two-way spanning voided flat plate slab system with approval is the “Eco-Line” system with spheres as void formers [2]. This system is suitable for slab depths of 30 to 60 cm and has already been presented here [1]. The “Slim-Line” system has now been developed so that slabs with a depth above 20 cm can also be used. The load bearing ability of the system has been determined within the framework of a research project funded by the AiF (Allianz Industrie Forschung = Industrial Research Alliance). Installation

Bemessung und Konstruktion von zweiachsig gespannten Stahlbetondecken mit abgeflachten rotationssymmetrischen Hohlkörpern

Zur Realisierung von leichten, zweiachsig gespannten Decken werden Hohlkörpersysteme vermehrt eingesetzt, was zu einer wirtschaftlichen und ressourcenschonenden Bauweise führt. Bei der Bemessung und Konstruktion muss das besondere Tragverhalten dieser Systeme berücksichtigt werden. Es werden experimentelle Untersuchungen notwendig, um ein abgesichertes Bemessungsmodell aufstellen zu können. Mittels numerischer Untersuchungen können die Versuche nachgerechnet und Parameterstudien durchgeführt werden. Vereinfachungen und Bemessungshilfen ermöglichen den Tragwerksplanern eine einfache Bemessung und Konstruktion analog der massiven Flachdecke. Bei Berücksichtigung der Bemessungs- und Konstruktionsregeln können zweiachsig gespannte Stahlbetondecken mit abgeflachten rotationssymmetrischen Hohlkörpern auf dem bauaufsichtlich geforderten Sicherheitsniveau hergestellt werden.

and design engineering rules have been specified in addition to design.

2 Manufacture and installation of the void formers

The void formers described in this article (Slim-Line void formers) for reinforced concrete slabs differ in shape from spherical void formers (Eco-Line void formers). However, both versions similarly have linear void former modules consisting of retaining cages with integrated void formers (Fig. 1). The retaining cages are made of reinforcement steel and the void formers of recycled plastic (polyethylene high-density, PE-HD or polypropylene, PP). These modules are installed between the upper and lower rebar layer for displacing the concrete using the cast-in-place method.

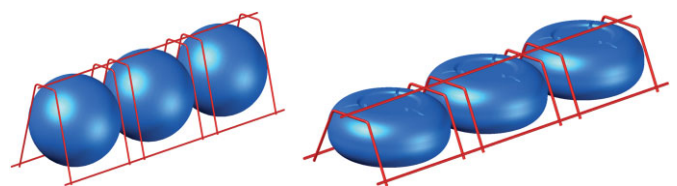


Fig. 1 Types of void formers Eco-Line (sphere) and Slim-Line (flat void former)
Hohlkörpertypen Eco-Line (Kugel) und Slim-Line (flacher Hohlkörper)



Fig. 2 Template to assure axis-centre distance
Anwendung einer Einbauhilfe für die Sicherstellung des Achs-
abstandes

Installation of the void former modules is carried out according to an installation drawing to be prepared separately. The installation plan is prepared allowing for the formwork plans and the structural calculation. In addition to details regarding the position of the void formers and the remaining solid zones, the laying plan also includes installation instructions. The minimum permissible distance between centres of the void former modules must be taken into account during installation.

This distance between centres is universally 35 cm for the Slim-Line type void formers. An appropriate installation aid must be used to ensure compliance with the minimum distance between centres (Fig. 2). Attention must also be paid to the specified void former grid. A staggered layout of void formers is not permitted. A consistently orthogonal grid must rather be maintained. The void former modules must be installed and fixed in such a way that it is not possible for them to drift sideways and move during concreting.

An imposed load or shifting stop on the formwork may be used as a countermeasure against the buoyancy effect of the void former modules during concreting. The normal procedure, however, is to concrete the void former areas in two layers. Care must be taken, however, when pouring the first concrete layer to ensure that the lower longitudinal bars of the void former modules are covered with between 2 cm and 4 cm of concrete. It must be ensured that complete compaction is also achieved underneath the void former by choosing an appropriate concrete consistency, a grading curve with a maximum grain of 16 mm and the number of compaction points. The first concrete layer fixes the void former modules in position after curing in preparation for pouring of the second concrete layer. To guarantee the bond between the two concrete layers in the construction joint, proof of a corresponding bond with reduced bond surface must be provided and arrangements must be made for joint reinforcement if necessary.






3 Special features of the design

3.1 General

Until now, slabs in general structural engineering have been designed in Germany in accordance with DIN-1045-1 [7] and since July 2012 in accordance with EC2 [9]. Neither of these standards include the design of slabs with rotationally symmetrical void formers. Although it is possible to refer to the rules for ribbed slabs when designing voided flat plate slabs, this leads to less cost-effective results. In addition, the distance between centres of the void formers has to be increased in order to ensure the minimum bridge widths to be maintained.

It is necessary when using the voided flat plate slabs to analyse the various failure modes and set up the design concepts. Table 1 shows an overview of the design's spe-

Table 1 Overview of special features of the design of hollow core slabs
Übersicht der Besonderheiten bei der Bemessung von Hohlkörperdecken

Failure type	Restriction	Illustration
Bending	Reduced flexural compression zone if required	
Shear force	Reduced load bearing ability	
Global punching	Solid zones required	
Local punching	Restriction of concentrated load	
Shear force transfer in manufactured construction joint	Reduced bonding surface	

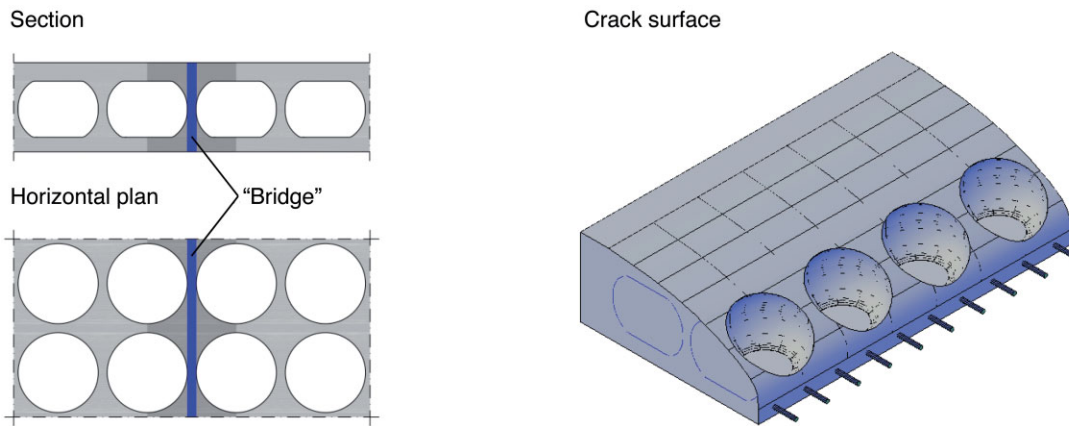


Fig. 3 Section, horizontal plan and crack surface of hollow core slabs (void formers high 220 mm)
Schnitt, Grundriss und Rissfläche bei Hohlkörperdecken (Hohlkörperhöhe 220 mm)

cial features. The individual approaches and possible solutions for designing the individual failure modes are described below.

3.2 General considerations with regard to load bearing behaviour

It may generally be assumed that the load transfer of voided flat plate slabs is comparable to that of customary structural engineering slabs. Although the reduced load bearing ability of specific percentage contact areas must be taken into account without exception, this does not present structural engineers with any great challenge if modified design equations are used. The shape of the rotationally symmetrical void formers described here gives rise to interstitial spaces which lead to a spatial load transfer. This can be seen in Fig. 3. In horizontal plan and section, it can be seen why designing the void formers using the equations for the ribbed slab is very conservative. When designing ribbed slabs, only the “bridge” between the void formers is taken into account. In actual fact, however, the entire remaining cross-section contributes to the load transfer. The crack surface of a shear force failure indicates the slab type’s spatial load transfer.

3.3 Bending

Usually the customary design aids, such as the k_d or ω method, can be applied for the rectangular section for bending dimensioning of the slabs. However, as with T-beam cross-sections, one must check whether the compression zone height in the ultimate limit state is higher than the area free from void formers. If this is the case, it is cost-efficient to take the compression zone between the void formers into account.

3.4 Shear resistance

The complex shear load bearing behaviour of the floor slabs had to be investigated experimentally. The tests

were conducted at Kaiserslautern University of Technology and are described in Section 5.2. In this case, the retaining cages were not installed. Although the retaining cages have a positive effect on the shear resistance, anchoring of the cages is not comparable to the secured anchoring forms in accordance with [7] and [9] which is why this percentage contact area which is on the safe side is disregarded. By means of the tests, it was possible to determine the ratio of the shear resistance of the voided flat plate slab to that of a solid slab so that the design can be effected in accordance with EC2, equation 6.2a [9] allowing for a reduction factor.

3.5 Global punching

Solid zones must be formed both near to columns and also on the margins of the voided flat plate slabs. The dimensions of the solid zone must first be specified for the punching calculation. The solid zone must be selected large enough that it is possible to verify the reduced shear resistance of the adjacent void former areas. Specified minimum dimensions ensure that the size of the solid zone is no smaller than the punching critical area of a solid slab. The punching calculation of the solid zone is then conducted in accordance with EC2, Section 6.4 [9] with or without punching reinforcement.

3.6 Local punching

Local punching of the reflected ceiling plan above the void formers represents a special feature of the voided flat plate slabs. Due to the geometry of these areas, the punching calculation in accordance with EC2 [9] does not lead to any realistic design which is why tests were carried out here too, cf. Section 5.3. Based on the tests, it is possible in the ultimate limit state (ULS) to demonstrate design loads up to $F_{Ed} = 10$ kN on a minimum contact area of 10×10 cm² even with a minimum reflected ceiling plan height of 5 cm and a concrete of strength C20/25. A design equation is currently being developed for local punching of the voided flat plate slabs.

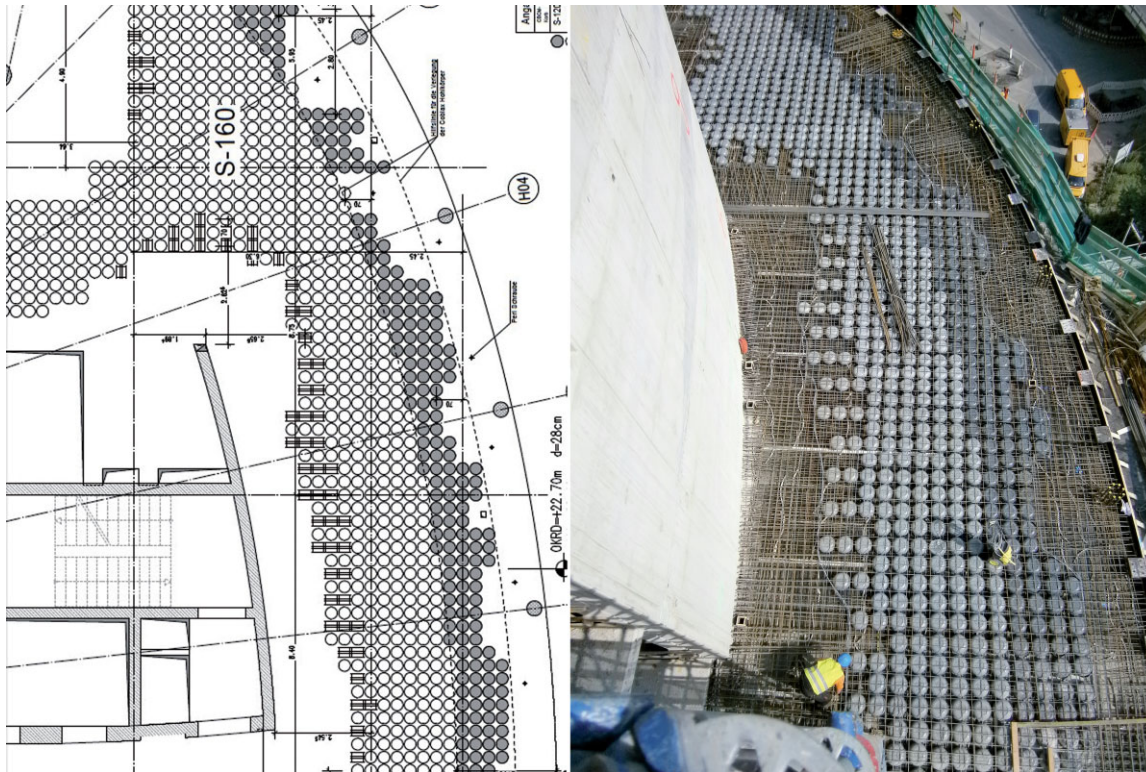


Fig. 4 Solid zones and void former areas in drawing and on site
Massivbereiche und Hohlkörperbereiche im Plan und bei der Ausführung

3.7 Bond resistance

For demonstration of the concreting joint, it is recommended to use the equation in accordance with EC2, Section 6.2.5 [9] in which the bond area must be reduced. So far no meaningful tests have been carried out for this which is why initially, as a conservative assumption, the complete base area of the void formers in the projection must be deducted. The retaining cage may be estimated for the bond resistance if demonstration of anchoring is successful in accordance with [9].

4 Design rules

The solid zones statically required are specified during the course of design (Section 3). Consideration must also be given to constructional requirements when designing and when preparing the layout plans for the void former modules (Fig. 4). These requirements will be summarised subsequently. In general, consideration must be given to the required distances between the void former modules and other building elements and assembly parts during detailed design and implementation.

Void formers must not be arranged above the supports of the slab to be created. A constructive solid zone at least as wide as the distance between centres of the void formers must additionally be provided to the side of the support's edge (Fig. 5). In the case of Slim-Line void formers, this corresponds to a constructive solid zone of 35 cm to the side of the support's front edge. A solid zone as wide



Fig. 5 Accomplishment of a constructive solid zone
Ausführung eines konstruktiven Randstreifens

as slab thickness h must be accomplished in the case of recesses and free slab edges.

5 Experimental investigations regarding the shear force and local punching shear behaviour

5.1. General

Tests were carried out regarding the shear resistance and local punching to determine the load bearing abilities. The minimum and maximum concrete strengths aimed for were tested in both test series. Void formers with the largest and smallest available void former height were used for the tests.

5.2 Experimental determination of the shear resistance

The aim of the tests was to determine the shear resistance of the voided flat plate slabs in the most unfavourable installation situation. For this purpose, the void formers – as already described in Section 3.4 – were installed without the retaining cages which meant that the positive effect of the retaining cages on the shear resistance lying on the safe side was disregarded. The height of the upper reflected ceiling plan in the tests was 45 mm which corresponds to the minimum thickness of the upper reflected ceiling plan aimed at of 50 mm minus an allowance of 5 mm. Thus, the tests were carried out with the minimum achievable percentage shear force contact area of the concrete pressure zone. In addition, the distance between centres of the void formers among themselves was also reduced by an allowance of 5 mm although in practice the void formers are fixed in position by the retaining cages. The width of the specimens was chosen as $b \geq 4 h$ in order to test a slab.

The specimens were designed in such a way that the shear force failure occurred in a previously defined zone due to the distances between the supports and the load transfer. It was possible to carry out two tests with one specimen which saved material and time when conducting the tests (Fig. 6).

So that realistic quantities of longitudinal rebars could be inserted in the specimens, threaded bar anchor steel St 900/1100 with rib rows and a diameter of 15 mm was

chosen. The slightly higher relative rib area of the steel bars was taken into account. The longitudinal rebar was dimensioned in such a way that a ratio of $M_{flexural failure} / M_{shear force failure} \approx 1.2$ was present in the reference tests. The tests with minimum and maximum concrete strength were carried out with the smallest and largest void formers respectively. Each combination was tested three times with void formers and once without void formers as a reference test. This resulted in a total of twelve tests with void formers and four reference tests.

The tests showed that failure of the voided flat plate slabs is comparable to failure of the solid slabs. Fig. 7 shows an example of the cracking pattern. Failure of the specimens with void formers occurred less abruptly by comparison with the reference tests.

For designing the shear resistance of the voided flat plate slabs tested, a reduction factor f for the solid slab should be determined in accordance with EC2, equation 6.2a [9] (cf. equation (5.1)):

$$V_{Rd,c} = \left[C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{\frac{1}{3}} + k_1 \cdot \sigma_{cp} \right] \cdot b_w \cdot d \quad (5.1)$$

For comparison with the experimental ultimate loads, the mean value of the shear resistance was calculated where $\gamma_c = 1.0$ and the actual building element width b_w . A prefactor 0.2 (cf. [5], re 10.3.3) and the mean concrete compressive strength were also assumed. The mean shear re-

Longitudinal section - C20/25 and C45/55

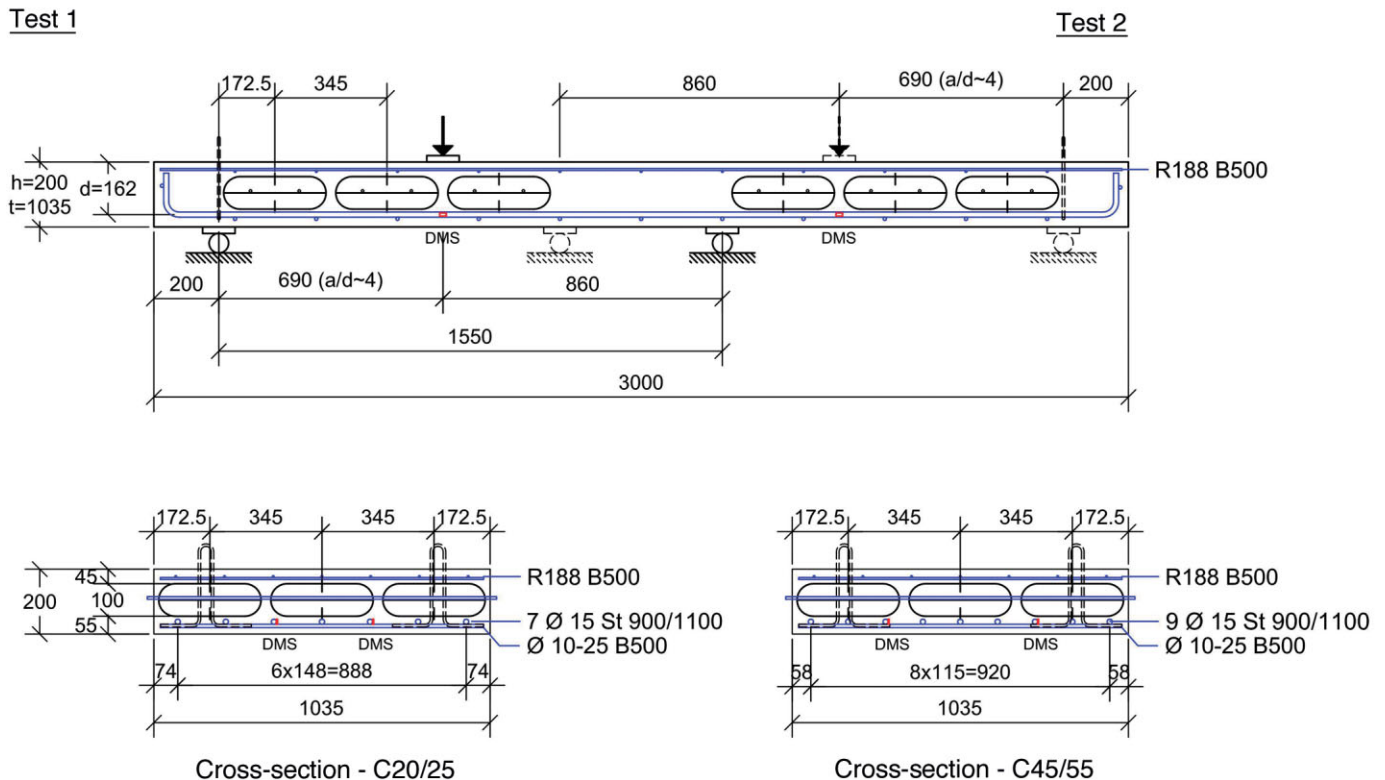


Fig. 6 Longitudinal and cross-section of the specimens using the example of the void formers 100 mm high
 Längs- und Querschnitt der Versuchskörper am Beispiel der 100 mm hohen Hohlkörper



Fig. 7 Sheared off specimens in the "Bridge" and in hollow body axis after the failure (void formers high 220 mm)
Aufgesägter Versuchskörper im „Steg“ und in Hohlkörperachse nach dem Versagen (Hohlkörperhöhe 220 mm)

distance can therefore be calculated according to equation (5.2), wherein the factor f for the reference tests is 1.0:

$$V_{Rm,c,co\text{biax}} = f \cdot 0,2 \cdot k \cdot (100 \cdot \rho_l \cdot f_{cm})^{\frac{1}{3}} \cdot b_w \cdot d \quad (5.2)$$

The reduction in the shear force of each individual test is then calculated according to equation (5.3):

$$f = \frac{V_u}{V_{Rm,c}} = \frac{V_u}{0,2 \cdot k \cdot (100 \cdot \rho_l \cdot f_{cm})^{\frac{1}{3}} \cdot b_w \cdot d} \quad (5.3)$$

As the concrete compressive strengths were tested on dry-stored cubes and the design equation for the shear force design calculation is based on concrete compressive

strengths in wet-stored cylinders, it was necessary to convert the concrete compressive strengths for evaluation of the limit loads – see equation (5.4):

$$f_{cm} = 0,92 \cdot f_{cm,dry} = 0,92 \cdot (0,7953 + 0,0003 \cdot f_{c,cube,dry}) \cdot f_{c,cube,dry} \quad (5.4)$$

Conversion from cube compressive strength to cylinder compressive strength was carried out by means of a linear trend line according to the concrete strengths in EC2, Table 3.1 [9]. Conversion from dry to wet stored cylinder compressive strengths was carried out in accordance with DIN 1045-2, Section 5.5.1.2 [8] with a factor of 0.92.

The test results in Tables 2 and 3 clearly show a difference between the tests performed with small and large void formers. The mean value of the factor f is 0.69 for the tests with 100 mm high void formers and 0.52 with the 220 mm high void formers. All factors f are above 0.5 except for test V-Q-22-20-2. It was possible to attribute the lower shear resistance of this test to a concreting error. It may be assumed that all intermediate sizes will deliver better results than the tests with the large void formers (220 mm). The difference as regards reduction of the shear resistance can be accounted for by the fact that the concrete pressure zone in the tests with the higher void formers was reduced much more significantly than in the tests with the flattened void formers due to their position.

Based on the experimental investigations, the shear resistance of voided flat plate slabs can be calculated according to equation (5.5):

$$V_{Rd,c,co\text{biax}} = f \cdot C_{Rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{\frac{1}{3}} \cdot b_w \cdot d \quad (5.5)$$

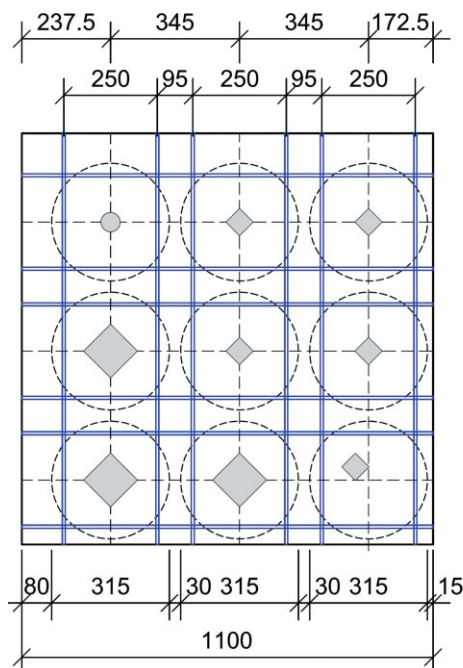


Fig. 8 Floor plan of the specimens of series 1 with load introduction surfaces on top and bottom (left) and experimental setup of the series 2 (right)
Grundriss der Versuchskörper der Serie 1 mit Lasteinleitungsflächen auf Ober- und Unterseite (links) und Versuchsaufbau der Serie 2 (rechts)

Table 2 Evaluation of the tests with 100 mm high void formers
Auswertung der Versuche mit 100 mm hohen Hohlkörpern

Information	Desig.	Unit	S-100												Mean value**
			C20/25						C45/55						
			V-Q-10-20-1	V-Q-10-20-2	V-Q-10-20-3	V-Q-10-20-4	V-Q-10-45-1	V-Q-10-45-2	V-Q-10-45-3	V-Q-10-45-4					
Void former	-	-	S-100	S-100	S-100	with out	S-100	S-100	S-100	S-100	S-100	S-100	with out	-	
Slab width	b	[m]	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	-	
Static height	d	[m]	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	-	
Rebar percentage	ρ_l	[-]	0.0074	0.0074	0.0074	0.0074	0.0074	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	-	
Shear forces from cylinder and load structure	$V_{u1} (V_{u1,Ref})$	[kN]	131.86	120.95	125.93	189.88	159.69	150.52	154.48	247.44	247.44	247.44	247.44	-	
Shear force from dead load	ΔV_1	[kN]	-0.30	-0.30	-0.83	0.22	-0.30	-0.30	-0.83	0.22	-0.83	0.22	0.22	-	
Shear forces in collapsed state	$V_u (V_{u,Ref})$	[kN]	131.56	120.65	125.10	190.09	159.39	150.22	153.65	247.65	247.65	247.65	247.65	-	
Cylinder compressive strength (from test cube)	f_{cm}	[N/mm ²]	21.71	21.71	21.09	21.09	49.59	49.59	49.59	49.59	49.59	49.59	49.59	-	
Mean shear resistance of solid slab	$V_{Rm,ct}$	[kN]	169.06	169.06	167.42	167.42	242.11	242.11	242.11	242.11	242.11	242.11	242.11	-	
Factor f*	$f = V_u/V_{Rm,c}$	-	0.78	0.71	0.75	(1.14)	0.66	0.62	0.63	0.62	0.63	(1.02)	0.69	-	

* Factors f correspond to the quotient of maximum shear force in the tests and the calculated mean shear resistance of a solid slab
** Mean value of factors $f = V_u/V_{Rm,c}$ except for the factors of the reference tests

In this case systematic compressive forces should be disregarded and systematic tensile forces should be ruled out. At the same time, the prefactor f may be specified as a function of the void former height or as a uniform factor taking the most unfavourable tests into account. Factor f can be taken from the General Technical Approval after it has been granted.

5.3 Experimental determination of the local punching resistance

Point loads with small contact areas may arise in both the as-constructed condition, e.g. due to formwork supports, and also during the useful life. The upper reflected ceiling plan above the void formers must be designed in such a way that local punching is ruled out. Until now there have been no design rules for local punching with the present geometry which is why 88 small tests have been carried out for this. The specimens were designed in such a way that no reinforcement steel lay inside the punching cones.

Two test series were carried out (Fig. 8). Test series 1 with an upper reflected ceiling plan without nominal stresses and test series 2 with an upper reflected ceiling plan under one-way spanning tensile stresses in state II.

The following parameters were varied during the test series:

- Concrete quality (C20/25 and C45/55)
- Reflected ceiling plan height above void former ($c_{cb} = 2$ to 12 cm)
- Load transfer area ($A_{load} = 5 \times 5$ cm² and 10×10 cm²)
- Void former height ($h_{HK} = 100$ mm and 180 mm)

In test series 1, several tests were carried out on the top and bottom of a specimen. The position and form of the load transfer was also varied at the same time. In test series 2, a bending moment was applied by means of steel tongs prior to the vertical load which led to rupturing of the upper reflected ceiling plan. The aimed-for tensile stress in the longitudinal rebar was 300 N/mm².

Table 3 Evaluation of the tests with 220 mm high void formers
Auswertung der Versuche mit 220 mm hohen Hohlkörpern

Information	Desig	Unit	S-220										Mean value**	
			C20/25					C45/55						
			V-Q-22-20-1	V-Q-22-20-2	V-Q-22-20-3	V-Q-22-20-4	with out	V-Q-22-45-1	V-Q-22-45-2	V-Q-22-45-3	V-Q-22-45-4	with out		
Void former	-	-	S-220	S-220	S-220	with out	S-220	S-220	S-220	S-220	S-220	S-220	with out	-
Slab width	b	[m]	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	-
Static height	d	[m]	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	-
Rebar percentage	ρ_l	[-]	0.0057	0.0057	0.0057	0.0057	0.0074	0.0074	0.0074	0.0074	0.0074	0.0074	0.0074	-
Shear forces from cylinder and load structure	$V_{u1}(V_{u1,Ref})$	[kN]	198.92	171.39	194.34	383.37	270.52	249.26	253.27	498.12	-	-	-	-
Shear force from dead load	ΔV_1	[kN]	2.19	2.19	0.22	4.27	2.19	2.19	0.22	4.27	-	-	-	-
Shear forces in collapsed state	$V_u(V_{u,Ref})$	[kN]	201.11	173.59	194.56	387.63	272.71	251.45	253.48	502.39	-	-	-	-
Cylinder compressive strength (from test cube)	f_{cm}	[N/mm ²]	22.76	22.76	24.40	24.40	42.75	42.75	46.02	46.02	-	-	-	-
Mean shear resistance of solid slab	$V_{Rm,ct}$	[kN]	365.32	365.32	373.88	373.88	490.14	490.14	502.51	502.51	-	-	-	-
Factor f*	$f = V_u/V_{Rm,c}$	-	0.55	0.48	0.52	(1.04)	0.56	0.51	0.50	(1.00)	0.52	0.52	0.52	0.52

* Factors f correspond to the quotient of maximum shear force in the tests and the calculated mean shear resistance of a solid slab

** Mean value of factors $f = V_u/V_{Rm,c}$ except for the factors of the reference tests

Fig. 9 shows a punching cone and a sawn-open specimen after the test. It can clearly be seen that the punching cone runs tangentially along the void formers starting at the outer edge of the load transfer. It becomes obvious in Fig. 10 how high the achievable point loads are. In most cases in practice, it is sufficient to limit the design load in the ultimate limit state to $F_{Ed} = 10$ kN for a contact area of at least 10×10 cm. In view of the test results, this value is well on the safe side. For all other cases, a design concept that included the geometry and concrete strength must be developed.

6 Numerical investigations regarding the shear load bearing behaviour

6.1 General

Alongside the large-scale tests, physical non-linear FEM calculations on solid models were carried out at Bochum University using the DIANA software [6]. It was possible use the calculations to realistically map the load bearing and deformation behaviour. The volume elements employed, CHX 60 with 20 nodes, and the laws of material behaviour used corresponded essentially to the models described in [1] for the investigations regarding shear resistance. To reduce the computing effort, the calculations were performed on slab strips having a sixth of the actual specimen width. The input variables for the selected fracture mechanics models were determined based on large-scale test, in material tests and in theoretical considerations. The accuracy of the calibrated computational models rendered it possible to conduct a parameter study on the influence of installation variants which made it possible to reduce the number of time-consuming and expensive large-scale tests.

Compared to the investigations on reinforced concrete slabs with spherical void formers described in [1], in the grid generation of the "Slim-Line" type void formers, element shapes arise in which the included angles between the element edges are sometimes very flat. Fig. 11 illustrates the FEM model of an embedded void former of the "Slim-



Fig. 9 Punching cone and sawed testing specimen after loading on top and bottom
 Ausbruchkegel und aufgeschnittener Versuchskörper nach einer Belastung auf der Ober- und Unterseite

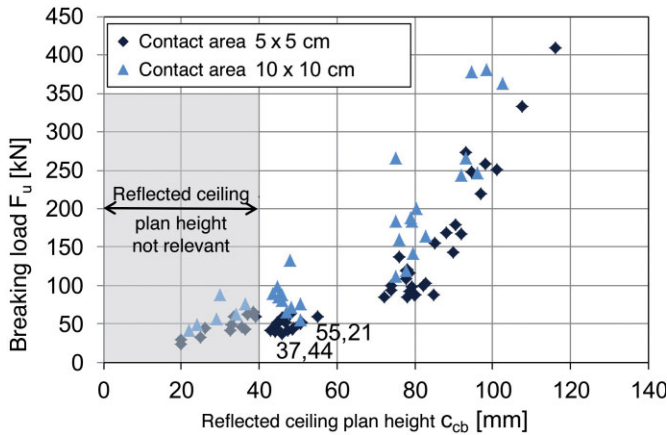


Fig. 10 Failure loads F_u as a function of the ceiling height mirrors c_{cb} (series 1 and 2)
 Bruchlasten F_u in Abhängigkeit von der Deckenspiegelhöhe c_{cb} (Versuchsserien 1 und 2)

Line” type without and with concealed edges. The influence of the element’s shape on the numerical stability of the models and the influence of the number of elements, the iteration method, the convergence criteria and convergence accuracy, the number of iterative steps per load step and the load step width were investigated during an extensive convergence study. The result of this was that, compared to the calculations of the “Eco-Line” type volume element models, a finer grid division is necessary with a correspondingly increased number of iterative steps per load step in order to achieve reliable calculation results with the desired convergence accuracy even in high load steps.

6.2 Modelling of the shear resistance

A realistic simulation of the cracking pattern in the concrete is particularly important for a numerical simulation of the shear load bearing behaviour. This is because it has a significant effect on both the system’s overall stiffness and also the shear force failure itself. The cracking pattern was recorded via the theoretical model of the “smeared” crack model. The cracks are not mapped discretely in this model but rather as dilatation in the element. The fracture energy and the crack bandwidth are crucial for a realistic description of the tension softening of the concrete elements without reinforcement. The fracture energy is described via the descending branch of the σ - ϵ relationship after exceeding the dilatation at maximum centric tensile strength in the element. In this case, the increasing dilatation in the element corresponds in reality to the increasing crack opening. The fracture energy is the energy required for complete crack opening and results from the integral via the descending branch of the σ - ϵ relationship. It depends essentially on the granular structure, the grain size and the concrete’s tensile strength and is assumed according to the computation formulations in [4]. The crack bandwidth is a dimension from the crack bandwidth theory according to [3] and describes the area of strain softening of a cross-section during cracking under tensile stress. It is necessary to establish the crack bandwidth in order to prevent the tension softening from being grid-dependent. It defines the damaged area in the direction of the main tensile stresses in the element. It is usually meaningful to determine the crack bandwidth as a function of the element volume. In the present case, however, manual determination of the crack bandwidth is more constructive due to the partly severe distortion of some elements.

It was possible to describe the tension resistance perpendicular to the crack with adequate accuracy using the material models explained. In reality, the shear stiffness remaining due to aggregate interlock in the cracking orientation is determined by the crack opening and therefore also by the size of the building element and the kinematics of the cracked system. In the FEM simulation, this effect is recorded by a reduction in the shear modulus (and therefore also of the elastic shear stiffness defined as a

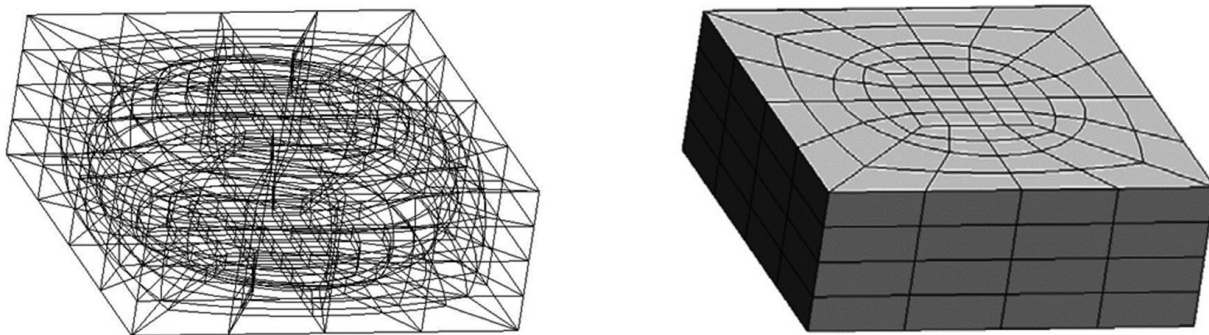


Fig. 11 FE-Model of the embedded void former of the „Slim-Line” type used for the numerical simulation of the shear bearing behaviour
 FE-Modell eines eingebetteten Hohlkörpers vom Typ „Slim-Line” für numerische Berechnungen zum Querkrafttragverhalten

product of the shear module and the cross-sectional area) using a shear retention factor. Due to the reduction in the shear stiffness of cracked elements, the stresses are redistributed leading both in the test and also in the numerical simulation under increasing load and cracking to load transfer via a tied-arch model. The investigations carried out showed that a reduction in the shear stiffness to an amount between 5–10% of the shear stiffness arising from state I as a function of the slab cross-section and of the void former geometry delivers appropriate results. Fig. 12 illustrates the excellent agreement between the stiffness curve and ultimate loads of test series V-Q-10-45 and the results of the FEM calculation based on load-displacement curves. The results of the numerical simulations regarding the test program are summarised in Table 4.

7 Summary and outlook

Voided flat plate slabs cannot be designed without additional considerations in accordance with Eurocode 2. The shear force in particular had to be determined experimentally. This article documents relevant tests conducted at Kaiserslautern University of Technology to determine the shear resistance of voided flat plate slabs of the “Slim-Line” type. The tests were successfully simulated at Bochum University using the finite element method with the result that it is now possible to examine other installation configurations with the help of parameter studies.

Reduction factors which will enable a shear force design calculation in accordance with the verification format of Eurocode 2 are being specified within the framework of an ongoing approval procedure at the Deutsches Institut für Bautechnik [*German Institute of Structural Engineering*]. A General Technical Approval should then also in-

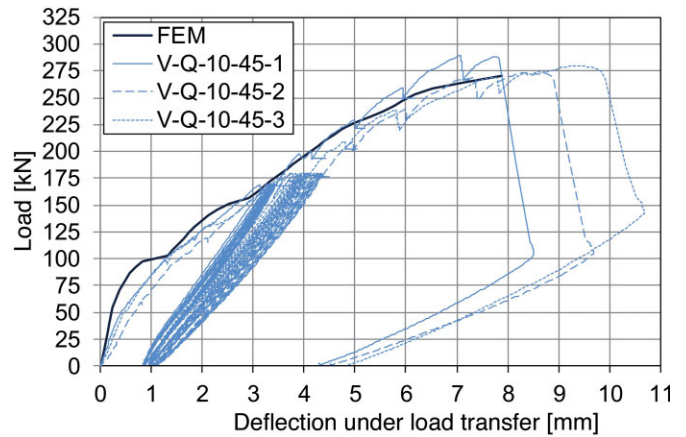


Fig. 12 Load-displacement diagram of test series V-Q-10-45 and according diagram obtained from the FE-simulation
Last-Verformungskurven der Versuchsreihe V-Q-10-45 zur Querkrafttragfähigkeit im Vergleich zur numerischen Berechnung

clude design rules which, similarly to the “Eco-Line” system, enable the slab system to be used safely in practice.

The punching resistance of the reflected ceiling plan above the void formers was also tested in an additional series of tests. These tests confirmed that the design loads up to 10 kN usually occurring in structural engineering can easily be transferred with a minimum contact area of $10 \times 10 \text{ cm}^2$.

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Table 4 Results from experimental tests and FE-simulations – Investigation of the shear force capacity
Versuchs- und Berechnungsergebnisse – Untersuchungen der Querkrafttragfähigkeit

Test	Shear force [kN]			Deflection under load transfer [mm]		
	Test	FE calculation	Test/FE**	Test	FE calculation	Test/FE**
V-Q-10-20-1	132	130	0.97	9.2	9.3	0.94
V-Q-10-20-2	121			8.8		
V-Q-10-20-3	126			8.3		
V-Q-10-45-1	160	149	1.04	7.8	7.9	1.11
V-Q-10-45-2	151			8.8		
V-Q-10-45-2	154			9.8		
V-Q-22-20-1	199	204	0.96	6.8	8.3	0.79
V-Q-22-20-2	171*			6		
V-Q-22-20-3	194			6.8		
V-Q-22-45-1	271	248	1.04	8.5	6.5	1.15
V-Q-22-45-2	249			6.5		
V-Q-22-45-3	253			7.5		

* Due to a concreting error – not taken into account for quotient of test and FE

** Quotient of the mean value of the test results and the result of the FE calculation

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