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Development of the modified clothoidal (MCL) shape of composite dowels against the background of fatigue and technological issues

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Abstract: Composite dowels opened new possibilities for engineers designing composite structures. The fundamental and most important characteristic of composite dowels is the shape of the cutting pattern (called line). It is important to understand why only one particular shape of the cutting line, the modified clothoidal (MCL) shape, is being 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 shape of the cutting line – is presented in this paper. The investigation, development, and evolution of the MCL shape, which is the final form of composite dowels for bridges and has been widely introduced in bridge engineering, are presented. The results of comparative tests of different shapes under cyclic loads are discussed. The background for the design formulas for the steel part and the fabrication aspects are highlighted.

Keywords: Composite dowels, shear connection, composite bridges, fatigue, MCL shape, modified clothoidal shape.

1 Introduction

Basically, the paper is a continuation of the content presented in [57], and therefore, the extensive introduction has been omitted (one can find it in [57]). Research leading to the invention of the first version of clothoidal shape (CL) is presented in [57] together with a description of composite dowels in general (for clarity and consistence reasons, the list of references is compatible with the list presented in [57] plus some publications are added). This publication presents the work carried out in Poland and following the research described in [57]. It is presented how the results of fatigue tests and the issues of production technology led to the creation of the modified clothoidal (MCL) shape, which is the only one currently used worldwide in bridges. The design of dowels of this shape is covered by the European approval CEN-TS 1994-1-102, currently being created.

2 Dimensions of connectors

Finally, after the introduction of the CL at some stages of the PreCo-Beam project [7], only two shapes have been seriously considered in the course of the project [7]: the puzzle shape (PZ) and the CL. First, the authors had to set the dimensions of the newly developed CL and the PZ (influence of the size factor is presented in [57]). In addition to CL, the object of consideration was also the shape of PZ, already used in bridge structures and tested under static and cyclic loads. Considering the minimum initial radius of the clothoid (Fig. 29b, [57]) for the CL shape and calculating the most appropriate a/h ratio (where a is spacing of the dowels and h is height of the dowel), it was found that shapes with a height of approximately 100 mm would be desirable because they ensured that the standard prefabricated concrete plates of prefabricated composite girders [7] could be used, and that the spacing of the dowels of approximately 250–300 mm was appropriate for correct placement of the transverse reinforcement of the girders. At this stage of the PreCo-Beam project, the researchers conducting this project were aware that fatigue was important, thanks to Berthellemy's contribution [57]. The first calculated coefficient values A_{el} [5] had been provided (notch factors for reduced and principal stress calculation in steel dowels due to shearing forces) for the PZ and CL shapes using the first version of the finite

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element simulations (FE models were then developed and evolved). In addition, first static push-out tests were conducted at the University of the German Federal Armed Forces Munich (UBWM) using the CL, SA (from the name "Shape A," i.e., the first shape on the list other than PZ from which the optimization started) and PZ shapes (Fig. 3). The tests (and FE calculations) confirmed the following assumptions: for relatively thin steel dowels (here, 10.2 mm, S460 steel), steel failure is achieved, and the shape of the steel dowel does not significantly affect the ultimate resistance. The geometry of the PZ shape assumed for further tests in the PreCo-Beam project [7] is presented in Fig. 1. Using the same height and dowel spacing, the first comparative push-out tests for the PZ, SA, and CL shapes were conducted in [7], and the results of the push-out tests (force per dowel vs. relative slip) are shown in Fig. 2. Fig. 2 presents the typical steel failure that was achieved, according to FE predictions from 1D1 models, because thin web (10 mm) was used for the steel dowels.

Fig. 2 shows that the CL shape presents lower ultimate resistance than those of the SA and PZ shapes. It is logical; the relative field (ratio of the steel dowel area in a side view to the dowel height multiplied by the dowel spacing) of the CL dowels is smaller than those of the SA and PZ dowels (some steel is wasted during cutting). On the other hand, the CL shape provides a greater coefficient A_{el} [6] than that of the PZ shape (the CL shape provides better fatigue characteristics than those of the PZ shape); simply, the CL shape has a lower stress concentration factor for shear. In this respect, it could be unequivocally stated that the CL shape should be used in bridge construction, but there was a technological problem here: it was not possible to produce the CL shape using a single cutting line without overheating the material, and two cutting lines were necessary. Hence, the main problem at that stage of [7] was fabrication of the CL shapes. Assuming that the shapes have to be cut out with one continuous cut for economic reasons, the authors of the PreCo-Beam project [7] decided that (at that time) it was not possible to obtain the CL shape in this way, unlike the PZ shape (Fig. 3).

The problem was not some material loss during cutting, but the production technology: the CL shape could not be combined with continuous cutting to exclude overheating of the steel at critical points of the steel dowel, resulting in fatigue problems (the author solved this problem later by proposing new production technology and the so-called MCL shape). A double cut was considered, but this was abandoned for two reasons: first, it is uneconomical and second, deformations under the influence of rolling and thermal stresses, which are released after the first cutting

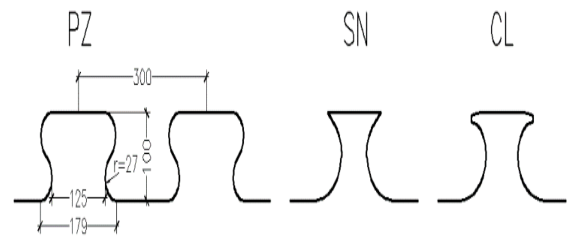

Figure 1: Dimensions accepted in further analysis of the PZ shape.

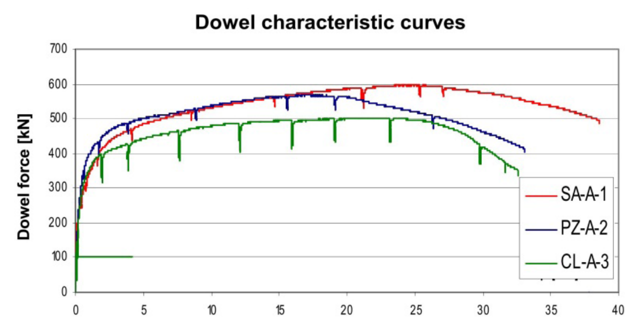

Figure 2: Results of push-out tests conducted by UBWM [7]: force per dowel versus relative slip for the SA, PZ, and CL shapes (the horizontal axis shows the slip displacement measured in the tests).

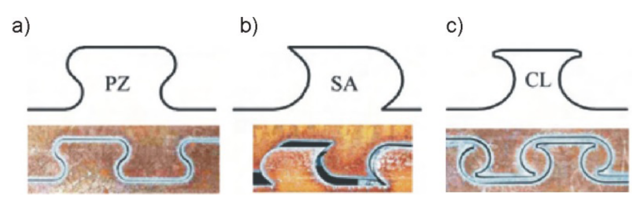

Figure 3: Cutting technology for production of test specimens for project [7]: a) and b) single cutting line for the PZ and SA shapes and c) two cutting lines for the CL shape.

is done, prevent efficient programming of the device for recutting. After tedious and long-lasting analyses, no efficient production technology for CL shape was found at that time. It was decided to mainly analyze the PZ shape and derive appropriate theories supported by research. It was assumed [5] that the theory (the basis for the dimensions of the steel dowels [6]) must be general (universal), and that the matter of dimensioning will always be limited to a specific value of the A_{el} coefficient. Therefore, extensive testing of various structural elements (beams, push-out standard tests [POSTs], and others) with the PZ shape was designed and carried out, and some research elements from the PZ, CL, and SA shapes were made to compare these shapes with each other. It was assumed [5] that it would be possible to numerically determine the state of stresses in the elements, which, in combination with the research that focused mainly on analysis of the strain state using strain gauges, would determine the general dependence, allowing the design of any shape, not just the PZ shape (later events confirmed this assumption to be correct). When analyzing the influence of the shape of the cut-out on the strength of the steel dowels, an important issue was the appropriate selection of a virtual modeling tool, both before and after the tests, to interpret the results. The finite element analysis was chosen due to its universal character, and Abaqus [1] was used for calculations of the composite elements. Next to FE studies of composite elements conducted in Poland, independent studies conducted in France focused on studies of fatigue using steel models alone; this is reported later in [4]. The researchers [7] concluded that "almost any" steel shape can be used for static loads (e.g., for application in building), but the shape can be fundamental regarding fatigue behavior, which is very important for bridges. At this step of research, it was fundamental to state whether the PZ shape was "good enough" for bridges (it was assumed and believed to be so at this stage, and there were no fatigue tests at this stage and no advanced FE studies had already been conducted). Hence, the team agreed to focus on the PZ shape, assuming that its resistance regarding the fatigue limit state would be sufficient for bridges (but there were doubts) and to "only marginally" study the CL shape experimentally. Finally, a large number of push-out tests were conducted on the PZ shape [13] and the behavior of this shape is well known and well investigated [14], thus providing mechanical models and design formulas [14]. However, there was only a single series of push-out tests on the CL shape conducted during the PreCo-Beam project [7] (Fig. 2). The fundamental decision made during the PreCo-Beam project was to focus on the development of reliable and well-established numerical models (see [1, 14]) and to verify the resistance of the PZ, SA, and CL shapes under cyclic (fatigue) loads using experiments. Regarding fatigue behavior and possible crack propagation, the new test was proposed in Poland (new push-out test [15] [NPOT]), in which only a single dowel is tested (no redistribution of forces between dowels) and the steel web at the front of the dowel is tensioned. The idea of NPOT is as follows: if a fatigue crack appears, it should propagate until the total failure of the steel part of the specimen. This is contrary to the standard push-out test, in which cracks are stopped after some distance of propagation due to compressed stress in the web at a dowel base. Hence, contrary to POST, which is dedicated to studying the ultimate resistance, NPOT focused on studying the fatigue resistance, which is directly connected to the problem of stress concentrations, and hence to the shape of the steel dowels. In summary, the idea of NPOT and the results that have been obtained was a fundamental step in the study of the shape of steel dowels and understanding of the fatigue behavior of composited dowels [27,45]. Moreover, at that time, there was no consensus regarding the transmission of forces to the steel dowels, and the concept of three effects (local, global, and uplift) [48] was considered before a final version of the design procedure based on two effects (local and global) had been proposed [5,6].

3 The idea of NPOT and the test outcomes

The main issue in the analysis of the stress state in steel dowels is the superposition of local and global stresses, according to the concept presented in [6] (local stress comes from longitudinal shear and global stress comes from tension of the steel web). A study of POST elements and beams carried out in Aachen [46, 47] showed the occurrence of fatigue cracks at the steel dowel base. These cracks did not propagate into the structure, and they were found after the composite specimen was demolished after tests covering 2 million load cycles. Thus, the crack stopped propagating after reaching a certain depth. Such a situation would occur in the externally reinforced beam in the hogging bending zone (shear connection under compression), where fatigue cracks are relatively harmless from the point of view of safety of the structure as long as it is possible to redistribute the forces between the connectors, which always takes place in practice. The basic issue was to check the behavior of the structure subjected to cyclic loads leading to the initiation of fatigue cracks at the base of the steel dowel in the sagging moment zone. According to [5], a crack at the base of one dowel in this region can lead to complete destruction of the beam, which was confirmed by beam tests [45] at the end of the PreCo-Beam project [7]. As part of the project [7], it was found necessary to carry out tests of dowels of various shapes, and the basic problem was to reflect in the model the conditions prevailing in the beam, that is, the state of stress allowing crack propagation. For this purpose, 10 specific specimens designed by the author were implemented with the working name NPOT, from which nine (3 × 3 different shapes of dowels: SA, PZ, and CL) elements were subjected to cyclic loading tests (2 million cycles) and one element with glued strain gauges (CL shape) was used for research under static and cyclic loads with a small number of cycles to determine the state of the stresses prevailing in the steel dowel and to compare the stresses with those in the numerical model. Three specimens of each shape were tested, and the steel structure of the tests was made with S460 steel. The elements have been designed to provide the superposition (in the stress concentration zone) of the tensile stresses in the web and the stresses originating from the essential work of the dowel as a part of the shear connection (so-called global G and local L effects [5,6]). For POST tests, at least two connectors are used on one side, and they are not stressed in the same way during the test.

To eliminate this effect from the considerations and to have a clearly defined state of stress in the connector, only a single connector on one side of the web was used. In the steel dowel area, no special measures were taken to eliminate adhesion between the steel and the concrete, while on the remaining parts, grease was used to eliminate friction. The idea of the NPOT specimen is presented in Fig. 4. Realization of the test required developing a complicated test stand with guides on ball bearings; the sample itself was placed on a cement pod. The test stand at Wroclaw University of Technology in Poland is shown in Fig. 5, and the sensor system is shown in Fig. 6.

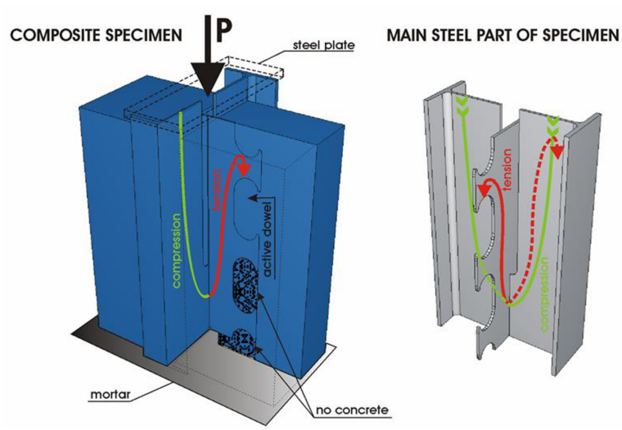

Figure 4: The idea of the new push-out-test (NPOT) specimen proposed by the author to be used for cyclic tests [7] (2 million cycles).

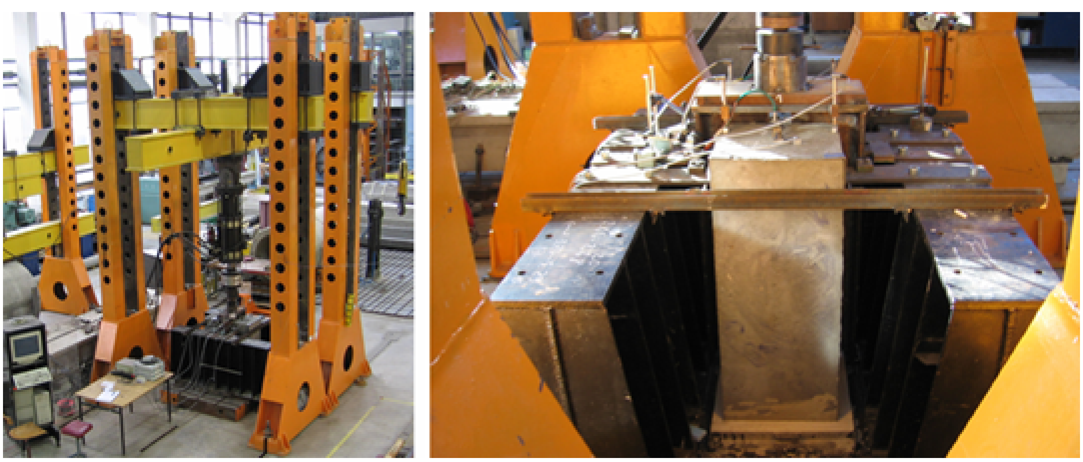

Figure 5: The test stand for NPOT.

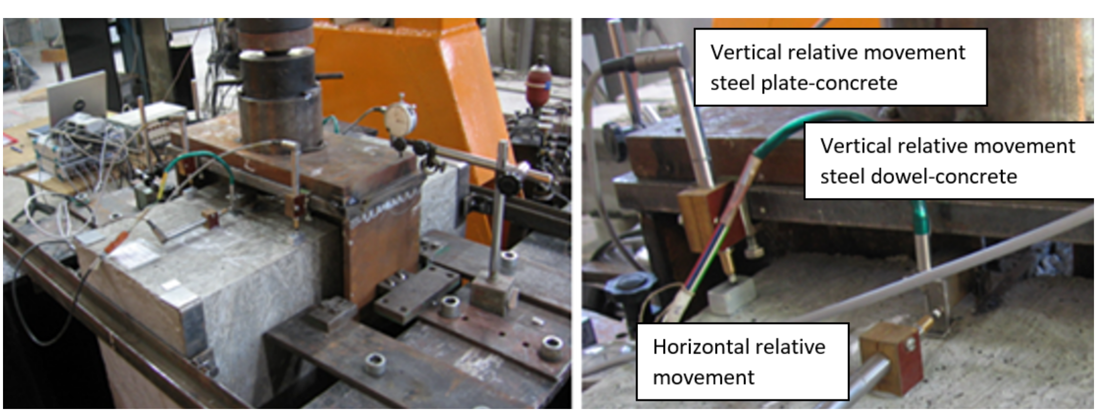

Figure 6: The sensor system and bearings for NPOT.

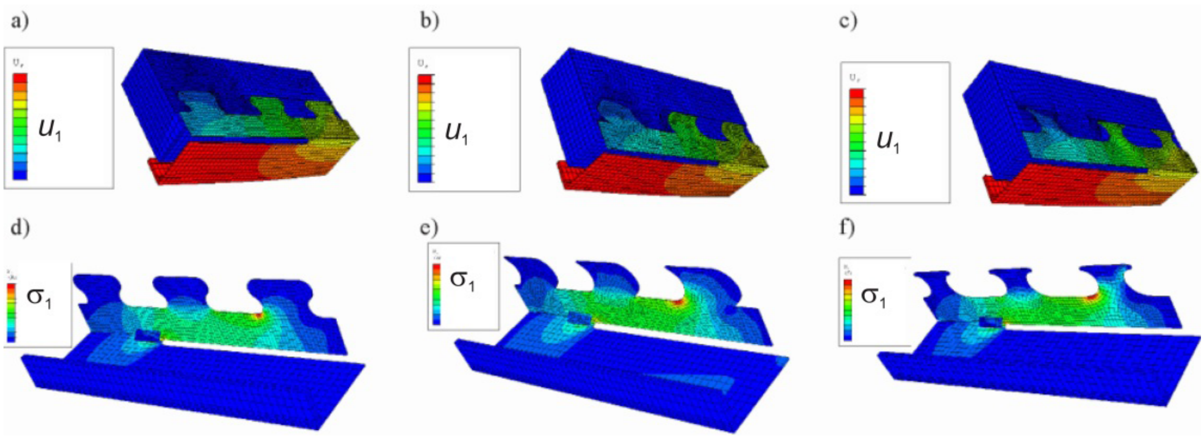

Figure 7: Numerical models of the NPOT specimen (only the steel part of the composite model is extruded for visualization of the stress layout): models with displacement visualization in the direction of the force (a, b, and c) and the steel part of the model and the principal stresses (d, e and f): u_1 stands for displacement according to the direction of acting force and σ_1 stands for maximum principal stress (tension).

Table 1: Main stress values (MPa) in the NPOT models estimated using FEA for coarse mesh density – the stress level is given at the minimum ($\sigma_{P=120\ kN}$) and maximum ($\sigma_{P=280\ kN}$) load level and their difference ($\Delta\sigma_{P=160\ kN}$).

	$\sigma_{P=120\ kN}$	$\Delta\sigma_{P=160\ kN}$	$\sigma_{P=280\ kN}$
CL	132.0	176.0	308.0
SA	134.6	179.4	314.0
PZ	157.6	210.2	367.8

Appropriate numerical models [1] were used to assess the behavior of the structure during tests and to estimate the stress level at the base of the steel dowel (so-called hot spot stress for fatigue design); a relatively coarse mesh of elements with similar density for all shapes was used. The FE model (Fig. 7) reflects the actual test and was loaded with a force of 160/4 = 40 kN (nonlinear static analysis due to contact). Models and illustrations of the main results are shown in Fig. 7. The behavior of the structure is essentially linear due to the principles of the numerical approach being used [14].

The highest value of geometric stresses in the base of the steel tooth estimated with finite element method occurs for the PZ shape (Table 1), and fatigue cracks were expected for this shape. Based on the analyses [7], models were made with the appropriate mesh density at the place of the highest stress concentration, and on this basis, the expected stress values were determined. The value of the principal stress amplitude from the cyclic load was approximately 270 MPa.

Analysis independently carried out in France [7] in the Code_Aster program [4] together with the fatigue life assessment confirmed that fatigue cracks should occur during the tests. During the tests, 2 million cycles of force load range of $\Delta P = 160$ kN were applied with a frequency of 4.5 Hz. The lower load level was 120 kN and the upper load level was 280 kN. The level of load was selected according to the tests [49], where the amplitude was approximately 137.5 kN per dowel, but with dowels at 400 mm spacing (in comparison to 300 mm, see Fig. 14, that is used for NPOT tests). Assuming a similar effort per unit length of the shear connection, approximately 100 kN per dowel is obtained (137.5·300/400 = 103 = ~100). A final value of 80 kN has been assumed to achieve cracking due to high cycle fatigue, guided by the criterion of not exceeding the yield point during the test (it was calculated that 100 kN is a bit too much). After the tests, the elements were cut, and it was found that some of the samples were not damaged after 2 million cycles. Some of the samples were destroyed due to fatigue cracking of the weld connecting the perpendicular steel sheets of the webs, and only one sample with the PZ shape suffered fatigue damage exactly as expected at the research design stage. The behavior of the displacement sensors is shown in Fig. 8 for the element with the SA shape in which the steel dowel was not damaged (but the joint broke after more than 1 million cycles) and in Fig. 9 for the element in which the steel dowel was destroyed (PZ shape). The shapes of the curves in Figs 8 and 9 are different. Based on the analysis of the curves in Fig. 9, it was found that fatigue cracking was initiated after approximately 350,000 load cycles [7]. Photographs in Fig. 10 show the nature of the crack in the element. Based on data from tests and FE done in Poland (on stress distribution at the junction between steel and concrete), a detailed analysis was carried out in France [4]

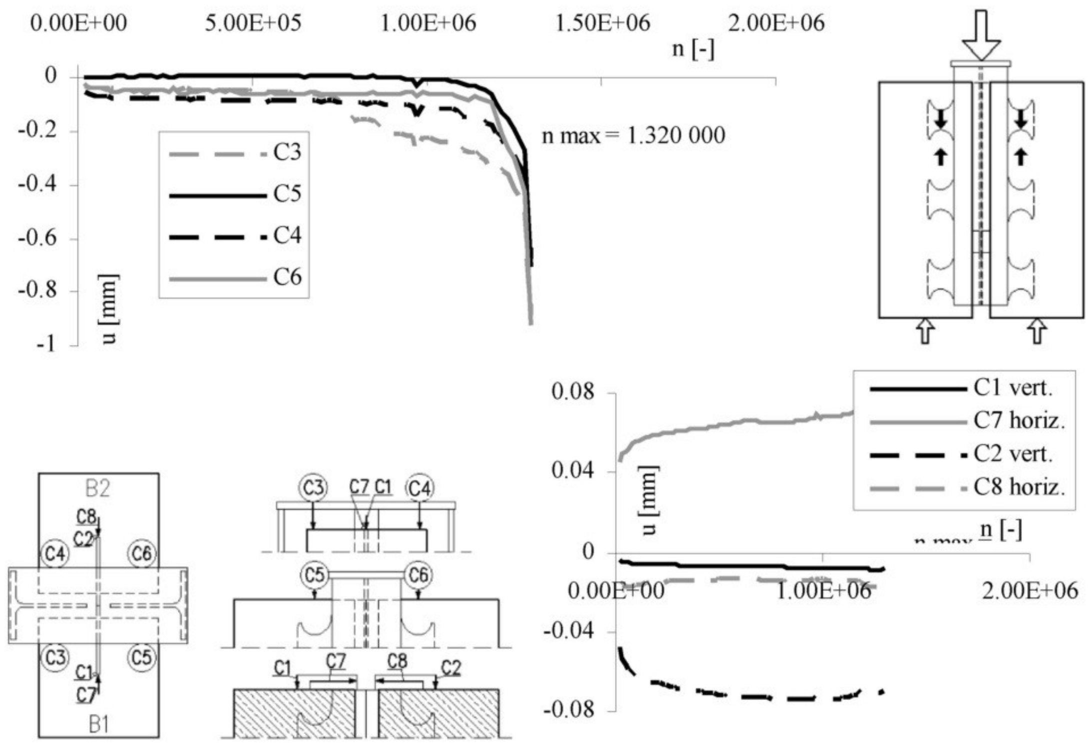

Figure 8: Results for the NPOT-SA1 element (CL shape drawing is for reference only): changes in displacement of the measuring points together with the number of load cycles (no teeth damage; however, there was a fatigue crack in the weld of the steel element transmitting the force to the webs).

(in the Code_Aster v. 9.0 software) regarding the state of the stress and fatigue life evaluation of the element under testing. The results are presented in [4]. The fatigue crack that is presented in Fig. 10 is described in more detail in [4]. Fig. 8 and Fig. 9 present the results for the SA and PZ shapes, respectively, and the CL shape results are provided only for the purposes of general presentation of the NPOT loading and support system.

Hence, NPOT led to important conclusions: shapes with sharp notches (such as the PZ shape) are worse than shapes where notches are not so sharp (such as the CL shape). Importantly, these conclusions were proven by the tests, and the failure mechanism was provided (Fig. 10). The superposition of stress coming from shear (the so-called local effect) and from tension of the web (the so-called global effect) results in a failure mechanism that is clearly visible in Fig. 10 – this behavior was the basis of the design of the NPOT specimen, and it was finally introduced by the author [6] into the design procedure for composite dowels [8] by means of two coefficients: $1/A_{el}$ (representing the local effect) and β (representing the global effect). A detailed microscopic study of fatigue cracks presented in Fig. 10 can be found in [5]. Later, different names of coefficients are used in [16] (concentration factors $k_{f,L}$ and $k_{f,G}$). Contrary to the POST results (Fig. 2), the NPOT results clearly showed that the dowel shape is a fundamental issue for bridges because of the fatigue problem.

4 The choice between the PZ and CL shapes and strategy of the PreCo-Beam project

The NPOT results were a fundamental step in understanding the behavior of composite dowels, and they were “the beginning of the end” of the perspective of using the PZ shape in bridges (together with more detailed FE calculations of stress concentration factors for the PZ and CL shapes [22,24]), but this shape was further analyzed and examined in the PreCo-Beam project [7] due to a lack of economic technology to fabricate the CL shape (and no perspectives for such a technology despite many discussions and efforts within the project [7]). The strategy was as follows: 1) the researchers would focus on

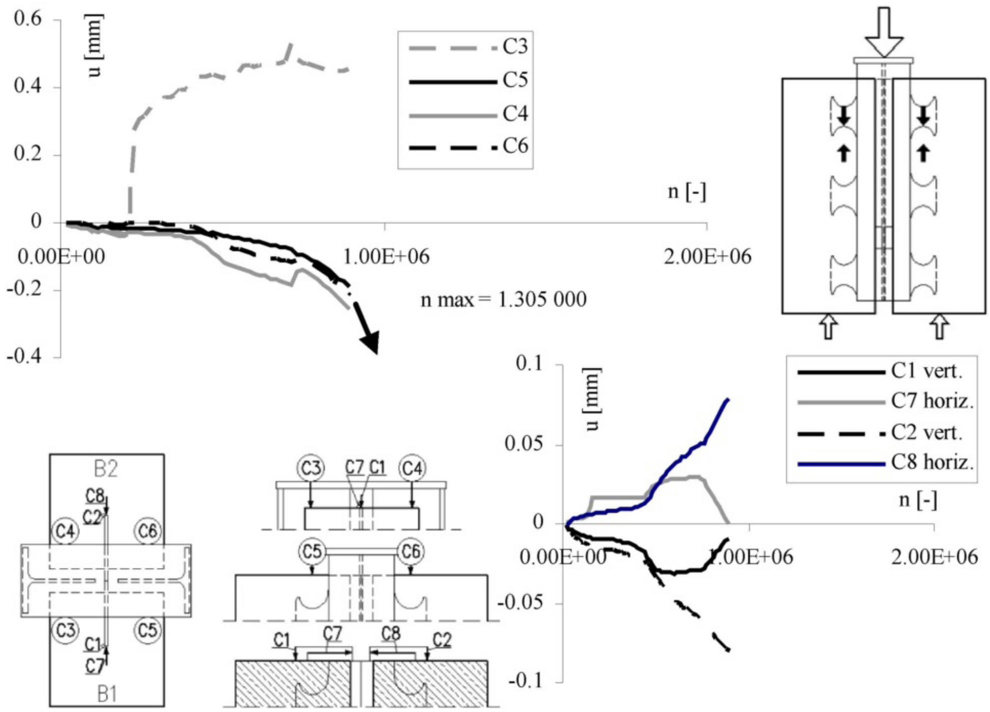

Figure 9: Results for the NPOT-PZ2 element (CL shape drawing is for reference only): changes in displacement of the measuring points with the number of load cycles (steel tooth crack as predicted).

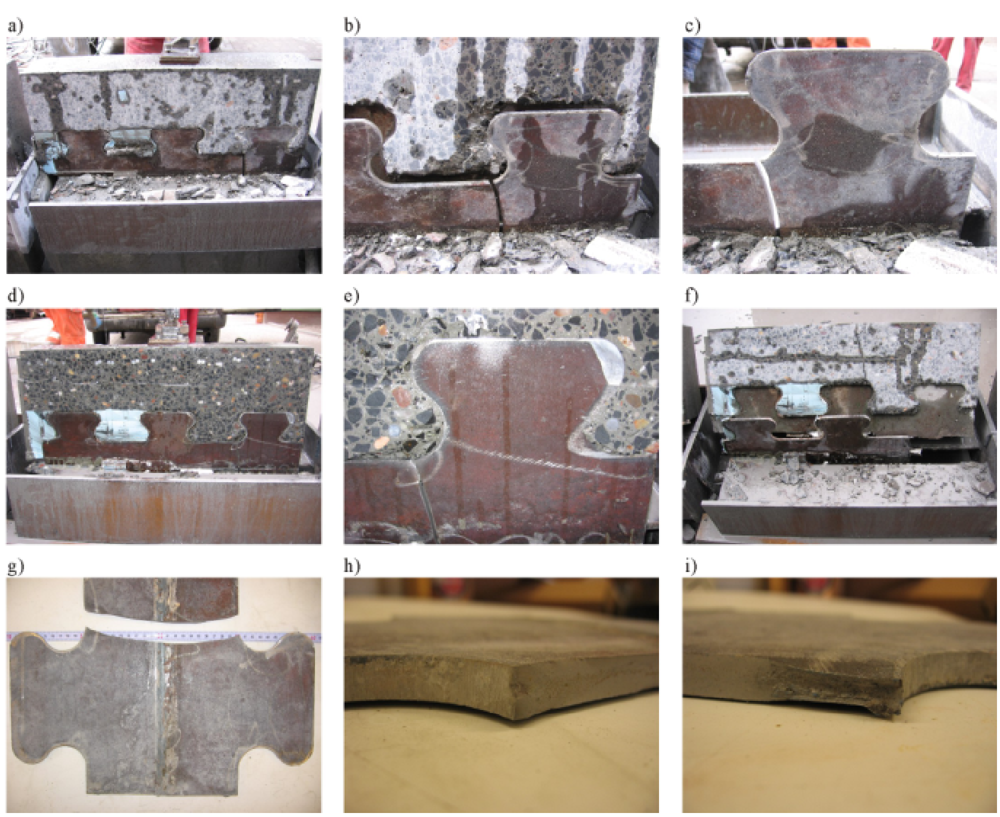

Figure 10: Documentation of fatigue cracks in the NPOT-PZ2 specimen tested in of the PreCo-Beam project [7]: a-f) view after cutting the concrete part, g) general view of the crack, h) beginning of the crack, and i) end of the crack

the PZ shape and develop a theory that will be universal for different shapes, 2) the PZ shape would be used in bridges (with the cost of bigger steel consumption) if the CL production technology has not been developed, 3) in the case of the development of the CL shape production technology, researchers would use the theory developed for the PZ shape (with different coefficients $k_{f,L}$ and $k_{f,G}$) and future tests would be carried out to verify the correctness of the assumptions. This appeared to be a very good approach as the technology for producing the CL shape had been indeed invented by the end of the PreCo-Beam project [7].

5 Detailed examination of the PZ shape during the PreCo-Beam project

The paper [6] presents how the design concept for the steel part of a composite dowel shear connection was developed using many tests during the PreCo-Beam project [7], including beam tests. The test specimens to establish the design concept [6] used only the PZ shape. The tests [7] proved that the FE models and the experimental results agree (a large number of strain gauges on the steel part confirmed the stress layout precisely predicted by the FE [6]). Finally, push-out tests [13] and the respective FE calculations [14] combined with beam tests under cyclic loads [45] and beam tests under static loads (reported in [7], not published yet, but partially reported in [5]) answered all the important questions and resulted in a design procedure for the PZ shape that can be currently used. The push-out tests proved the ultimate resistance, for both steel and concrete failure mechanisms, and the influence of the size of dowels was established [6]. The beam tests under static load confirmed the push-out tests and proved that there is no influence such as uplift on the composite dowels [48], and that only two coefficients (global and local actions) [6] are to be considered in design. The beam tests under cyclic loads [45] proved the design concept for fatigue and presented the respective failure mechanism (failure of the steel flange due to propagation of fatigue cracks). These results are important from scientific but not practical perspectives: the PZ shape is not used in bridges because a better shape, a modification of the initial form of CL, appeared (the MCL shape in Fig. 4d [57]), and the fatigue limit state appeared to be an important verification criterion for composite dowels in bridges (and usually decisive in both road and railway bridges, where the PZ shape is not economic). However, this is exactly what the members of the PreCo-Beam project expected. Having no technology for production of CL, they had decided to follow with tests and analysis, working on the PZ shape and knowing that the procedures they would derive would be valid for any shape of composite dowels. With know-how, it is easy to obtain the appropriate coefficients in the equations using FE and to confirm them by using the same tests as during the PreCo-Beam project (exactly such a procedure appeared later). Moreover, no change in ultimate limit state for the steel part was needed and only coefficients for fatigue [6] had to be calculated [25,19,28]. One can see (Fig. 11) that the authors of [7] focused on PZ shape to get the calculation procedures, but the "better" shape regarding fatigue was expected (see the description for Fig. 13d in [6]: "*possible shape with smaller stress concentration factors, e.g., a kind of CL shape*.") The right part of the figure qualitatively shows the difference in fatigue resistance between the PZ shape and a virtual "better" shape like CL. The exact "loop" (for MCL) was provided a few years later [28].

6 Transition from PZ shape to CL shape

In the course of the PreCo-Beam project [7], the PZ shape was tested in detail, and the theory and design formulas are based on those results. Notably, in the context of [7], there was only a single series of POST specimens tested with the CL shape (Fig. 2), and after that, four NPOT specimens with CL shapes were tested.

Three NPOT specimens were subjected to cyclic loads of up to 2 million cycles, and they did not suffer any fatigue problems in the steel dowels. One NPOT specimen was used to compare the readings of the strain gauges attached to the steel dowels (Fig. 12) with the FE results of the CL shape (Fig. 13). Different load levels were evaluated, and the FE results agreed with the experimental results quite well [5]. There were plenty of arguments from which to draw conclusions regarding the assumptions for the numerical models and simulations. It was proven that assumptions regarding the stress concentration factor for the CL shape are quite correct. It was stated that the CL shape is better than the PZ shape, but no more tests and studies on the CL shape were performed at that time [7] because despite much time spent discussing how to produce the CL shape with a single cutting line, no idea appeared at that time. The tests for the PreCo-Beam project [7] had to be designed and conducted, and the PZ shape was selected because there was no guarantee that economic production of the CL shape was possible. State-

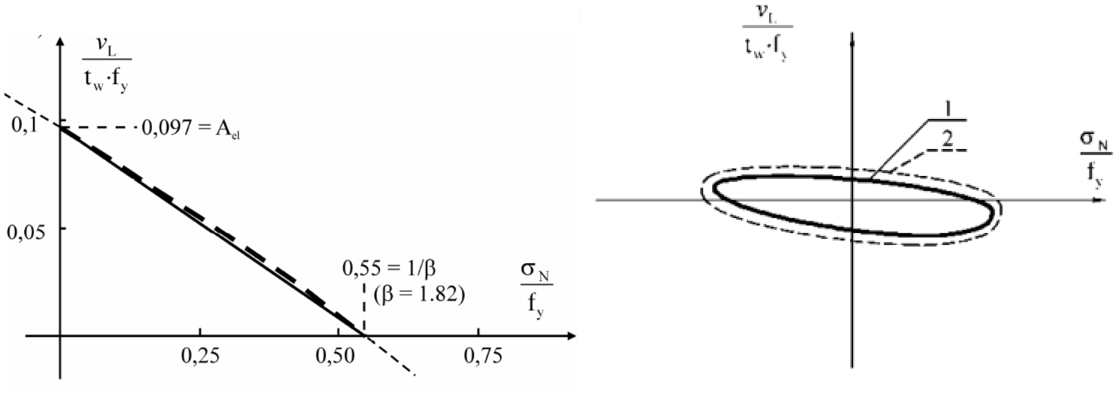

Figure 11: The original concept of dimensionless resistance of steel dowels regarding local and global effects [5,6] (Fig. 13d in [6]): fatigue coefficients for tension stress for PZ shape (at the left; to be compared with Fig. 20 and [22] for the clothoidal shape) and general prediction for complete stress set (at the right).

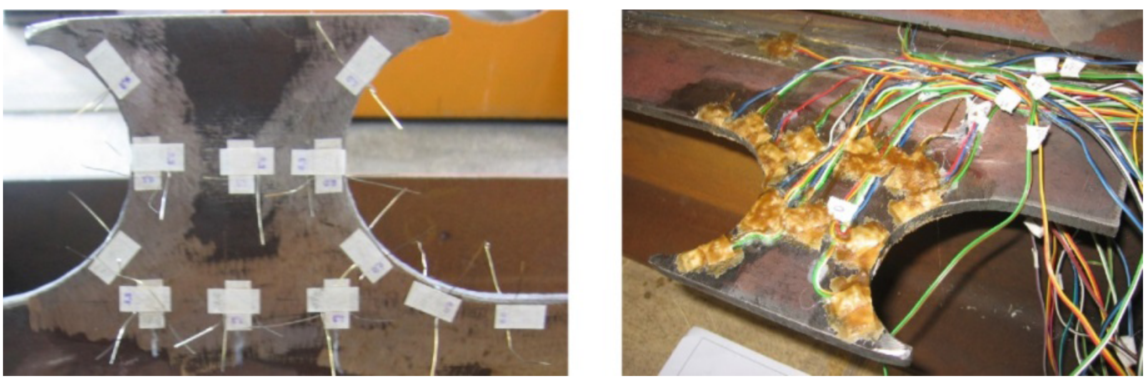

Figure 12: Strain gauges on NPOT specimens with CL shapes for purposes of [7].

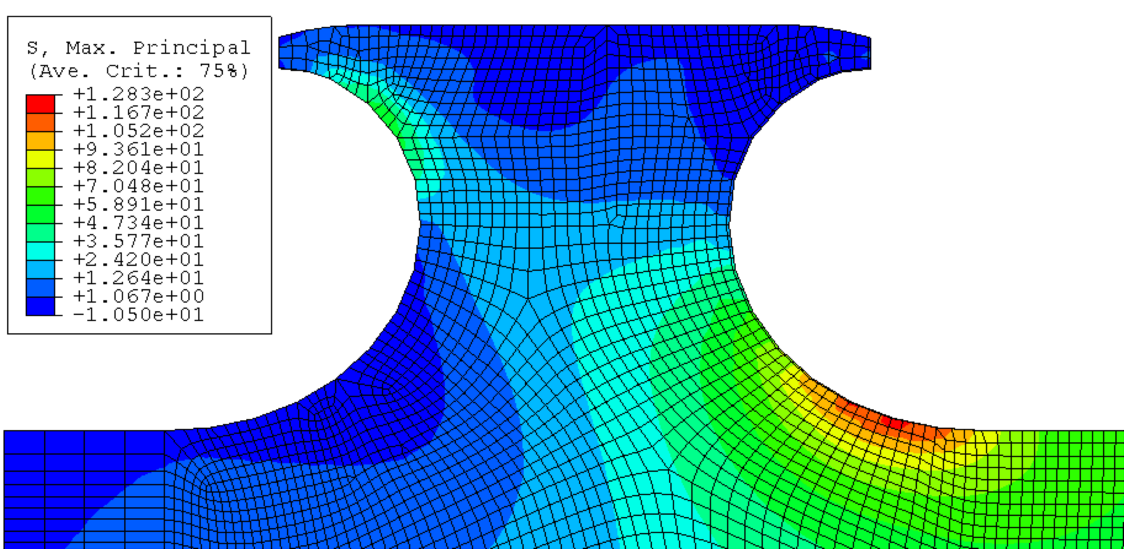

Figure 13: Principal (maximum) stress layout in the tooth for the NPOT model according to FE simulations.

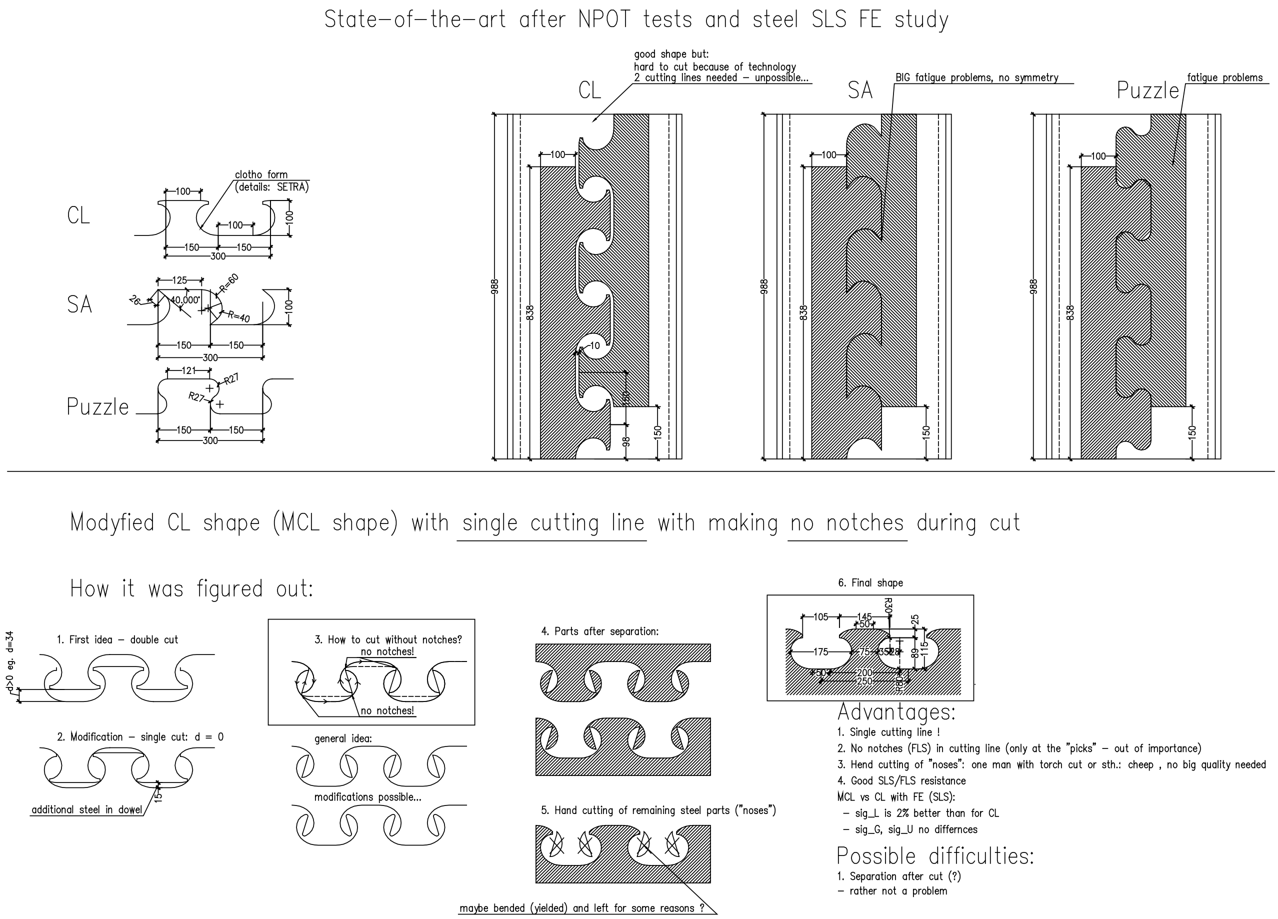

Figure 14: Summary of characteristics of the basic shapes highlighting the problems with the idea of a new cutting line and the basis standing behind this idea (original drawing of steel parts of NPOT specimens for discussions with partners of the PreCo-Beam [7] project: only the SA and PZ shapes were used in bridges before construction of the "Wierna Rzeka" Bridge in Poland [62]).

of-the-art technology and the knowledge gained during NPOT and the main problems are presented in Fig. 14 (a drawing of the steel part of the NPOT specimen is used to highlight the main problems).

7 Invention of MCL

In autumn 2008, the query appeared (at Polish bridge market) for alternative solution for a new railway bridge in Poland (Fig. 17). In connection with the R&D works carried out at that time on new bridge construction technologies in Poland (the so-called M3M project), it turned out that it was possible to use new technologies that could be very innovative: the idea appeared [5] that it could be the first railway bridge using composite dowels, but high fatigue resistance was needed. Then came the idea (against the background of known solutions and problems: Fig. 14) that "topology and technology can differ" to result in the same solution: the self-crossing cutting line (resulting in steel overheating) can be substituted with a line that is not self-crossing (Fig. 15). Using an additional simple operation for removing scratches, the appropriate shape (Fig. 16) could be obtained. Hence, the main idea is presented in Fig. 15.

Thus [5], in a very short time, a solution to the problem of the shape and technology of manufacturing connectors for railway bridges appeared at the same time, as well as a new bridge (de facto the first bridge with a hybrid cross section defined more than 10 years later [58]). What is more, after the cutting technology was developed, in addition to the railway bridge, another new highway bridge was designed, which was built in parallel (basically two different structures with the MCL dowels were built simultaneously) [5]. Figure 15 shows the photos of the first MCL cuttings taken in Wrocław on 10.17.2008 (this date can be considered as the beginning of the production of MCL connectors): the company that undertook the production of the steel structure of the bridge was promised that it would get a contract if it delivered test fragments cut

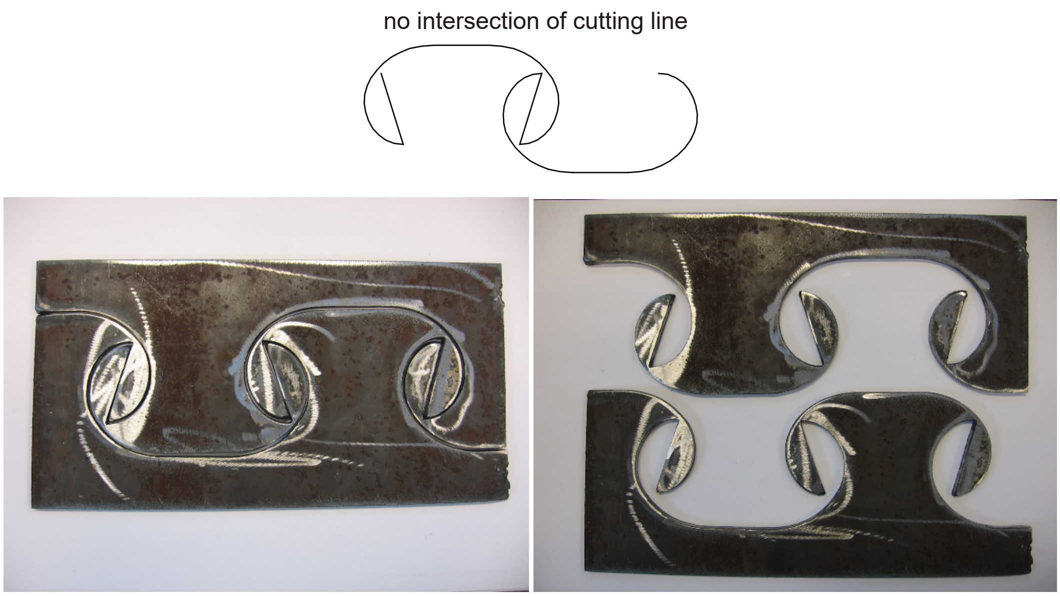

Figure 15: Production technology of the clothoidal symmetrical shape without problems with overheating of the steel (the process results in a shape with a more extensive upper part of the steel dowel compared to the initial CL shape): the idea of cutting line (at the top) and the first-cut sheet fragments delivered by the contractor for acceptance of the technology (pictures taken in Wrocław on 10.17.2008)

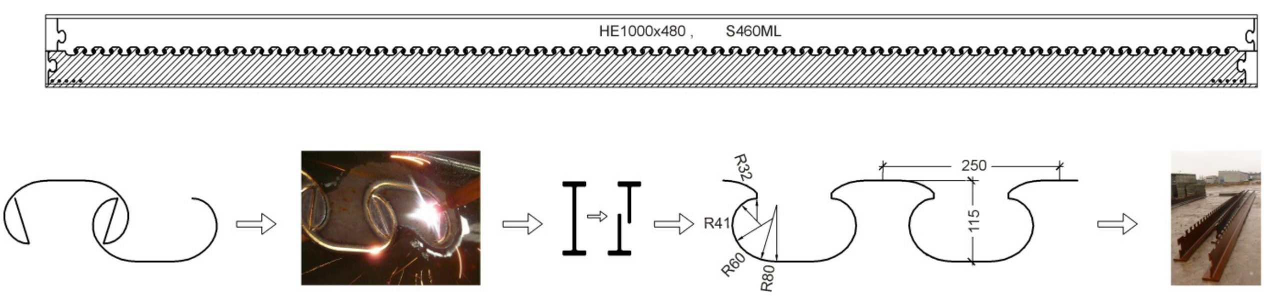

Figure 16: Application of the new cutting line for the production of beams for the "Wierna Rzeka" Bridge with a new shape with dimensions of 115/250 mm (the left picture shows the cutting line by ArcelorMittal, where this procedure was implemented later on).

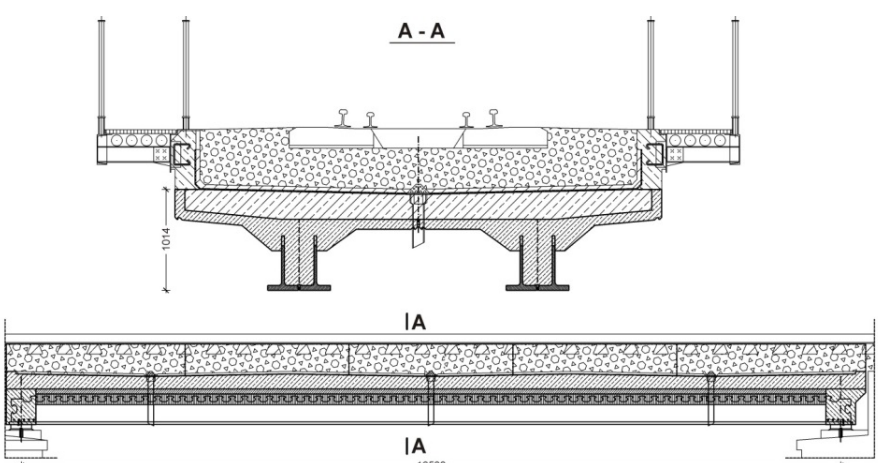

Figure 17: Drawings of composite spans of the innovative "Wierna Rzeka" Bridge in Poland, the first implementation of the clothoidal shape in structural engineering and the first railway bridge using composite dowels (no welding of T-sections).

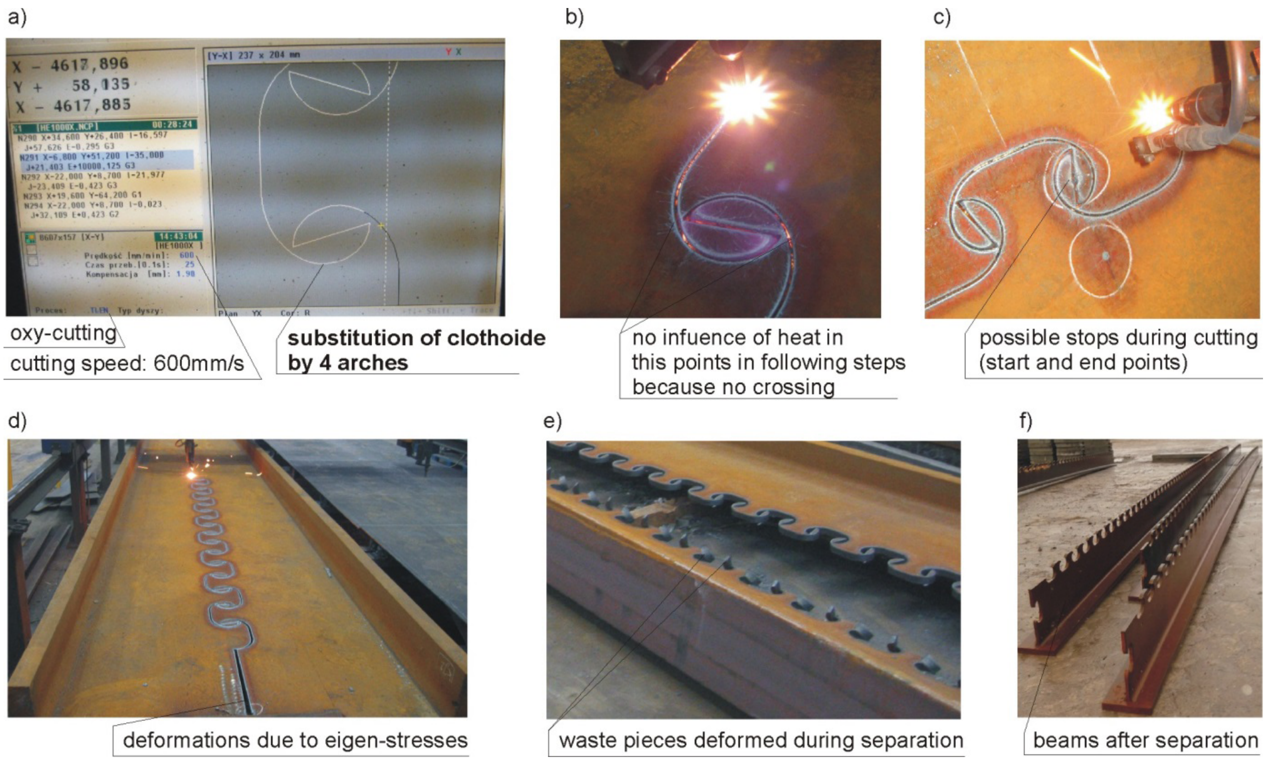

Figure 18: Cutting specification for the first implementation of the modified clothoidal shape for the "Wierna Rzeka" Bridge (cutting done in Poland): a) geometry and specification of the cutting process (screen view during cutting), b) cutting progress, c) stops during cutting, d) deformation of the separated T-section due to eigenstresses, e) the separation process, and f) beams after separation with the final shape of the steel dowels.

out. So, it happened. Steel beams were ordered from Luxembourg and then cut in Poland (Fig. 18).

The important point is that no cutting line itself results in successful implementation, but the cutting line is strictly connected to the technology (Fig. 18) that became possible. A single line was economic (Fig. 18a). Stops during cutting (Fig. 18c) and easy separation (Fig. 18e) became possible. Modification (MCL) does not only concern the cutting procedure and the extended geometry of the upper part of the tooth, but is implemented in geometry by substitution of the clothoide with four arches (Fig. 16) to avoid trouble during cutting due to processing in the cutting machines (Fig. 18a), which was initially noticed in the case of clothoide.

Appropriate numerical simulations (Fig. 19) have been conducted using the so-called sector model (developed in [5]), which is presented in [6,7,14]. Having experience reported in [1] and after discussions in [7], a standard procedure in Abaqus using linear materials and a friction coefficient of 0.3 was used, and such a specification for the FE simulations of composite dowels for the purposes of elastic calculations of the steel parts was established to be valid for years later. Based on the first principal stress layout (Fig. 50), the factor A_{el} = 0.161 to be used for the design of the MCL 115/250 shape was calculated [22]. In the same way, using the steel model, stress concentration factor β = 1.54 was calculated. In this way, "the better shape" (compare Fig. 11) has been established (Fig. 20). The entire loop (Fig. 11) in regard to local and global effects was provided later by Kożuch in his PhD research and is reported in [28].

The dissemination project [8] proposes design guidance for the MCL 115/250 shape. The value of the stress concentration factor regarding local effects (longitudinal shear) $1/A_{el}$ = 6.21 (Fig. 20) is smaller than the value currently used in design [3,16] $k_{f,L,CL}$ = 7.3 according to [16] (and the same value is proposed for CEN-TS 1994-1-102). This is because later, in Germany, the idea of changing the ratio of the shape to MCL 100/250 appeared just to keep rounded values (100 instead of 115), and this change was somehow applied, even though the fatigue resistance after this modification slightly decreased. However, this is a secondary topic (small change in the values of factors), but it is important to report it and understand why different shapes were used in different years. In Germany, many efforts [17] have been made to propose design guidelines

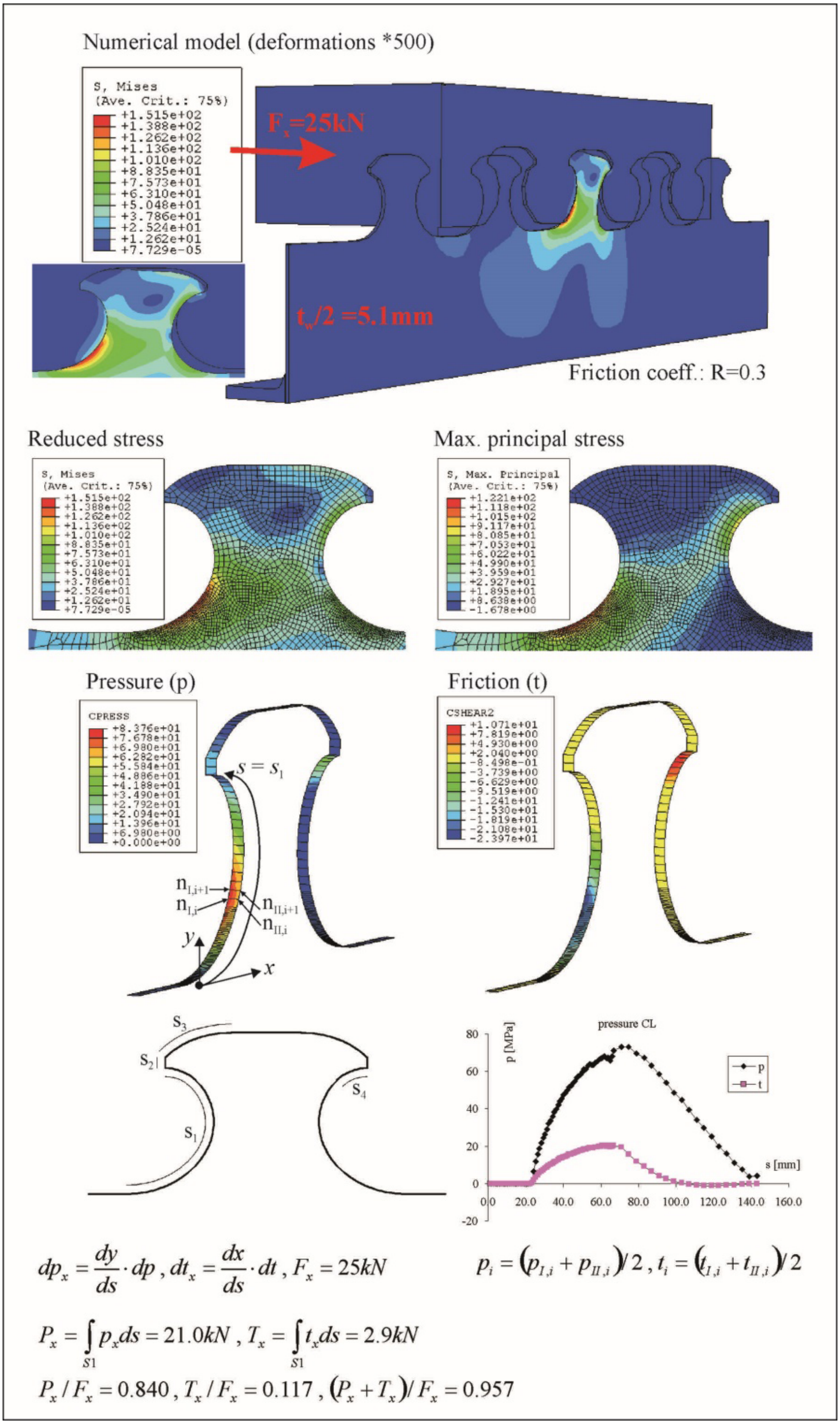

Figure 19: Results of the numerical simulations of the MCL 115/250 shape (the shape after optimization of the ratio according to the procedure presented in Fig. 30 in [57]) by Abaqus software.

[22], and once such a modification was implemented (and the formal document [16] appeared), it started to be used both in Germany and Poland (even in Poland, it was just easier to use MCL 100/250 with a formal German design procedure [22] than MCL 115/250 with a better coefficient, but with no formal documents and with only the informal design guide [8]). Thus, the shape MCL 100/250 was widely accepted and now is to be covered by CEN-TS 1994-1-102. Meanwhile, a slight but useful modification (adjustment) of the cutting line according to Fig. 21 was implemented at ArcelorMittal in Luxembourg to enable a fully automatic cut in which waste pieces fell down during cutting and the final shape was obtained without needing to remove wastes after cutting (Fig. 18e). Hence, this cutting technology and the MCL 100/250 shape are used for bridges all over Europe (and recently, in Australia [59]).

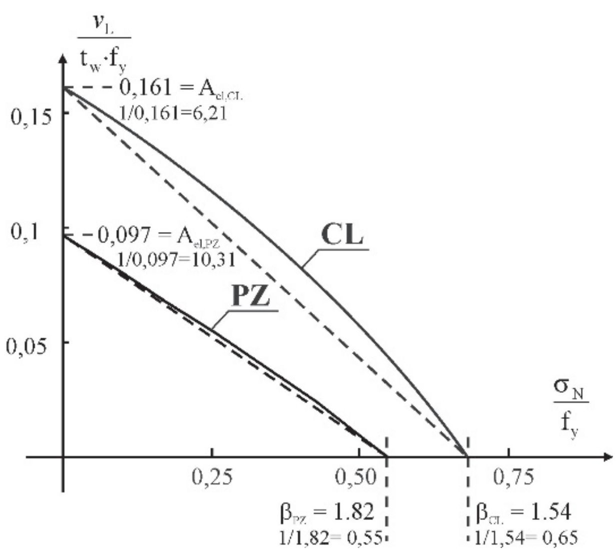

Figure 20: Dimensionless stress concentration factors (according to [5,6]) for the MCL 115/250 shape and the PZ 300/100 shape.

After the first implementation of MCL, a large number of R&D projects in European Union (EU) have been conducted and a large number of different bridges have been realized. Experience was collected (Fig. 22), and rules were well established. This shear connection is currently being considered to obtain European Technical Specification (consistent with the rules of Eurocode 4). The first appropriate rules have been proposed by the project team SC4.T1 (the project team preparing new sections for Eurocode 4) [52], but they have been a starting point only for new rules being developed by a separate team (working on CEN-TS 1994-1-102). For the purposes of the first part of work (at the level of SC4.T1), a list of papers that can be considered as a kind of "background documents" for the design procedure of composite dowels have been investigated and referenced, and more information regarding design, construction, and R&D can be found there. The list contains the following: publications, which include design guides [8,16,23], practical applications (bridges) [2,18,36-42], and research

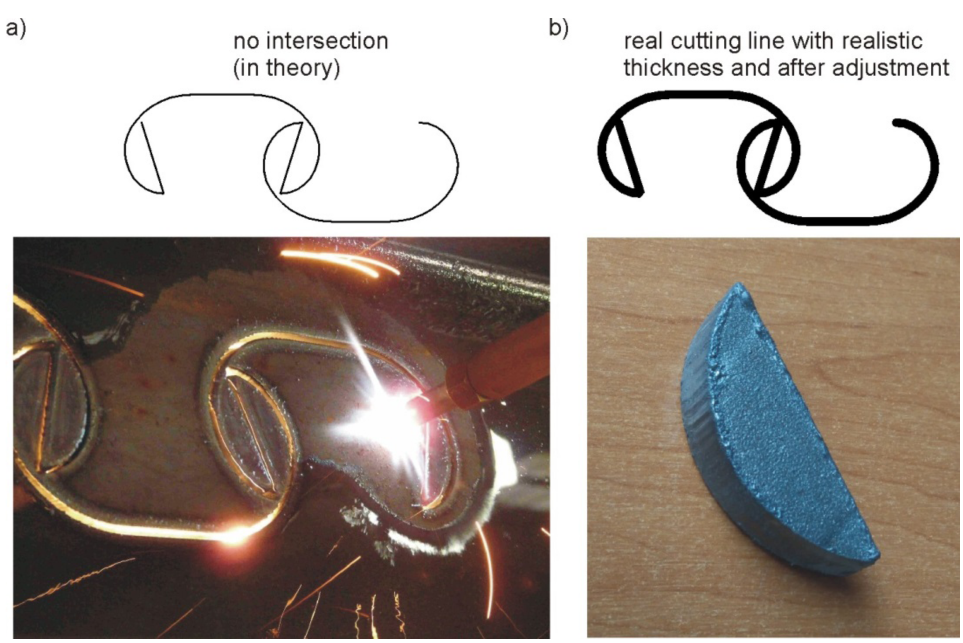

Figure 21: Adjustment of the cutting line by ArcelorMittal (the left picture by ArcelorMittal): a) first version of the line with wastes to remove, b) adjustment of the line results in the wastes falling down during cutting because the line has a realistic thickness (however, no overheating occurs).

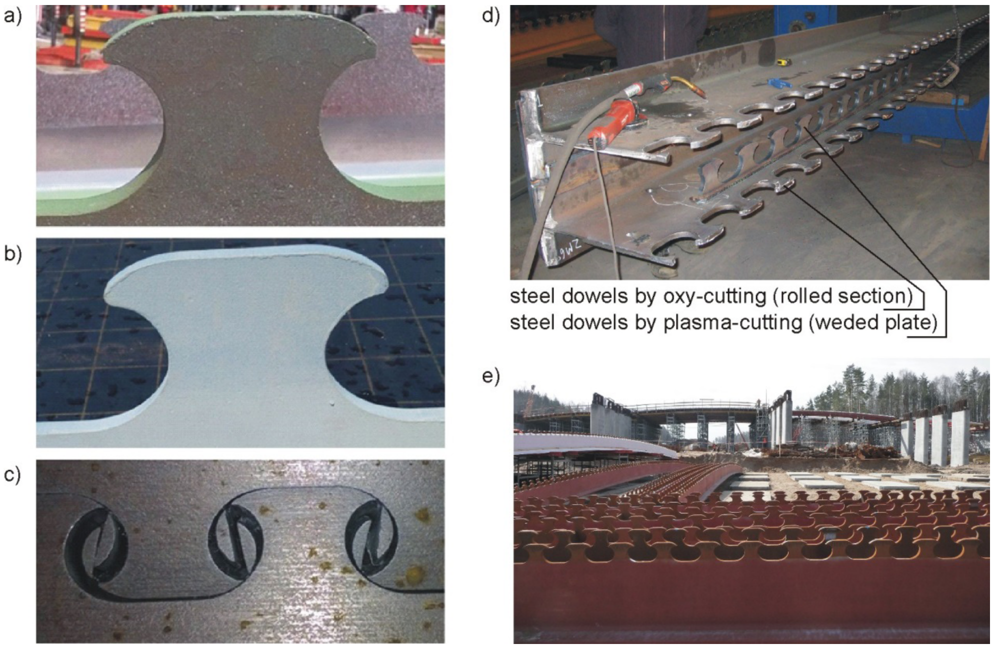

Figure 22: Different shapes and technologies of production of steel dowels with the clothoidal shape: a and b) different shapes of the "nose" of steel dowels by different producers fabricated in Poland out of plates by oxy-cutting, c) small dowels fabricated in Luxembourg by plasma cutting, d) elements of the PE4 bridge design by the author in Poland [12] fabricated in Luxembourg by oxy-cutting and plasma cutting, and e) steel elements of the PE4 bridge at the construction site (a large number of elements were produced with the MCL 115/250 shape).

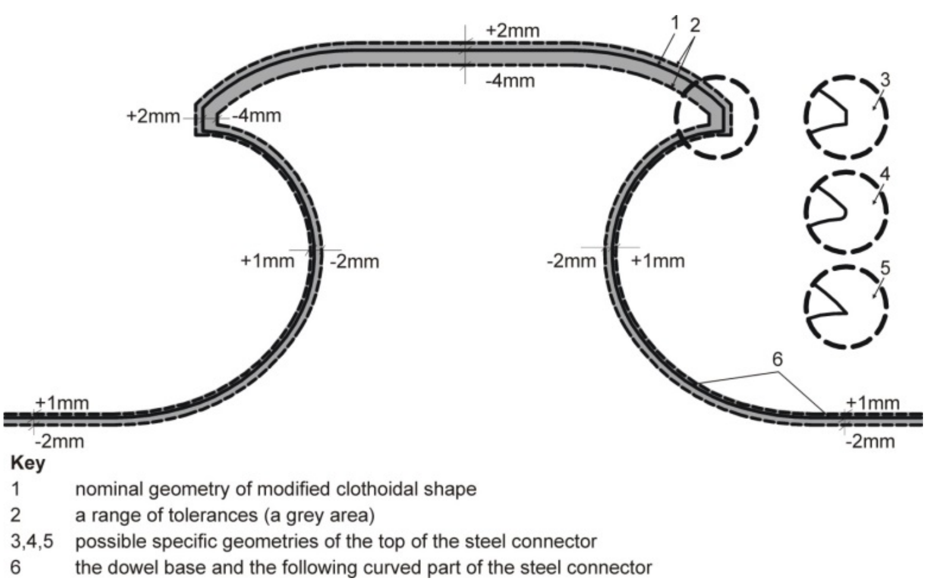

Figure 23: Tolerances for production of steel connectors using the geometry of the modified clothoidal shape of connector.

[5,6,7,9,13,14,17,20,21,22,24-35]. Publication [3], which appeared after preparation of the input for SC4.T1, presents German activity and a large number of German R&D projects, and publications are referenced in [3]. Currently, a significantly expanded list of publications, especially by German authors, deal with the issue of concrete failure mechanisms; the information regarding this topic can be found in [64-67]. For purposes of the work of SC4.T1, fabrication tolerances (Fig. 23) have been proposed (with cooperation from ArcelorMittal on the background of dimensions proposed in [16]), and this is described in [56]. This fabrication tolerances will be proposed to be kept in future design rules at the European level.

Currently, the MCL shape of dowels is used in bridge engineering in Europe and is well established. Since the first bridge using the MCL form of composite dowels (Fig. 24), many other forms of composite beams using composite dowels have been developed and used in different bridges (e.g., in Poland, see Fig. 25).

All EU experiences with MCL shape for bridges are very positive. The are positive experiences in Australia too [59]. This shear connection is being implemented (stage of R&D projects) in Japan [60] and China [61]. Hence, the MCL shape of dowels can be a well-established shear connection for bridge engineering.

Figure 24: "Wierna Rzeka" railway bridge in Poland, the first implementation of the clothoidal shape of dowels

8 Summary

The MCL cutting line (and the respective cutting procedure) enabled economic production of clothoidal-like shapes. This shape of composite dowels (MCL) was applied for the first time in a bridge that is presented in Fig. 24. Since that point, searching for the best shape in the development of composite dowels has ended, and the next stage has involved production, implementation, research (including a large number of different tests), collecting experiences, and evolution of CL to its final form as presented in Fig. 26. Construction of the "Wierna Rzeka" railway bridge (Fig. 24) in Poland (designed in 2008/2009) was a turning point in the development of composite dowels for bridge engineering. Appropriate tests conducted (push-out tests and cyclic beam tests were performed with the MCL 115/250 shape for the construction of the "Wierna Rzeka" Bridge) and experience gained during the fabrication of steel beams resulted in new knowledge and led to further

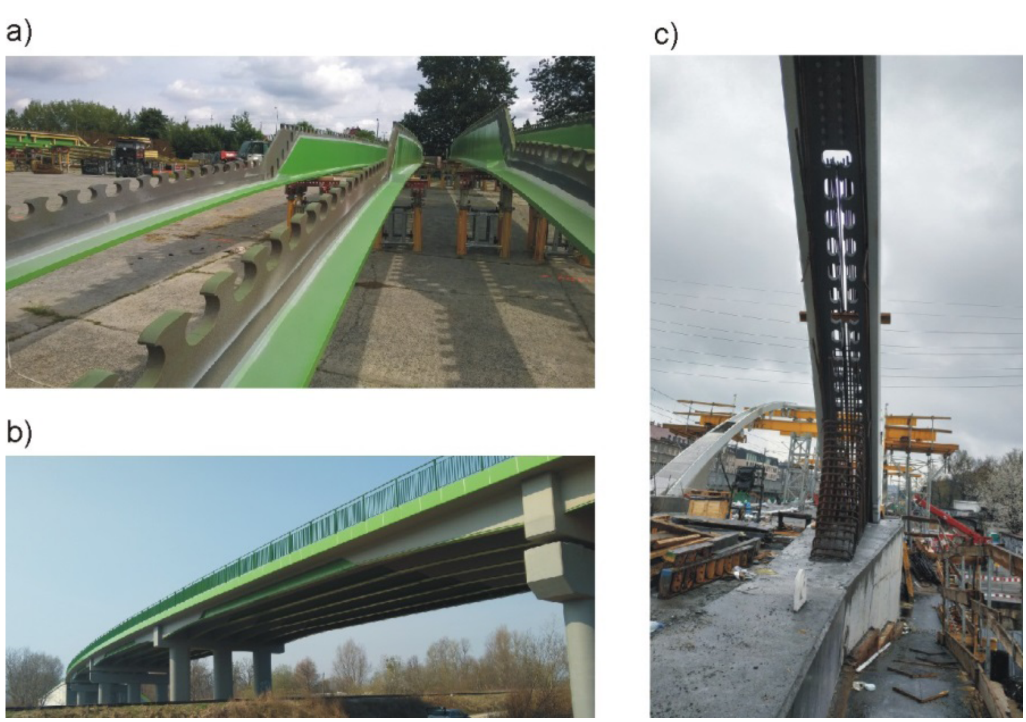

Figure 25: Implementation of composite dowels in innovative composite bridges in Poland: a) and b) implementation in beams – bridge in Elbląg (presented in [41]) and c) implementation in arches – a new solution as part of a network arch bridge using composite dowels [63].

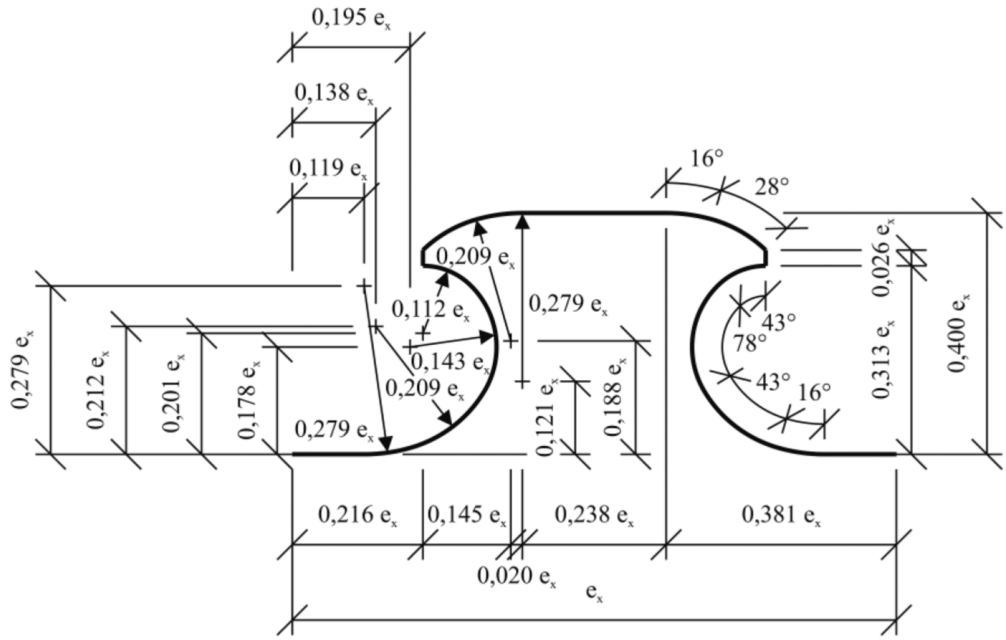

Figure 26: Nominal geometry of the modified clothoidal shape of a single connector MCL 100/250 according to [16] given as a function of the spacing of connectors e_x.

development of CLs, fabrication procedures, and design for fatigue. An extensive numerical analysis of this new form of CL using FE models of the steel part alone (in Code_Aster) has been conducted in France [4]. An extensive FE simulation of composite models using Abaqus and combined Polish and German results (elaboration of [30] during [7]) enabled the establishment of a coherent design procedure for a new shape [22,24]. The PZ shape has been out of the circle of interest for bridges since then, and searching for “the best shape” is over. Finally, a large number of R&D works have been conducted in Germany, especially the project [17] is important, and design guidelines have been proposed in Germany [16]. Similar tests conducted in Germany confirmed the Polish results; hence, independent verification was provided, and the results are reported in [3]. The nomenclature MCL appeared in some publications (e.g., important publication [22]), but the shape that is currently used in bridges is often called just a “CL.” This is because the initial form of CL was never used; hence, there was no need to distinguish CL/MCL. This is just to avoid confusion and to clarify to the reader that both symbols (CL/MCL) appear now in scientific papers, discussion, and design specifications. The CL applied in the first bridge (Fig. 16) was covered by a design procedure according to [8], and it was next used in bridges in Poland, but it evolved slightly later (modification implemented in Germany of “flattening” the shape) to its final form presented in Fig. 26 (to fit into “full” dimensions: 100 mm height instead of 115 mm height, but it resulted in slightly worse stress concentration factors). This modification was made while working on [16,17]. Some very important aspects concerning fabrication technology (regarding economy and easy production) appeared, and they were solved successfully during the production of the steel parts for different bridges by different steel producers (mainly, ArcelorMittal). The composite dowels for buildings can be done with CL, PZ, or other (logical) shape because the topic of shape is secondary for static loads. The formulas for concrete resistance differ very slightly for CL and PZ (and only for shearing criteria, which are usually not decisive in design). These two shapes (CL and PZ) are covered by technical approval in Germany [16] (the PZ geometry is not presented because it is not being used in bridges). Additional PZ will be covered by CEN-TS 1994-1-102 (PZT). Hence, there are three shapes being covered by detailed design rules of CEN-TS 1994-1-102: PZ, PZT, and MCL. The last one is dedicated for bridges.

Since approximately 2005, intensive research and development has started to establish the proper form of the new shear connection, named composite dowels, that enable direct connection of the steel beam web and the concrete slab. Composite dowels opened new possibilities for engineers designing composite structures, and they are the result of extensive international work. Basically, the PreCo-Beam project was about searching for the shape and learning the working principles of a new shear connection. The complicated process of development and evolution of the shape of the cutting line is presented in [57] and in this paper to enable a deeper understanding of the behavior of this new shear connection. Herein, the unpublished results of the NPOT study and information about the fabrication process of the MCL shape are presented. The appropriate papers are referenced to improve navigating a complex topic of composite dowels.

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