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The evolution of the shape of composite dowels

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Abstract: Composite dowels have opened new possibilities for engineers designing composite structures. The fundamental and most important characteristic of composite dowels is the shape of the cutting line. It is important to understand why only one particular shape of the cutting line is used in bridge engineering, while so many different shapes have been investigated by many researchers. The essential part of the process of developing composite dowels – the development of the shape of the cutting line – is presented in this paper. The influence of the steel web thickness is presented, and technological problems of steel fabrication are highlighted. The role of empirical experience from the first bridges, push-out tests, and finite element simulations is presented. Assumptions for numerical procedures are given. The distinction between the steel failure and concrete failure modes is introduced for composite dowels. The paper presents how the concept of "shape" was divided into "shape," "ratio," and finally "size," and how, because of the fatigue problems in bridges, all the three factors have emerged to result in the form of shapes that can satisfy the requirements for bridges. Research leading to the invention of the first version of the clothoidal shape is presented.

Keywords: Composite dowels; shear connection; composite bridges; fatigue; FEM, hybrid beams.

1 Introduction

Composite dowels are a type of shear connector that have been recently used to build innovative composite structures across Europe [57]. Thanks to such connectors, composite beams can be effectively and economically constructed without using the top steel flange, that is, by directly connecting the steel beam web and the concrete slab. Bridge in Elbląg (Poland) [41], which is presented in Fig. 1, is an example of application of composite dowels.

This shear connection is currently being proceeded to obtain European Technical Specification (consistent with rules of Eurocode 4), and appropriate rules have been proposed by the project team SC4.T1 [52], and for purposes of this work, a list of papers considered as "background documents" for the design procedure of composite dowels are investigated and referenced. The list contains publications that include design guides [8,16,23], practical applications (bridges) [2,18,36-42], and research [5,6,7,9,13,14,17,20,21,22,24-35]. One can compare this list, which was compiled from the point of view of the author from Poland, with the papers being referenced in German publications [3] to obtain a wide and objective point of view (the first bridges were designed in these two countries as a cooperation between the first two co-authors).

The aim of this paper is to show how the shape evolved to clothoidal form (CL shape) (which, after introducing modifications related to the cutting technology, made it possible to use the solution in bridges). The aim is to present the procedure of the shape development chronologically. This was a complicated chain of innovations, tests, bridge designs [55], and analytical works supplemented with many ideas, and this is unknown to most researchers, excluding a small group of people involved in the project [7]. Understanding this is needed to comprehend why the modified version of clothoidal form is the "final one" and why so many shapes (some examples are presented in Fig. 2) studied in the past have been finally rejected in bridge engineering (there is agreement among people designing bridges with composite dowels that the current form does need improvement and such work is not currently being conducted). Fig. 2 shows the different forms that have been considered by different researchers while showing the evolution from PBL (Perfobond strip) to composite dowels.

The dowels currently in use have been derived from the Perfobond strip developed in the 1980s by Leonhardt and Andrä [53]. The assembly of the reinforcement through insertion into holes proved troublesome, and in the 1990s, Wurzer [54] and Zapfe [11] conducted some research and

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Figure 1: Steel–concrete hybrid beams of innovative composite bridge constructed using composite dowels in Poland, 2016.

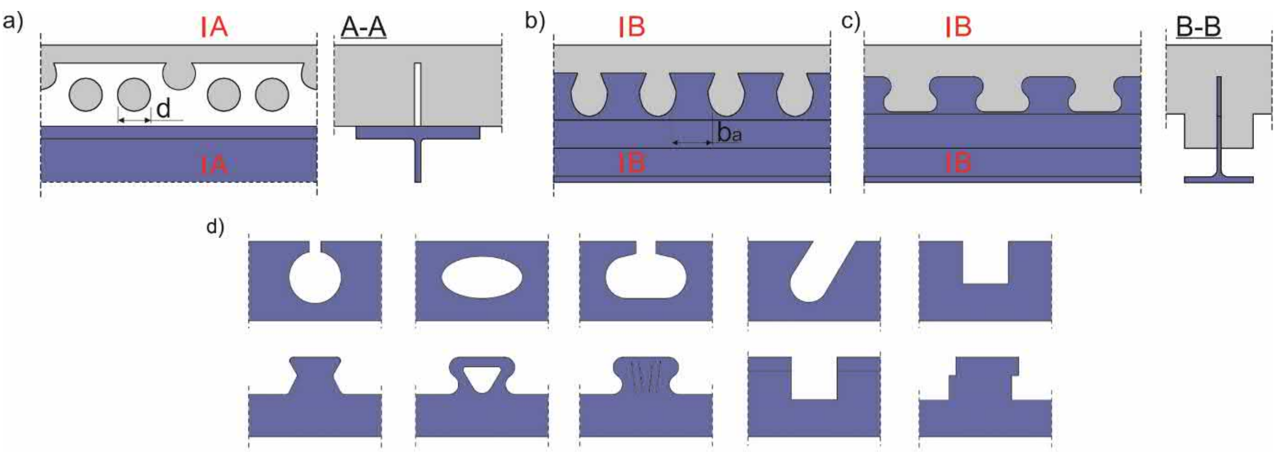

Figure 2: Continuous shear connectors [13]: a) Perfobond, b) kombi, and c) composite dowels using puzzle shapes that have been tested in the context of [7] project and d) additional shapes of shear connectors studied by different researchers [44].

Figure 3: Model of the "PreCo-Beam" girder (picture and model by SSF).

formulated principles for calculating strips with open cut-outs (Fig. 1). Characteristics of composite dowels at the background of the other shear connectors are presented in [13]; there were many forms of concrete dowels (and finally composite dowels – the nomenclature "composite dowels" was introduced in the context of the PreCo-Beam project [7]) studied by different researchers (Fig. 3).

The problem of optimizing the shape of composite dowels had begun to be studied seriously in detail in the context of an international project [7]. The purpose of the project [7] was to develop a new type of shear connection and girders using this type of shear connection proposed by the German company SSF (Fig. 3).

The first bridges using composite dowels used different shapes of steel dowels compared to those on current structures (due to later international cooperation [7], the final shape of composite dowels was established and designs have been developed; this is briefly presented in [57]). The composite dowels were designed using the results of static and cyclic push-out tests and the first design formulas for concrete dowels [8,9]. These pioneer road and pedestrian bridges were built in Germany, Poland, and Austria, and the shapes of the dowels applied

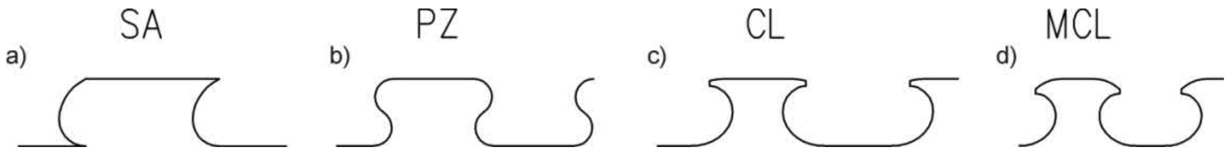

Figure 4: Shapes of composite dowels a) fin SA, b) puzzle PZ, c) clothoidal CL, and d) modified clothoidal MCL.

in their girders are not currently used. The three shapes experimentally studied in the context of the PreCo-Beam project [7] are presented in Fig. 4a–c, and the shape finally used in bridges is presented in Fig. 4d, together with appropriate naming according to [7]. The first CL shape (Fig. 4c) was designed for fatigue by SETRA in France to introduce the clothoidal shape in order to multiply by a factor of 3 the radius of the cutting line at the bottom, where a notch can be harmful. At the beginning of this program, the total height was limited to 90 mm for the first tests. This was an embarrassing limitation due to the height of the already delivered steel profiles. The consequence was a not very strong design in order to resist also, for instance, a lifting force. Wrocław University of Technology in Poland insisted to increase the height and for purposes of construction of Wierna Rzeka bridge, the MCL (Modified Clothoidal Shape) shape with a total height of 115 mm has been finally designed in Poland (Fig. 4d). The new chapter in the development of composite dowels and use on bridges started with the construction of the first railway bridge using composite dowels [12], where the clothoidal shape of the dowel was applied for the first time. The distinction between the CL and MCL [58] dowels resulted from optimization of the shape and cutting technology [57]. The CL shape was studied only in tests [7], the SA (Shape "A": the first being considered in [7]) and PZ (Puzzle Shape) shapes were used first in road bridges, and finally, the MCL shape is currently used in bridges and is called the clothoidal shape (shape MCL 115/250 was finally substituted by MCL100/250 just to round off dimensions, but somewhat to the detriment of fatigue strength).

2 First bridges and push-out tests

The serious investigations regarding shape optimization started after construction of a bridge in Pöcking (Germany) [50]. The first bridges using composite dowels were designed and constructed by the SSF company and, in parallel, the problem of resistance of the shear connection was studied in [30]. The cross section of the Pöcking Bridge (Figs 5 and 6) consists of three vft-wib girders with a width of the concrete flange of 3.20 m. The girders span over 33.20 m, integrating two bays [30]. The two halved and rolled girders of the series HEM1000 are located flange by flange in the cross section and are connected to the concrete flange using a "puzzle" line cut (Fig. 5), which was developed for this application to avoid the loss of web material and steel web height of the rolled section [30]. The existing analytical models for concrete dowels were not applicable to the geometry of the new shear connection, and the construction elements were tested in advance [30]. The form of the shape that was used in the Pöcking Bridge was later called (for purposes of the PreCo-Beam project [7]) the PZ shape (Fig. 1). This particular form of the PZ shape used for the Pöcking Bridge used the following parameters: 80 mm height, 2 × 210 mm spacing of steel teeth, and 22 mm radius in the curved region (later, different geometries were tested in the context of [7]; this is reported in [13,14]). The first projects using a new cross section with a single steel T-shape (Fig. 3) embedded in a concrete web (so-called external reinforcement) were carried out in Przemyśl, Poland, and Vigaun, Austria [30].

The shape of the steel dowels was also modified in these projects, and a new shape was designed by Marc Hever [30], the so-called "fin" shape, to achieve a higher shear force capacity. The form of the shape that was used in the first bridges using external reinforcement was later called (for purposes of the PreCo-Beam project [7]) the SA shape (Fig. 4a). Such a form was applied in the bridge in Przemyśl, Poland (Figs 7 and 8).

Both static and cyclic push-out tests were conducted on both puzzle shapes (Fig. 5), and the results are presented in [30]. At the request of Arcelor Long Commercial and SSF Ingenieure, static and cyclic tests were carried out with a new dowel shape – called the fin shape (Fig. 9) – and they are referenced in [30].

In addition to concrete failure, ductile deformation of the steel dowels was observed, indicating that the yielding limit of the structural steel had exceeded [30]. Such a behavior was characteristic for what was later called composite dowels (both concrete and steel failure). The form presented in Fig. 9 was not used in bridges, but provided much interesting information from a scientific point of view regarding the behavior of composite dowels. This is discussed in [30]. However, for

Figure 5: Shear connection for the viaduct in Pöcking [50] with puzzle-shaped dowels.

Figure 6: Composite girders of the viaduct in Pöcking [50] with puzzle-shaped dowels.

Figure 7: Steel part ("external reinforcement") of the girders for the pedestrian bridge in Przemyśl, Poland (picture from the proposal of the PreCo-Beam project [7]).

Figure 8: Steel dowels (SA shape according to [7]) used in the girders for the pedestrian bridge in Przemyśl, Poland (picture from the proposal of the PreCo-Beam project [7]).

Figure 9: Fin-shaped dowel [30].

the pedestrian bridge in Przemyśl (Poland), the shape presented in Fig. 4a was directly applied (Fig. 8). For the second application in the road bridge in Vigaun (Austria) [12], an important modification was implemented: part of the steel dowel was removed by additional cutting (Fig. 10) to ensure appropriate fatigue behavior and to remove a sharp notch that appeared in the first SA shape. This modified SA shape is shown in Fig. 11. This stage of the development of composite dowels (modification of the SA shape in regard to fatigue) is an important moment in the history of the development of composite dowels. The authors of [7] were aware that steel fatigue would be a fundamental issue in searching for the best shape, and finite element (FE) studies (including hotspots) were required for later investigations (in addition to push-out tests). Moreover, the technological problems of the steel fabrication (cutting) procedure appeared to be important because they could lead to overheating in hotspot regions. For the purposes of [7], the authors conducted extensive FE studies and they proposed models that enabled wide FE investigations of the composite dowels in linear and nonlinear ranges [1]. In addition to the ultimate resistance and failure mechanisms observed during the push-out tests, a detailed study of the stress state at the local level becomes possible [13,14].

Figure 10: Modification of the SA shape (elimination of sharp notch) [7].

3 FE investigations in study on the shape of composite dowels

At the beginning of [7], many extensive parametrical simulations were conducted to establish a reliable numerical model [1]. Push-out tests conducted for the Vigaun Bridge [51] were the basis for the initial FEM (Finite Element Method) study. Three fundamental concrete failure mechanisms and steel failure had to be considered. The proposed FE model, which was partly validated by experimental results, predicted this specific behavior of the structure. Abaqus software was used. For numerical simulation of the composite dowels, the complex geometry combined with many nonlinearities had to be taken into account. Establishing an elementary model was difficult, especially due to the concrete part, which is highly graded nonlinear over the entire load range. Therefore, the following aspects were focused: material nonlinearities, contact interactions, and complex geometry.

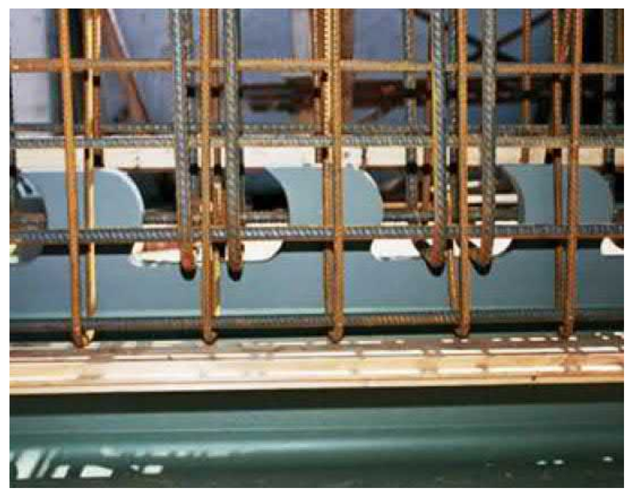

Figure 11: Modified SA shape (without the sharp notch) used in the Vigaun Bridge [7].

All of these aspects were handled [1,7]. A stable model of the push-out test was defined; some general statements needed to be made, and different structural elements needed to be analyzed. It was obvious that many parameters can influence the behavior of the model, and their influence is discussed in [1]. A simplified model was necessary to derive the parameters that influence the structural behavior. Therefore, different material laws were combined, and the failure mechanisms due to the influence of the parameters were evaluated. The following combinations were investigated: nonlinear steel/nonlinear concrete (NLsNLc), nonlinear steel/linear concrete (NLsLc), linear steel/nonlinear concrete (LsNLc), and linear steel/linear concrete (LsLc) [7]. The push-out test is a good tool for the experimental study of ultimate resistance, but there are no well-defined forces acting on particular shear connectors because the connectors are not forced equally (Fig. 12). Hence, it was necessary to calibrate the FE models with push-out tests and to develop virtual models (simpler) for numerical simulations only in the next stage. The general approach to calculate the shear transmission of composite dowels (at the early stages of shape optimization) was the “one-steel-tooth-model” embedded in reinforced concrete, which was called the 1D1 model [1] (Fig. 13). Appropriate boundary conditions and interactions were necessary to represent the behavior of the structure. The geometry and boundary conditions and interactions are shown in Fig. 13. The 1D1 model was a basic tool for the initial study of the concrete behavior and extensive parametric study of the steel shape in the context of [7].

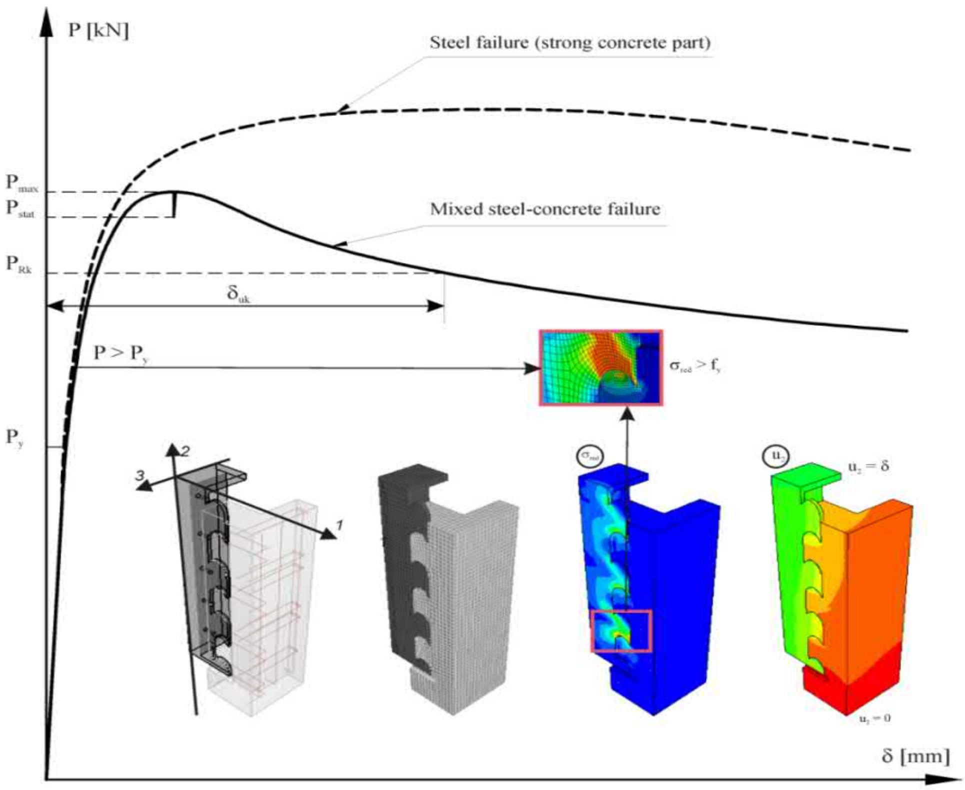

Figure 12: Illustration of the FE study of the push-out test [13].

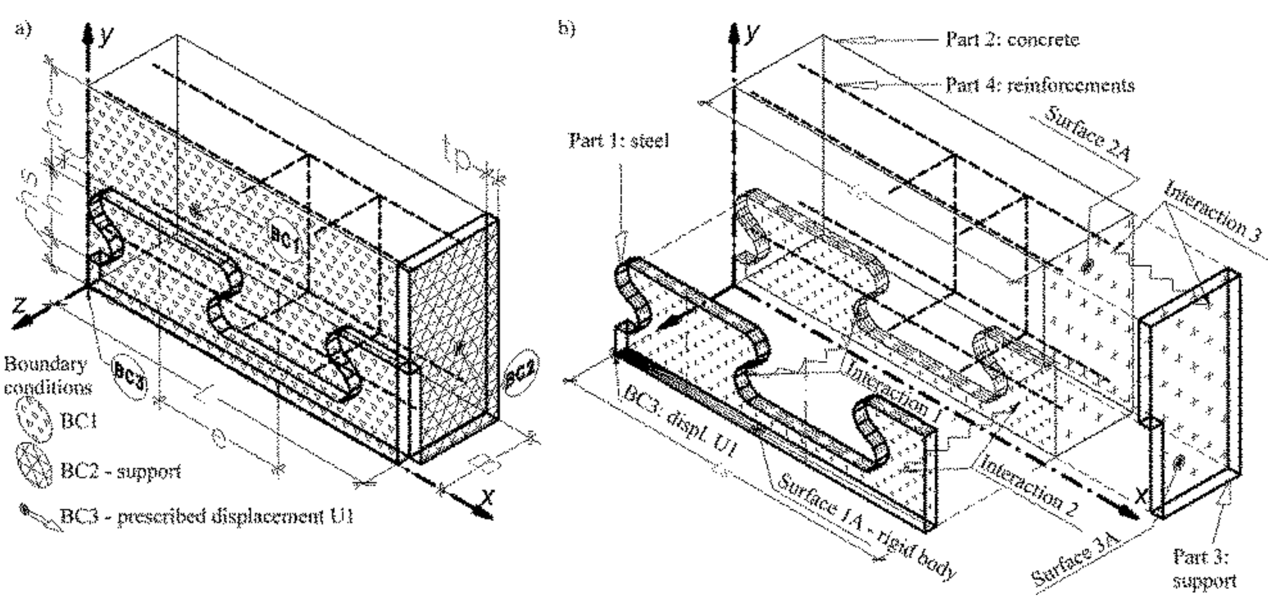

Figure 13: Assumptions for the 1D1 model used for the purposes of [7].

The concrete failure was extensively studied in [30]. There are basically two types of concrete failure: pry-out cone in the case of small concrete coverage and shear failure in the case of steel dowels being deeply embedded in the concrete body. Such concrete modes are convergent with what was experienced for concrete dowels [11,54]. At the early stage of [7], the researchers focused on the appropriate handling of the shear mode with numerical simulations using FE, and in this way, they had two possible failure modes: steel failure and concrete failure

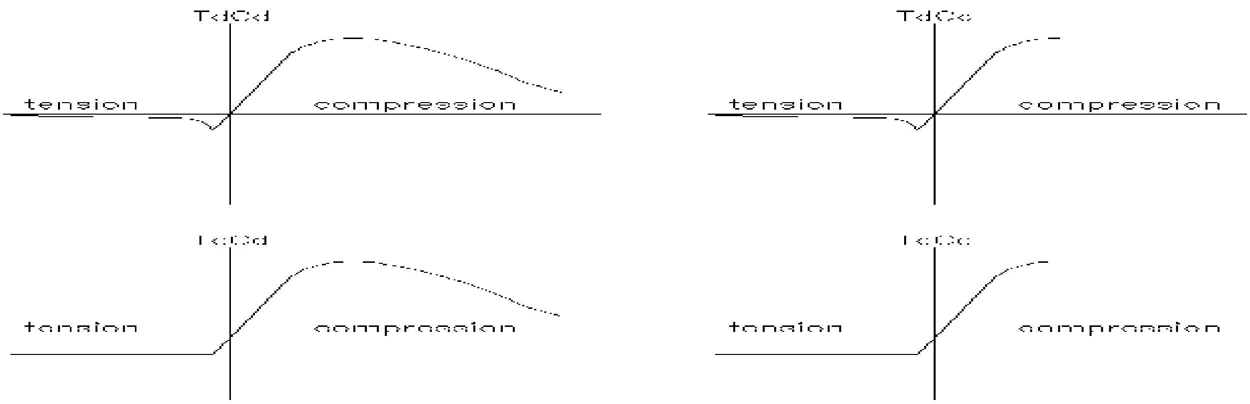

Figure 14: Modifications of the concrete material law (uniaxial strain–stress curves, concrete-damaged plasticity model) for purposes of different numerical simulations.

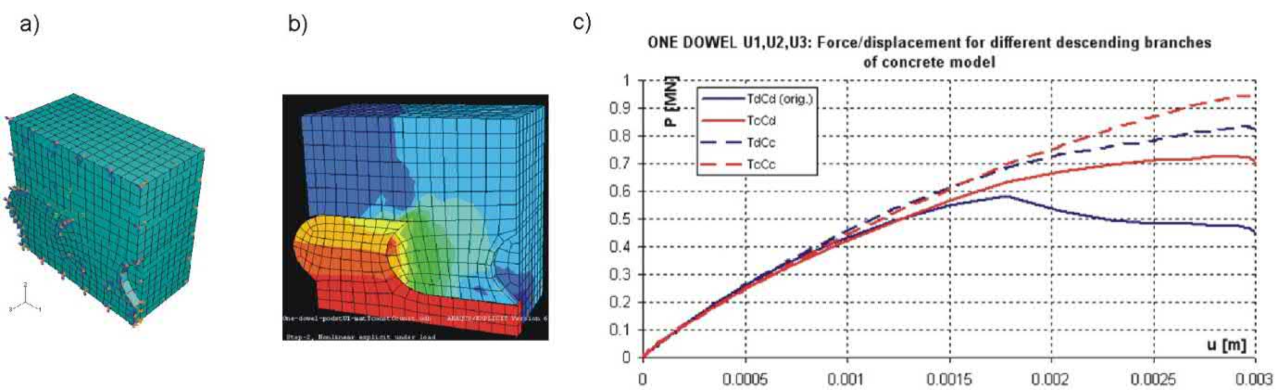

Figure 15: The 1D1 model is one of the first models prepared for the purposes of the PreCo-Beam project [7]. The displacement layout of the model with a maximum value (red) of 3 mm results in force displacement for particular material curves according to Fig. 14.

by shear. This procedure was implemented in the 1D1 models [1]. For the purposes of the concrete failure study, specific modifications of the stress–strain material curve for concrete were investigated, as described in [7] and in [1]. The modification of the material law (Fig. 14), especially tension-constant/compression-decreased (TcDc) type, enabled the first studies of concrete shear failure, excluding the pry-out cone problem (Fig. 15). A detailed description of this problem and conclusions are presented in [7] and [1]. In Fig. 14, "T" stands for tension, "C" stands for compression, "d" stands for decreasing part of material law, and "c" stands for constant part of material law. More information regarding the problem that is presented in Figs 14 and 15 can be found in [1].

Numerical simulations were extremely complicated and time-consuming tasks during the PreCo-Beam project [7]. The results of the push-out tests for the purposes of the Vigaun Bridge according to [51] were used for calibration of the FE models at the beginning, and the SA shape was used at this stage (Figs 15 and 17). Once the authors obtained a stable numerical model and the results agreed (Fig. 17) with the shear failure mechanism provided analytically in [30] (on the basis of mechanics and experimental results) (Fig. 16), they started simulations using different configurations of the 1D1 models (different shapes and steel tooth thickness).

The pry-out concrete failure mechanism, which is not basically dependent on the shape of the dowel, was studied extensively [30] during [7], and further complicated numerical simulations of the concrete behavior were performed by other partners of the PreCo-Beam project in Germany (University of Federal Armed Forces, Munich). The point was that 1) the shear failure of the concrete and 2) the steel failure mechanism (isotropic hardening [1]) implemented in the FE procedure for the 1D1 models enabled the first comprehensive comparative study of the shape of dowels that led to important conclusions regarding the behavior of composite dowels and extended the knowledge from push-out tests. In addition to these studies performed in Poland, independent studies of steel

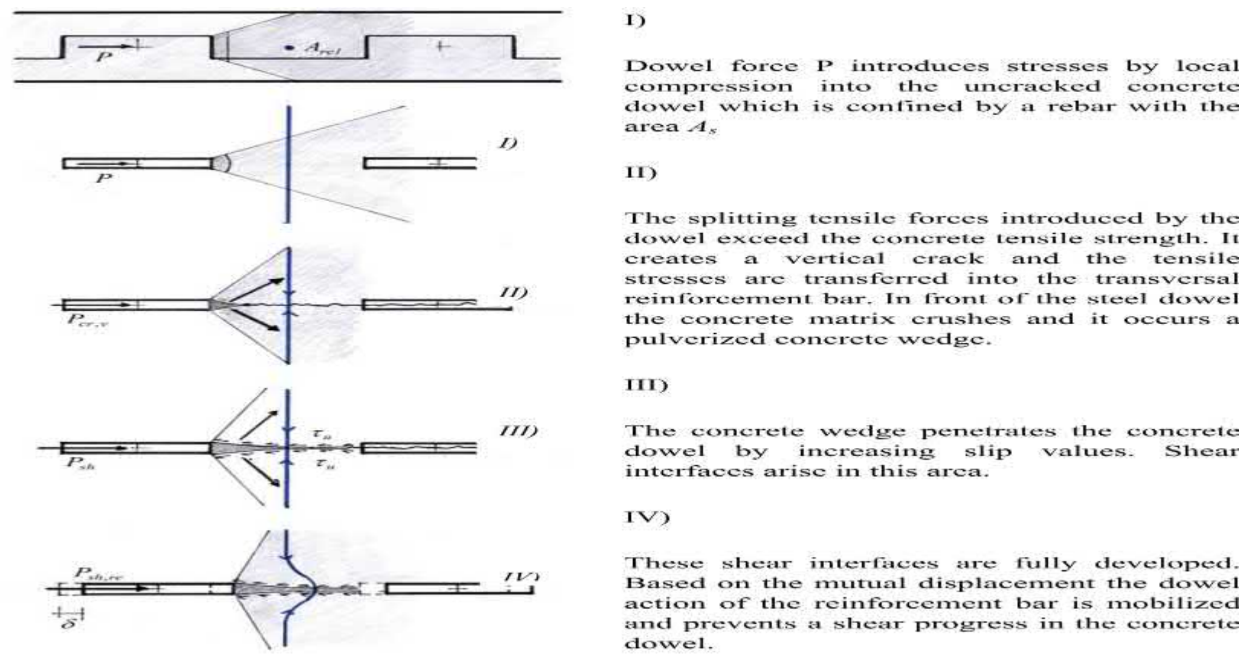

Figure 16: Shear failure mechanism of concrete dowel by Seidl [30] (last two stages of drawing from the final report [7]: III – the concrete wedge penetrates the concrete dowel and IV – the fully developed shear interfaces and mobilized the reinforcement bar).

plane models have been conducted in France (SETRA was a partner in the PreCo-Beam project [7]); SETRA studied both yielding (Fig. 18) and stress concentration problems for purposes of fatigue studies (details were later reported in [4]). Fig. 18 presents simple plane models of steel dowels calculated using Code_Aster software by SETRA, while complicated models of composite elements were calculated by Wrocław University od Technology using Abaqus software, and the results have been deeply discussed and exchanged. There was an important exchange of knowledge with L. Ondris from Vienna, who (independent research) studied the so-called crown-type connector [43] (Fig. 2: bottom-left connector), and using the Abaqus Explicit procedure, faced similar problems with the complicated behavior of the concrete in composite dowel simulations [1]. Hence, there was quite a large discussion and exchange of knowledge regarding the FE simulations. The work of SETRA (reported in [4] in detail) made the partners of the PreCo-BEAM project [7] aware that fatigue is a fundamental issue in the study of the shape of composite dowels and that sharp notches must definitively be avoided (Fig. 19) because they can lead to fatigue cracks. This was the reason why shapes such as the SA shape (Figs 4a and 19), the crone-type connector [43], other similar shapes proposed by other researchers, that is, the “crestbond” connector [10] that was described later in [10] but also studied by the authors for purposes of the [7] project (see Fig. 20), and even finally the PZ shape (Fig. 4b) had to be rejected from consideration for bridges. The crestbond connector [10] is considered by the authors as a kind of puzzle shape, but with straight lines between the curved parts at the front surface of the steel dowel (compare Fig. 1m vs. Fig. 1n of paper [10]), which results in a larger stress concentration factor (smaller radius) compared to that in the PZ shape. The crone connector [43] provides an even larger stress concentration factor [10]. Such shapes provide worse fatigue resistance compared to that of the PZ shape (Fig. 4b). The SA shape with an extremely sharp notch (Fig. 19) could result in even low cyclic fatigue, which is why this shape was modified with additional cutting for the purposes of the first road bridges (Figs 10 and 11).

Comparison of the PZ shapes in Figs 4b, 5, and 18b shows that they present different ratios (height to spacing of dowels) and different front surfaces. The question was posed: what PZ shape is the best one (not considering even other shapes, but only PZ)? It was easy to fluently transmit the PZ shape to other forms and finally to obtain any new form (Fig. 21). In this way, a so-called anvil shape or SN shape (Fig. 18c) and a so-called SV shape (Fig. 22c) were proposed in the context of [7] and studied with 1D1 models. Hence, a large number of FE calculations using different geometries have been conducted [7], and some chosen examples of the models are presented in Fig. 22. Different shapes resulted in different resistances, and the FE calculations enabled estimation of this effect.

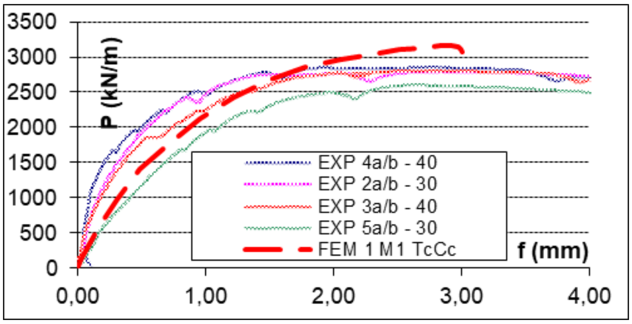

Figure 17: Comparison of the numerical results for the model according to Fig. 12 with the experimental results of the push-out tests according to [51,30].

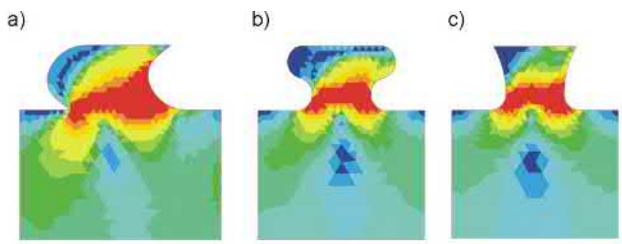

Figure 18: Steel shapes studied by SETRA at early stages of project [7] presenting yielding of plane models (reduced stress layouts): a) fin shape, b) early version of puzzle shape, c) one of the shapes that has been studied but was never used for testing.

Figure 19: Plastic deformations of steel dowels in the region of the sharp notch in the SA shape (push-out specimen [30]).

It was concluded that where the concrete dowel sizes were similar, for large web thicknesses (such as 30 mm), the concrete failure mode and resistance were similar and did not depend much on the shape (Fig. 23). Different material configurations, FE sizes, and calculation procedures have been considered [1], and only exemplary results are presented in Fig. 23. During the study of the 1D1 models, it was decided [5] to separate steel failure from concrete failure, and using a linear concrete body [14], just to focus on the problem of dowel shape regarding steel

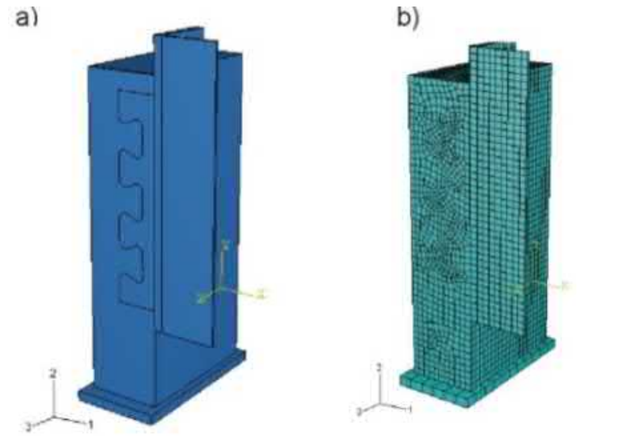

Figure 20: Numerical model of the so-called "crestbond" connector [10] studied for purposes of [7]: a) the geometry of solid model using ¼ symmetry, b) the net of finite elements used in the model for nonlinear analysis.

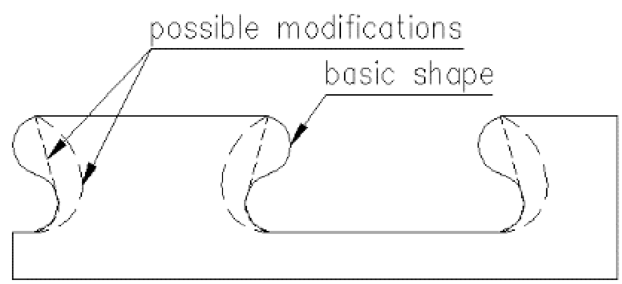

Figure 21: Topology of the shapes of steel dowels considered for the purposes of [7].

failure. This is described in detail in [6] and [31] for elastic design (fatigue) and nonlinear design (ultimate limit state), respectively. It became obvious for the partners of [7] that the problem of the shape of the steel dowels is the problem of steel resistance, and it was desired to separate somehow the "steel problems" from the "concrete problems." In the context of [7], the researchers from France and Poland focused on the fatigue problems of the steel dowels [4] and the author of [30] (from Germany) focused on concrete and he proposed models of concrete failure [30] (for purposes of design formulas for [16], the experience gained from [30] and [44] was combined). The authors were looking for an idea of how to optimize the steel shape and considering the SN shape (Fig. 24a: this shape was never tested experimentally, but its FE study led to many important conclusions). It was proposed in [5] to resolve the relative steel and concrete resistance (shearing) problem based on the area (side view) of the steel dowels compared to the area of the concrete dowels

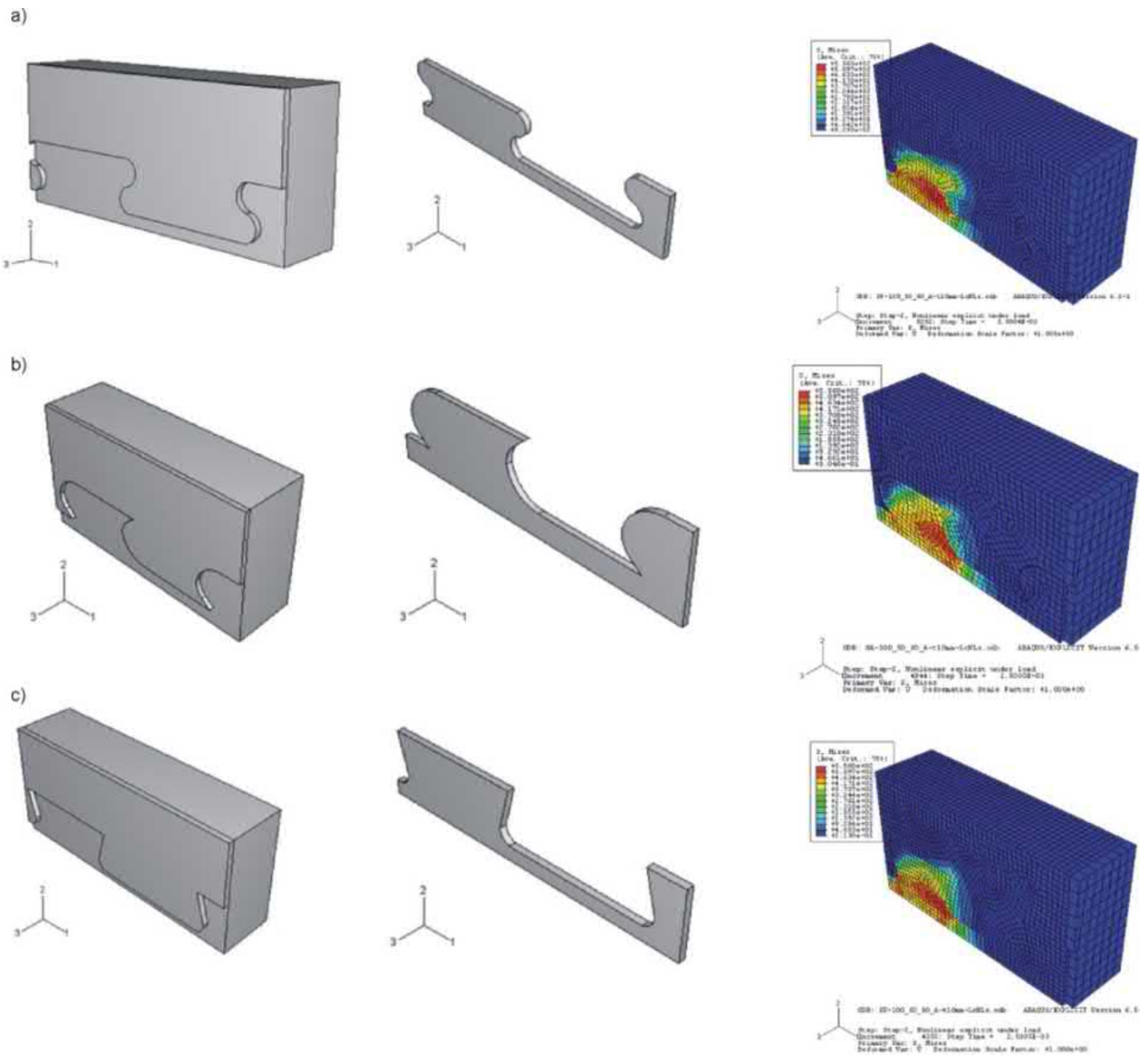

Figure 22: 1D1 models (geometry of the concrete part, steel part, and reduced stress layout, providing a general view of the yielded steel part) studied for the purposes of [7]: a) PZ shape (also called SP), b) SA shape, and c) SV shape.

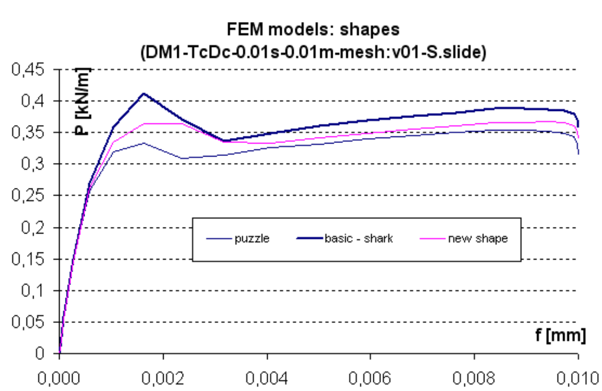

Figure 23: Results of 1D1 models (PZ, SA, and SN shapes) for particular specifications of the FE model: force–displacement curve, material curve for concrete TcCd according to Fig. 14 and isotropic hardening for steel [1]; time of 1 s for the explicit procedure [1] and approximately 0.01 m size of the finite elements (solid elements, reduced integration) [1].

(Fig. 24a, b). It was considered how large the steel dowels can be compared to the concrete dowels, and this result was combined with the realistic technology of cutting. In particular, for a single cutting line (Fig. 24a), steel dowels will never be larger than concrete dowels.

At this stage, splitting of the general idea of "shape" into two aspects was proposed [5]: "shape" (the shape of the front surface of the steel dowel) and "ratio," which was defined as half of the spacing of the steel dowels to the height of the steel dowel. One could easily estimate the upper bound of resistance, independent of shape, as reported in [25]. Regarding the ultimate resistance of the steel dowel (yielding), it has become logical (for reasonable shapes being considered and material properties being assumed) that this resistance does not depend much on the shape of the dowel and that the relation between

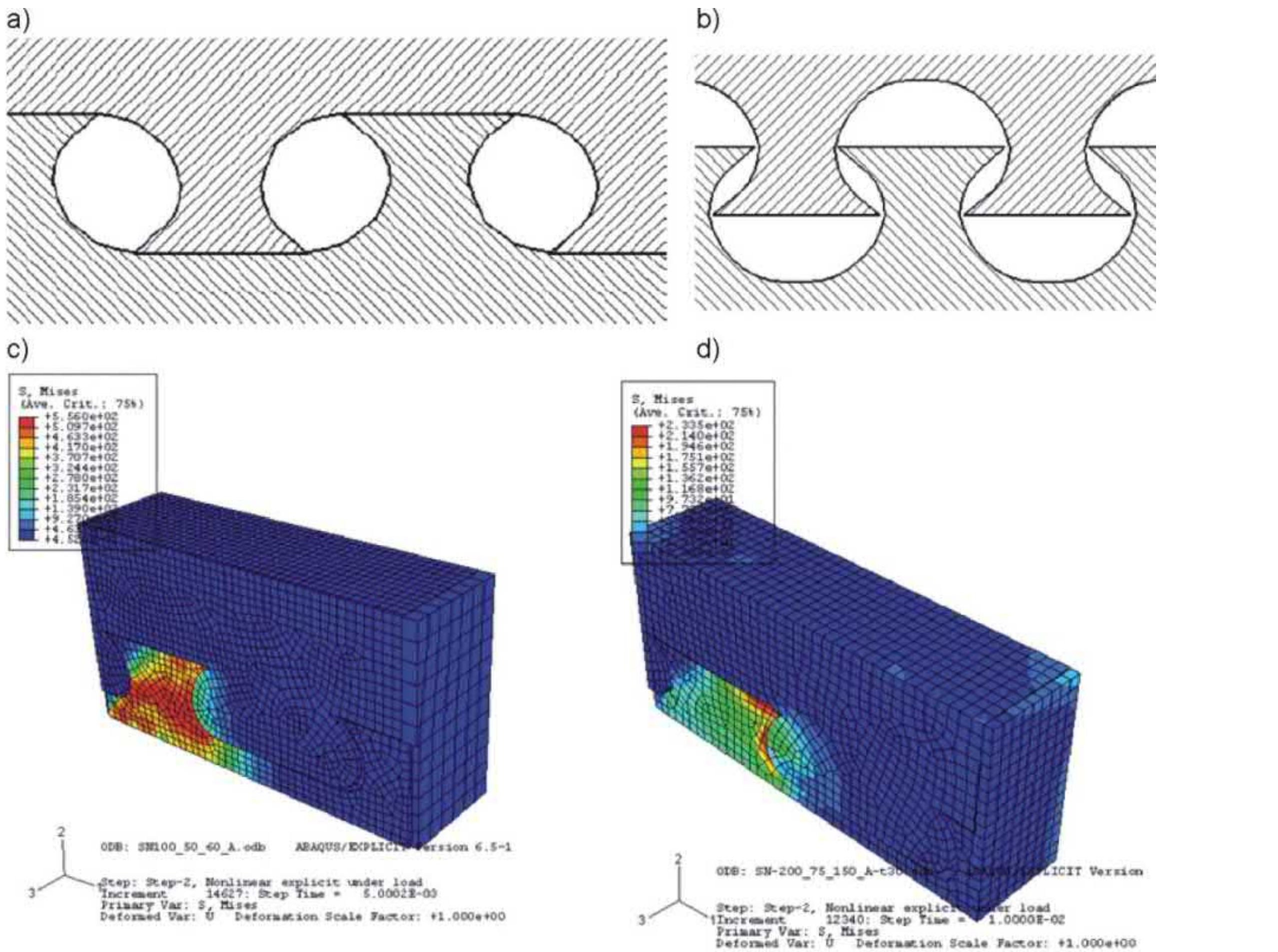

Figure 24: Study of the SN shape: a) the basic idea of cutting, b) modification of cutting to achieve a stronger steel part compared to the concrete part, c) reduced stress layout for the chosen geometry of the SN shape (short steel dowel) with steel web thickness equal to 10 mm (steel failure), and d) reduced stress layout for the chosen geometry of the SN shape (long steel dowel) with steel web thickness equal to 30 mm (concrete failure).

the concrete resistance and steel resistance depends on the ratio of the dowel and web thickness of the steel dowel (Fig. 24c, d). The 1D1 models enabled to handle the problem in a quantitative sense. Finally, the FE models with linear concrete law have become the basic (and fast) tool for calculations of steel failure (Fig. 25), and they are well established [14]. On comparing the experimental results from [13], Fig. 23 presents the characteristics of typical concrete failure and Fig. 25 presents the characteristics of typical steel failure (compare Fig. 12). By conducting a large number of studies (as presented in Fig. 24), it was possible to obtain conclusions regarding the influence of the shape, ratio, and rational thickness of the steel dowels. A large number of such studies using different material laws and combinations of geometries were done for the purposes of [7], and using FE, it was possible to estimate 1) the influence of the web thickness on the failure mechanism (e.g., for a particular shape: steel failure for a web thickness of 10 mm and concrete failure for a web thickness of 30 mm) (see Fig. 24c vs. Fig. 24d and Fig. 23 vs. Fig. 25) and 2) the best ratio of length to height regarding the resistance per unit length of shear connection (this issue is the basic of steel design concept presented in [6] and is discussed later). At that stage of the PreCo-Beam project [7], researchers involved in this project started using nomenclature of “composite dowels” instead of concrete dowels (studied by Zapfe [11] and others) to underline that, depending on geometry (and especially on web thickness), both steel failure and concrete failure mechanisms are possible.

However, the design concept presented in [6] was not known yet at that time, and there were many results available for many shapes, but no idea about the criteria for choosing the best shape. FE made it possible to evaluate the best ratio for a particular shape [6] regarding steel failure (Fig. 25). Moreover, considering the conclusions

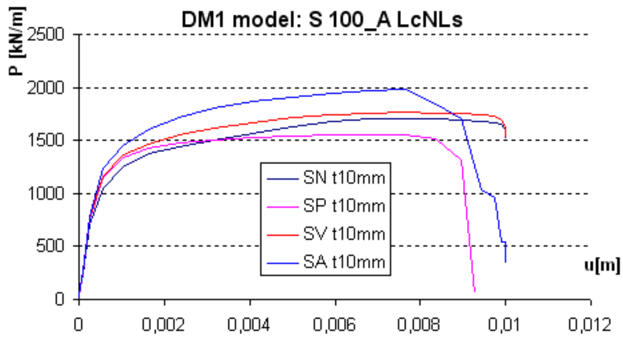

Figure 25: Comparative study of shapes for particular ratios (force–displacement curve, 1D1 model, linear concrete material and nonlinear steel material): typical curve presenting steel failure.

regarding fatigue [4], elastic calculations considering yielding as the first criterion for elastic design (for the purposes of fatigue calculations) have been undertaken. Turning to the elastic design concept for steel (finally presented in [5] and [6]) was a milestone in the process of shape optimization, but one can notice that it was efficient at that stage of project [7] only because of the background of knowledge already gained regarding ultimate resistance and failure modes (e.g., Fig. 12): knowing from experimental tests and 1D1 results that the rational steel web thickness would be between approximately 10 m and 30 mm, it was possible to estimate whether fatigue would be a problem; and it appeared it would, especially for railway bridges (but none was designed or built yet at that time). Some boundary conditions started to appear regarding the size of the dowels. Hence, looking for the best ratio for a particular shape was possible and it was found (Fig. 26). It was calculated for the SA shape and the SN shape at the beginning. The results are presented in Fig. 25, and one can notice that the SA shape results in larger resistance (which is logical), and that the best ratio is approximately 1 for both shapes. For both shapes, the criterion was reduced stress at the front of the steel dowel equal to the yield strength of steel. Having in mind that the ratio influences how many dowels can be placed per unit length of shear connection (1 m), the concept of resistance per unit length was introduced [5,6]. Hence, the shear force per unit length is presented in Fig. 26.

4 Searching for “the best” shape

Different shapes and dimensions were considered, and many numerical models in different configurations were analyzed. For ultimate resistance, a criterion for determining the shape and dimensions was proposed [5], in which the bearing capacity of a steel dowel is equal to the load-bearing capacity of the concrete filling, assuming its bearing capacity as concrete shearing resistance and treating the remaining criteria (the other failure modes such as pry-out-cone) as boundary conditions [5]. Of course, the stress values in a steel dowel depend on many factors adopted in the numerical model, but one can initially determine the required thickness of steel dowels of various shapes and sizes, assuming the load-bearing capacity of the filling concrete does not depend on the shape of the cut-out and depends only on the surface subjected to shear, which is initially a good approximation. Alternatively, the bearing capacity of the filling concrete can be obtained directly from the numerical model. Abaqus [1] program and the CDP (Concrete Damaged Plasticity) model have been used and this is described in detail in [1]. By doing so, one can analyze both the elastic bearing capacity (this has sense in relation to the steel dowel only) and the limit load (both in relation to the filling concrete and the steel dowels). It is obvious that (in side view) the increase in the field of the steel dowel in relation to the concrete field leads to a situation in which concrete failure (shearing) is a decisive criterion, not steel, and vice versa. Concrete failure models are studied in detail in [30]. Therefore, a criterion relating to technology has been introduced: steel dowels are to be made with one continuous cut, that is, before separation, the steel dowels are in the place of the holes of the second element resulting from the cut and vice versa. In this way, the upper limitation of the steel load capacity arises; the field of the steel dowel can never be larger than the fill concrete field, but it can be smaller as shown, for example, in Fig. 24a. Analyzing various configurations of connectors, the following hypothesis was drawn: the elastic bearing capacity of the steel dowels per unit of length depends only on their shape and not on the size [6]. This theorem applies to realistic ranges of values based on the assumption of a flat state of stresses in the steel dowels and can be indicated numerically or using a simple beam model [31]. In particular, it applies to the proportions used in the concrete dowels because the thickness of the web is smaller here compared to the other dimensions, that is, the height and length of the steel dowel. This theorem (regarding the size factor) can also be used as an inelastic load, and it was confirmed by tests (Figs 27 and 28).

A consistent design concept for steel dowels has been finally proposed, which is published in [6] regarding elastic resistance and in [31] regarding ultimate loads. This claim has far-reaching consequences as the removal of the size element from the considerations and the analysis of the bearing capacity in relation to the length unit reduces

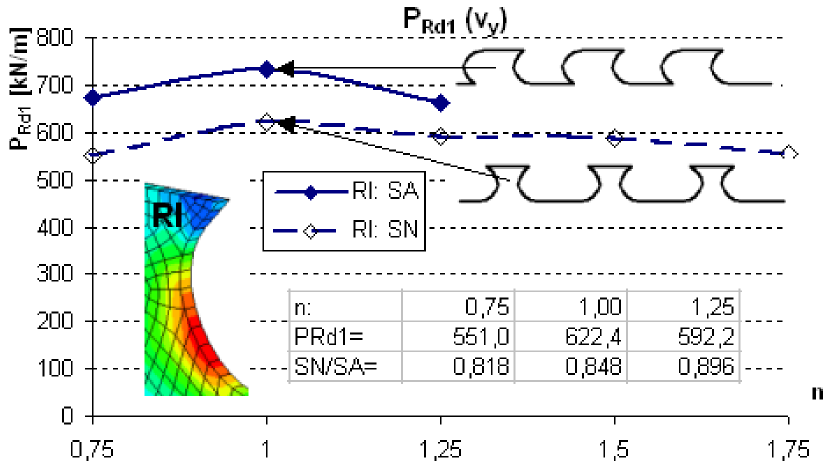

Figure 26: Results of shape optimization presenting the force per unit length versus shape ratio (1D1 model, linear concrete material and linear steel material; RI represents reduced integration in finite elements [1]).

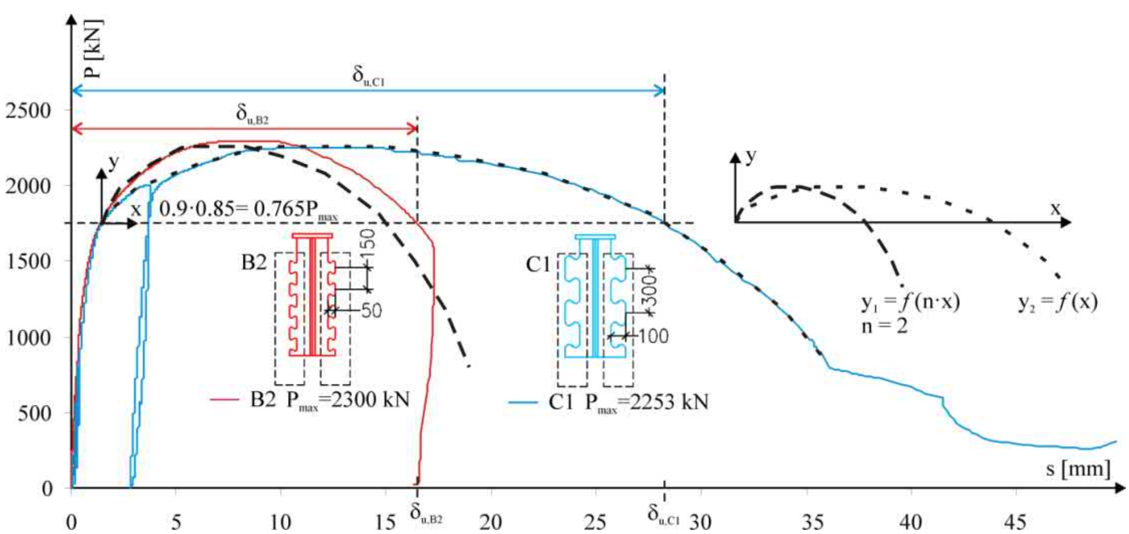

Figure 27: Results of tests for different sizes of dowel [5] (later [13,31]).

the complicated problem of many variables determining the geometry of the steel dowel to a single aspect ratio. This, in turn, combined with the assumption of a flat state of stress, reduces the entire problem to equation (1) [6, 7], which determines the elastic bearing capacity of the steel dowels in relation to the unit of length (longitudinal shear or force per unit of length) in the following form:

$$v_r = A_{el} \cdot t_w \cdot f_y \qquad (1)$$

where: A_{el} is the shape factor for local effects, t_w is the steel web thickness, and f_y is the steel yield strength.

The original notation from the early stages of the PreCo-Beam project is kept in equation (1). Next, it was proposed to introduce a parameter in the analysis of the ratio *a*/*h*, where *a* expresses the length of the steel dowel (half the spacing is assumed) and *h* is the height of the dowel. For all the analyzed shapes of steel dowels, the common feature is that they have two straight sections, the dowel base and the top of the dowel. The difference is in the case of the face shape. Therefore, the concept of shape was broken into a shape understood as the shape of the frontal surface and the proportions of the dowel were understood as the ratio *a*/*h*. Following this line of reasoning, it was stated that considering the bearing capacity per unit length of the shear connection, the optimal proportions can be determined for each dowel shape (in the case of long dowels in the load

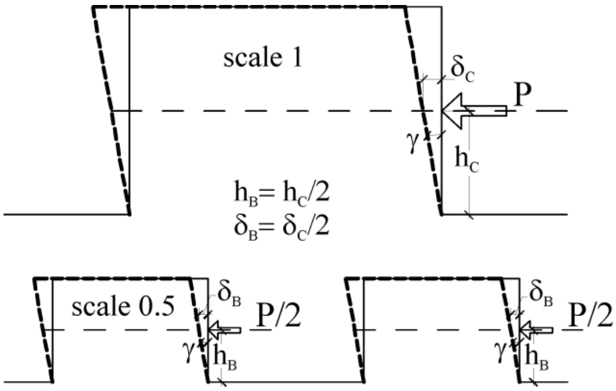

Figure 28: Effect of the size of steel dowels: illustration of ductility δ defined by the angle and height of the dowel [5] (later [13,31]).

transfer, only the front part of the dowel is involved). When performing calculations using the FE method, it is possible to iteratively determine the best proportions for a given shape, as mentioned previously (Fig. 26). Such a study was conducted and is reported in [7]. It was concluded that the optimal proportions, depending on the shape, were in the range of 1.25–1.5. Symmetrical and asymmetrical shapes were analyzed, but ultimately, it was decided to prefer symmetrical shapes [7]. In the case of unsymmetrical SA-like shapes (Fig. 4a), the small radius (notch) generates problems in the form of concentration of stresses from so-called global effects [6] (normal stress due to bending of the composite element) and, moreover, because longitudinal shear with different signs appears in bridge structures (from moving loads), unsymmetrical shapes have finally been eliminated. Knowing that there is the most appropriate ratio a/h and that only symmetrical shapes are considered, the determination of the shape of the frontal surface of the steel dowel becomes the final issue (and later, determination of the size of the dowel). It was desirable to obtain small dowels, so as not to unnecessarily lose the web material and to obtain the highest possible tee (finally, it was proved [5] that there is a lower limit of dowel size in regard to steel failure, and that this is connected to the criterion of ductility [31], and the second point is concrete shearing). The milestone in the shape development was reached when SETRA proposed a solution where the base of the steel dowel is a clothoid whose radius at the base of the tooth is 80 mm and decreases to approximately 30 mm at the top. This solution is justified by the good fatigue capacity of such a shape, based on existing structural solutions (i.e., the web of the crossbeams in the region of passage of longitudinal stringers in the orthotropic deck of a steel bridge). This shape was called a clothoidal shape or CL shape (Fig. 29). The existing structural solution for an orthotropic deck provided (next to the general concept of the shape) the basis for the dimensions (80 mm radius), and hence, a height of 100 mm for the steel dowels was assumed at this stage of the project [7]. Hence, both the shape and size have been predefined, and the basis for the solution could be found in existing bridge solutions.

This step is important because 1) it provides a well-established background (a shape already used in bridges) and clearly defines the front surface (which is actually very similar to – intuitively assumed – the SA shape form applied in bridges using this shape) and 2) it results in better fixation of the steel dowels in the concrete due to the stronger top part of the steel dowel (contrary to the SN shape that was considered only theoretically). In summary, the SN shape implements symmetry (contrary to the SA shape) and eliminates the notch, but the CL sets a well-defined basis of the shape plus it implements a good solution for the upper part of the dowel (fixing the steel dowel in the concrete). In the upper part, the tangent to the end of the clothoid is horizontal; then, there is a straight vertical section of up to 10 mm, which results in some kind of restraint, that is, longitudinal shear in addition to the front surface also results in pressure at the back surface of the dowel in the upper part of the curved surface. The CL shape has a higher load capacity compared to that of the SN shape (in contrast to the previously defined SN shape in which the same face shape was used as in SA shape, imposing symmetry) because insertion of the upper part of the rigid anchoring element affects the upper part of the dowel in the concrete, limiting the ability of the dowel to rotate under the influence of bending. The results of optimization of the ratio for the CL shape are presented in Fig. 30.

The coefficient A_{el} for the optimized geometry of the CL shape was calculated to be 0.14 (at this stage of the project [7] for the 1D1 model according to [1]). This method provided the simple equation (2) for the resistance of the optimized CL shape that was implemented in testing for the purposes of the [7] project (Fig. 31):

$$v_r = 0.14 \cdot t_w \cdot f_y \qquad (2)$$

The geometry of composite dowels using a clothoidal shape that has been used for the first time for the purposes of first push-out tests in the context of [7] is presented in Fig. 31. Further research and development of the first form of the clothoidal shape (Fig. 4c) to its final form introduced in bridge engineering (Fig. 4d) was connected to construction of "Wierna Rzeka" bridge in Poland [59,60].

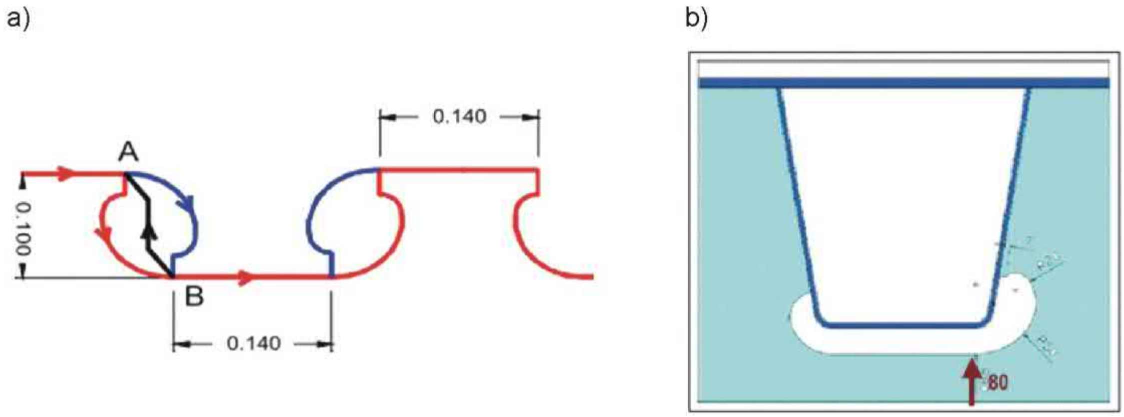

Figure 29: Clothoidal shape (CL) by Berthellemy: a) idea for geometry and cutting line, b) structural solution for an orthotropic deck as the basis for the geometry and dimensions.

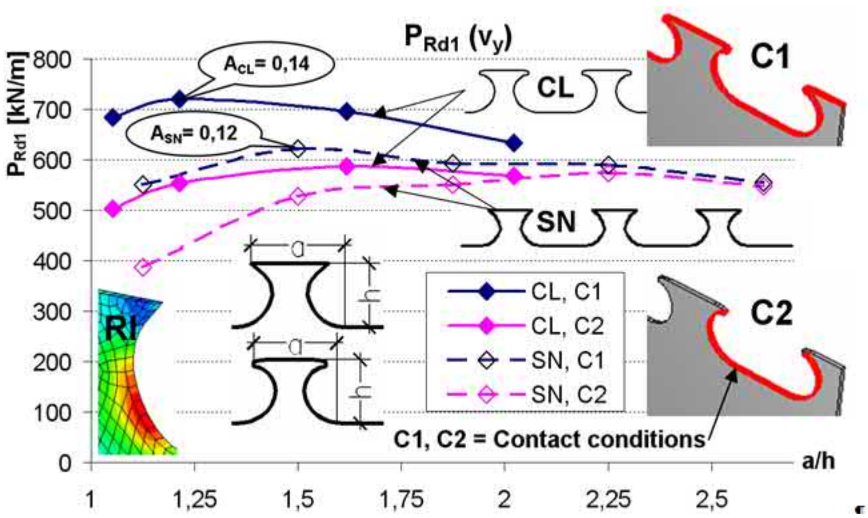

Figure 30: Results of the optimization of the CL shape versus the SN shape, presenting the force per unit length versus shape ratio (1D1 model, linear concrete material and linear steel material; RI represents reduced integration in finite elements [1] and C1 and C2 represent different contact interactions).

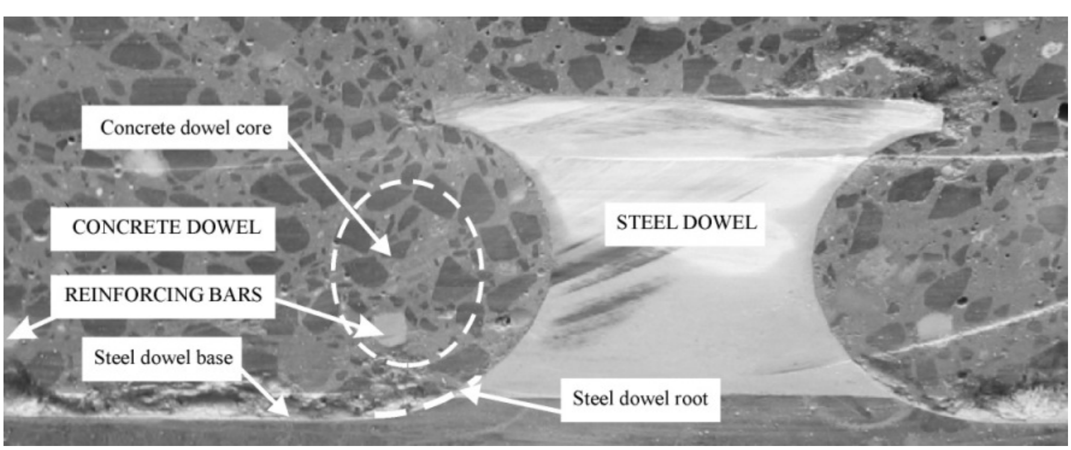

Figure 31: General view of the CL shape tested in the PreCo-Beam project [7] with a height of 100 mm and spacing between dowels equal to 300 mm (specific nomenclature used for composite dowels is given).

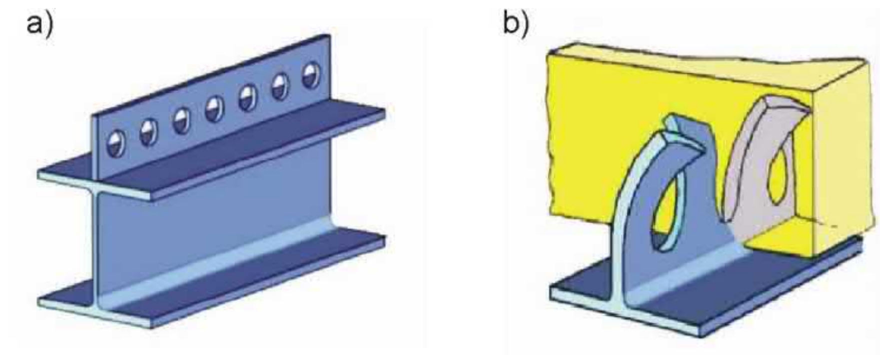

Figure 32: "Perfobond" by Fritz Leonhardt (a) and system by Pierre Trouillet (b).

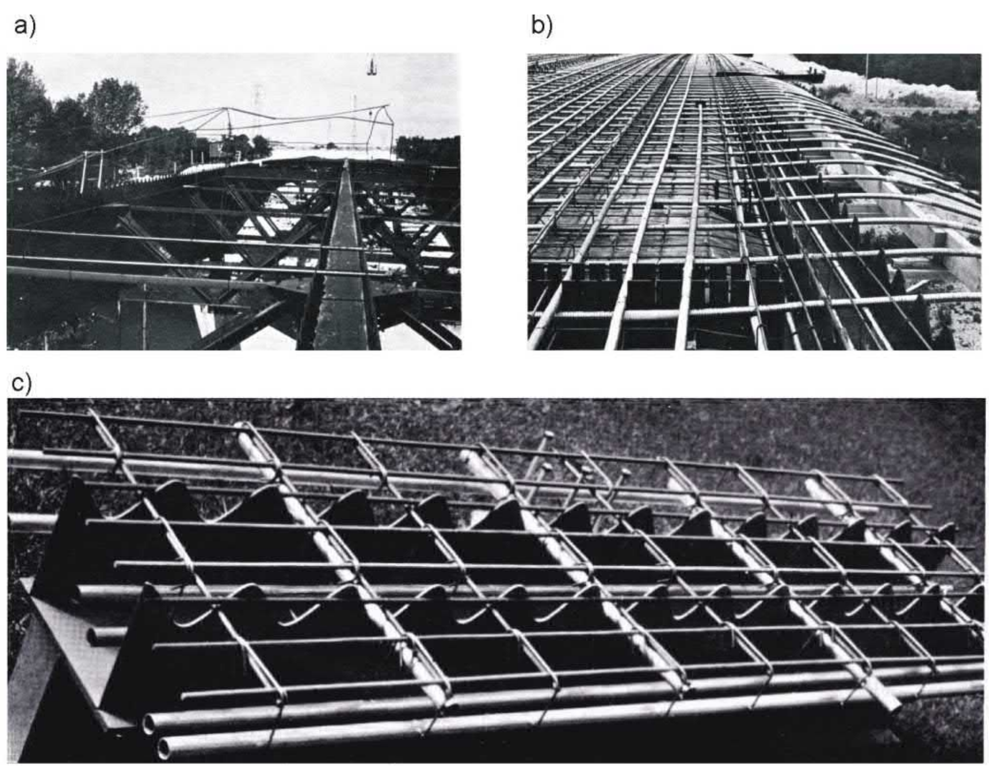

Figure 33: Girders of bridges with continuous shear connection based on friction: a) main girders with shear connection plates, b) transversal tendons, and c) beam specimen for tests (tests achieved in 1965).

5 Bridges built by the pioneers of the continuous connection

However, the first early dowel connection was designed by Fritz Leonhardt (Fig. 32a) with the Perfobond system and more recently, Pierre Trouillet (Fig. 32b) registered the patent of an opened connection dowel cut into a rolled beam (this patent was registered on behalf of the French road directorate and it was put in the public domain at the occasion of the PrEco-Beam [7] research program). A simple sinusoidal dowel associated with a transversal prestressing force (Fig. 33) was also used for several large motorway bridges during the 60s (Fig. 34), mobilizing friction as the principal favorable effect achieving a really continuous connection that avoids local transversal cracks. All the slabs of these French bridges carrying heavy motorway traffic are in very good condition today (Fig. 35).

Friction for bridges in former national codes was taken into account. Friction coefficients exist in the British standards and in the French code of 1966 for composite bridges. A coefficient of 0.40 was obtained by beam tests that were required by SETRA before construction of

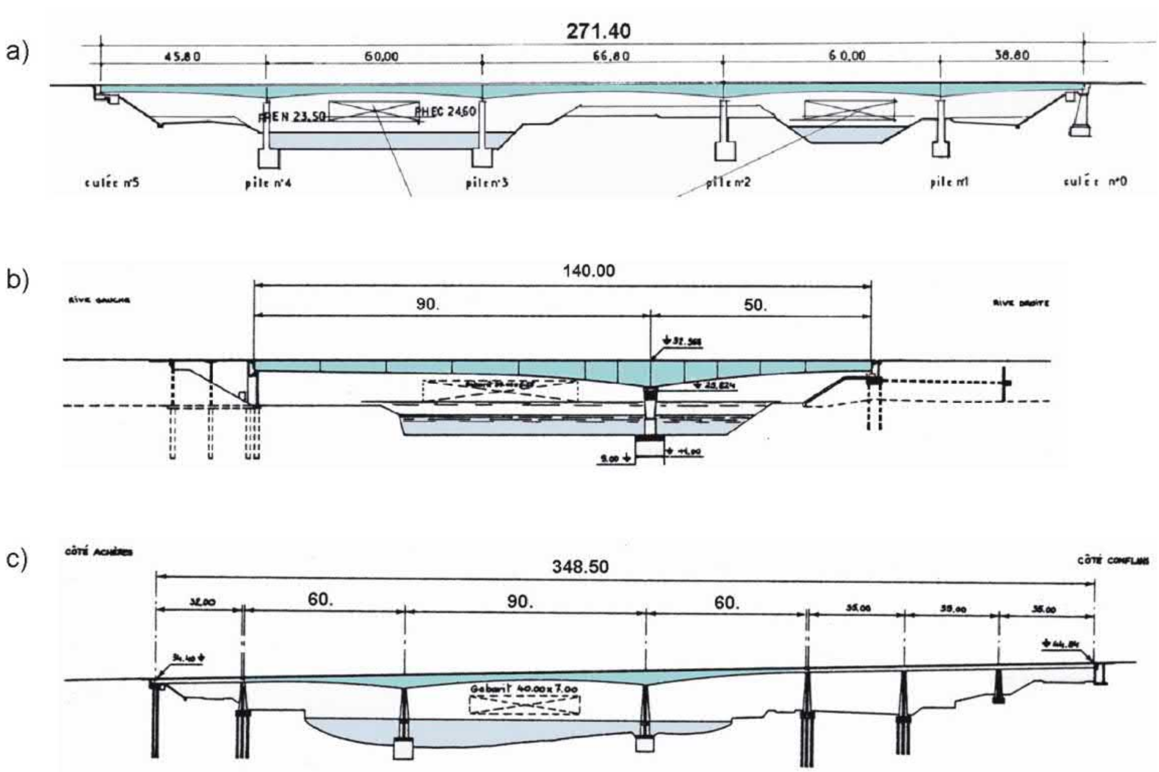

Figure 34: Bridges described in OTUA bulletin n°6 by Henri Grelu: a) l'Oise A15 (1966), b) Cergy l'Hautil RD203 (1969), and c) Conflans RN 184 (1973).

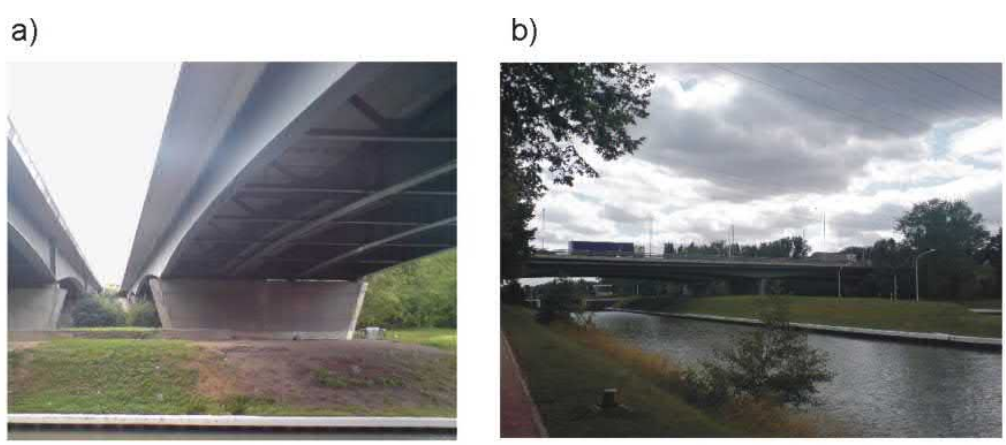

Figure 35: Pictures of the A15 motorway bridge over River Oise in 2008: good structural condition (slab condition of the second bridge on the left – built more recently without tendons – is not so good).

the first A15 motorway bridge over River Oise. A 6.3-m-long element (Fig. 33c) was tested with two megacycles reproducing the most severe cases of characteristic longitudinal shear force. This endurance test was then followed by a rupture test.

The bridges using continuous shear connection based on friction (Figs 33 and 34) are very important for future development of composite dowels: they prove that friction-based solution is possible and working well. The cutting line in Fig. 33 was one very simple sinusoidal cut because effects other than friction (contrary to composite dowels) were regarded as negligible at that time and were not allowed.

Even without transverse prestressing force, the CL connection has an excellent fatigue resistance when it is used over an upper flange. Its fatigue resistance was

Figure 36: Bottom view of “Wierna Rzeka” bridge.

estimated as well by theoretical consideration and by tests, while the studs fatigue resistance was estimated only by tests. When the web is cut by the CL shape to achieve a CL connection, the consequence of the crack is more important and it is recommended to use a more prudent safety factor.

6 Summary

Since approximately 2005, intensive research and development has started to establish the proper form of the new shear connection, named composite dowels, which enable direct connection of the steel beam web and the concrete slab. Composite dowels have opened new possibilities for engineers designing composite structures; they are the result of extensive international work. According to [55], *“German, French and Polish engineers and scientists worked together successfully across the whole chain of invention, innovation and dissemination*” [55, page 627]. A complicated process of evolution of the shape of the cutting line is presented. The paper presents an essential part of this process up to the development of the first version of the clothoidal shape (Fig. 4c) of a composite dowel (its final form introduced in bridge engineering is presented in Fig. 4d). Fatigue problems in bridges appeared to be decisive factors in determining the shape of composite dowels. The information and the process described in this paper are fundamental for a full understanding of the complicated behavior of composite dowels and why only the clothoidal shape of dowels is currently used in bridges, while so many researchers have been working on so many shapes (Figs 2, 4, 9, 18, and 20). The shape presented in Fig. 31 is the result of extensive work of people involved in [7], and it is based on experience gained during the execution of bridges using other shapes, the results of push-out tests, and a large number of numerical simulations using advanced nonlinear procedures. It is the result of international collaboration with many discussions, important insights, and the ideas that led to milestones in the process of the development of the shape. The paper presents how a concept such as “shape” was divided into “shape,” “ratio,” and finally “size” and how, because of fatigue problem in bridges, all three factors have emerged to result in the form of shape presented in Fig. 31 that could satisfy the requirements for bridges. The role of FE simulation (and appropriate models, procedures, and simplifications) is emphasized, but in combination with push-out tests and critical judgment.

The first version of the clothoidal shape could not be produced on a massive scale because of technological problems with cutting (the necessity of two independent cutting lines); hence, the shape was developed further in Poland [4,59]. In autumn 2008, the solution was provided, wherein the self-crossing cutting line (resulting in steel overheating) could be substituted with a line that was not self-crossing (Fig. 37b), and a new railway bridge in Poland was designed: the first railway bridge using composite dowels [59]. 17.12.2009 the spans under the first track have been completed [60]. At the same time, Wierna

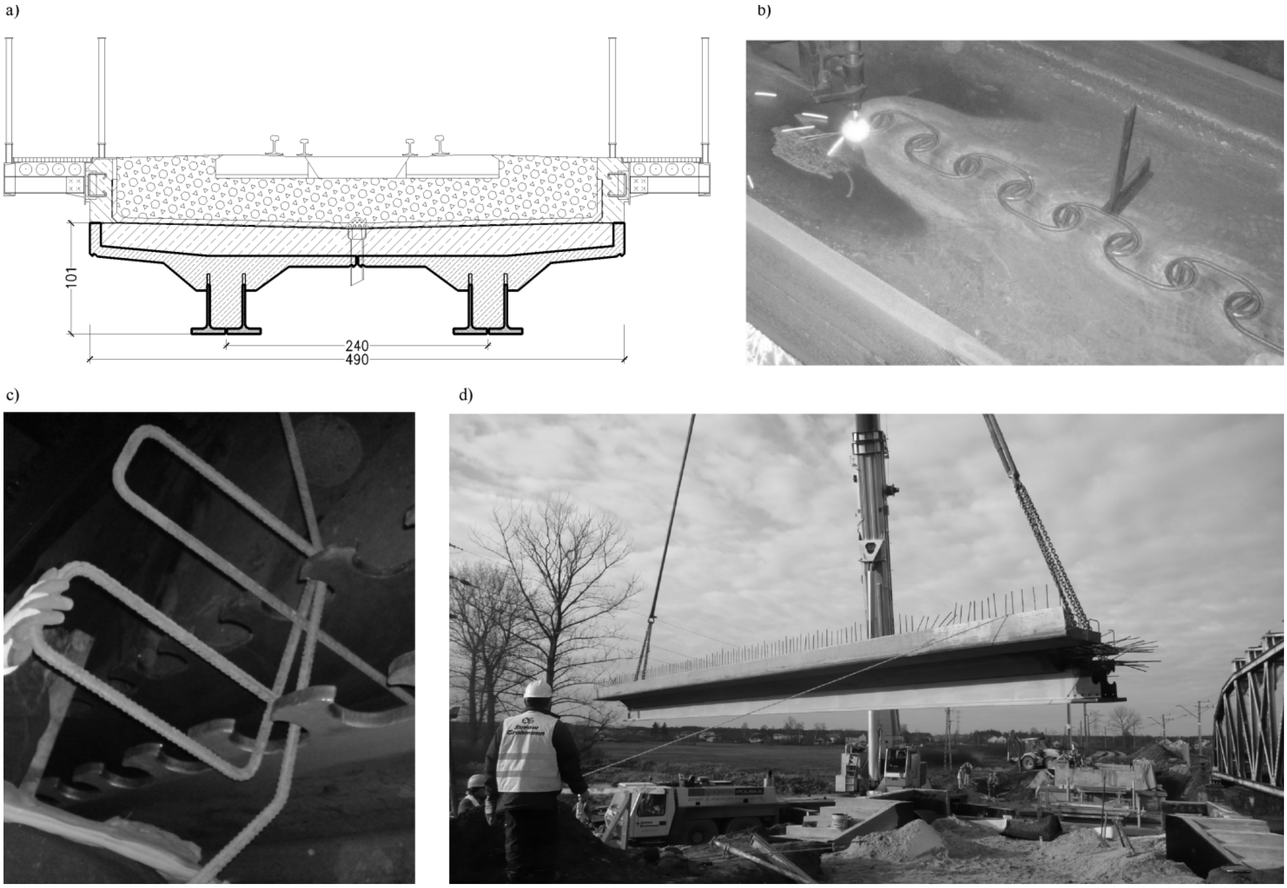

Figure 37: First railway bridge with composite dowel shear connection: a) cross section; b) fabrication of a clothoidal-shaped dowel cutting line substituting the cutting line presented in Fig. 29a; c) basic reinforcement forming composite dowels; and d) a prefabricated composite beam girder lifted by a crane [6].

Rzeka bridge (Figs 36 and 37) was the first structure using new fatigue-resistant shape of composite dowels, and this shape has been used in all subsequent bridges in Europe since then [57].

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