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MODERN DESIGN OF STEEL-CONCRETE COMPOSITE STRUCTURES

Introduction

Due to the heavy emphasis on economic aspects of the newly designed buildings, newer solutions for structural construction are sought. One of the most desirable are solutions enabling to shorten construction time and to reduce the labour intensity of building process thanks to an increase in the level of prefabrication, smaller survey heights together with increased efficiency of its capacity usage at the same time. An achievement of these objectives is possible thanks to reduction of the material consumption as well as efficient optimization at the stage of forming the cross-sections and longitudinal shape, and the relevant technology choice. Willingness to meet market demands resulted in the development of steel-concrete composite structures which with their assumptions combine the advantages of concrete and steel, while eliminating the disadvantages of those two materials. Besides the material properties of steel, concrete and reinforcement, the capacity of composite element is also determined by the carrying capacity of shear connection, which should have sufficient strength and stiffness to limit the longitudinal slip between concrete and steel and the separation of one component from the other.

1. Different types of shear connectors

Mechanical connectors used in steel-concrete composite structure can be divided into two major types. The first one includes discrete connectors which are usually located along the girder. Each of this connectors was shop-welded for instance to upper flange of steel beam and after that got embedded in concrete on site. The block connectors, bar hoops or welded studs were shown in Figure 1 as an example of discrete connectors. Among all mentioned, the most widely used is the Nelson stud, which consists of a shank and a head which contributes to the shear transfer and prevents the uplift. Despite the fact that strength and stiffness of the discrete connectors, especially Nelson one, are well recognized and described in detail in codes and technical literature, they also have some drawbacks. Most of them present an important restriction due to time-consuming fabrication, not fully automatic installations and small carrying capacity under cyclic load.

Fig. 1. Examples of discrete connectors

The other type includes continuous types of shear connectors - group of members, formed in one piece, which were assumed to act as a continuous shearing medium along the beam. The first shear continuous shear connector was a perfobond-strip, which was a flat steel plate containing a number of holes [1]. This connector resisted horizontal shear and vertical uplift forces at the steel-concrete interface by using transverse rebars in the rib holes, concrete dowels and a concrete end-bearing zone [2]. After over ten years of doing research and trying to substitute or improve Leonhardt's connector, a European research project called PreCo-Beam has started [3]. It aimed to develop a solution of using prefabricated elements which would be both price-competitive to commonly used headed studs, durable, and appropriate for bridges and decks monolithically connected to substructure. The new form of shear transmission was found - the composite dowels. The role of steel girder changed from an independent structural I-beam element to a T-shaped beam with external reinforcement placed on tension side. It is produced by cutting a beam with a special determined curved cutting-line into two parts, which enables to reach fully automated structural fabrication. The most important thing offered by an innovative shear connection is the shape of cut web of the steel beam that obtains dowels in each part, because after concreting them into the slab, they would form mechanical connectors in concrete too. Neither for producing the steel element nor for placing the connectors welding is necessary. The production costs for steel girders can be reduced to 60% of those of welded steel girder with headed studs [4].

The composite dowels method is a very flexible one offering different cross--sections and dowels' shape geometries possibilities according to design requirements. These were the geometries which were of main interest in FEM simulations and destructive tests [3,6]. Among shapes considered for the analysis at the PreCo-Beam project puzzle (PZ), fin (SA), clothoidal (CL) and modified-clothoidal (MCL) dowel shapes were studied. According to the conducted analysis, the asymmetric fin-shape (SA) offers high load-bearing capacity but it depends on force direction and after forces being changed bearing capacities need to be reduced. In contrast, the puzzle (PZ) and clothoidal-geometry (CL/MCL) symmetrically shaped dowels have comparable bearing capacities for changing directions of forces. The modified clothoidal-shape (MCL) provides the highest fatigue resistance for cyclic loads thanks to the smooth cutting radius [3].

a)

b)

c)

d)

e)

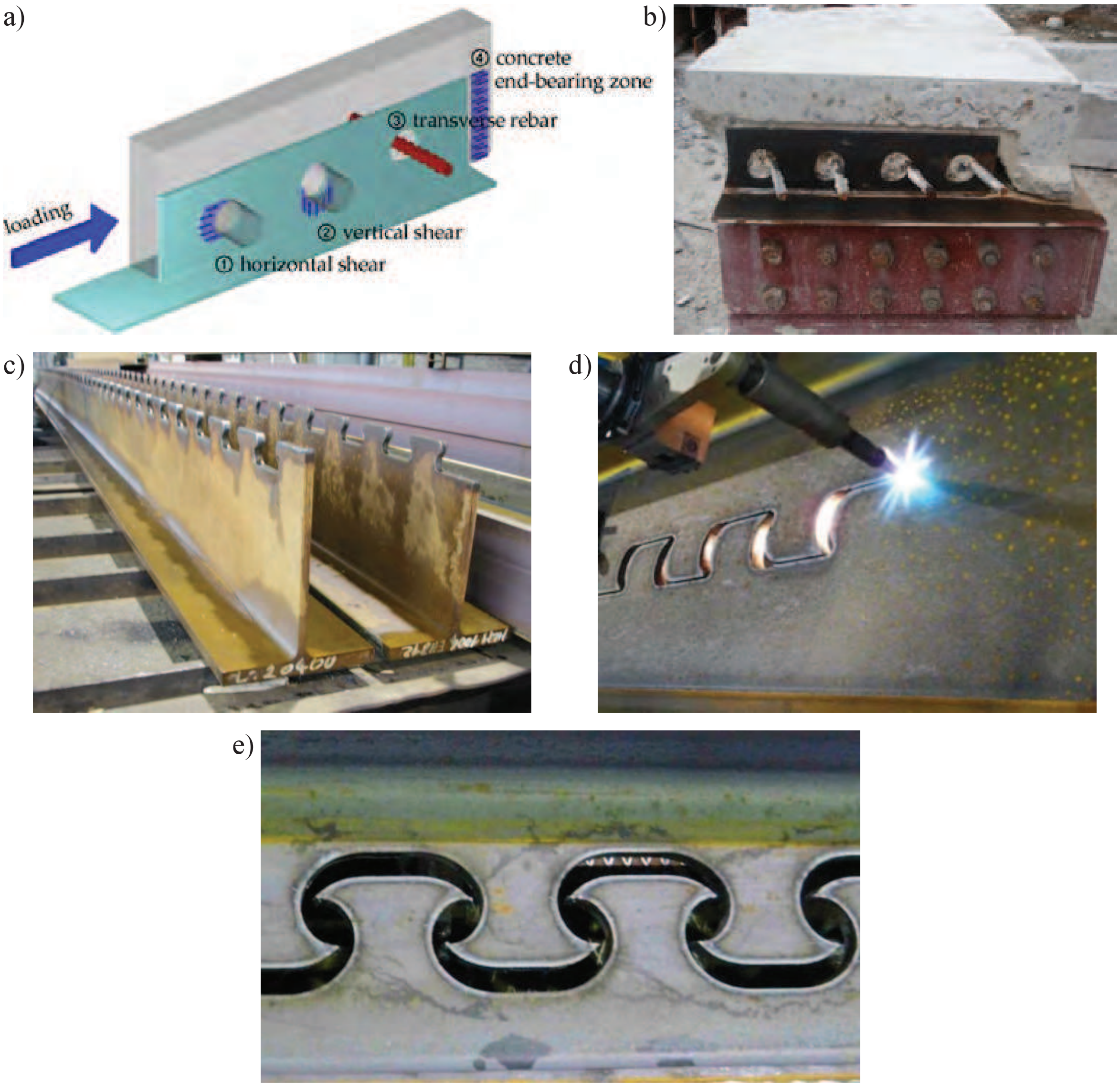

Fig. 2. Different kinds of continuous shear connectors: a) mechanical behaviour of a perfobond-strip shear connector [2], b) perfobond-strip [2], c) puzzle shape PZ [3], d) fin-shape SA [5], e) modified-clothoidal shape MCL [5]

2. Results of experimental investigations

Due to the fact that concrete dowels are formed in the recesses of the steel web, the area of concrete in a longitudinal section approximately corresponds to the area of steel. Hence the failure mechanism of both steel and concrete dowels occurs and should be checked during composite construction design process by meeting the guidelines and recommendations of code design [7, 8]. Based on the investigations of Wurzer [9], Zapfe [10] and Seidl [11] three main failure mechanisms of the concrete part are pointed out and described in empirical formulas for calculations. These are: exceeding of possible compression in the concrete dowel core, pry-out of concrete either below or above the dowel strip and shear failure of the concrete dowel. Which failure mode occurs depends on the boundary conditions like geometry, concrete grade or reinforcement design.

In case of low yielding strength and thin webs of the steel strip in combination with considerably high-strength concrete a steel failure is most likely to occur. Steel failure is limited in the ULS (Ultimate Limit State) by: the shear resistance (Fig. 3a), yielding due to bending of the dowel (Fig. 3b) and in the FLS (Fatigue Limit State) by fatigue cracks due to dynamic loading (Fig. 3c) [12]. The dowel base is for a steel dowel the critical region of stress concentration and fatigue crack initiation as assumed on the basis of experimental and FEA results [3, 7, 13] and shown in Figure 3. However, load-bearing capacity of the steel part, among the others with the connection using MCL shape is presented in [13-15].

Fig. 3. Failure modes for steel dowel [12]

One crucial aspect of the structural behaviour of steel dowels is superposition of two major components: local dowel action and stresses from global bending. The former one results from shear in the composite joint and the latter from bending of the beam (normal stresses in the web). In the case of a steel dowel located in a tension zone of the web, fatigue cracks initiated in dowel base would propagate through the web and possibly into the flange, which causes not only failure of the shear connection but, what is more, causes collapse of the whole composite beam. Hence new POST[1] specimens (NPOT) had to be developed to simulate the behaviour of a shear connector located in the tension zone (Fig. 4b). An additional steel part (Fig. 4a) is used, which changed the place of force application from the upper to the lower part of the specimen.

[1] POST - "Push-out Test" is one of the major tests conducted on steel-concrete composites for determining the shear connector capacity and load slip behaviour of the shear connector [PN-EN 1994-1-1].

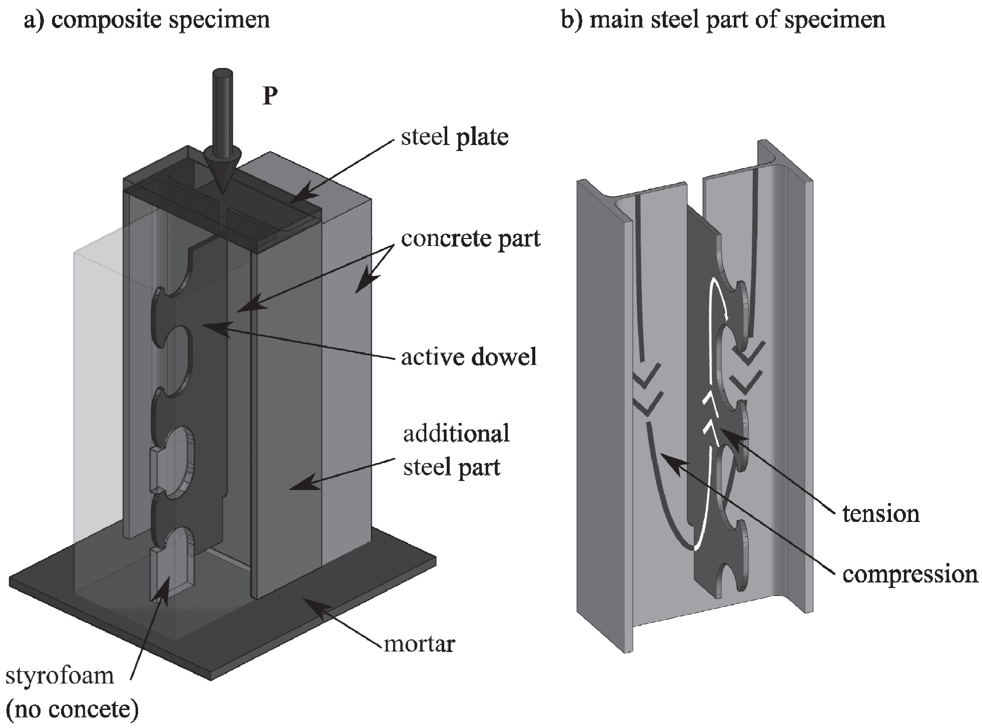

Fig. 4. NPOT specimen: a) schema of NPOT testing construction,
b) flow of internal forces

3. Construction of composite dowel connection

The composite dowels consist of different structural components described in Figure 5 interacting with each other to establish the bond between the compound materials-steel and concrete. Its main component is a steel dowel (1), which transfers the shear forces from steel part to the concrete one. The steel dowels have a substantially regular geometry, and repeat every e_x over the length of the beam (where e_x is the axial spacing between the dowels). In their constructions there are some characteristic points, for instance: dowel base (4), dowel core (5) and dowel top (7). The base (4) is located at the bottom of the steel strip and in the introduction zone of the first arc-segment turns into the dowel root (6). The dowel top (7) anchors the steel part in concrete and also prevents from uplift. The zone which introduces longitudinal forces from concrete to steel connector is at the dowel core (5). As an effect of high concentrated loads, there is a multiaxial compressive stress state in the dowel core. Between the adjacent steel dowels a concrete dowel is formed (2). Its geometry and longitudinal spacing e_x result directly from the shape of the steel dowel. The concrete dowel is typically reinforced with at least two transverse rebars (3). These rods are usually located in the middle of the concrete dowel. In addition to the reinforcement (3), the upper reinforcement (8) arranged above the steel dowel and confinement reinforcement (9) are used in the webs of a girder to prevent a pry-out failure and assure a ductile bearing behaviour [7].

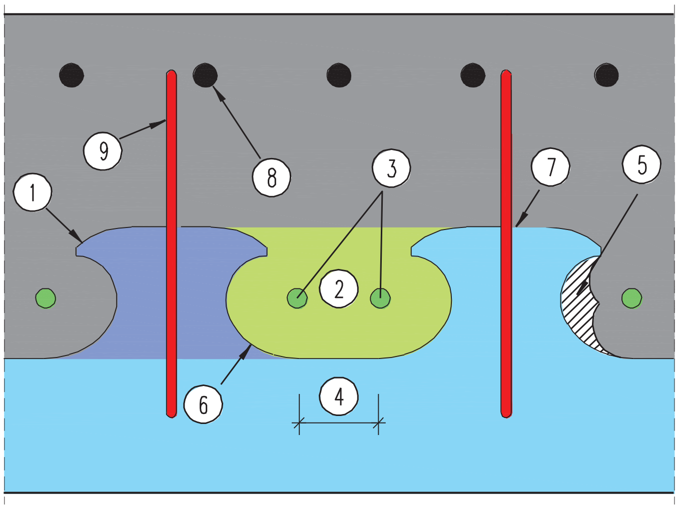

Fig. 5. Components of a composite dowel: 1) steel dowel, 2) concrete dowel, 3) reinforcement of concrete dowel, 4) dowel base, 5) dowel core, 6) dowel root, 7) dowel top, 8) upper reinforcement, 9) confinement reinforcement [7]

4. Current and future applications

Because of the numerous advantages of composite structures, including high strength to weight ratio, high slenderness, extreme durability, high level of prefabrication and hence high quality products, cost efficiency, applications of composite structures in civil engineering industry. Due to design flexibility and high-strength steel and concrete usage, there are lots of different composite members such as columns, beams, slabs and others. The innovative continuous shear connectors could be used in high point loaded multi-storeyed car parks and buildings such as apartment buildings or tower blocks. But the main field of their application, thanks to high fatigue resistance of structure, are highway and railway bridges. These examples include steel-concrete composite slabs, bridge span or rigid connections between pillar and beams. For railway bridges it is important to obtain a stiff structure with small deflection caused by high traffic loads to ensure a fixed position of the rail.

Several bridges have been already built successfully. Examples of realisation: Kuchl and Viagun Viaduct (Austria), Simmerbach and Pöcking (Germany), "Wierna rzeka" bridge, WD4 bridge with S5 expressway and ecological corridor over S7 expressway (Poland) are described in detail in (mentioning order) [7, 16-19, 20, 21]. One of the most recently built bridges was built in Romania between Orastie and Sibiu in the north of the South Carpathians (Fig. 6b). The bridge with its span over 39 m has a total height of beam which varies between 1.95 m at embedding and 1.65m at the key. In the central part of the bridge, where the concrete is compressed, the top flange is completely removed and the steel web of the beam is directly connected by CL-cutting to the longitudinal formwork-slab. The steel top flange is restored in the zone where the concrete works in tension (Fig. 6a). In these zones, the connection is ensured by two bands of CL-cuttings welded above the steel top flange [22].

a) b)

Fig. 6. Views of one of the bridges (photographs by Victor Schmitt): a) steel frames on site with CL-shape cuts and studs, b) terminated bridge [22]

Conclusions

In this paper, the actual solution used in composite constructions and their advantages are presented. Additionally, the main aspects in design and development of innovative continuous shear connection have been identified based on experimental investigation conducted in last years. Different realisations highlighted in article approved the effectiveness and cost-efficiency of innovative composite dowels continuous connectors.

a) b)

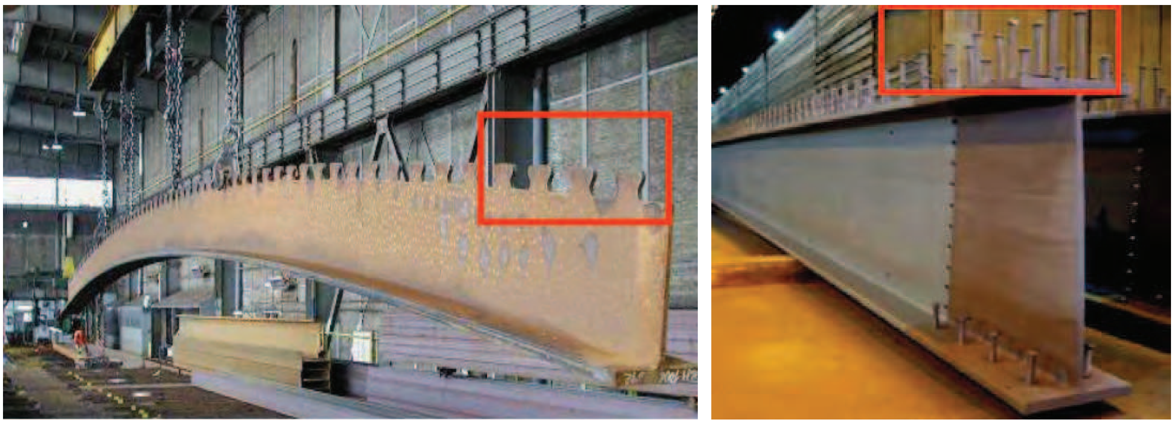

Fig. 7. There is only one remaining question: what to choose: 1 m long composite dowel or about 20 connectors? [23]

Composite constructions, such as the modular composition, move principal works for the structures from the site to the workshop. It also reduces the construction time and improves the quality to reduce maintenance costs. The developed and optimized shear connectors have become an alternative solution to commonly used Nelson studs. In spite of being more complicated from designer's point of view, because of a common problem for both steel and concrete construction which appears during the design phase, durability and strength advance it to a solution of great interest for the future.

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HUMAN CAPITAL
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Abstract

In this article, innovative approach for the design of steel-concrete composite structure and the development of continuous shear connector are described. The main purpose of this paper is to highlight the common aspects of an innovative system of prefabricated composite beams with various types of shear connectors and to review the papers and research reports with experimental analysis of composite dowels connection. The possible failure mechanisms related to steel and concrete part of composite construction are presented and the components of the composite dowels connection are discussed. Additionally, the various applications realized in different European countries over past few years are mentioned, showing clearly the interest in this technology among designers and investors. This paper introduces problem of composite construction design, however, the focus is on the steel part of shear connector design.

Keywords: composite constructions, composite dowels, shear connection, push-out test

Innowacyjne rozwiązania w stalowo-betonowych konstrukcjach zespolonych

Streszczenie

W pracy przedstawiono nowatorskie podejście do projektowania stalowo-betonowych konstrukcji zespolonych, opierające się na wykorzystaniu ciągłych łączników otwartych. Celem opracowania jest zaprezentowanie podstawowych cech innowacyjnego systemu prefabrykowanych belek zespolonych z zastosowaniem różnych typów łączników ścinanych, wykonanego na podstawie analiz artykułów i raportów z badań łączników composite dowels. Wskazano możliwe mechanizmy zniszczenia w odniesieniu do stalowej i betonowej części zespolenia oraz omówiono elementy składowe połączenia composite dowels. Opis uzupełniono przykładami obiektów wzniesionych w różnych państwach europejskich w ciągu minionych kilku lat, które wskazują na znaczne zainteresowanie tą technologią wśród projektantów i inwestorów. W artykule przedstawiono problematykę konstrukcji zespolonych, jednakże główną uwagę poświęcono części stalowej połączenia ścinanego.

Słowa kluczowe: konstrukcje zespolone, composite dowels, połączenie ścinane, próba POST