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CRACKING IN CONCRETE NEAR JOINTS IN STEEL-CONCRETE COMPOSITE SLAB

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Abstract

In this paper results of the experimental tests of four full-scale composite steel-concrete elements are reported. In the steel-concrete composite elements, a steel beam was connected with a slab cast on profiled sheeting, by shear studs. The end-plates were (the thickness of 8 mm, 10 mm and 12 mm) thinner than in ordinary design. Joints between the column and the beams have been designed as semi-rigid, i.e. the deformations of end-plates affect the distribution of forces in the adjacent parts of the slab. The paper presents the theory of cracking in reinforced concrete and steel-concrete composite members (according to the codes), view of crack pattern on the surface of the slabs and a comparison of the tests results and the code calculations. It was observed, that some factors influencing on crack widths are not taken in Eurocode 4 (which is based on Eurocode 2 with taking into account the phenomenon called „tension stiffening”).

Keywords: cracking, steel-concrete composite slab, semi-rigid joints

1. INTRODUCTION

Cracking phenomenon in reinforced concrete structures was noticed and considered by researchers at the beginning of the development of concrete structures. The first papers considering the extension of reinforced concrete and cracking date back to the turn of 19th and 20th century (e.g.: [3, 1]). Nowadays, the literature concerning this subject is very rich. Among the Polish investigations on problems similar to those examined in this paper, there are e.g.

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articles written by K. Furtak [4, 5] and an article written by K. Flaga, M. Pańtak [6].

The basic model used in the theory of cracking is an element subjected to axial tension, which can also be regarded as a model of tension zones in bending elements and eccentrically loaded elements with a tension zone [7]. It is assumed that the first crack is formed in the cross-section, in which the concrete strength will be the lowest. Then, the load increase causes additional cracks (at similar distances). In the section through the crack, the stresses in the concrete fall to zero and, on both sides of cracks, so called "relaxation zones" are formed. The stresses in this part of the concrete are too small to cause the appearance of the next crack. To both sides of the crack the load is partially transmited to the concrete. It is assumed that after reaching the stage of stabilized cracking, load increments do not cause any new cracks but only an increase in width of existing cracks. Cracking model used to calculate the width of the cracks is shown in Fig. 1. It was derived from [7].

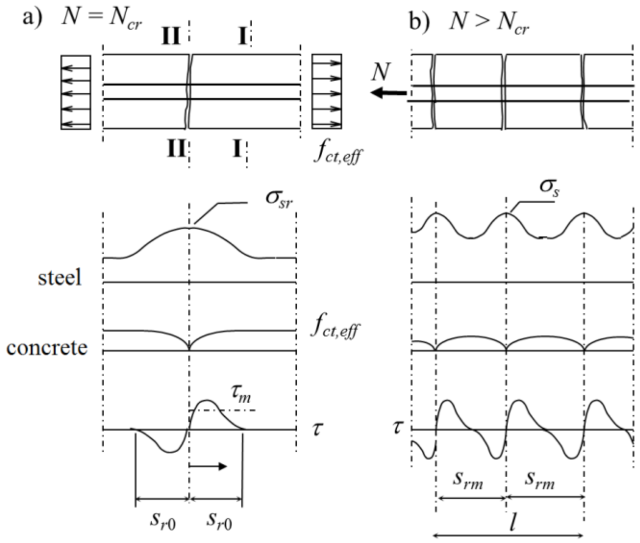


Fig. 1. The model of cracking in the reinforced concrete element under tension at the time of the appearance of the first crack (a) and at the stage of stabilized cracking (b) [7]

2. CRACKING EFFECT ACCORDING TO STANDARDS

Until the eighties of the twentieth century, problems of composite structures had not been reflected in the Polish standardization. The first standard for the design of composite steel - concrete structures was developed and established between 1982 and 1991 [10, 11, 14]. In 2006, a new standard for design of composite steel - concrete structures [12] was released that replaced the previous three standards. It was based on the provisions of the Eurocode 4. In addition to the principles of design of beams and columns, this standard contained information and guidance on how to analyze the structure, how to design composite slabs on steel decking and composite connections, how to test connectors and composite slabs and how to design elements due to the fatigue. This standard was replaced in 2008 by PN-EN 1994-1-1:2008 Eurocode 4 [16].

Until 2006, the Polish standards for composite structures had used a theory for design of cracking in reinforced concrete structures drawn from standards prior to the first Polish standard containing provisions of the Eurocode (1999) [9]. As in the current standards, crack width was calculated as the product of the average strain of the reinforcement and a distance between cracks. Characteristic feature of the older standards is factor called Ψ_a, determining the ratio of average strains of the reinforcement to the maximum strains occurring in cracks.

For the first time the theory based on the Eurocode appeared in 2006 in the standard for design of composite structures. According to [13] the width of the cracks was tested in compliance with the standard [10]. Concepts of the effective tension area and "tension stiffening" taken from Eurocode were established.

"Tension stiffening" phenomenon involves the fact that the average strain of the reinforcement is smaller than the strain calculated from the stress achieved in the crack. In order to reduce the crack width to its width limit and avoid uncontrolled cracks between rarely spaced bars, it must be assured that at the time of the first crack appearance, reinforcement remains in its elastic state and a distance and a diameter of the bars are limited.

According to the current standard [16] the width of the cracks can be evaluated using [15] with regard to the phenomenon of "tension stiffening". Tensile stresses in the reinforcement can be determined from the following formulas:

$$\sigma_s = \sigma_{s,0} + \Delta\sigma_s \tag{2.1}$$

$$\Delta\sigma_s = \frac{0{,}4 f_{ctm}}{\alpha_{st}\rho_s} \tag{2.2}$$

in which f_{ctm} is the average tensile strength of concrete, α_{st} is the ratio of the product of the cross-sectional area and the moment of inertia of the effective composite section excluding the tension concrete and profiled sheet (if any) to the product of the sectional area and the moment of inertia of the composite section, and ρ_s is the degree of reinforcement in the element. Formulas (2.3) and 2.4) are used to calculate the spacing and width of cracks:

$$w_k = s_{r,\max}\left(\varepsilon_{sm} - \varepsilon_{cm}\right) \tag{2.3}$$

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \dfrac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \text{, but not less than } 0{,}6\frac{\sigma_s}{E_s} \tag{2.4}$$

in which s_{rmax} is the maximum crack spacing, ε_{sm} is the average strain of the reinforcement, ε_{cm} is the average strain of the concrete between the cracks, k_t is a coefficient depending on the duration of the load, $\rho_{p,eff}$ is the ratio of area of tension reinforcement to the effective tension area of concrete around the reinforcement, α_e is the ratio of the modulus of elasticity of reinforcement to the modulus of elasticity of concrete, a E_s is the modulus of elasticity of reinforcement.
If in the tension zone spacing of the reinforcement, with a bond to the concrete, is not higher than $5(c+\phi/2)$), the maximum final crack spacing can be calculated as:

$$s_{r,\max} = k_3 c + k_1 k_2 k_4 \frac{\phi}{\rho_{p,eff}} \tag{2.5}$$

In (2.5) k_1, k_2, k_3, k_4 are coefficients given in [15], c is the concrete cover.

3. PROGRAM AND COURSE OF INVESTIGATIONS

Experimental tests were carried out in the laboratory of the Institute of Building Engineering at the Faculty of Civil Engineering at Warsaw University of Technology. The summary of data analyzed in this paper is given in Table 1. Moreover, tests of the following materials - concrete, structural steel and reinforcing steel were made.

Table 1. The summary of data

Name of the specimen	Reinforcement	Number of bolts	Thickness of the end-plate [mm]
EZ5	6ø12	4 M20	10
EZ6	6ø12	6 M20	10
EZ7	6ø12	6 M20	8
EZ8	6ø12	4 M20	12

Specimens consisted of a composite slab on profiled sheet (the trapezoidal steel sheets with open ribs and specific embossment for composite slabs - Cofraplus 60, fold spacing 207 mm) attached to steel beams by shear studs (Ø19x100 mm, spacing 207 mm). The steel beams were attached to a steel column through the flush end-plate (elements EZ5, EZ8) or the extended end-plate (elements EZ6, EZ7).

Longitudinal reinforcement of the slab consisted of 6 rebars (steel BSt500S) with a diameter of 12 mm (1.37% degree of reinforcement) arranged for three on both sides of the beams. The longitudinal rebars are connected together by transverse bars made of mild steel (steel S235JR) of a diameter of 6 mm, placed at a spacing of 103.5 mm (two bars in each fold). The slab was made using concrete class C25/30. The view of the element and the arrangement of measuring equipment is shown in Fig. 2. The view of the slab surface, the reading levels of crack widths and the location of the strain gauges on the reinforcement is shown on Fig. 3. Detailed information can be found in [8] and [2] (PhD thesis made under the supervision of prof. M. Giżejowski).

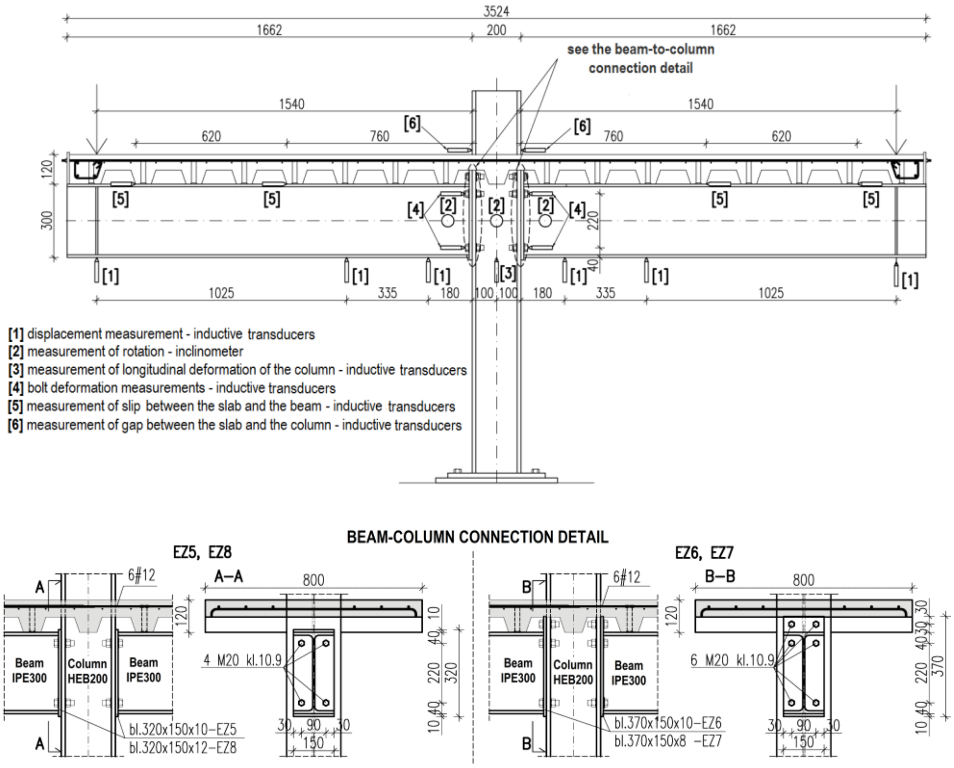


Fig. 2. Scheme of the tested elements

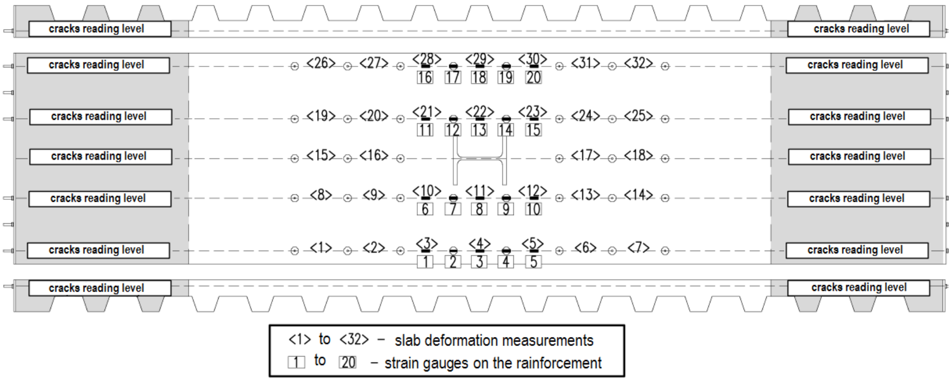


Fig. 3. The view of the tested slab - the distribution of benchmarks on the slab surface, the strain gauges on the reinforcement and crack width reading levels

In order to permit reading the strains in the reinforcement directly in a crack in the axis of symmetry, an "artificial crack" - thin oiled sheet forcing a discontinuity of slab was introduced (Fig. 4).

Fig. 4. The view of the "artificial crack"

The detailed description of the tested elements and methods of measurement is presented in [8].

4. RESULTS

The greatest widths achieved the cracks extending over the entire width of the element, in the direct vicinity of the column and the cracks extending from the corners of the columns. Each crack, from the moment of appearance, crossed the entire thickness of the slab. It was due to the fact that the entire slab was in tension zone. Fig. 5 shows the view of cracks on the surface of the slab directly before failture.

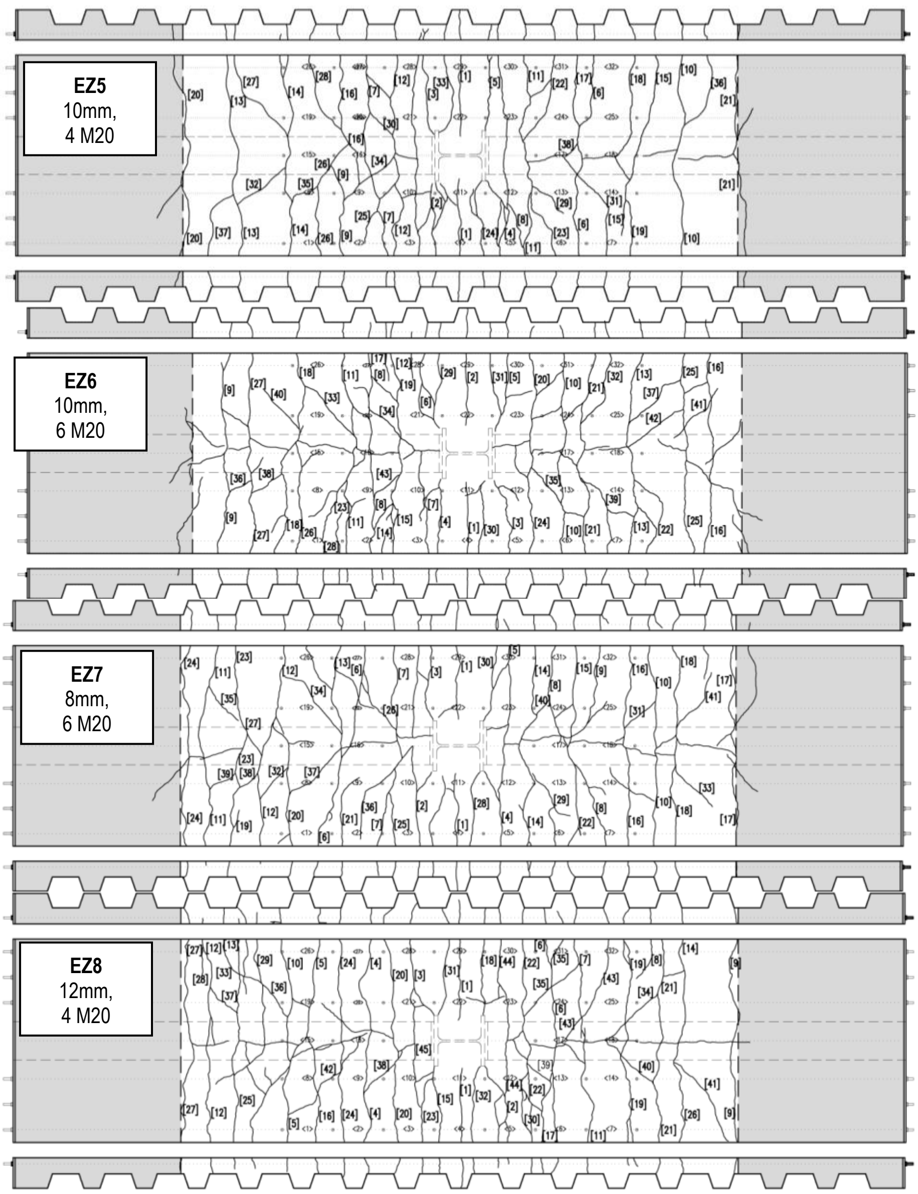


Fig. 5. The view of cracks on the surface of the slab directly before failture

5. ANALYSIS OF THE RESULTS

In order to analyze cracking, the slab was divided into three zones shown in Fig. 6.

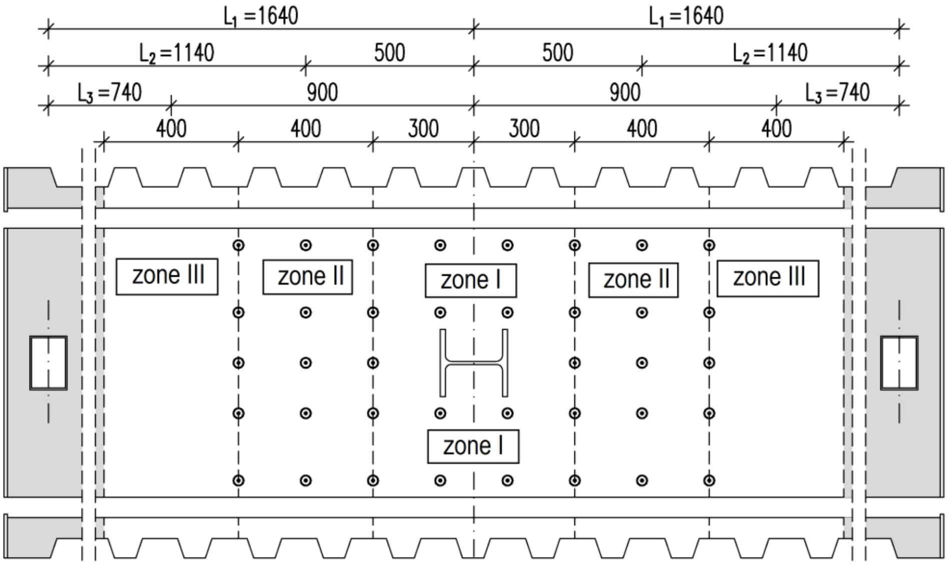


Fig. 6. The division of the slab into zones for analysis cracking

Fig. 7 and Fig. 8 show the average crack spacing depending on the load. The graphs present values calculated according to [15] (marked as $s_{rm,standard}$) and values characterizing the shape of the sheet - the spacing between folds (equal spacing of shear studs) and the spacing of the thinner parts of the slab, equal to the half of the distance between the folds.

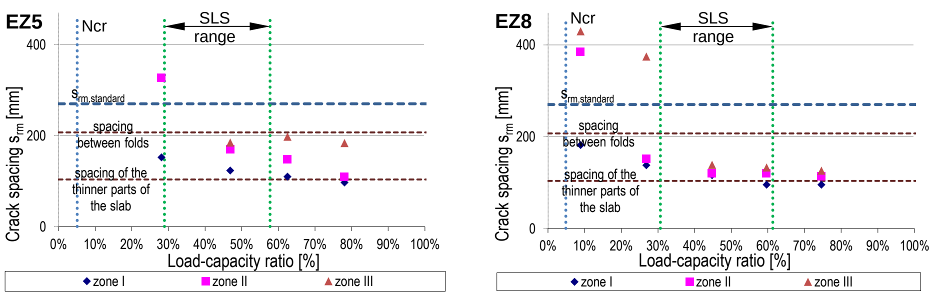


Fig. 7. The average crack spacing - specimens with the flush end-plate connections

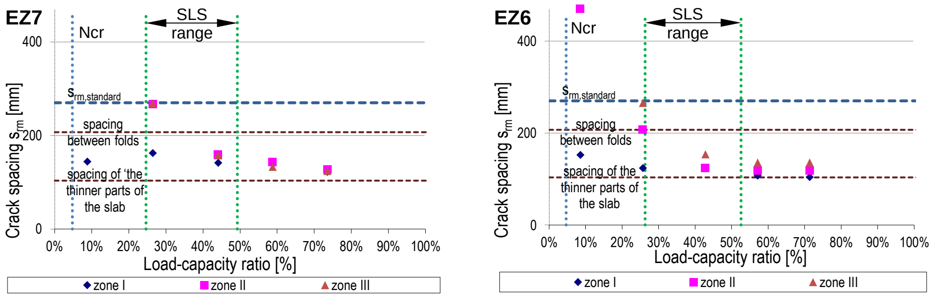
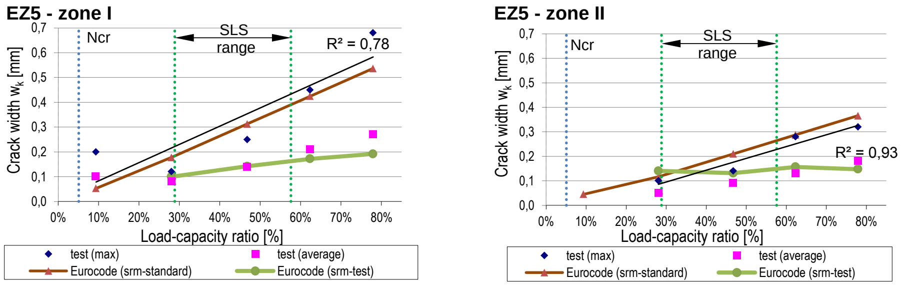


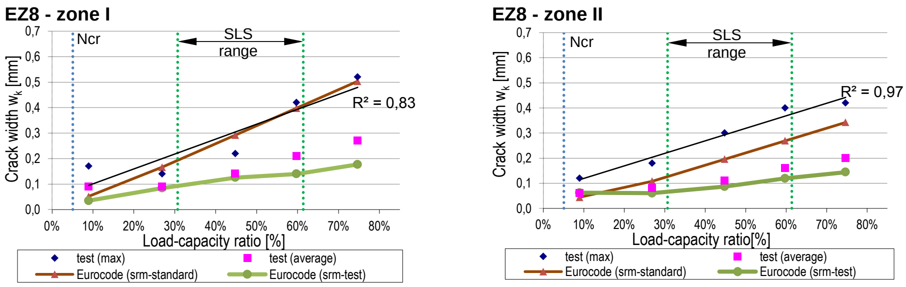
Fig. 8. The average crack spacing - specimens with the extended end-plate connections

It was noticed (Fig. 5) that cracks were formed principally at the interface between the slab and the rib and their spacing was similar to the spacing of the thinner parts of the slab. The summary of crack widths is shown in Fig. 9 and Fig. 10. The figures show the crack widths calculated in accordance with current standards. Calculations were carried out in two options: using the crack spacing in accordance with the formulas given in the standard (Eurocode (srm-standard)) and using the crack spacing obtained from the tests (Eurocode (srm-test)). In the graphs a trend line was plotted, showing the growth of the crack width in the range of the elastic reinforcement behaviour as well as the measurement of fit to the trend line (R^2). Considering the limit state of cracking, the long-term load is analyzed, which typically ranges from 40% to 80% of the design resistance of the element (calculated by using of the design values of the strength of materials), which corresponds to 24% to 62% of the failure load obtained from the investigations. This load range was marked on the charts as 'SLS range'.

During the tests, it was observed that the first cracks appeared earlier than it would be expected, calculating the cracking moment with the use of the concrete tensile strength obtained from the tests. The composite slab connected with a steel beam and sheet has no freedom of shrinkage deformation. Therefore, during the drying of concrete mixture, tensile stresses and cracks appear in the slab. It seems that due to this phenomenon, in the calculation of stresses in the reinforcement of the composite structures, a smaller value of the tensile strength of concrete should be taken into consideration (f_{ctm} is present in the formula for the stresses in the steel taking into account the phenomenon of 'tension stiffening'). In these calculations, after the comparison with the stress calculated using the balance of the joint and $\Delta\sigma_s$ addition, a good agreement with the experimental results was obtained, after taking the concrete tensile strength at the level of 50% of the splitting tensile strength.

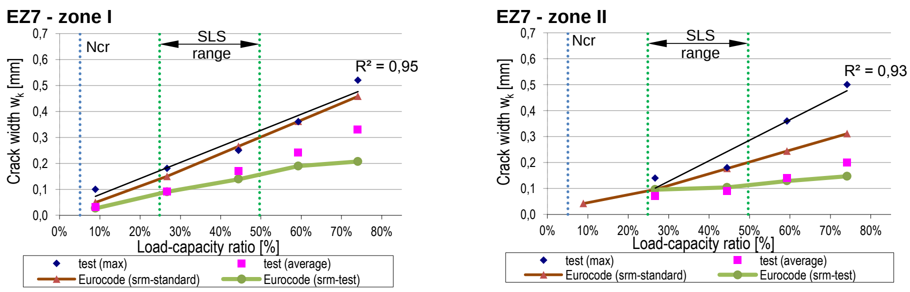


flush end-plate 10mm, 4 M20,

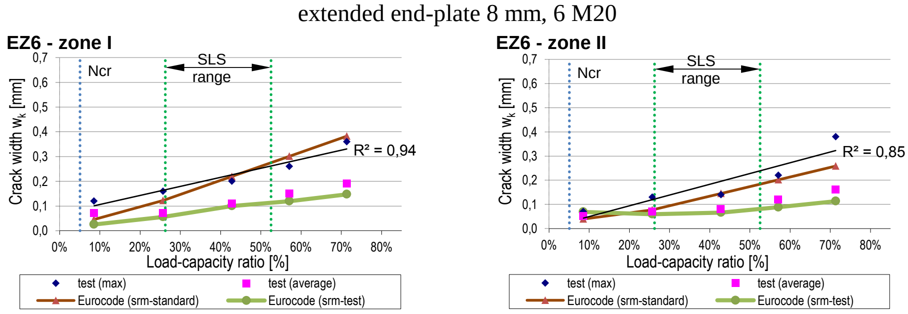


flush end-plate 12 mm, 4 M20,

Fig. 9. The crack spacing - specimens with the flush end-plate connections



extended end-plate 8 mm, 6 M20



extended end-plate 10mm, 6 M20

Fig. 10. The crack spacing - specimens with the extended end-plate connections

6. SUMMARY AND CONCLUSIONS

In the specimens with the flush end-plate and 4 M20 bolts, influence of the end-plate thickness on the crack width became significant only in the case of the maximum crack width in zone II (away from the joint). For elements with the extended end-plate, slightly wider cracks (either maximum or average) were observed while using thinner end-plates. Analyzing the influence of the number of bolts (at a constant thickness of the end-plate) on crack width it can be observed that in the case of the flush end-plate and 4 M20 bolts maximum cracks, located in zone I, were slightly wider than for the element with the extended end-plate. However, in the case of maximum crack width in zone II and the average crack widths in zones I and II, there was no such influence.

The crack width depends on the spacing of cracks in the final stage of stabilized cracking. The standard [16] does not provide additional guidance related to the composite slabs on steel decking, refering a designer to [15], which refers to the reinforced concrete slabs. In fact, in addition to the factors listed in the standard, the final crack spacing in a composite element is also affected by the shape of the steel sheeting (distance between folds), the ratio of the thickness of the concrete slab above the fold to the thickness of the concrete in the fold and a spacing of shear connectors assuming composite action between the slab and the beam. In the analysed elements, fold spacing effect on the crack spacing was observed. In all investigated elements the same steel decking was used, which did not allow to wider recognition of this phenomenon. Better compatibility between the calculated crack width and crack width determined experimentally is obtained by substituting in the calculation of the crack width, the standard value of crack spacing, different from that obtained in the study.

In the calculation of reinforced concrete structures, it is assumed that the ratio of the maximum crack width to its average value is 1.7. In the studied composite elements, the ratio ranged from 1.5 to 2.3 (average 1.8) in zone I and from 1.6 to 2.8 (average 2.1) in zone II. The seemingly greater difference between the maximum and the average crack width in zone II than in zone I is due to a greater difference between the bending moment at the beginning of the zone and the bending moment at the end of zone II (42%) than in the case of zone I (22%).

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ZARYSOWANIE PŁYTY ŻELBETOWEJ W STREFIE PRZYWĘZŁOWEJ STROPU ZESPOLONEGO

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań czterech elementów zespolonych. Kształtownik stalowy połączony był z betonowym stropem wykonanym na blasze fałdowej. W modelu zastosowano cienkie blachy czołowe (o grubości 8 mm, 10 mm i 12 mm), cieńsze niż zwykle przyjmowane w praktyce projektowej. Połączenie to zaprojektowano jako podatne tzn. takie, w którym odkształcenia blach czołowych mają istotny wpływ na rozkład sił w połączeniu. Przedstawiono normową teorię dotyczącą zarysowania elementów żelbetowych i zespolonych, obraz zarysowania stropu oraz porównano otrzymane wyniki z obliczeniami wykonanymi wg aktualnych norm. Zauważono, iż nie wszystkie czynniki obliczania szerokości rys w konstrukcjach zespolonych są zdefiniowane w normie projektowania konstrukcji zespolonych (która w tej kwestii odwołuje się do normy projektowania konstrukcji żelbetowych z uwzględnieniem zjawiska „tension stiffening”).

Słowa kluczowe: zarysowanie, strop zespolony, węzły podatne

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