# Verification and actual behavior of shear connection of composite steel and concrete structures using pcb-W technology

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***Abstract***— The paper deals with the problems of the theoretical and experimental investigation of load carrying capacity of steel and concrete composite members using pcb-W (precast composite beam - coupled in Web) technology. Pcb-W technology is new and economic solution of continuous shear connection of composite steel and concrete beams and walls. This construction method is based on a rolled steel beam cut longitudinally, with a special unique cut, in two T-sections and a concrete top chord is concreted. The shape of the cut hereby allows the shear transmission in the shear joint. The longitudinal shear forces between steel and concrete parts of a composite member are transmitted by composite dowels, generated by the special cut of steel surrounded by concrete, instead of headed studs as it is common in traditional composite structures.

The paper deals with the actual behavior and corresponding relevant failure mechanism 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. Within the framework of this research, three types of shear connection have been (or will be, respectively) investigated, all of them composed of three specimens.

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

## I. Introduction

The paper presents some results of a specific study realized on the author´s workplace (Institute of Metal and Timber Structures, University of Technology Brno) amongst other studies regarding to composite steel and concrete structures. The paper author´s workplace deals with the problems of high-strength materials for composite steel and concrete structural members, see e.g. [10], and introduces the use of advanced, non-traditional materials in traditional structural members and also participates on the process of the development, structural design and experimental verification of steel and concrete composite columns composed of high-strength steels and high-performance concretes.

One of the topics of the author´s workplace research field is the application of new progressive concrete types in composite steel-concrete structural members and structures. The author´s research is inspired, among other things, by the theoretical and experimental investigation of the usage of glass-fiber-concrete for slab of steel and concrete beams, mentioned for example in [11] and [12].

Another reason that enables the study of pcb-W technology is the possibility to cooperate with the companies of structural design and realization sphere, in the professional field of the usage of advanced materials and technologies, namely with the Vladimír Fišer Company oriented on the research field and development and Firesta-Fišer, rekonstrukce, stavby a.s. oriented to the structural design, technology and realization of modern and efficient composite construction using structural members combined of high-performance concretes and high-strength steels.

Fig. 1: Implementation of pcb technology in Germany

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 the recent studies the author 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 author´s research is to specify the shear connection of the steel

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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 author´s research and about the forthcoming laboratory tests.

### *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.

Fig. 2: Pcb girder for pedestrian bridge in Czech Republic

Fig. 3: Implementation of pcb technology in Czech Republic

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. 4. 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].

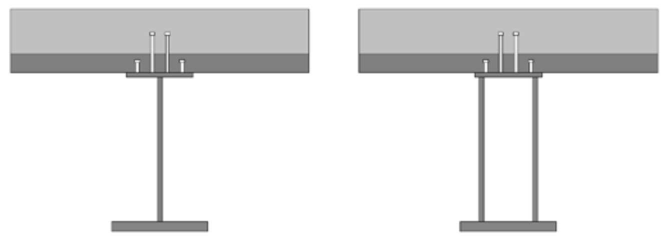

Fig.4: Open and closed pcb girder

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, see Fig. 5, because the closure of traffic ways underneath can be minimized to only a few minutes for the assembling of each girder.

Fig. 5: Bridge using pcb technology crossing existing motorway

### *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.

Load-bearing structures of deck railway bridges with encased filler beams have been used for short and middle spans of a maximum of 24 meters. For over a hundred years they have been designed in cases with little headroom. The first bridges were constructed with no interaction between steel beams and concrete floor slabs, the structural steel working as a bearing element and the concrete in the structure as a hardening and filling element. Later, in the second half of the 20th century, more developed bridge designs were introduced where encased steel beams were used acting compositely with a concrete floor slab – the concrete transmitting actions in compression and the steel acting in tension. These structural designs were based on the method of permissible stresses and have been in use up to present [13]. The encasement of the steel shapes in concrete is applied primarily for the following purposes: flexural stiffening and strengthening of compression elements, fire protection, potentially easier repairs after moderate damage and economy with respect both to material and construction [14].

However, the rate of bridges using this method has been degreasing for the last decades due to high consumption of steel, high costs and 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. 6.

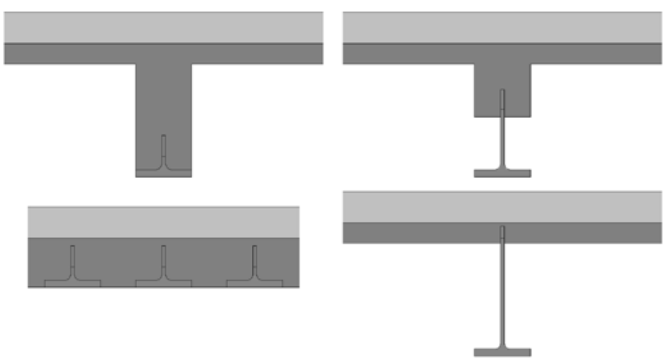

Fig. 6: Cross-sections of pcb-W girders

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. 7).

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].

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.

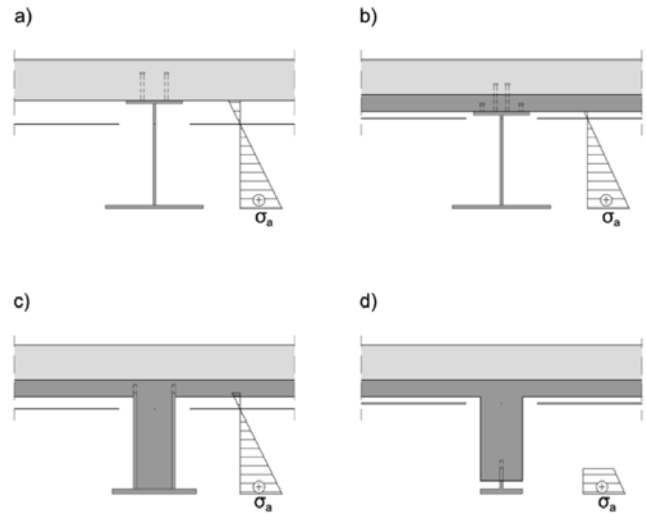


Fig. 7: Stress distribution on: a) common composite steel and concrete beam, b) pcb girder, c) + d) pcb-W girder [5]

## 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].

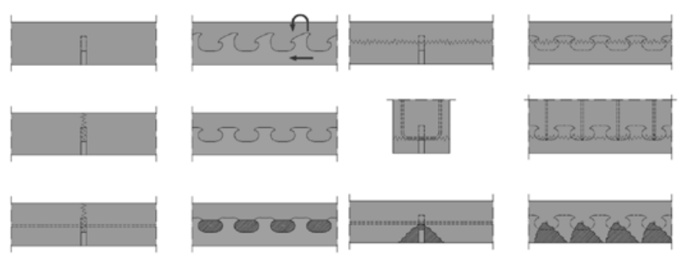

Fig. 8: Failure modes of composite dowels – yielding of steel dowel by bending and shearing, vertical crack in the non-reinforced concrete deck, shearing of concrete dowel, horizontal crack in concrete deck, spalling of concrete cover, pry-out cone in the concrete cover [7]

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.

## III. Verification of composite dowels´ behavior

The main aim of author´s 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. The amount of work is divided 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 is the standard push out test itself.

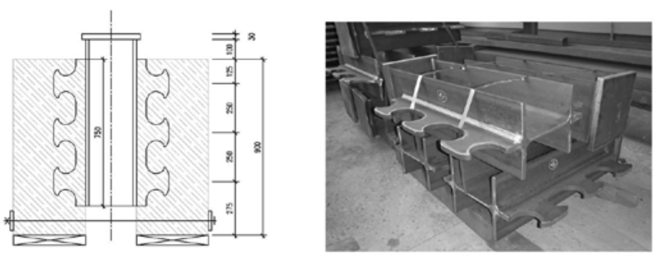

Fig. 9: The geometry of the numerical model meets the requirements of standard push out test

## 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

| **Strength grade of steel** | **Yield strength** | **Ultimate strength** | **Axial distance between dowels** | **Thickness of the steel plate** |
|---|---|---|---|---|
| - | $f_y$ [MPa] | $f_u$ [MPa] | a [mm] | t [mm] |
| S 355 | 355 | 490 | 250 | 20 |

Table 2: The properties of concrete deck

| **Strength grade of concrete** | **Char. comp. strength** | **Reinforcement of concrete dowel** | **Reinforcement above concrete dowel** | **Thickness of concrete deck** |
|---|---|---|---|---|
| - | [MPa] | $A_b$ | $A_t$ | $h_c$ [mm] |
| C 30/37 | 30 | 2$\phi$12 | 2$\phi$12 | 230 |

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

| **Design of steel dowel** | **Shearing of concrete dowel** | **Pry-out cone in the concrete cover** | **Spalling of the concrete cover** |
|---|---|---|---|
| $P_{pl,k}$ | $P_{sh,k}$ | $P_{po,k}$ | $P_{cov,k}$ |
| $\mathbf{P_{pl,k}}$ | **1,65·$P_{pl,k}$** | **0,63·$P_{pl,k}$** | **0,38·$P_{pl,k}$** |

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. 10.

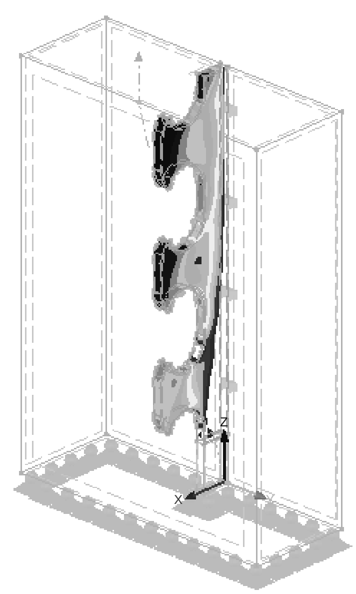


Fig. 10: The numerical model

The model was exposed to different load conditions, which correspond to the values of bearing capacity of composite dowels for all the failure modes, Fig. 11. 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.

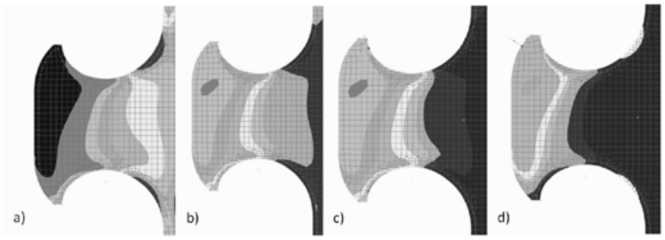


Fig. 11: FEM model, stress distribution in steel dowel under different load condition

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 the third step for comparing the results of the numerical model and an experiment, see Fig. 12.

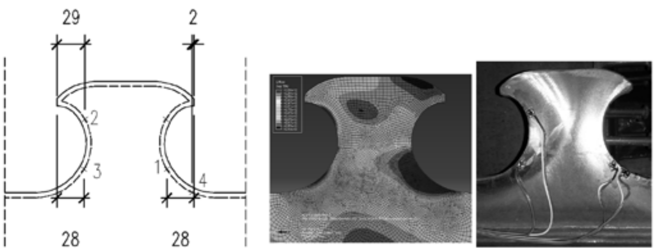


Fig. 12: Location of HOT SPOT

## IV. THE STANDARD PUSH OUT TEST

Within the framework of the mentioned research the standard push out test has been carried out at the Institute of Metal and Timber structures according to [1]. The experiment should verify the correctness and justification of the theoretical calculation.

For the easier comparison of the test results, the specimens were arranged according to [7]. It means that the reinforcement area of the concrete dowels was designed as recommended, see Fig. 13.

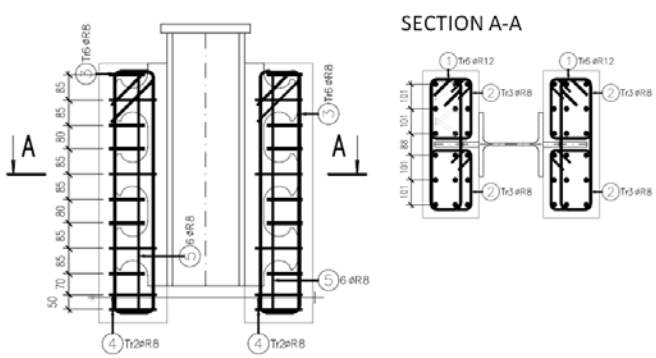


Fig. 13: The recommended reinforcement of concrete dowels

The test specimens consist of two steel flanges welded on steel column HEB 260. This steel flanges, cut with the specific, unique cut are embedded into concrete flanges which simulate concrete slab of a composite steel and concrete beam. After realization of the loading force on the steel column, the composite dowels begin to transfer the shear forces.

So far, the results bring very promising outcomes. The behavior of the composite dowels corresponds to the expectations and to the results of experiments carried out in Germany. The result of this basic experiment will be used for comparing with further forthcoming experiments and further development of pcb-W technology.

## V. CONCLUSION

The paper presents several important outcomes of author´s 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. So far, the results show 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. 14.

Fig. 14: Examples of reinforcement of composite dowels

For this reason, other specimens are prepared for the standard push-out test, some with fiber reinforced concrete and lower degree of reinforcement and some with fiber-reinforced concrete and no reinforcement bars. The results of this upcoming experiment may be useful for further development of pcb-W technology since they may allow using 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 tests 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.

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