Shear connection of composite steel and concrete structures using pcb-W technology

V. Přívrželová

Abstract—The paper presents one of the possibilities of shear connection of steel and concrete parts of a composite beam. Using this innovative system, called pcb-W (precast composite beam – coupled in Web) technology, the longitudinal shear forces between steel and concrete are transmitted by composite dowels instead of headed studs. The paper deals with the verification of the behavior of these composite dowels in particular with the failure modes and bearing capacity of the composite dowels and with the stress distribution in the steel dowels. At the end the paper gives some suggestions for the further development of the pcb-W technology.

Keywords—composite beams, fiber reinforced concrete, high performance concrete, high strength steel, pcb-W technology.

I. INTRODUCTION

Composite constructions are gaining more and more importance across Europe. This increase in demand leads to very innovative and more economical solutions for such composite structures. During my recent studies I focused on the topic of material strength classes, material properties and added values of materials for composite steel and concrete single supported beams designed according to [1]. The purpose of such research, mentioned also in [2]-[4], was to evaluate the most suitable cross section of steel and concrete beam with high strength materials. A further step of my research is to specify the shear connection of the steel and concrete part of the composite beam. The choice of the shear connection was highly influenced by previous parametric study and by the possibility to cooperate with the Vladimír Fišer Company. Thus, the final choice of shear connection is pcb-W technology, as was described in greater detail in [5].

The aim of this paper is to introduce this innovative system as well as the pcb technology which is the base for pcb-W technology. The paper is going to focus on the failure modes of shear connectors when using pcb-W technology; it mentions a few words about the intentions of my research and about the forthcoming laboratory test.

A. pcb construction technology

The development of pcb technology, which is the abbreviation of “precast composite beam”, was initiated by Munich engineering office Schmitt Stumpf Frühauf und Partner (today known as SSF Ingenieure GmbH) especially for composite bridges. The pcb technology can be applied to road bridges, railway bridges as well as pedestrian bridges. So far, about 300 bridges have been realized in Germany using this technology, of which approximately 150 have been designed by SSF Company [6].

In Czech Republic two road bridges, one railway bridge and a pedestrian bridge have been realized so far. The Vladimír Fišer Company bought know-how and rights to this protected solution in 2010 and continues with the development.

Pcb girders are composite elements that consist of an open or closed welded steel-section and a thin prefabricated concrete flange, see Fig. 1. Such elements are completed with additional concrete on the construction site which is especially economic and time-efficient since no formwork is required. The shear transmission between steel and concrete is accomplished by headed studs using short studs for the prefabricated concrete and longer ones for in-situ concrete [7]. The prefabricated concrete flange is engaged as structural concrete and as formwork for covering in-situ concrete plate. After setting the prefabricated girders on sub-structure the concrete deck is cast in-situ without any further formwork. This is a big advantage especially for bridges crossing existing railways or highways, because the closure of traffic ways underneath can be minimized to only a few minutes for the assembling of each girder.

B. pcb-W technology

For the bridge spans up to 30 m and high slenderness of the bridge fields it is worth to leave out the upper steel flange and use the pcb-W technology. It is the combination of pcb technology and a method of rolled girders in concrete (W), which is a traditional method used frequently for railway bridges since the 1st half of 20th century. The rolled girders are with this method cast-in in a concrete slab. However, the rate of bridges using this method has been degreasing for the last decades due to high consumption of steel, high costs and

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bad dynamic properties [8].

Since 2003 SSF Ingenieure GmbH has been developing the pcb-W construction method, which combines the advantages of pcb and W construction technologies. Pcb-W (precast composite beam coupled in web) uses rolled sections cut into two halves along the web using a specific cutting geometry that two T-sections arise. These T-sections are embedded into lower part of concrete deck or into a concrete beam which generates the composite dowels, see Fig. 2.

The longitudinal shear force is then transformed by these composite dowels instead of headed studs. This system leads to great economic advantages compared to welded sections because material-consumptions for the upper flange, headed studs and effort for welding can be saved. Major advantage of external reinforcement elements compared to conventional concrete or pre-stressed solutions is an increased internal lever arm (Fig. 3). Compared to pre-stressed cross-sections an increase up to 20% can be realized for the internal lever arm which leads to more efficient cross-sections with considerably increased stiffness and more economical use of materials [7].

Fig. 2: Cross-sections pf pcb-W girders

The standard push-out tests according to [1] have been performed at the University of Federal Army in Munich to investigate new geometry of cut-line developed by SSF. It has been concluded, that the ULS resistance of the steel is almost independent from the shape of the dowel. However fatigue cracks have been observed. So far, the MCL shape dowels seem to have the best fatigue load bearing capacity.

II. FAILURE MODES OF COMPOSITE DOWELS

The bearing capacity of a composite dowel is limited by steel or concrete failure. In a good design both failures of a steel and concrete dowel are balanced up to the maximum load.

Steel failure is limited in the ultimate limit state by the shear resistance, yielding due to bending of the dowel and in the fatigue limit state by fatigue cracks due to dynamic loading.

Concrete failure is characterized by several failure modes. Which mode finally occurs depends on the boundary conditions like geometry, concrete grade, reinforcement design, adding of fibers etc. [9].

Fig. 4: Failure modes of composite dowels – yielding of steel dowel by bending and shearing, vertical crack in the non-reinforced concrete deck, shearing of concrete dowel, horizontal crack in concrete deck, spalling of concrete cover, pry-out cone in the concrete cover [7]

Pcb-W girders can be used in industrial buildings and bridges due to their high strength, high stiffness and large slenderness at the same time. Mainly for railway bridges the high strength and convenient slenderness providing small deformation is desirable. The composite dowels provide a high fatigue bearing capacity.

III. VERIFICATION OF COMPOSITE DOWELS’ BEHAVIOR

The main aim of my recent work is to verify the behavior of the composite dowels in particular to determine the bearing capacity of both steel and concrete dowels, decide which failure mode finally occurs, what is the influence of using high strength steel or high performance concrete and to specify the necessary reinforcement area in the concrete dowels.

The results of this work are required for further development of pcb-W technology.

I have divided the amount of work into three major steps. The first step includes the choice of material strength grades, geometry of composite dowels and calculation of the bearing capacity of steel and concrete dowels. Such parameters are based on the results of a parametric study. The second step is to verify the results of the first step using FEM modeling. For determining the bearing capacity of shear connectors
according to [1] it is common practice to perform standard push out test. Therefore the FEM numerical models are arranged in order to meet the requirements of standard push out test. The third step, which is for the large volume of information not included in this papers, is the standard push out test itself.

Fig. 5: The geometry of the numerical model meets the requirements of standard push out test

A. The material properties

The choice of strength grades of steel and concrete dowels is based on the results of previous parametric study. The main aim of the study was to find the most effective combination of high strength steel and high performance concrete. It is very important to choose the strength grades properly, since there were several cases identified in the study, where the bearing capacity of a composite cross-section was lower with the use of steel of higher strength grade than with the use of lower strength grade.

Taking into account the results of parametric study and parameters of available molding machine, the strength grade of steel and concrete were chosen according to Table 1 and 2.

Table 1: The properties of steel cross-section

<table>
<thead>
<tr>
<th>Strength grade of steel</th>
<th>Yield strength $f_y$ [MPa]</th>
<th>Ultimate strength $f_u$ [MPa]</th>
<th>Axial distance between dowels $a$ [mm]</th>
<th>Thickness of the steel plate $t$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 355</td>
<td>355</td>
<td>490</td>
<td>250</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 2: The properties of concrete deck

<table>
<thead>
<tr>
<th>Strength grade of concrete</th>
<th>Char. comp. strength $A_s$ [MPa]</th>
<th>Reinforcement of concrete dowel $A_d$</th>
<th>Reinforcement above concrete dowel $A_{d}$</th>
<th>Thickness of concrete deck $b_c$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 30/37</td>
<td>30</td>
<td>2$\phi$12</td>
<td>2$\phi$12</td>
<td>230</td>
</tr>
</tbody>
</table>

With the given parameters, the bearing capacity of the concrete dowel was calculated according to [7]. The values of the bearing capacities for all the possible failure modes related to the bearing capacity of the steel dowel are given in Table 3.

Table 3: The bearing capacities of concrete dowel related to the bearing capacity of steel dowel

<table>
<thead>
<tr>
<th>Design of steel dowel</th>
<th>Shearing of concrete dowel $P_{d,k}$</th>
<th>Pry-out cone in the concrete cover $P_{d,k}$</th>
<th>Spalling of the concrete cover $P_{d,k}$</th>
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<tr>
<td>$P_{d,k}$</td>
<td>$1.65P_{d,k}$</td>
<td>$0.63P_{d,k}$</td>
<td>$0.38P_{d,k}$</td>
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The results show, that with the chosen configuration of the composite cross-section, the critical failure modes for ULS are spalling of the concrete cover and pry-out cone in the concrete cover, which are mainly affected by the reinforcement area.

B. Numerical models

To verify the behavior of the composite dowels during standard push out test, the numerical model was created in FEM software RFEM of the Dlubal Software Ltd. Company. The geometric parameters of the model corresponds to those of the specimens for the standard push out test, see Fig. 6.

Fig. 6: The numerical model

The model was exposed to different load conditions, that correspond to the values of bearing capacity of composite dowels for all the failure modes, Fig. 7. The numerical model shows, that the first failure to appear is the concrete failure.

C. Determining of the location with the greatest value of stress - HOT SPOT

Another purpose of the numerical model is to specify the stress distribution which is important for comparison with results of an experiment.

Fig. 7: FEM model, stress distribution in steel dowel under different load condition

Thanks to the numerical model, it is possible to identify the place with the highest value of the stress, so called HOT SPOT. This is the place where the strain gauges are located in

Fig. 7: FEM model, stress distribution in steel dowel under different load condition
the third step for comparing the results of the numerical model and an experiment, see Fig. 8.

![Fig. 8: Location of HOT SPOT](image)

Fig. 8: Location of HOT SPOT

**IV. CONCLUSION**

The paper presents several important outcomes of my recent work on composite steel and concrete structures using pcb-W technology. One of the main aspects is the determination of the right material strength grades, which is very important since it influences the behavior of the composite cross-section and load bearing capacity of the composite dowel as well. The choice of the material strength grades was based on the parametric study. The further step is the verification of the composite dowel which consists of numerical approach according to [7], numerical modeling and experimental verification which is not part of this paper. So far, the results shows, that the first failure to occur is the concrete failure.

The bearing capacity of the concrete dowel is mainly affected by the reinforcement area. The minimum or recommended area of the reinforcement is given in [7]. If greater bearing capacity of concrete dowel was required, it would be possible to employ more reinforcement bars or use reinforcement bars of larger diameters. However, we have to consider the armoring and mounting of the structure which is more complicated the more reinforcement we use, see Fig. 9.

![Fig. 9: Examples of reinforcement of composite dowels](image)

Fig. 9: Examples of reinforcement of composite dowels

For this reason, another specimens are prepared for the standard push-out test, some with common concrete and recommended area of reinforcement and some with fiber reinforced concrete and lower degree of reinforcement. The results of this upcoming experiment may be useful for further development of pcb-W technology since they may allow to use less reinforcement in the concrete dowel to make the technology even less laborious to manufacture.

The pcb-W technology is quite a newborn in composite steel and concrete structures given that the method has been developing since 2003. In Czech republic, this innovative system has been used since 2010 and several laboratory test have been made. So far, the technology uses only common concrete. However the ongoing laboratory tests show very promising results with fiber reinforced concrete. The combination of pcb-W technology and fiber reinforced concrete promises wide use in bridge construction for its economical, structural and low laborious advantages.

**REFERENCES**


V. Přívřelová (M’15) was born in Olomouc, Czech republic in 1987. She graduated in 2013 at Brno University of Technology and got the degree Master of Civil Engineering (Ing.). Her major was Steel structures and Building construction. She also got Bachelor’s degree in Law at Masaryk University in Brno. Her major field of study was Land law and Real estate register. In 2009/2010 she had an internship at Vilniaus Gedimino technikos universitetas in Vilnius, Lithuania. So far, the author continues with her studies to get the Doctor’s degree of Civil engineering. So far, she is in her third year of study.

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