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SPECIAL SECTION

The influence of a polyurea coating on bent reinforced concrete beams with various reinforcement ratios

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Abstract. "Polyurea coatings as a possible structural reinforcement system" is a research project aimed at exploring possible applications of polyurea coatings for improving structural performance (including steel, concrete, wooden and other structures used in the construction industry). As part of the project, this paper focuses on evaluating the performance of bent reinforced concrete (RC) beams covered with a polyurea coating system. Easy polyurea application and its numerous advantages can prove very useful when existing RC structural elements are repaired or retrofitted. Laboratory tests of three types of RC beams with three different longitudinal reinforcement ratios were performed for the purposes of this paper. The tests were designed to determine the bending strength, performance and cracking patterns of the coated RC beams. In addition, a theoretical model was developed to predict the impact of the polyurea coating on the bending strength of the RC beams. On this basis, the effect of the coating on the bending strength and the performance of the coated beams at the ultimate limit state (ULS) was examined and analyzed. The results showed that the use of the polyurea coating has a positive impact on the cracking state of the RC beams subject to bending and little effect on their bending strength

Key words: reinforced concrete beams; polyurea; cracks; durability of reinforced concrete elements.

1. INTRODUCTION

Reinforced concrete (RC) beams are widespread in existing and designed building structures and are frequently used under severe operating conditions, which is why research work has intensified and new materials have been introduced to produce and protect such parts of building facilities. Civil engineers commonly select RC elements to construct both traditional buildings and bridge structures, including various and even very unusual structural arrangements. The performance and aesthetic qualities of RC elements often degrade for a number of internal and external reasons such as a change in the arrangement and level of service loads, the extension of service life, a change in the occupancy or an unexpected change in service conditions. If that is the case, such structural elements should be repaired, reinforced or replaced with new ones to increase their strength and service life. Traditionally, the reinforcement of RC beams has been achieved by reducing internal forces or increasing the load-carrying capacity of a component. To improve its load-carrying capacity, suitable reinforcement techniques are used such as extending the cross-section, prestressing and mounting external steel elements or carbon fiber tapes [1–4].

As an alternative to traditional ways of reinforcing RC elements, polyurea coatings can be applied for this purpose. Although this system is mainly used to increase resistance against external factors, it can also improve the durability, elasticity and bending strength of concrete components. The clear advantage of polyurea is the fast process of preparing the substrate and applying the membrane that effectively protects RC elements. This system can significantly speed up the process of repairing a structure and reduce the workload required to improve the performance of existing RC structures [5–7].

The polyurea coating system was invented in the 1980s in the United States. Polyurea is the reaction product of two components: isocyanate and resin blend. The finished product has a chain structure, good durability and good elasticity with many methods of application in the construction industry. Polyurea coatings have been commonly used to increase the resistance of concrete and RC structures against corrosion and the adverse impacts of water [5–7].

Research on polyurea, which started at the turn of the 21st century, included an analysis of the basic properties of this material. Studies [8–12] focus on analyzing the basic properties of the polyurea, mainly its elasticity. Articles [13–16] describe the coating properties in various ambient conditions (for example high temperature). In another series of papers, possible applications of composite materials in ballistic equipment are described. Papers [17–21] analyze the effect of polyurea on elements of ballistic systems (such as protective helmets or aluminum and steel plates). Articles [22–26] focus on how polymer products protect unusual structural elements against the effect of an explosion.

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In contrast to numerous studies on the properties of polyurea coatings, only a few articles that focus on the use of this coating to improve the properties of structural components can be found in the literature. Articles [27–34] show the results of studies on the effect of polyurea applications on the performance properties of chosen components used in the construction industry (such as concrete rings, wooden connections, steel plates, water pipes and RC beams).

However, the known papers provide no general explanation as to how the use of a polyurea impacts the performance properties of reinforced concrete components. The present paper aims at extending this knowledge by providing more information on how the application of polyurea coatings impacts the performance of bent RC beams. Tests of RC beams with various longitudinal reinforcement ratios were carried out to analyze how the use of an external layer of a polyurea coating influences the bending strength of such elements.

2. MATERIALS

2.1. Polyurea

Polyurea coating is the reaction product of an isocyanate component and a resin blend component mixing at a high temperature (between 65°C and 80°C) and at high pressure (between 120 bar and 200 bar). This coating is an elastomer that is derived from the chemical reaction – polyaddition of an isocyanate component (aromatic or aliphatic) and multifunctional amine.

The final product has good chemical and water resistance, a very short time of bonding and good elasticity. Polyurea exhibits extremely high adhesion to many materials (such as steel, plastics, wood and concrete) [5–7].

In the tests, aromatic polyurea was used as the most common type of coating utilized in the construction industry. The product supplied was used to produce specimens in order to determine the basic properties of polyurea and to apply them on reinforced concrete beams.

The basic properties of the coating were obtained in a static tension test according to EN ISO 527:2012 [35]. All the tension tests were carried out using the INSTRON 5582 tensile tester (INSTRON, Norwood, USA). The results of the polyurea coating tension tests are listed in Table 1. The coating tensile strength was 24.08 MPa with an engineering strain of 417% at a test speed of 50 mm/min and 23.03 MPa with an engineering strain of 391% at a test speed of 100 mm/min (Table 1).

Polyurea coatings are resistant to high and low temperatures. Final products do not soften at higher temperatures and remain plastic at low temperatures. The glass transition temperature of the final product is $T_g = -45$°C [5,7].

Table 1
Strength properties of a polyurea coating

Test speed (mm/min)	Number of tests (–)	Tensile strength (MPa)	Engineering strain (%)	Young's modulus (MPa)
50	5	24.08	417	39.95
100	5	23.03	391	44.76

Polyurea coatings can be safely used (without significant changes in their properties) under the following conditions [5,7]:

- In a dry environment, at temperatures up to +120°C.
- In a wet environment, at temperatures up to +60°C.

2.2. Concrete

The concrete mix used in the tested beams was made of pit sand, gravel of grain size 2–8 mm and 8–16 mm, Portland cement CEM I 42.5 (pure Portland cement without any additives – class of 42.5), water and certain concrete admixtures. The main components of the mix per 1 m^3 of concrete are listed in Table 2.

Table 2
The summary of the main components of the concrete mix

Component (–)	Amount per 1 m^3 (kg)
Sand (0–2 mm)	610
Gravel (2–8 mm)	470
Gravel (8–16 mm)	690
Cement CEM I 42.5	400
Water	100
Admixtures (plasticizers)	3.3

While the RC beams were concreted, eighteen cube-shaped specimens of side 150 mm were produced (for each series of RC beams separately). The samples were used to determine the strength properties of the concrete according to EN 12390-3:2019 [36] and EN 12390-6:2011 [37]. The results of the concrete strength tests are listed in Tables 3–5.

Table 3
Basic strength properties of the concrete in the 1st series of RC beams

Specimen number (–)	Specimen dimensions (mm)	Compression strength (MPa)		Tensile splitting strength (MPa)	
		Result	Average	Result	Average
01	150 × 150 × 150	71.01	72.35	–	–
02	150 × 150 × 150	72.56		–	
03	150 × 150 × 150	73.49		–	
04	150 × 150 × 150	–	–	3.54	3.63
05	150 × 150 × 150	–		3.83	
06	150 × 150 × 150	–		3.50	

Table 4

Basic strength properties of the concrete in the 2nd series of RC beams

Specimen number (–)	Specimen dimensions (mm)	Compression strength (MPa)		Tensile splitting strength (MPa)	
		Result	Average	Result	Average
01	150 × 150 × 150	65.48		–	
02	150 × 150 × 150	70.91	68.54	–	–
03	150 × 150 × 150	69.22		–	
04	150 × 150 × 150	–		3.71	
05	150 × 150 × 150	–	–	4.04	3.70
06	150 × 150 × 150	–		3.35	

Table 5

Basic strength properties of the concrete in the 3rd series of RC beams

Specimen number (–)	Specimen dimensions (mm)	Compression strength (MPa)		Tensile splitting strength (MPa)	
		Result	Average	Result	Average
01	150 × 150 × 150	66.23		–	
02	150 × 150 × 150	69.60	64.69	–	–
03	150 × 150 × 150	58.23		–	
04	150 × 150 × 150	–		3.61	
05	150 × 150 × 150	–	–	3.83	3.60
06	150 × 150 × 150	–		3.36	

2.3. Reinforcing steel

The upper longitudinal reinforcement of the RC beams (for each series) was made of #10 mm steel rebars (B 500 B), with the lower one made from #14 mm steel rebars (B 500 B) and the transverse reinforcement in the form of stirrups made from #6 mm rebars (B 500 B).

All rebars were made of A-III ribbed steel. Mechanical tests of steel rebars were determined according to EN ISO 15630-1:2019 [38]. The results of the strength properties of reinforcing steel are listed in Table 6.

Table 6

Basic strength properties of reinforcing steel

Rebar diameter (mm)	Number of tests (–)	Lower yield stress (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
#6	6	520.80	584.07	199.90
#10	6	535.10	647.60	200.57
#14	6	508.68	611.10	204.52

2.4. Reinforcing concrete beams

In total, eighteen RC beams made of concrete characterized in Section 2.2 were subjected to laboratory bending tests. All the RC beams were reinforced with two #10 mm rebars in the upper area (the compression zone). In the lower area (the tension zone), the beams were reinforced with two (beams B.2.../P.2...), three (beams B.3.../P.3...), and four (beams B.4.../P.4...) #14 mm rebars. The transverse reinforcement of all the RC beams was made of #6 mm rebars in the form of stirrups with the spacing of 15 cm (beams B.2.../P.2... and B.4.../P.4...) and 20 cm (beams B.3.../P.3...) at the midspan and with smaller spacing in support areas. The dimensions and arrangement of the reinforcement used in the RC beams are shown in Fig. 1.

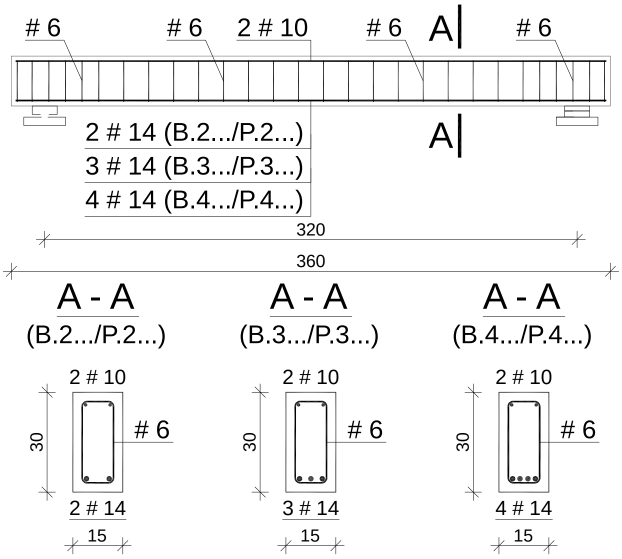

Fig. 1. Dimensions and arrangement of rebars in the RC beams (dimensions in cm)

The bending reinforcement ratio (ρ_s) is defined as the ratio of the area of the longitudinal reinforcement under tension (A_s) to the cross-sectional area of the bent beam (A_c) by the formula:

$$\rho_s = A_s / A_c . \tag{1}$$

The RC beams divided into test series are listed in Table 7 with descriptions of the reinforcement and the longitudinal reinforcement ratios according to the above definition.

Each series of RC beams (consisting of six elements) were divided into two batches. Three specimens comprising the first batch were marked as control specimens and had no polyurea coating. Three specimens of the second batch were polyurea-coated on all of their outer surfaces.

The three RC beams of the second batch were polyurea-coated on all of their outer surfaces. The diagram is shown in Fig. 2.

The polyurea application process involved three main phases: surface preparation of the RC beams, prime coat application and polyurea coating application. The process of preparing the

Table 7
Description of test specimens

Parameter	Series no 1		Series no 2		Series no 3	
	Control batch	With polyurea	Control batch	With polyurea	Control batch	With polyurea
Beam designation	B.2.1 B.2.2 B.2.3	P.2.1 P.2.2 P.2.3	B.3.1 B.3.2 B.3.3	P.3.1 P.3.2 P.3.3	B.4.1 B.4.2 B.4.3	P.4.1 P.4.2 P.4.3
Number of elements	3	3	3	3	3	3
Coating thickness*	–	2.5–3.0 mm	–	2.5–3.0 mm	–	2.5–3.0 mm
Upper reinforcement	2#10	2#10	2#10	2#10	2#10	2#10
Lower reinforcement	2#14	2#14	3#14	3#14	4#14	4#14
Transverse reinforcement	#6 (15 cm / 10 cm)	#6 (15 cm / 10 cm)	#6 (20 cm / 6 cm)	#6 (20 cm / 6 cm)	#6 (15 cm / 10 cm)	#6 (15 cm / 10 cm)
Reinforcement ratio (ρ_s)	0.7%	0.7%	1.0%	1.0%	1.4%	1.4%

* In our own course of research, it was observed that the thickness of the polyurea coating should be in the range of 2.5–3.0 mm to ensure appropriate crack bridging efficiency in reinforced concrete components.

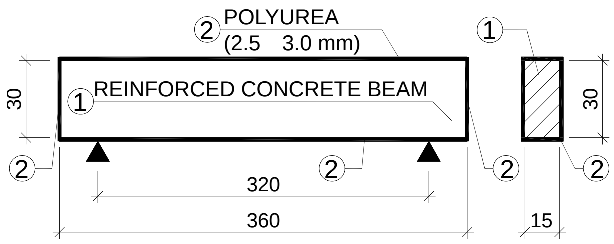

Fig. 2. Polyurea-coated elements – coating arrangement (dimensions in cm)

RC elements for tests is shown in Fig. 3. More details and descriptions of each phase of the polyurea application process are shown in [34].

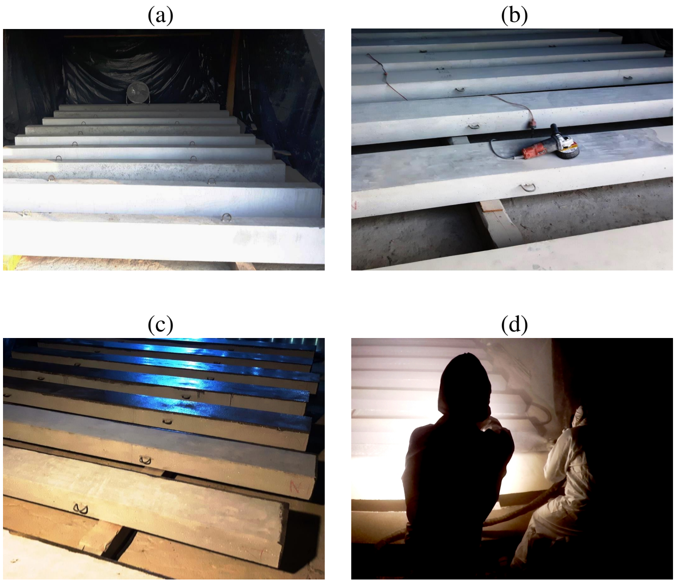

Fig. 3. Polyurea application process: (a) positioning the RC beams; (b) polishing the beams; (c) prime coat application; (d) polyurea application

3. EXPERIMENTAL INVESTIGATION

All RC beams (uncoated and polyurea-coated elements) were tested on one test stand presented in Figs. 4 and 5.

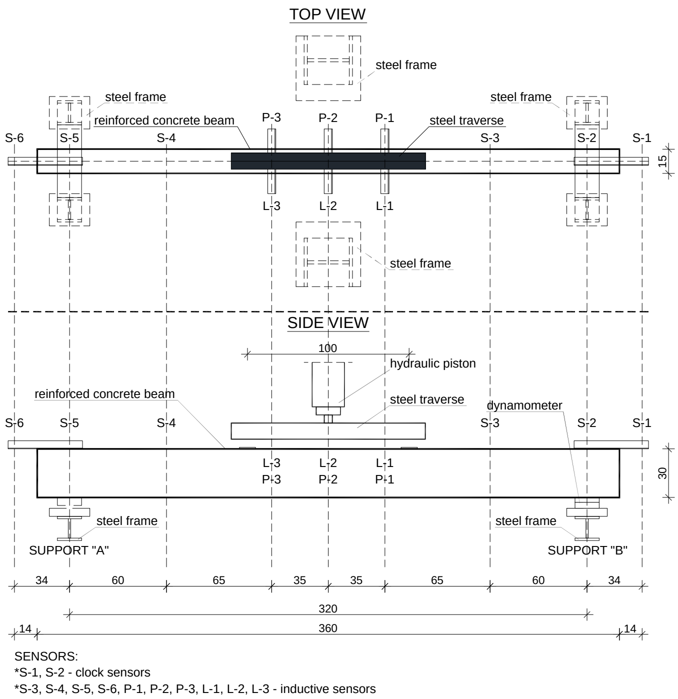

Fig. 4. The test stand for testing RC beams (dimensions in cm)

The main elements of the test stand included the main steel frame, the steel frame for supporting the RC beams, the steel frame for supporting the strain sensors, the hydraulic piston, the hydraulic pump and the workstation. More information is available in the authors' previous paper [34].

The reinforced concrete beams were loaded by a steel traverse, which was symmetrically oriented to the beam perpendicular axis and produced load in the form of two concentrated

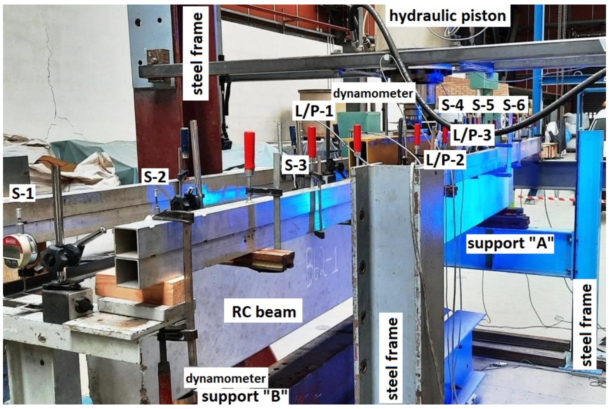

Fig. 5. General view of the test stand

forces 1.0 m apart. Reinforced concrete beams were loaded with step force increments of 5 kN or 10 kN. Vertical displacements, the force exerted by the hydraulic piston, and the response value at one of the supports were measured during the tests.

4. RESULTS

4.1. Bending strength of RC beams

The relations between the force (exerted by the hydraulic piston) and the midspan beam deflections are shown in Figs. 6–8. Table 8 lists breaking forces and breaking moments, their average values, and gains compared with breaking moments obtained for the uncoated reference beams. The average breaking moment (bending strength) of the RC beams was calculated as the arithmetic mean of the three tests of each type of beam. Table 8 also includes the average gain in the load-carrying capacity of the polyurea-coated RC beams over the reference ones. The load-carrying capacity gain was defined in (kN·m) and (%) as a difference between the destructive moments for the coated specimens and the reference specimens (without any coatings).

The summary of breaking forces and breaking moments indicates that breaking forces and breaking moments are higher

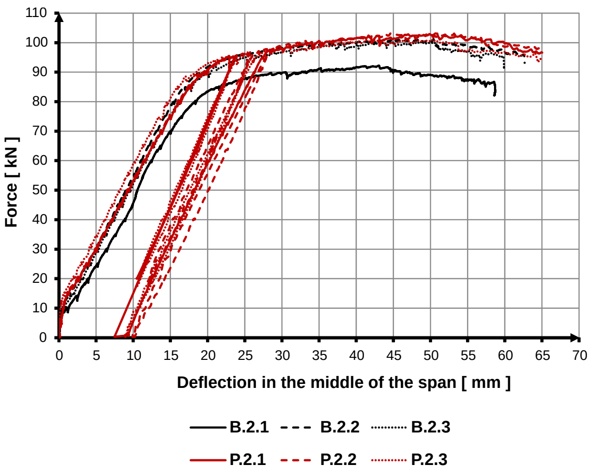

Fig. 6. Force (exerted by the hydraulic piston) vs. beam deflection for the 1st series of the RC beams (two #14 mm rebars in the tension area)

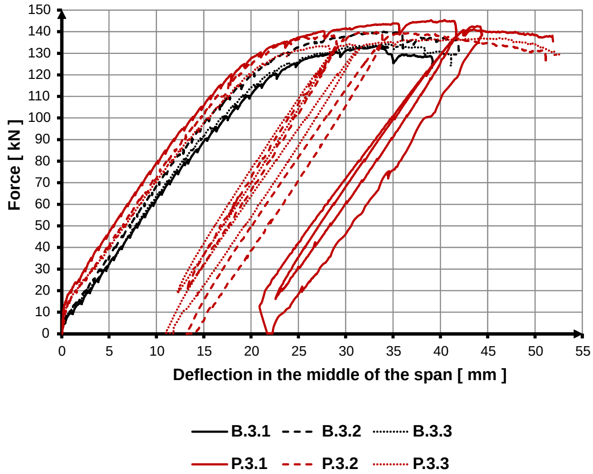

Fig. 7. Force (exerted by the hydraulic piston) vs. beam deflection for the 2nd series of the RC beams (three #14 mm rebars in the tension area)

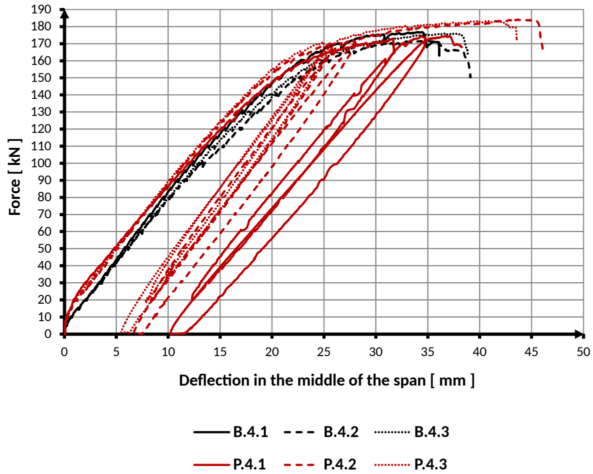

Fig. 8. Force (exerted by the hydraulic piston) vs. beam deflection for the 3rd series of the RC beams (four #14 mm rebars in the tension area)

for the polyurea-coated RC beams than for the reference beams (for each series of RC beams).

Due to the application of the coating on the RC beams, the average breaking moment (bending strength) increased by:

- 9.2% (5.5 kN·m) for the 1st series of RC beams (two #14 mm rebars in the tension area)
- 5.1% (4.2 kN·m) for the 2nd series of RC beams (three #14 mm rebars in the tension area)
- 7.0% (7.1 kN·m) for the 3rd series of RC beams (four #14 mm rebars in the tension area)

The reason for the weak reinforcement effect of polyurea may be the mechanical properties of the membrane: Young's modulus (E) is significantly lower than Young's modulus (E) of concrete or reinforcing steel.

In polyurea-coated reinforced concrete beams, the coating made it possible to make an unloading/loading cycle on the test specimens; the unloading point was set at 90% of the breaking force found for the uncoated RC beams. This is the funda-

Table 8
Summary of breaking forces and breaking moments for each series of RC beams

Series (–)	Beam designation (mm)	Breaking force exerted by the piston* (kN)	Breaking moment (kN·m)	Average breaking moment (kN·m)	Breaking moment gain (kN·m /%)
Series no 1 (2#14)	B.2.1	92.2	56.4	59.8	–
	B.2.2	101.2	61.8		
	B.2.3	100.3	61.2		
	P.2.1	103.1	62.4	65.3	+5.5 kN·m (+9.2%)
	P.2.2	103.2	67.6		
	P.2.3	101.2	65.8		
Series no 2 (3#14)	B.3.1	133.2	80.7	82.5	–
	B.3.2	140.0	85.3		
	B.3.3	134.4	81.6		
	P.3.1	145.4	88.3	86.7	+4.2 kN·m (+5.1%)
	P.3.2	139.9	84.8		
	P.3.3	137.1	86.9		
Series no 3 (4#14)	B.4.1	176.8	99.7	101.5	–
	B.4.2	171.8	99.6		
	B.4.3	176.0	105.1		
	P.4.1	174.7	106.8	108.6	+7.1 kN·m (+7.0%)
	P.4.2	184.2	108.4		
	P.4.3	183.4	110.5		

* Breaking force exerted by the piston is the maximum recorded value of the force in the main hydraulic piston during the examination of the reinforced concrete beam.

(a)

(b)

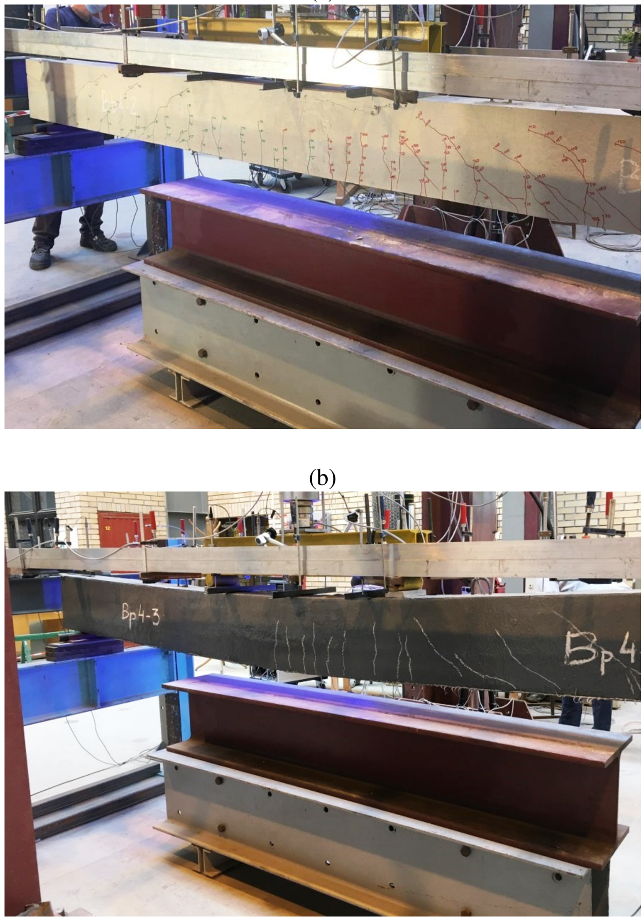

Fig. 9. Beams under loading – views along the elements: (a) a beam without the polyurea coating; (b) a polyurea-coated beam

mental difference between the polyurea-coated beams and the beams without any coating under load. The load-carrying capacity after the unloading/loading cycle of the polyurea-coated beams was achieved without any excess increase in the deflection of these specimens, i.e., without any loss of bending stiffness (Figs. 6–8).

4.2. Displacements of the RC beams

The increase in load resulted in larger displacements of RC beams but no torsion of the beams was observed during the experiments (Fig. 9). The level of deflection of a specimen at measurement points was measured continuously throughout each test (Fig. 10). The relations between the midspan beams deflection and the loads (the force exerted by the hydraulic piston) are shown in Figs. 6–8.

In order to compare deformations of the RC beams covered by polyurea with those of the RC beams without any coating, beam displacements along their longitudinal axes are shown in Fig. 10. Displacements observed along the beams under the loads corresponding to 90% of the breaking force for the reference beams (for each series of RC beams) can be seen in Fig. 10a, Fig. 10b and Fig. 10c, respectively.

The displacement diagrams (Figs. 6–8) show that the maximum breaking forces for the coated specimens (beams P.2...; P.3...; P.4...) were obtained with very similar deflections of the reference beams (beams B.2...; B.3...; B.4...). This means that although the unloading/loading cycles were performed, for specimens (P.2...; P.3...; P.4...) their total displacements were close to the reference specimens.

The analysis of curves displayed in Figs. 10a, 10b, and 10c indicates that both the displacements of the RC beams with three and four #14 mm rebars in the tension area closely match each other. Some differences are seen in RC beams with two #14 mm rebars in the tension area, where one beam (B.2.1) has the largest displacements. This beam (B.2.1) was the first one to be tested, so some strains of this beam are related to the settlement of the new test stand structure. The displacement curves of each test series of RC beams show that the polyurea coating has no effect on the values of displacement of these elements at load levels close to the maximum load.

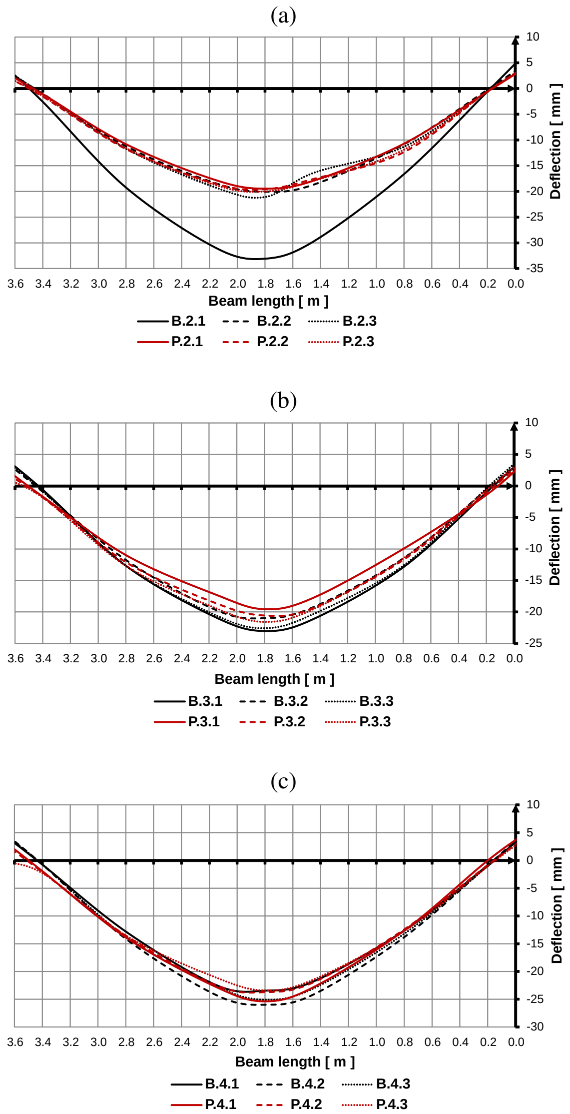

Fig. 10. Beams displacements along the specimens under loads equal to 90% of the breaking forces for the reference beams: (a) 1st series of the RC beams ($F = 90\% \cdot F_{\max} = 90$ kN); (b) 2nd series of the RC beams ($F = 90\% \cdot F_{\max} = 120$ kN); (c) 3rd series of the RC beams ($F = 90\% \cdot F_{\max} = 160$ kN)

4.3. Beams cracking

The cracking layout was observed during the tests on a continuous basis using two cameras located on both sides of the test stand. For chosen RC beams, the cracking layout on the surface of the components was also captured by marking near each crack the load value at which the crack appeared (Fig. 11).

In the case of the uncoated RC beams (beams B.2…; B.3…; B.4…) in each series of test specimens, numerous vertical cracks were observed in the midspan (Figs. 11a, 11c, and 11e). Such cracking layout in this area was forced by the pure bending area between two concentrated forces, which is in line with the assumed structural arrangement. Some oblique cracks were also observed outside of the pure bending area and these were more intense mainly in the support areas of the RC beams. The occurrence of cracks on the surface of these elements and the increasing width of the cracks under a higher load can significantly reduce the durability of these elements.

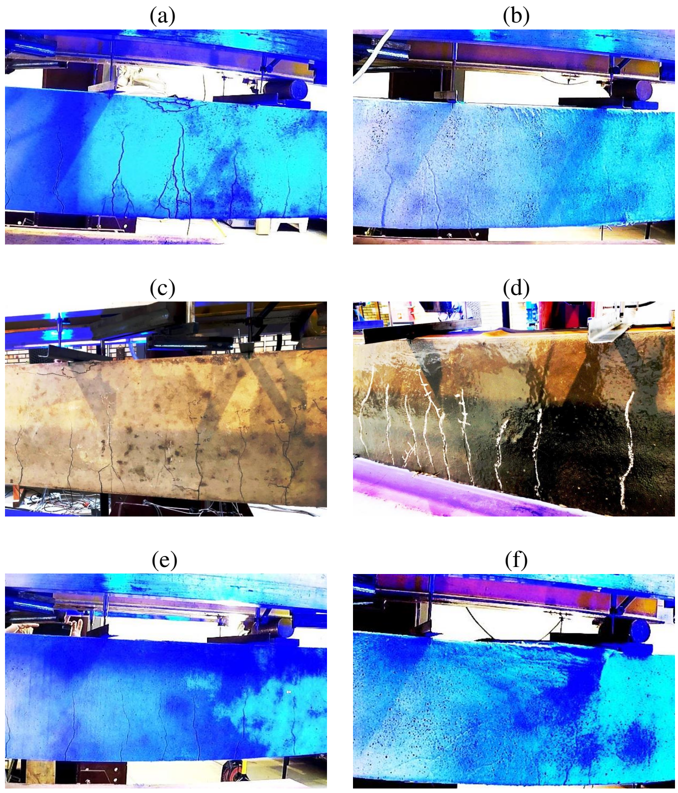

Fig. 11. The cracking layout at the midspan of the RC beams: (a) 1st series of the RC beam without the polyurea coating; (b) 1st series of the polyurea-coated RC beam; (c) 2nd series of the RC beam without the polyurea coating; (d) 2nd series of the polyurea-coated RC beam; (e) 3rd series of the RC beam without the polyurea coating; (f) 3rd series of the polyurea-coated RC beam

In the polyurea-coated RC beams (specimens P.2…; P.3…; P.4…), the greatest number of cracks were observed in the midspan of beams. Oblique cracks were also found on these specimens, with more intense cracks in the support areas. In the case of these beams, the polyurea coating efficiently covered the cracked surface to the extent that only wide cracks could be seen (by the naked eye). It should be emphasized that the polyurea coating application did not change the mechanism of crack formation in the beams nor the arrangement (spacing) of cracks on the elements. The cracked state of these elements (specimens P.2…; P.3…; P.4…), when combined with the coating that is highly elastic up to its breaking point, effectively covers cracks and protects the internal structure of the RC beams, should significantly postpone reaching the serviceability limit state (SLS). Cracks on the surface of the polyurea-coated RC beams are shown in Figs. 11b, 11d, and 11f.

5. THEORETICAL PREDICTION

The failure of RC elements subjected to bending occurs when their bending strength or shear strength is exceeded. The point when the bending strength is exceeded is determined by the maximum bending moment (M_n). This moment (M_n) is defined as the value of the bending moment at which the concrete compression strength (in the compression area of the beam cross-section) or the reinforcement strength (in the tension area of the beam cross-section) are exceeded.

In order to provide calculations describing the performance of polyurea-coated RC beams subjected to bending, the calculation approach described by the American Concrete Institute®(ACI) in publications [39, 40] was implemented. The theoretical distribution of strains, stresses and forces in a bent RC beam cross-section at the ultimate limit state (ULS) reached due to bending is shown in Fig. 12.

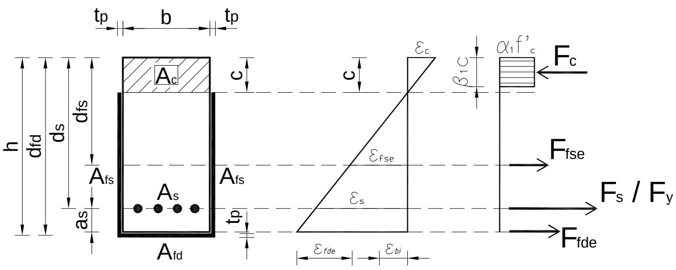

Fig. 12. Internal strain and stress distribution model for a rectangular section under flexure at ultimate limit state (ULS) for beam with polyurea coating

Parameters (b) and (h) shown in Fig. 12 represent the dimensions of the beam cross-section. Component (d_{fd}) is the usable height of the coating at the lower part of the beam, (d_s) of the lower reinforcement of the beam and (d_{fs}) of the coating on the side surfaces of the beam. Parameter (A_{fs}) denotes the area of polyurea on the side surfaces of the beam, (A_{fd}) is the area of polyurea on the bottom part of the beam and (A_s) is the area of the lower reinforcement of the beam. Symbol (t_p) is the thickness of the polyurea coating, and (a_s) is the thickness of the concrete cover of the lower reinforcement of the beam. Terms (ε_c), (ε_{fse}), (ε_s), (ε_{fde}), and (ε_{bi}) refer to strain levels for each element (concrete, reinforcement and polyurea) of the polyurea-coated RC beam cross-section. Symbol (c) denotes the depth to the neutral axis of the cross-section, while (f'_c) is the compression strength of the concrete. Terms (α_1) and (β_1) define a rectangular stress block in the concrete equivalent to the actual non-linear distribution of stress in a bent RC beam cross-section and depend on the class of the concrete and the calculation model used. Symbols (F_c), (F_{fse}), (F_s), (F_y) and (F_{fde}) represent forces for each element (concrete, reinforcement, and polyurea) of a polyurea-coated RC beam cross-section.

The bending strength of polyurea-coated RC beams was calculated from the following formula:

$$\begin{aligned} M_{ns+f} = & 2\cdot A_{fs}\cdot f_{fse}\cdot\left(d_{fs}-\frac{\beta_1\cdot c}{2}\right) \\ & + A_{fd}\cdot f_{fde}\cdot\left(d_{fd}-\frac{\beta_1\cdot c}{2}\right) \\ & + A_s\cdot f_s\cdot\left(d_s-\frac{\beta_1\cdot c}{2}\right). \end{aligned} \tag{2}$$

Each term in equation (2) is explained in Fig. 12. Stress levels in each element of the RC beam cross-section were calculated from equations (3), (4) and (5):

$$f_{fse} = E_f\cdot\varepsilon_{fse} \le f_{yd}\,, \tag{3}$$

$$f_{fde} = E_f\cdot\varepsilon_{fde} \le f_{yd}\,, \tag{4}$$

$$f_s = E_s\cdot\varepsilon_s \le f_{ys}\,. \tag{5}$$

Equations (3) and (4) employ component (E_f) being the modulus of elasticity of the polyurea coating, and (E_s) in equation (5) is the modulus of elasticity of reinforcing steel. It should be noted that values of each stress component in the elements of a beam may not exceed maximum stress levels for these materials: tensile strength of polyurea (f_{yd}) and tensile strength of steel (f_{ys}).

Strain levels in each element of the RC beam cross-section were calculated from equations (6), (7) and (8):

$$\varepsilon_{fse} = \varepsilon_c\cdot\left(\frac{d_{fs}-c}{c}\right)-\varepsilon_{bi} \le \varepsilon_{fd}\,, \tag{6}$$

$$\varepsilon_{fde} = \varepsilon_c\cdot\left(\frac{d_{fd}-c}{c}\right)-\varepsilon_{bi} \le \varepsilon_{fd}\,, \tag{7}$$

$$\varepsilon_s = \left(\varepsilon_{fde}-\varepsilon_{bi}\right)\cdot\left(\frac{d_s-c}{d_{fd}-c}\right) \le \varepsilon_{fs}\,. \tag{8}$$

Term (ε_c) used in equations (6), (7) and (8) refers to the maximum compressive strain in the concrete and was taken as 0.003 according to [39]. Variable (ε_{bi}) is the strain level in the RC beam cross-section at the time of the polyurea coating application. In this case, this strain level (ε_{bi}) was taken as 0.0, as the polyurea coating was applied when no load was exerted on the RC beams. Note that values of each strain in the beam elements may not exceed maximum strain levels in these elements: the maximum strain of the polyurea coating (ε_{fd}) and the maximum strain of reinforcing steel (ε_{fs}).

Depths to the neutral axis in the cross-section of the bent RC beam (c) were calculated according to the procedure given in [40] and the following formula:

$$c = \frac{2\cdot A_{fs}\cdot f_{fse}+A_{fd}\cdot f_{fde}+A_s\cdot f_s}{\alpha_1\cdot f'_c\cdot\beta_1\cdot b}\,. \tag{9}$$

The parameter (α_1) in equation (9) was taken as 0.85, as the Whitney stress block was used as the calculation model for the bent RC beam cross-section [40]. The value of (β_1) depends on the compression strength of concrete and according to [39]:

- It is equal to 0.85 for:
  17.23 MPa (2500 psi) $< f'_c <$ 27.58 MPa (4000 psi).
- It is reduced by 0.05 per 6.90 MPa (1000 psi) above
  $f'_c =$ 27.58 MPa (4000 psi).
- It should be no smaller than 0.65.

The actual depth to the neutral axis (c) is at a height at which the strain level in the cross-section is being kept and there is an equilibrium between the internal forces. The depth to the neutral axis (c) was found by employing a procedure that has to be solved in an iterative process. In the first step, the position of the neutral axis (c) was taken as $0.2d_s$. On this basis, strain and stress levels in the cross-section, and the new position of the neutral axis (c) were calculated. If the new depth to the neutral axis did not match the assumed one, a new value of (c) was taken and the whole process was repeated until matching depths to the neutral axis (c) were found in two consecutive steps.

The following assumptions were taken in the above calculations of theoretical strength levels of bent RC beams:

- The Whitney stress block was used as the calculation model for the bent RC beam cross-section.
- The tensile strength of the polyurea coating was only taken into account.
- An ideal adherence of the coating to concrete was assumed.
- The calculations took no account of reduction factors and safety factors.
- The elastic performance of the polyurea coating in tension was assumed.
- The forces in each element of the RC beam (concrete, reinforcing steel, and polyurea coating) were assumed to act in the centers of gravity of these elements.
- The impact of the reinforcement in the compression area of the RC beam cross-section (two #10 mm rebars) was not taken into account.
- Actual strength properties of each element of the RC beam (concrete, reinforcing steel, and polyurea coating) were assumed.

Table 9 lists the results of calculations of the theoretical compression strength which are compared with the results of the experiment.

The results summarized in Table 9 indicate that the experimental values of breaking moments for the RC beams are slightly different than the results of the analysis. However, the differences do not exceed 10% of the theoretical values, so the results match each other with satisfactory accuracy. It should be noted that these differences result from a number of factors such as variable concrete properties, repeatability of mechanical properties of steel, and keeping a constant thickness of the coating on the whole surface of the RC beams.

It is important to note that the polyurea coating application has a marginal impact on changing the depth to the neutral axis (c), and this impact decreases at a higher bending reinforcement ratio. The same relation occurs with changing values of breaking moments. At a higher bending reinforcement ratio of the beams, the share of the polyurea coating in the bending strength is smaller (Table 9).

The reason for this may be the mechanical properties of reinforcing steel: its tensile strength (f_{ys}) is over 26 times higher than that of the polyurea coating (f_{yd}).

6. CONCLUSIONS

This paper focuses on evaluating the performance of bent RC beams covered with a polyurea coating system depending on the bending reinforcement ratio of these elements. The effect of the coating application on deflection and the cracking layout of the RC elements tested was also analyzed. The results of the experimental research and the analyses make it possible to draw the following conclusions:

- The application of polyurea coatings on reinforced concrete beams increases their bending strength by 5.1% to 9.2%, depending on the longitudinal reinforcement ratio.
- The theoretical model used in the calculations proved to be satisfactory and facilitated the analytical determination of the impact of the polyurea coating on the bending strength of RC beams with different reinforcement ratios.
- The experimental results and analytical calculations show that this impact on the bending strength of RC beams is smaller for a higher longitudinal reinforcement ratio of these elements.

Table 9
The flexural capacity of beams

Parameter	Series no 1 (2#14)		Series no 2 (3#14)		Series no 3 (4#14)	
	Control batch	With polyurea	Control batch	With polyurea	Control batch	With polyurea
Beam designation	B.2.1 B.2.2 B.2.3	P.2.1 P.2.2 P.2.3	B.3.1 B.3.2 B.3.3	P.3.1 P.3.2 P.3.3	B.4.1 B.4.2 B.4.3	P.4.1 P.4.2 P.4.3
Concrete parameters	$f'_c = 72.35$ MPa, $\varepsilon_c = 0.00300$		$f'_c = 68.54$ MPa, $\varepsilon_c = 0.00300$		$f'_c = 64.69$ MPa, $\varepsilon_c = 0.00300$	
Reinforcing steel parameters	$f_{ys} = 611.10$ MPa, $E_s = 204.52$ GPa, $\varepsilon_{fs} = 0.00299$					
Polyurea parameters	$f_{yd} = 23.03$ MPa, $E_f = 44.76$ MPa, $\varepsilon_{fd} = 0.51450$					
Final position of neutral axis	$c = 40.98$ mm	$c = 41.16$ mm	$c = 64.89$ Mm	$c = 64.99$ mm	$c = 91.67$ mm	$c = 91.73$ mm
Flexural strength	58.7 kN·m	60.08 kN·m	85.11 kN·m	85.22 kN·m	109.21 kN·m	109.27 kN·m
Breaking moment (experiment)	59.8 kN·m	65.3 kN·m	82.5 kN·m	86.7 kN·m	101.5 kN·m	108.6 kN·m
Variation from theoretical	1.9%	8.7%	3.1%	1.7%	7.1%	0.6%

- The theoretical analysis of polyurea-coated beams found that the membrane application has a marginal impact on the position of the neutral axis in the cross-section of the beams. This is extremely important as this means that the coating application insignificantly impacts the arrangement of internal forces in bent RC elements.
- The experiments showed that RC beams which are covered by polyurea can be subjected to a loading/unloading process (up to a value of 90%, which was used in the tests); this is the fundamental difference between them and common RC beams that cannot be safely subjected to this process.
- The polyurea coating successfully covers cracks in reinforced concrete elements and protects them against penetration by corrosive fluids (water, air, and chemical compounds).
- The polyurea coating can improve the safety of people and RC structures as it makes these elements integral and durable in imminent failure conditions.

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