The behaviour of puzzle-shaped composite dowels — Part II: Theoretical investigations

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A B S T R A C T

Theoretical investigations of an innovative form of shear connection with puzzle-shaped composite dowels PZ300/100 are presented on the basis of the experimental study outlined in the companion paper — Part I: experimental study. Detailed FEM computations in ABAQUS were performed to analyse the behaviour of steel dowels under pressure in the entire loading range until failure. The contact behaviour between the steel and concrete part, the nonlinear material model curve for steel and the linear material model curve for concrete are assumed in the FE model. This virtual model is highly convergent with the experimental results in the entire loading range. The failure mechanism of steel dowels is explained and a standard nonlinear slip–force path for the PZ300/100 (Fig. 2) connector is proposed. A new model of the stress system in steel dowels at the stage of their ultimate limit is proposed. Although the tensile strength of the steel is a major factor influencing the ultimate bearing capacity of the dowel, it is suggested that the design approach based on yield strength is more adequate for steel dowels than the standard approach used for welded studs and based on the ultimate tensile strength. Finally a new connector characterization, consisting of three components: the slip–force dependence, a synthetic mechanical model and the stress system in the critical section of the connector was proposed. All the three components constitute a new approach.

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1. Introduction

A general introduction was presented in Part I, where one can find an outline of the history of the research in this field, a description of the PZ300/100 composite dowel and a programme of the tests and their results. This paper (Part II) presents a detailed analysis of the experimental results for the connector, taking into account the state of stress in the successive phases of the behaviour of the structure. The result of the research is a new characterization of the behaviour of the connector under loading. The finite element method, ABAQUS software [30] and the experimental results presented in Part I were used in the analysis. The experience gained in implementing another connector shape, referred to as MCL250/115, in bridge construction [28] was found to be valuable.

The design approach for composite dowels was introduced to a group of civil engineers in five European countries in the frame of workshops. It was widely discussed in the frame of Preco + dissemination knowledge international project [28]. It is already supported with national technical approval in Germany [35] and attempts have been undertaken for its introduction into Eurocode 4. A comprehensive analysis of state of the art, concerning the shape of dowels, and appropriate

references are presented in the companion paper (Part I). Hence one can investigate how concrete dowels developed towards composite dowels. In parallel semi-empirical design formulas for concrete, used in the past for the design of the perfobond strip, evolved to four design formulas in ultimate limit states [28] to be used for composite dowels. This included three basic formulas for concrete dowels (based on structural mechanics) [6] and a single design formula (A1) for steel dowels based on the approach presented in Ref. [7]. These are presented in Part I. The scope of the current paper is the steel failure mechanism. The design formula for steel failure at ultimate limit state (1) with factor $\beta_{pl} = 0.25$ presented in Ref. [28] remains valid in national technical approval in Germany [35]. It concerns a specific form of puzzle shape and specific form of modified clothoidal shape [35].

$$P_{Rd} = \beta \cdot t_w \cdot f_y / \gamma_v \qquad (1)$$

Formula (1) expresses the design resistance of one metre of connection by composite dowels with t_w demonstrating the thickness of the steel dowel, f_y standing for the yield strength of the steel, γ_v representing the partial safety factor (equal 1.25 according to Eurocode 4 [29]) and β showing the shape factor. The shape factor referring to the resistance of the unit length (one metre) of connection was introduced by Lorenc in Ref. [7]. It is useful for continuous shear connection by composite dowels, because the longer the dowels (hence bigger resistance than the single dowels), the smaller the amount of dowels appears

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considering the same length of connection and finally resistance of unit length of connection, which will remain similar considering the failure of steel dowels. Different shapes and sizes of dowels can be considered this way. This is the background of current design rules of composite dowels, considering steel failure in ultimate limit states, serviceability limit states and fatigue limit states [28]. The shape factor was initially denoted A_{el} in Ref. [7] if referring to the yielding of steel dowels at serviceability limit state (and hot spot stress category at fatigue limit state) and it was denoted A_{ult} in Ref. [7] if referring to the plastic resistance of steel dowels. A detailed study on the factor A_{el} is presented in Ref. [2] for modified clothoidal shape (MCL) and it is renamed to β in Ref. [5]. Using the FE model proposed in Ref. [7] it was proved by Kożuch [9], that factor β referred to plastic resistance of steel dowels is to be $β_{pl} = 0.254$ [5] if steel hardening is neglected (elastic perfectly plastic model of material), $β_{pl} = 0.344$ [5] if steel hardening is considered (however in a simplified manner) and this value coincides well with experimental results [5]. The point is that the mechanical model presented in Ref. [5] and proposed by Kożuch in Ref. [9] for modified clothoidal shape (Fig. 3b) is quite different when comparing it to the model proposed in Ref. [20] with the puzzle shape (Fig. 3a). The model proposed in Ref. [20] is still supported by a great deal of research nowadays for puzzle shapes [21] and for clothoidal shapes [35]. The models representing steel failure for MCL presented in Refs. [35] and [5] are different. The scope of this study is to present that the model proposed for the PZ shape is different when comparing it to Ref. [21]. It will lead to the conclusion that models for puzzle shapes (herein) and for clothoidal shapes [5] are quite convergent and they are based on a different approach and assumption in comparison to the models proposed by other researchers [21,35]. Moreover, the application of the safety factor with a value of 1.00 is discussed instead of the value of 1.25, which is currently used.

2. State of the art

2.1. Genesis of the PZ shape

This research concerns the PZ300/100 shape, where PZ stands for the puzzle shape of the dowel, the first number denotes the spacing between dowels and the second number stands for the height of the dowels [in mm]. Currently, the dowel shape most often used in new structures is MCL (Fig. 1) [31].

Fig. 1. Bridge girders with MCL250/115 dowels during construction of wildlife overpass PE4 over Olsztynek-Nidzica stretch of road S7 in Poland.

In Germany, the composite dowels have been formally approved for use in construction [26,27]. The MCL dowel in its specific form MCL 250/115 and its manufacturing technology were developed in Poland in 2008 for the construction of a railway bridge over the Łososina River on the Kielce-Fosowskie 2-track railway line no. 61 (the 23.093 km) [31]. The bridge design and its construction are described in detail in Ref. [32]. The prototype of dowel MCL250/115 was dowel CL proposed by Berthellemy [4], but because of the double cutting line (Fig. 2), no effective manufacturing technology was developed for it [1,4]. It was originally assumed that the PZ dowel behaves similarly as a cantilever. However, owing to the development of the connector's upper part (the SN- to-CL shape transition) the latter is fixed in concrete whereby better strength parameters are achieved. The use of terms like the "best" or "optimal" shape seems rather dubious, since the critical factors connected with fast and economical production technology need to be taken into account. The shape optimization problem is complex and multifaceted and considering the current state of knowledge, this research should rather focus on shapes suitable for particular applications in construction. The problem was extensively studied by an international team as part of the project [1]. Various shapes (Fig. 2) were considered and satisfactory strength parameter values were obtained for the PZ and MCL shapes [2].

2.2. Basis for dowel geometry optimization [7]

The aim of dowel shape optimization was mainly to minimize the notch effect on fatigue life. Fatigue cracking and crack propagation under cyclic loading for the PZ300/100 dowel were studied in Ref. [14]. A comparison with the fatigue test results for the MCL250/115 dowel [8] shows that the MCL shape is characterized by a longer fatigue life. However, a major factor is the cutting line, which has a direct bearing on the connector manufacturing technology. The latter is more complicated for the MCL shape than for the PZ shape (Fig. 2). The shear connection fatigue life considerations are the determining factor here [4]. There was a need to develop a coherent system for evaluating the suitability of different dowel shapes in terms of quality and quantity. Lorenc [7] proposed a new approach to the analysis of the steel dowel load-bearing capacity, in which the broadly understood dowel geometry problem was divided into the dowel front face shape (the key problem) and other proportions (the elementary problem). The proportions are defined as a ratio of dowel spacing to dowel height, e.g. 300/100 or 250/115, and they can be determined by FEM for any shape by maximizing the shear connection load capacity per unit length and adopting the value of the elastic state (principal or reduced) stresses in the critical point at the dowel base, as the criterion. In the elastic state, the stresses generated by the shear of the dowels and the normal stresses accumulate (in the cross section of the steel shape), which is effected by augmenting the stresses with stress concentration coefficients. On this basis, the concept of the design in the elastic state used in checking the serviceability limit state (though mainly in assessing fatigue) was developed [3]. In this approach, in the elastic state of the load capacity of a dowel with a given shape is described by two coefficients. Ultimately, attention focused on the PZ and MCL shapes, which, taking into consideration the material strength and the manufacturing technology, was assigned in proportions 300/100 and 250/115, respectively. The coefficients for the PZ300/100 dowel and for the MCL250/115 dowel are specified in Refs. [1,7] and [2,3] respectively. This dowel design concept could be developed after eliminating the dowel size problem from consideration. The experimental confirmation of this assumption was of key importance, as shown by the ultimate bearing capacity in Part I. For the elastic state, the assumption was proved using FEM in Ref. [7]. Moreover, a very simple model indicating the validity of this thesis was presented in Ref. [1]. As shown in Part I, in the case of a yielded connector in the ultimate limit state, the dowel size effect is reflected by ductility. This was taken into account in the model proposed in this paper.