Analyses of the loadbearing behaviour of deep-embedded concrete dowels, CoSFB

The development of the “CoSFB-Betondübel” is presented in this paper. The “CoSFB-Betondübel” is a deep-embedded concrete dowel connecting in situ concrete with a steel section to assure composite action and thus allow for composite beam design. The load-bearing behaviour and parameters influencing this behaviour were determined through experimental tests. Special focus was given to the influence of the ratio of the resistance of the concrete dowel to the concrete compression class. The evaluation of the results concluded in a National Technical Approval [1]. Further investigations were performed via FE analysis in ABAQUS. Further, 3D models with non-linear material and geometry were prepared and validation undertaken. In addition, a real application example of CoSFB is shown.

1 Deep-embedded concrete dowels – “CoSFB-Betondübel”

Concrete dowels consist of circular openings in the web of a hot-rolled steel section, reinforcing bars passing through the openings and a concrete infill (Fig. 1), see [2].

Owing to the connection of the in situ concrete with the web of the steel section, the concrete topping above the upper flange can be reduced to a minimum, which also allows for optimum structural use of the depth of the construction. In the absence of design rules for this kind of application for concrete dowels, beam tests and push-out tests had to be performed to allow for safe and optimized use of this technology (see section 3). Compared with other types of concrete dowel [3], deep-embedded dowels are defined by the absence of possible concrete failure towards a free edge of the cross-section. The “CoSFB-Betondübel” is a concrete dowel placed between the flanges of a hot-rolled section [1]. As the concrete here is restrained by the upper and lower flanges and the web of the steel section, failure of the concrete as a result of expansion towards a free edge cannot occur [4].

2 Slim-floor construction

Slim-floor construction is characterized by the integration of the steel beam into the slab, which results in a very slim structure. Owing to the absence of downstand beams, the installation of building services (e.g. for cooling, heating) is not affected by the loadbearing members. This leads to major simplifications in the design and erection phases of the structure (Fig. 2).

Further, the integration of a slim-floor beam (SFB) into the slab results in a significant increase in the fire resistance of the beam. The combination of SFB with partially prefabricated concrete slabs or deep composite decking allows for large beam spacings and leads to an optimized steel consumption (beam weight per square metre of slab). Restricting the construction depth consequently leads to a limited inertia and stiffness of the slim-floor beam. Therefore,

Fig. 1. CoSFB – composite slim-floor beam [2]

Fig. 2. Typical slim-floor construction
spans of non-composite slim-floor beams are typically limited to about 7 m. Searching to enlarge the range of applications for slim-floor construction, the structural activation of the in situ concrete was analysed. To connect the in situ concrete with the steel beam, allowing for composite beam design, the use of traditional shear studs was analysed first. As shown in Fig. 3, shear studs welded to the upper flange of the SFB would require either a reduction in the steel section or an increase in the slab thickness h, which would not lead to the required gain in stiffness and resistance. Therefore, the use of standard shear studs is less satisfactory.

Hence, to enlarge the range of applications for slim-floor construction via composite beam design, a solution for the shear connection had to be found. It need hardly be mentioned that no complexity should be introduced into the erection phase of the structure or the fabrication process.

3 Test campaign

3.1 Beam tests

The global behaviour of the composite slim-floor beam was investigated with two shear beam tests and two beam tests (Fig. 4). Analyses were focused on the activation of the effective width of the concrete chord, the deflection and vibration behaviour as well as the overall structural behaviour. The beam test programme is summarized in Table 1. All tests showed a very ductile behaviour with large deformations up to failure. Failure occurred due to failure of the concrete at the upper edge of the section – the edge undergoing maximum compression. Close to the load introduction zone, the concrete constricted and parts of the concrete started to spall. Based on the measured strain distribution, the effective width of the concrete chord at mid-span was calculated. The whole width of the concrete slab of the specimen was activated. Further, full composite action between the steel section and the concrete chord could be proved. For further details see [5].

### 3.1 Push-out tests

To investigate the characteristics of the shear connection, 27 push-out tests with varied parameters were performed. The test configuration is shown in Fig. 5.

The most important parameters for the loadbearing behaviour and loadbearing resistance are: diameter of dowel reinforcement $d_b$, concrete compression class $f_{c,\text{cyl}}$ and diameter

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**Table 1. Beam test overview**

<table>
<thead>
<tr>
<th>Type</th>
<th>Geometry length × width</th>
<th>$\beta$ [%]</th>
<th>$P_{\text{max}}$ [kN]</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>4.0 × 2.5 m</td>
<td>100</td>
<td>1882</td>
<td>Shear force capacity, structural behaviour (loadbearing capacity, effective width of concrete chord)</td>
</tr>
<tr>
<td>S2</td>
<td>50</td>
<td>1689</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>8.0 × 2.5 m</td>
<td>100</td>
<td>945</td>
<td>Structural behaviour (loadbearing capacity, effective width of concrete chord), deflection, vibration analysis</td>
</tr>
<tr>
<td>B2</td>
<td>100</td>
<td>953</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Theoretical degree of shear connection*
of hole in web of steel section \(d_D\). A series of three push-out tests was performed for each test configuration. The value of the cylindrical concrete compression strength and the given value of the maximum load of the press \(P_{\text{max}}\) represent the mean value of the three tests. Other parameters that were varied, such as the web thickness of the steel section \(t_w\) and the thickness of the concrete slab \(h_c\), are of minor importance. The tests were performed with displacement control. To allow for the influence of short-term relaxation, the displacement of the press was stopped regularly and kept constant for approx. 5 min. During testing, the jacking force \(P_j\), slip and inclination were recorded continuously by deflection measurement devices, likewise the strains in the reinforcing bar at selected locations. Further information can be found in [5]. An overview of the parameters is given in Table 2.

### 3.2 Evaluation of the shear connection

All push-out tests performed reached a slip > 6 mm and can be classified as ductile in accordance with EN 1994-1-1 [6]. As described in the previous section, the concrete dowels were embedded deep and a concrete failure towards the free edge of the specimen was not observed. Failure occurred due to the maximum elongation of the dowel reinforcement being exceeded. Shear block failure was not observed, either. The test results are described in detail in [5]. In the following, the phenomena observed – an increase in the concrete compression class – curve 1b – leads to an increase in the stiffness; the specimen behaves elastically until a higher load level is reached. However, this increase in the concrete compression class results in a decrease in the loadbearing resistance of the “CoSFB-Betondübel”. The explanation for this effect is rather simple: the higher the concrete compression class in relation to the shear resistance of the dowel reinforcement, the lower is its ability to generate local damage in the concrete. The dowel reinforcement has no space to deform, its axis remains rather straight, and the dowel reinforcement is subjected to shear only (shear is dominant). The greater the ability of the bar to create a space locally (by compressing the concrete locally), the more the axis of the bar can deform.

### Table 2. Push-out test overview (2009 and 2011)

<table>
<thead>
<tr>
<th>Series</th>
<th>Year</th>
<th>(t_w) [mm]</th>
<th>(d_D) [mm]</th>
<th>(d_b) [mm]</th>
<th>(h_c) [cm]</th>
<th>(f_{c,cyl}) [N/mm²]</th>
<th>(P_{\text{max}}) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2009</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>13.4</td>
<td>34.0</td>
<td>2168</td>
</tr>
<tr>
<td>P2</td>
<td>2009</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>13.4</td>
<td>39.4 a</td>
<td>2282</td>
</tr>
<tr>
<td>1a</td>
<td>2011</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>16</td>
<td>26.7</td>
<td>1964</td>
</tr>
<tr>
<td>1b</td>
<td>2011</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>16</td>
<td>55.1</td>
<td>1655</td>
</tr>
<tr>
<td>2–1a</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>15</td>
<td>29.5</td>
<td>1728</td>
<td></td>
</tr>
<tr>
<td>2–1b</td>
<td>15.5</td>
<td>40</td>
<td>12</td>
<td>15</td>
<td>58.2</td>
<td>1591</td>
<td></td>
</tr>
<tr>
<td>2–2a</td>
<td>15.5</td>
<td>25</td>
<td>12</td>
<td>14.5</td>
<td>32.7</td>
<td>2030</td>
<td></td>
</tr>
<tr>
<td>2–2b</td>
<td>15.5</td>
<td>40</td>
<td>25</td>
<td>15</td>
<td>40.0</td>
<td>3978</td>
<td></td>
</tr>
<tr>
<td>2–3c</td>
<td>15.5</td>
<td>25</td>
<td>25</td>
<td>14.4</td>
<td>14.4</td>
<td>1417</td>
<td></td>
</tr>
</tbody>
</table>

- a Different concrete compressive strength of one specimen in the series
- b Failure of dowel reinforcement could not be achieved
- c No concrete infill to web openings

### Fig. 6. CoSFB push-out tests – load–slip curves 1a-P1, 1b-P3
The pure shear is transformed into shear and tension – “kinking”, which results in a lower stiffness of the shear connection. As the tension resistance is higher than for shear, a further load increase is possible. This behaviour is similar to the observed behaviour of shear studs in normal- and high-strength concrete [7].

4 National Technical Approval – “CoSFB-Betondübel”

The application and the design of the “CoSFB-Betondübel” at ULS and SLS are covered by a German National Technical Approval [1]. The main content of the approval is values for the resistance of the shear connection, which were derived from the results of the push-out and beam tests [5]. It is important to mention that in all the tests performed, the shear connection showed sufficient stiffness at SLS, the activation of the concrete chord was verified and a ductile behaviour, as required by EN 1994-1-1 [6], was proved by the beam tests. The values presented in Table 3 were obtained via statistical evaluation according to EN 1990 [8] with a safety factor \( \gamma_r = 1.25 \).

An equidistant distribution of the concrete dowels in the longitudinal direction of the beam is possible and a partial shear connection – by respecting a minimum degree of shear connection – can be used. The spacing of the web holes should be 123 mm at least. Verification of the longitudinal shear in the critical sections of the concrete slab and the design of the transverse reinforcement has to be performed according to [6]. At least minimum reinforcement and an anti-cracking mesh are required above the upper flange. The dowel reinforcement has to be anchored in the concrete chord, outside the area between the flanges of the hot-rolled section. Verification of the concrete compression stresses at the upper edge of the section is recommended. Placing slab elements with a partial concrete section in the area between the flanges of the hot-rolled section is not allowed. Generally, the design rules given in [6] should be used, unless given differently in [1].

5 Numerical analysis

Detailed investigation of the push-out tests permitted an in-depth understanding of the mechanical behaviour of the shear connectors within the range of parameters covered by the experimental investigations. However, for the reliable further optimization of the system and the development of an analytical design formula, extensive numerical analyses had to be performed.

Numerical simulation of the composite system described above was a highly non-linear problem with material and contact non-linearities and large displacements. For solving such a complex problem, ABAQUS [9], a commercial FE package, was used, which is typically applied by many researchers to simulate composite structures.

5.1 Geometry, boundary conditions and load

The geometry represents the specimen from the experimental tests and consists of: steel beam HE220M, concrete dowel \( d_b = 12 \) mm, concrete slab C25/30 \( (f_{c,\text{cyl}} = 26.7 \text{ N/mm}^2) \), reinforcing mesh Q237 (150 \( \times \) 150 mm).

Two planes of symmetry were used in the numerical model, which allowed for a reduction in the problem size and, consequently, the computing time. In addition, the stability of the system was improved for the numerical calculations. The load, in the form of a displacement, was introduced on the top of the steel section, while the displacement at the bottom of the concrete slab was blocked in the direction of the applied displacement (Fig. 7).

5.2 Material models

An elasto-plastic material model was applied to all the steel parts with the following parameters:

- Steel beam \( f_y = 555 \text{ N/mm}^2 \), Young's modulus 210 GPa, density 7850 kg/m\(^3\), Poisson's ratio 0.3
- Reinforcement \( f_y = 550 \text{ N/mm}^2 \), Young's modulus 200 GPa, density 8000 kg/m\(^3\), Poisson's ratio 0.3

Parameters for the concrete model were as follows:

- Compressive strength 26.7 N/mm\(^2\), tensile strength 3 N/mm\(^2\), Young's modulus 31 GPa, density 2643 kg/m\(^3\), Poisson's ratio 0.2

The concrete was modelled using the well-recognized Concrete Damaged Plasticity (CDP) model, with the default values of the plastic parameters proposed in ABAQUS:

1. Dilation angle \( \psi \), 36°
2. Flow potential eccentricity \( e \), 0.1

### Table 3. Characteristic values of dowel resistance \( P_{Rk} \) in kN per dowel

<table>
<thead>
<tr>
<th>Concrete class / web thickness ( t_w )</th>
<th>C25/30</th>
<th>C30/37</th>
<th>C35/45</th>
<th>C40/50–C55/67</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5 mm ≤ ( t_w &lt; 15.5 ) mm</td>
<td>117</td>
<td>125</td>
<td>135</td>
<td>122</td>
</tr>
<tr>
<td>15.5 mm ≤ ( t_w )</td>
<td>148</td>
<td>157</td>
<td>166</td>
<td>122</td>
</tr>
</tbody>
</table>
5.5 Preliminary results

The aim of this ongoing research is to develop a model suitable for simulating the behaviour of the CoSFB system, especially local behaviour and the failure modes of the shear connection. The model will be validated with the results of the experimental tests, where different sections for the beam and different concrete grades were used.

The authors of the paper are at the very beginning of the process. So far, a model representing experimental test “1a” has been prepared, with the specifications described above, to simulate the test. In this test the concrete model was relatively soft, allowing for greater deformation of the bars and creating the “kinking” effect. The deformed shape of the dowels obtained from the simulation is comparable with the shape of the dowels observed in the experimental test as illustrated in Fig. 10.

Owing to the use of the material concrete model with damage (CPD), any contact definition as the elements of the reinforcing mesh lie embedded in the host elements – the concrete slab. The remaining interactions were defined as contact pairs with contact in the normal direction specified by an exponential pressure-overclosure relationship, which makes the contact a bit softer and is beneficial for the converging of the model. In the tangential direction, a friction coefficient was specified. For the contact between beam and slab, a value of zero is used, and a value of 0.3 for the contact between dowel reinforcement and slab.

Two types of procedures available in ABAQUS/STANDARD were used for the simulations: *STATIC, STABILIZE and *STATIC, RIKS. Both of them are non-linear static incremental procedures recommended for problems with stabilities, in this case caused by non-linear material and contacts. The procedures were investigated and compared in simulations of similar tests by Fink et al. [11].

Fig. 8. Concrete compressive and tensile material law used in CDP model: a) compression hardening, b) tension stiffening

Fig. 9. Mesh of the model and details of mesh around a dowel in beam web
it can be observed where the damage, in the form of crushing, cracking and degradation of the stiffness, appears in the model. Fig. 11 illustrates the damage developing in the connection area.

It has been noticed that parameters defining plasticity of concrete as well as parameters defining contacts have an influence on the results obtained. Therefore, it is important that the final defined parameters for the model that will be used for predicting the results are adequately selected. These parameters should give satisfactory results for the simulation of all experimental tests within agreed tolerances and should not be fitted to one experimental test only. This is a long way to obtain a trustworthy model that can be used to predict results and not just reproduce the experimental tests. The comparative results will be shown once the authors are fully confident of their findings.

Once the model has been validated and is fully reliable, a parametric study will be performed. The parameters to be verified are mainly: diameter of dowel, diameter of hole in web and strength of materials (steel and concrete). One aim of these investigations is to identify when the failure mode shifts from “kinking” to “shear” for a given connector geometry. Another aim is to identify the optimum geometry of the shear connectors in relation to the materials used.

### 6 Application example – CoSFB

An application example of a CoSFB (= composite slim-floor beam with “CoSFB-Betondübel”) is presented in Fig. 12.

This project used a combination of a CoSFB with a Cofradal 200 slab element – a steel deck with insulation and in situ concrete topping. This solution fulfilled the customer’s needs most adequately, i.e. short erection time and long spans with intervening columns. With a construction depth $h$ of only 29 cm, a beam span $L$ of 10 m was possible, which gives a slender-ness ratio $L/h = 351$. The relatively small beam spacing of only 4 m led to low actions for the CoSFB at ULS but also to a low modal mass, which had to be considered in the vibration analysis. The CoSFB fulfils the requirements of fire resistance class R60 without any additional measures. In addition, an aesthetical solution for the roof structure was used – curved cellular beams.

### 7 Conclusions and outlook

The “CoSFB-Betondübel” (deep-embedded concrete dowel) enables the benefits of slim-floor construction to be combined with those of composite construction. The results presented here show that using this shear connection significantly increases the loadbearing capacity of the floor beam. The immediate consequence of this is a reduction in the slab depth and increase in the beam span depending on the requirements for the structure. Furthermore, column-free open interiors can be increased and foundation sizes reduced. It is important that all these benefits can be achieved with easy fabrication and erection.
The German National Technical Approval summarizes the design rules for the “CoSFB-Betondübel” for a wide range of applications derived from the experimental tests.

Once the validation of the numerical model and intense parametrical study are completed it will be possible to extend the scope of applications beyond the range of parameters tested experimentally and develop optimized design rules.

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References


Fig. 12. CoSFB building “Offermann”, Mersch, Luxembourg: a) CoSFB before concreting, b) finished building