Concrete dowels in composite construction

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1 Preface

In composite construction method axial shear forces between concrete and steel structural members commonly are transferred applying stud head connectors. Various research activities on alternative mechanical connection systems revealed concrete dowels as mechanically suitable and economical solution for safe shear force transmission.
Concrete dowels are produced by various shaped web plate perforation of standard steel profiles fitted with crossing reinforcement bars before concrete casting. Closed circle shapes are distinct from open formats. Open concrete dowels as sketched in Fig. 1 offer some advantages concerning placement of reinforcement structures.

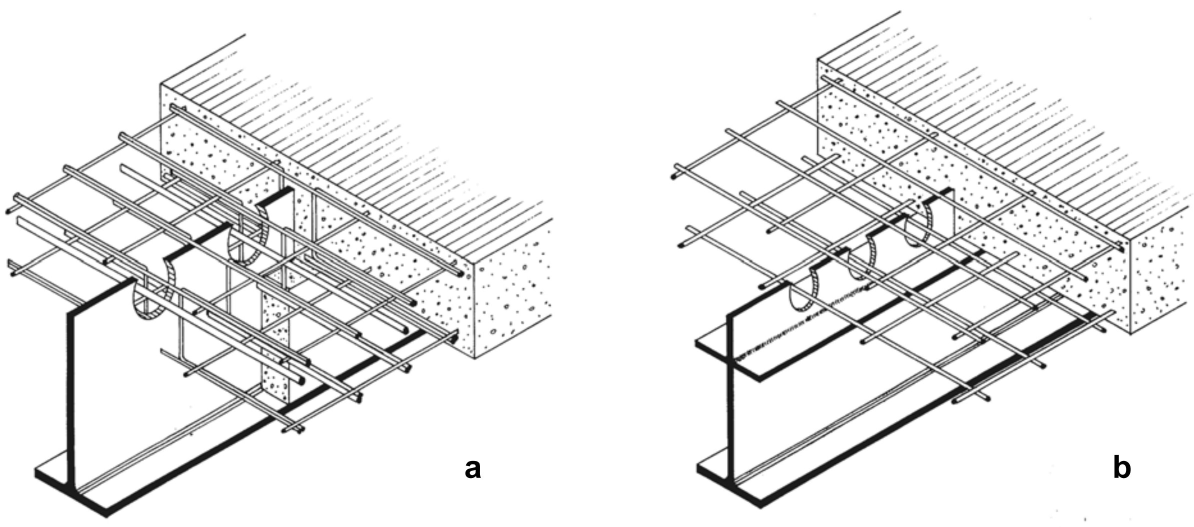

Fig. 1 Alternative designs of composite beams with concrete dowels for shear force transmission

Composite girder structures are imaginable applying double symmetric standard steel profile types with additional welded concrete dowel plates (Fig. 1b) as well as combining standard steel profiles with removed upper flanges together with concrete slabs (Fig. 1a). A new design procedure for concrete dowels, which was developed based on scientific methods, is explained in the framework of this publication considering some additional examinations of fatigue properties.

2 Recommendations for dimensioning of concrete dowels

The derivation of rules for concrete dowel dimensioning [3] was performed based on previous experimental and theoretical research activities within a period from 1985 to 2002. Results from 102 experimental assessments ob bearing capacities of specific girder types are included in the total evaluation, which were partly taken from scientific publications but mainly from tests in the laboratory facilities of the University of the Federal Armed Forces in Munich. The experimental assessment of bearing capacities and deformation behaviour of

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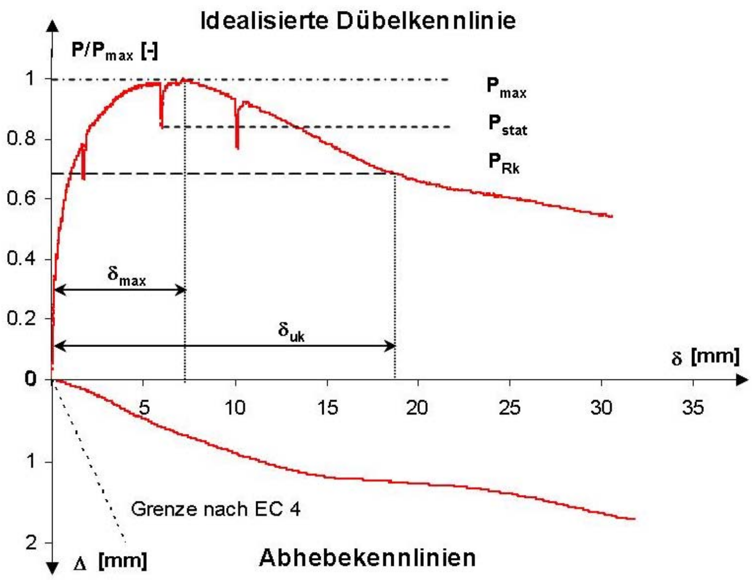
connection systems for composite structures usually is performed by means of standard shear force failure test respectively as described in the Annex 10 of Eurocode 4 for example. In the international context these standard test are called push-out test as well.
A test specimen consists of a steel profile with on both sides symmetric placement of specific connection systems fitted with the designed amount of reinforcement within both side arranged concrete slabs (Fig. 2). Main measuring values for evaluation purposes are the relative movement between concrete slabs and steel profiles parallel to the test load direction and perpendicular to the test load orientation. The relative translation measurement transversal to the test load direction describes the lifting extent. The evaluation of push-out tests is performed by assessment of a characteristic dowel curve as shown in Fig. 2. Relative translation δ parallel to the test load direction is drawn in relation to the force size portion that is adopted by one single transmission member like e.g. one concrete dowel. The underneath characteristic lift extension curve describes the concrete slab lift extension Δ transversal to the test load direction in relation to the parallel relative movement. The load deformation characteristic of those experiments permits conclusions on the bearing capacity of transmission systems as well as on deformation properties.
One peculiarity of experiments with constant velocity of elongation of the hydraulic test cylinder is that on interruptions on all load levels pressures decrease on a level of 85% within a duration of approximately 30 minutes. Those effects are visible in the characteristic dowel curve as downward oriented peaks. Intensive analysis on this behaviour revealed, that the quasi static bearing capacity P_{stat} as lowest value of the maximum test load level P_{max} is authoritative for assessment of the total bearing capacity. Based on experiment series the characteristic bearing capacity P_{Rk} and the corresponding deformation capacity δ_{uk} can be determined applying standard statistic evaluation methods. The lift extensions curve in the idea of Eurocode 4 serves as an additional check considering lifting limitations.



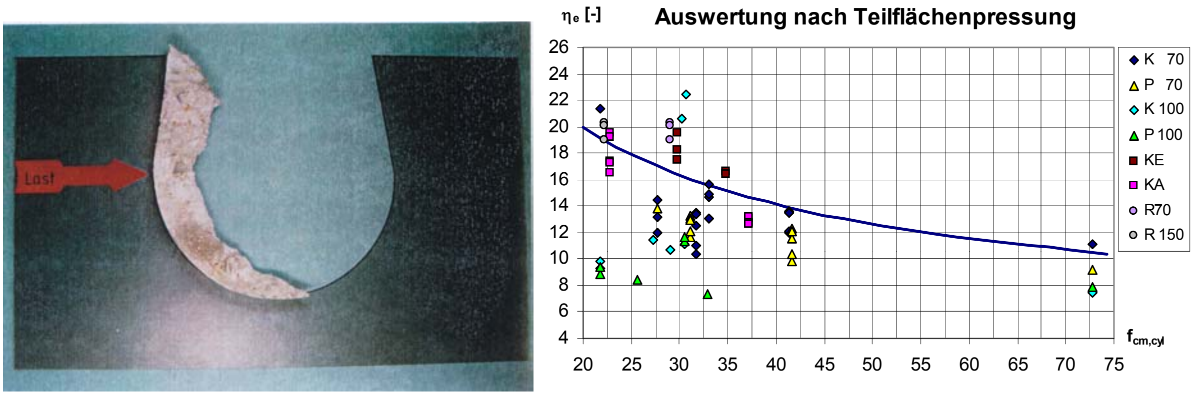
Load-deformation characteristics

Push-Out-Test installation

Fig. 2 Experimental assessment of bearing and deformation properties of shear force transmission elements

Calculation models, which describe failure behaviour in a semi-realistic manner, could be developed based on a total amount of more than 100 single tests by means of the observed failure mechanisms considering the variation of several parameters. An initial calculation model covering the complexity of the bearing behaviour of concrete dowels founded on the ultimate local pressure of concrete materials was derived in [4]. The ultimate three-axial concrete pressure was assumed as limiting factor.

Based on dismantled concrete dowels after push-out-test execution the existence of a highly stressed zone in the contact areas between steel faces and concrete dowels could be proved, where load influences effected an approximate hydrostatic stress state depending on the concrete dowel shape and the grade of cording effectiveness of the surrounding concrete material (Fig. 3). A comparison between local pressures calculated from test results and theoretical ultimate concrete pressures is summarized in the diagram of Fig. 3. The unidirectional compressive strength of concrete material is marked at the horizontal axis. The vertical axis represents the ratio between calculated concrete pressure on the projection of the contact area per shear force transmission element and the unidirectional compressive strength η_e. The range of all evaluated push-out –tests covers values η_e between 7 and 22 for this notion of a calculation model. The curve of theoretical endurable local concrete pressures confirms the suitability of a criterion of the local concrete compressive strength for assessment of limits of the total bearing capacity of single concrete dowels. However relative wide spread of test results reveals that other failure criterions can effect premature fractures.



Compressed concrete in the zone of maximum local pressure

Fig. 3 Evaluation of total experimental base on the ultimate local pressure criterion

Coming from observation that a large number of push-out-test ended in layer formed fracture appearances on approximately maximum load level a further failure criterion similar to punching problems could get authoritative particular for topological constellations with concrete dowels close to the edge of concrete slabs. In this cases a punching concrete fracture formed as a crooking cone got visible caused by transversal tensile stresses exceeding concrete tensile strength (Fig. 4). Due to a total concrete dowel failure concurrently with initial concrete cracking a failure criterion can be defined applying shear stresses along the coating surface of a regular cone, which can be preserved through toothing effects between stone particles. The transformation to the mechanical calculation model is sketched in Fig. 5. A good correspondence of the theoretical opening angle of the punch cone β´ with test results could be observed in the experiment series.

Fig. 4 Punch cone of a dismantled test specimen

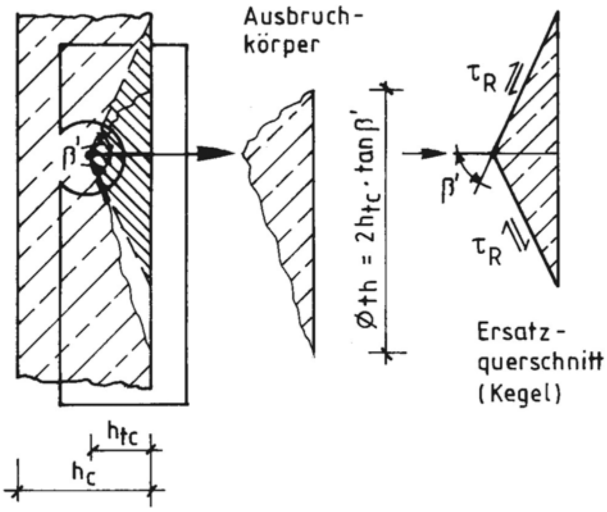
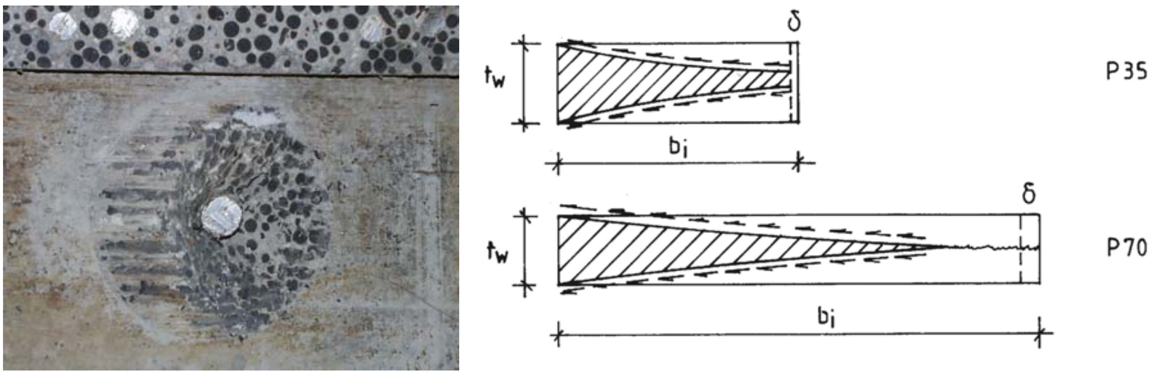


Fig. 5 Idealization of fracture geometry for application in a calculation procedure

Dimensioning rules for *Perfobond*-Plates [3] and *Kombi*-Bond Systems [4] were developed based on a few grope tests applying a so called dowel shearing model, which assumes that failure of a shear force transmission system occurs as double cut shearing off within concrete material at the edges of the steel web perforation. By means of the total spectrum of test results with open perforation in the web edge zones and closed perforation with bigger diameters as in Perfobond Systems could be found that this concept does not describe the bearing behaviour of concrete dowels completely in a generally valid mode. Lots of experiment results are evidence for limitation of the appearance of this failure criterion on cases, if concrete dowels are placed deeply within the concrete slabs or if thick web plates are used. A new formulation of a calculation procedure considers that shearing surfaces are not located parallel to the web surfaces completely but they approach to the web plate axis with increasing distance from the contact surfaces. This knowledge effects that big size perforations require reduction of shear surface size due to an obvious contact within the dowel zone. An empiric form factor was defined on base of the total test spectrum in order to consider such effects in a reliable calculation procedure for final design purposes.



Dismantled shear fracture of a light weight concrete dowel

Shearing surfaces in a plan view cut
t_w= web plate thickness
b_i= concrete dowel diameter

Fig. 6 Dowel shearing off model – depiction of shearing surfaces

The dimensioning method for concrete dowel, which refers to the described failure criteria is summarized in table 1. The calculation rules for assessment of characteristic bearing capacity are statistically risk proved according to the concept of Eurocode 3, Annex Z independently for each failure criterion. The partial safety factor for each bonding element is assessed as γ_V = 1,25 in correspondence with notation of Eurocode 4.

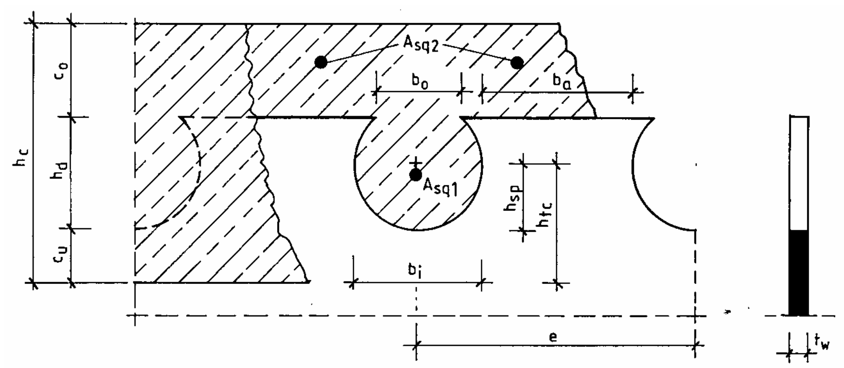


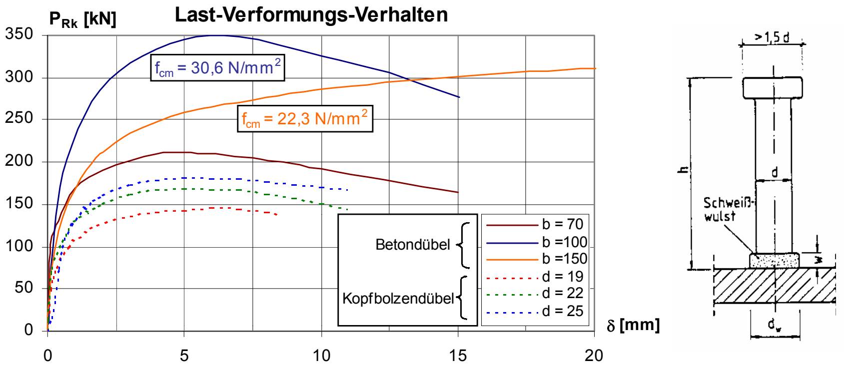
Fig. 7 Terms for the recommended dimensioning concept for concrete dowels

Tab. 1 Extract from regulations of the recommended dimensioning concept

Dowel bearing capacity		
local pressure failure	$P_{Rd1} = 72{,}7 \cdot f_{ck}^{1/2} \cdot h_d \cdot t_w \cdot \frac{1}{\gamma_v}$	$\gamma_v = 1{,}25$
Punching failure	$P_{Rd2} = 25{,}6 \cdot h_{tc}^2 \cdot f_{ctk} \cdot \rho_i \cdot \frac{1}{\gamma_v}$ mit: $\rho_i = 1+(E_s/E_{cm} - 1) \cdot A_{sq1}/A_d$	
Shearing off failure	$P_{Rd3} = 23{,}4 \cdot A_d \cdot f_{ctk} \cdot \rho_i \cdot f_h \cdot \frac{1}{\gamma_v}$ mit: $f_h = (1{,}2 - h_d/180) \leq 1$	
Minimum distance	$\min e = b_i + P_{Rd} / (0{,}7 \cdot t_w \cdot f_{yd})$	
Terms	b_i effective with of web perforation b_o width of edge gap b_a minimum length of steel teeth t_w web plate thickness c_u concrete coverage of dowel root c_o conrete coverage of slab surface h_d dowel height A_d Area of perforation cross-section h_{sp} distance of dowel center from dovel root h_{tc} height of substitute fracture cone ($h_{tc} = h_{sp} + c_u$) f_{ck} characteristic compressive strength of concrete material f_{ctk} characteristic tensile strength of concrete material e distance of adjacent concrete dowels along force direction	
Lateral reinforcement	$A_{sq} = 0{,}5 \cdot P_{Rd} / f_{yd} = (A_{sq1} + A_{sq2})$	
Ductility	$\delta_{uk} = \frac{1}{10} \cdot (0{,}64 \cdot (b_i+h_d)/\rho_i/\eta_c + {}^1/_2 \cdot b_o)$ mit $\eta_c = \sqrt[4]{31{,}28/f_{cm}}$	
Application restrictions	$35 \leq h_d \leq 135$ mm $h/b_i \leq 1$ Concrete C 20/25 - C 70/85	

One main aspect of competitive chance of concrete dowels against commonly applied stud head connector technology is the achievable bearing capacity of one single shear force transmission element in relation to the corresponding manufacturing cost. The production of perforation through manually conventional oxy-acetylene cutting is more expensive for one single concrete dowel in comparison to one single stud head connector. Adequate facilities for machine punching or automatic guided NC-cutting facilitate very economic manufacturing.

Costs per length unit of bond joints of automatic produced concrete dowels may be expected to be lower than for stud head connectors. One essential advantage of concrete dowel technology is visible in the example of Fig. 8 by means of comparative depiction of bearing and deformation capacity. Improvements to total bearing capacities of concrete dowel arrangements can be gained with more extended freedom in design of the geometry like e.g. perforation size and shape. In difference the bearing capacity of stud head connector technology from usual materials is strictly limited by a maximum diameter of 25 mm from a present point of view.



Characteristic bearing capacity of stud head connectors:

$$P_{Rk1} = 0{,}29 \cdot d^2 \cdot \alpha \cdot \sqrt{E_{cm} \cdot f_{ck}}$$

$$P_{Rk2} = 0{,}8 \cdot f_{uk} \cdot \frac{\pi \cdot d^2}{4}$$

Fig. 8 Characteristic dowel curve of concrete dowels and stud head connectors

A comparative view on safety level of test results with stud head connectors (Fig. 9) with concrete dowels (Fig. 10) shows more advantageous correlation properties for concrete dowel technology independent from specific failure criteria. Both diagrams show the relation between calculated bearing capacities P_t in accordance with the demonstrated dimensioning rules and the measured ultimate loads $P_{e,max}$. Small deviations from P_t'-line document a good correspondence between calculated values and tested values and offer a scale for the quality of a calculation model. Supplemental should be noticed, that the concrete dowel calculation method refers to the quasi-static bearing capacity, while stud head connector dimensioning rules base on the upper ultimate load horizon.

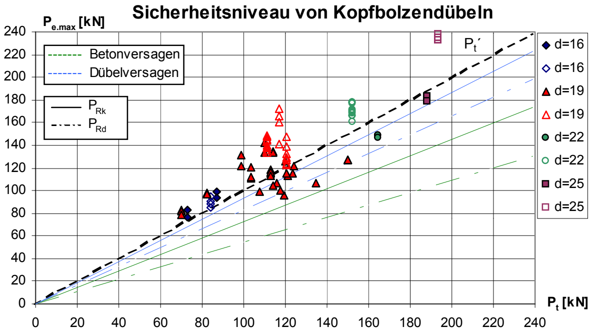


Fig. 9 Safety level of stud head connectors

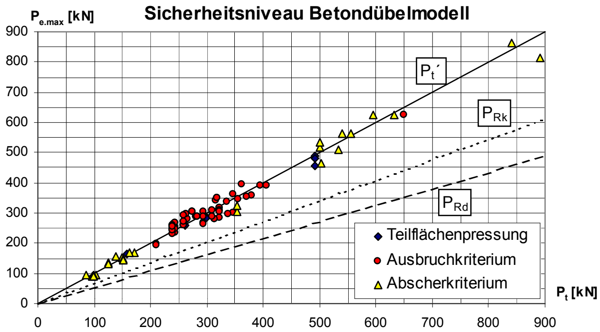


Fig. 10 Safety level of concrete dowels

Summarizing may be stated, that an experimental and statistical proved dimensioning method for practical application of concrete dowels for shear force transmission between steel and concrete members of composite girders exists in accordance with modern international technical standards. Engineer's and construction company's interest and acceptance for this effective and economical new composite bond technology was lastly promoted by some pilot projects initiated by public infrastructure organisations in Germany.

3 Fatigue properties of concrete dowels

Research on fatigue properties of concrete dowel technology was performed with an extensive analysis and test program in order to enable an application in bridge construction and for buildings with significant moving loads next to common buildings. 16 experiments were conducted in the laboratory of Institute for Constructive Engineering at the University of Federal Armed Forces in Munich for verification of suitability for constructive applications with requirements on fatigue properties of structural elements. 4 additional fatigue test results taken from literature are included in the total evaluation of the fatigue test series. Push-out-tests were conducted in the laboratory of Institute for Constructive Engineering at the University of Federal Armed Forces in Munich similar to the tests for assessment of static bearing and deformation capacities. The specific test procedure is sketched schematically in Fig. 11. In the initial test phase I test specimen were force controlled loaded with the planned upper test load level in order to assess deformation properties of concrete dowels under initial load. Test phase II covers a cyclic load program of single step load collectives with a fixed upper and lower load level and multiple step load collectives up to an approximation to an assumed service load collective. 16 test specimen were exposed lo load cycles in a range from 2,0 to 7,2 million with upper loads between 70% and 90% of the quasi static load bearing capacity. If no fatigue failure occurred while cyclic loading test phase III followed as assessment of remaining static load bearing capacity.

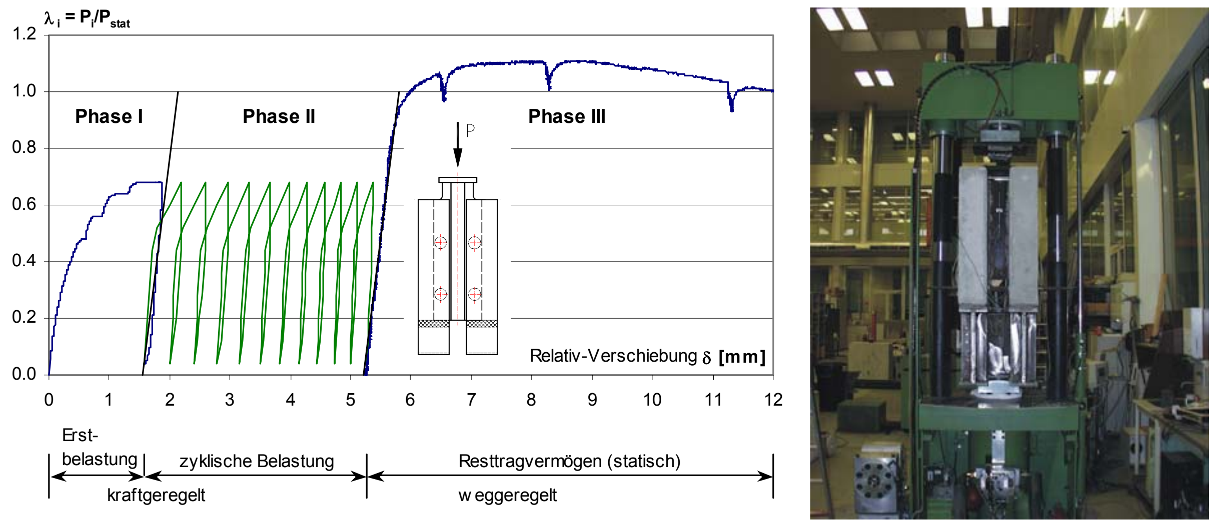


Fig. 11 Experimental procedure for fatigue testing

All fatigue tests were executed in a servo-hydraulic test machine with maximum loading capability of 1000 kN as pressure. Geometry of perforation, material strength of concrete slabs and the amount of immediately involved reinforcement were altered as variable parameters within the test program. The perforation size covered the range of medium size concrete dowels with a diameter of 70 mm. As example relative movements between steel members a concrete slabs in relation to the quantity of load cycles are shown in Fig. 12 for test result explanation purposes. This example refers to closed circle shaped concrete dowels with the test series number ED1. Main measuring value was the development of relative movements under upper load level, which was significant higher than common service load levels in all test series. In a double-logarithmic diagram an approximately linear progress of plastic relative movement along load force direction could be observed.

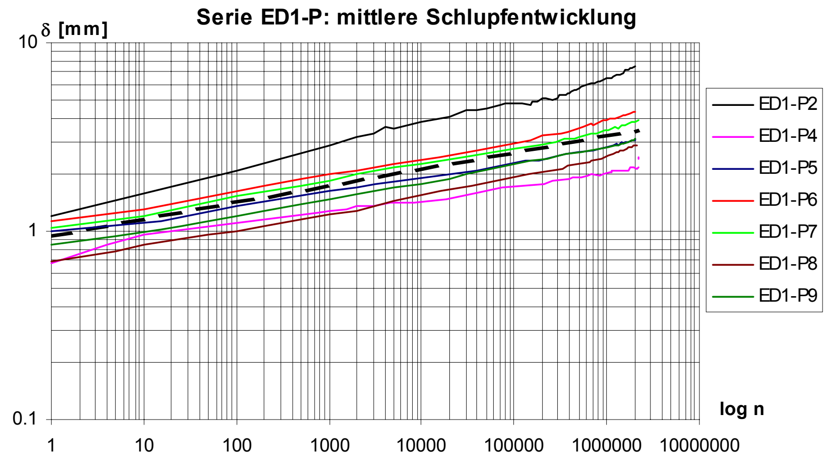


Fig. 12 Measuring records of relative movement under upper loads on fatigue testing

These regular properties confirmed through the total test program permits an assessment of relative translation between steel profiles and concrete slabs and subsequently an approximate calculation of deformation of composite bridge constructions for the whole service life duration due to plastic flexibility of bond systems. Relative movements in real constructions under service load conditions will reach a significant lower deformation level as figured in Fig. 12. The test program was conducted with upper load intensities, which usually do not occur in real buildings according to the main focus on the total number of load cycles before failure. In the framework of test series could be discovered that concrete dowels possess highly advantageous fatigue properties. This result could be confirmed with phase III static tests for remaining bearing capacity assessment after 7.2 million load cycles. The remaining bearing capacity can be expected to increase in correspondence to the P_t/P_e-Diagram in Fig. 13, where phase III test results are depicted with coloured signature together with some exclusively static tested push-out arrangements in a grey signature. This observation can be explained with a micro crack occurrence in the contact zone between steel and concrete members, which causes balance effects to stress peaks under fatigue relevant load events. Comparable research results on remaining load bearing capacities of stud head connectors reveal a decreasing tendency. Different from exclusively static test results for concrete dowels after dynamic tests a specific fracture appearance was observed frequently, which consisted of one small and simultaneous one bigger fracture cone.

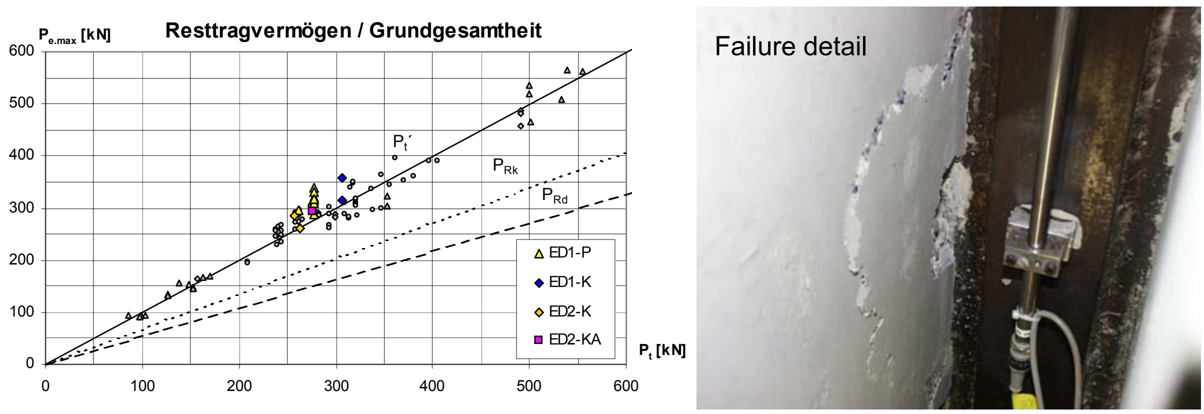


Fig. 13 Integration of remaining bearing capacity to the statistic theoretical calculation model

4 Tests on composite girders

Next to analysis of local effects of load bearing behaviour of bond systems through push-out-tests additional examinations of global bearing behaviour of composite girders with concrete dowels as bond system were executed. The test program included two test series with each 3 experiments. Span, dowel arrangement and dowel's utilization degree were altered as variable parameters regarding to the partial bond theory. Composite girders were made from upper flangeless standard steel profiles with a perforation immediately within the web plates. Simulations with the finite element method were calculated parallel to the girder tests. Measured load deformation curves of test girders in relation to the test load level are shown in Fig. 14 next to calculated curves with a dashed signature. A high correspondence between test measurement and calculation confirms the high suitability of the developed calculation procedure for assessment of ultimate loads of composite girders with concrete dowels as bond systems as well as for deformation assessment.

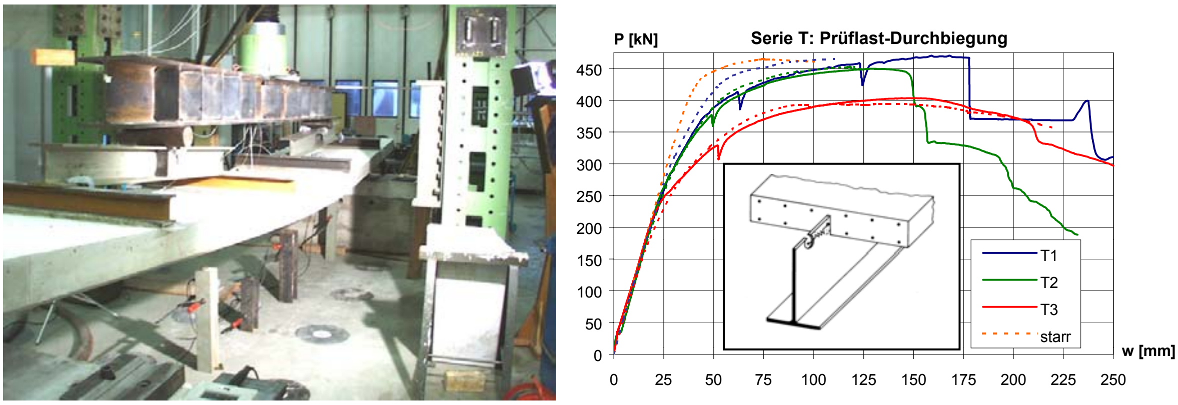


Fig. 14 Verification of the calculation method by means of girder tests

One further analysis focused on local bearing behaviour of composite girders with upper flangeless steel profiles with concrete dowel perforation. Main issue was the influence of blade support upon the edge of the web plate, which could require additional web side concrete fillings for shear force support due to a danger of local damage. Experimental analysis was conducted on headfirst girder sections. Manufacturing of test specimen considered especially measures to suppress any friction effects in order to ensure, that isolated blade support effects are tested. Both measured ultimate loads and observed failure mechanisms shown that a safe load transfer without web side concrete fillings is possible as well as a reliable crack width limitation.

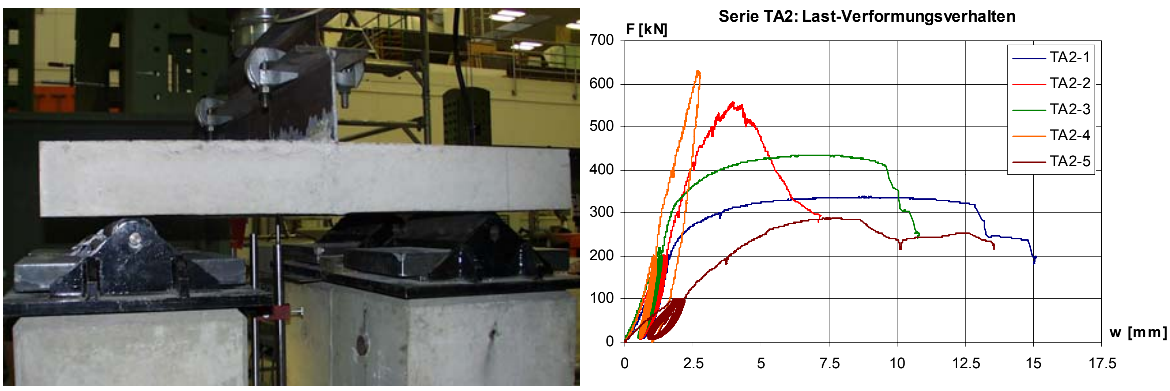


Fig. 15 Girder section tests for examination of local stress effects in concrete slabs under transversal load transmission over the upper web edge of upper flangeless standard steel profiles

5 Opportunities for concrete dowel technology application

The main advantage of concrete dowel technology is the high bearing capacity of one single bond element in comparison to alternative bond methods in composite construction. Furthermore the presented bond type permits a high pre-fabrication degree with acceptable duration of machine employments. The dowel geometry can be cut into steel plates completely automatically. On sufficient demand employment of punch facilities can cat an economical alternative. Two flangeless girders can be made from one standard steel profile through oxy-acetylene cutting including dowel perforation of the web plates. Completely finished steel elements can be processed to composite girders on building site without further metal work.

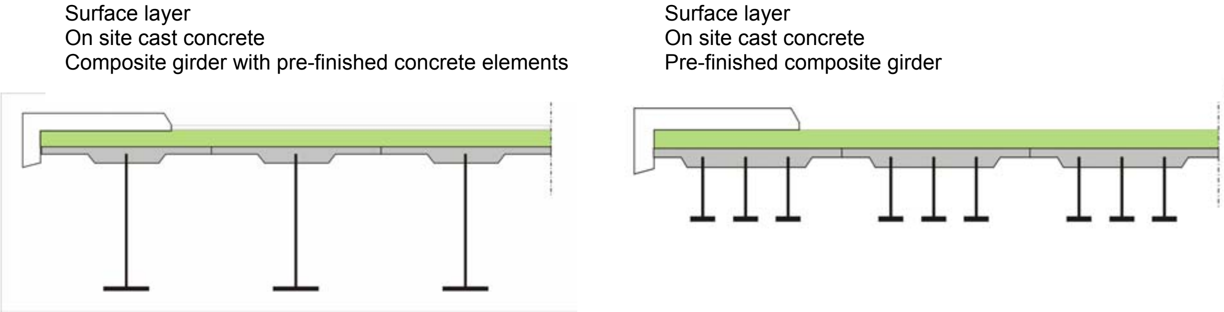


Fig. 16 Utilization of pre-finished composite girders with concrete dowels in bridge construction

Examples for application of flangeless steel profiles in composite girders for bridge constructions are shown in fig. 16. The steel profiles are supplemented with concrete slabs on pre-fabrication facilities to composite girders. Depending on restrictions of construction height respectively on stiffness requirement girders are manufactures with single or multiple steel profiles. Through filigree concrete slabs sufficient stiffness for transportation purposes and for support of an additional upper on site concrete pavement can be obtained. Stirrups in the filigree concrete members ensure a reliable bond with the concrete deck. Dieser Aufbeton ist über Bügel mit dem Betonfertigteil des Verbundträgers verbunden. Short to medium range span bridges can be built without shuttering and scaffolding. Composite girders initially act as shuttering and later as an essential structural member of the whole construction. The application of flangeless steel profiles ensures, that required bund function between steel profiles and concrete slabs can be provided solely by concrete dowels.

Further opportunities for application of concrete dowel technology can be found in building construction. Two proposals for Slim-Floor-Constructions are depicted in Fig. 17 as examples.

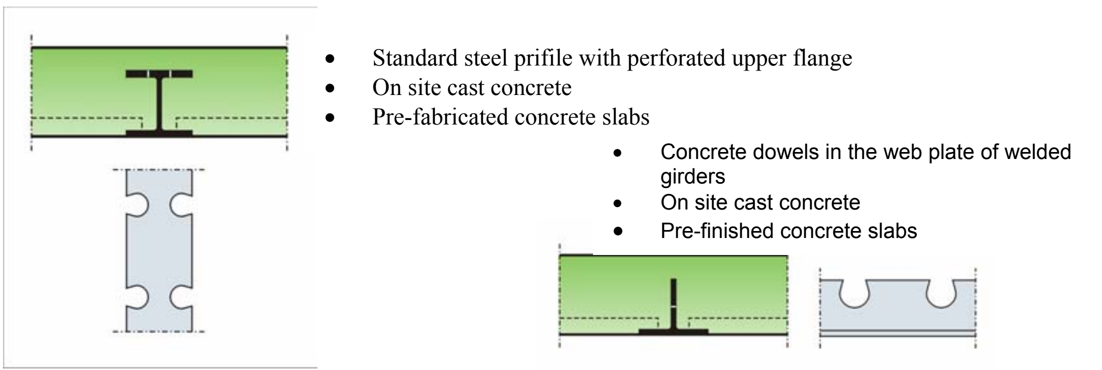


Fig. 17 Application of concrete dowels for Slim-Floor-Constructions

6 Summary

An overview on experimental research on bearing and deformation behaviour of concrete dowels including significant findings is given in this report. A stochastically proved and commonly applicable dimensioning procedure for shear force transmission between steel components and concrete members of composite girders was derived from results of 102 tests. Due to pleasant research results concerning fatigue properties of concrete dowels concrete dowels can also be recommended for industry buildings with non-resting loads and for bridge constructions.

As a condition for economical structural design of composite girders with concrete dowels local support effects were thoroughly examined in order to reliably enable constructions with flangeless standard steel profiles without arrangement of web side filling concrete. Bearing capacity reserves due to friction effects were analysed but not exploited for the development of a dimensioning method.

Based on extensive examinations of concrete dowel bond applications in bridge constructions should be possible. The competitive chance in comparison to conventional stud head connectors consists of the development of structural elements with a high pre-fabrication degree, which can be delivered ready to build in on the building site. This publication presents opportunities for application of concrete dowel technology in building construction and bridge construction as well. The acceptance of engineers and building companies for the innovative bond technology in composite structures requires sufficient reference objects. Pilot projects in building construction are already completed. Bridge projects are in the planning phase.

6 Literature

[1] Mangerig, O. Wurzer
Zum Tragverhalten von Betondübeln. Tagungsband zur Fachtagung Verbundkonstruktionen, neues aus Forschung, Entwicklung und Normung. Herausgeber: DFG – Forschergruppe Verbundbau an der Universität Kaiserslautern, 1997

[2] Mangerig I., Zapfe C.
Ermüdungsfestigkeit von Betondübeln, Theorie und Praxis im Konstruktiven Ingenieurbau-Festschrift zu Ehren von Helmut Bode, ISBN 3-89821-055-3, Stuttgart 2000

[3] Zapfe C.
Trag- und Verformungsverhalten von Verbundträgern mit Betondübeln zur Übertragung der Längsschubkräfte. Berichte aus dem Konstruktiven Ingenieurbau (2001/01), Universität der Bundeswehr, Juli 2001

[4] Wurzer O.
Zur Tragfähigkeit von Betondübel, Dissertation am Institut für Konstruktiven Ingenieurbau, Universität der Bundeswehr, München, Juni 1997

[5] Deutsches Institut für Bautechnik: Zulassungsbescheid Perfobondleiste, Zulassungsnummer Z-26.1-23, Berlin 22.07.1991

[6] Deutsches Institut für Bautechnik: Allgemeine bauaufsichtliche Zulassung der Kombi-Verdübelung 2000, Zulassungsnummer Z-26.4-39