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Management of the Special Processes – An Experimental Study of Bent Reinforced Concrete Beams

Dorota Michałowska-Maziejuk[1], Dorota Klimecka-Tatar[2], Manuela Ingaldi[2], Bożena Kaczmarska[1] Agnieszka Czajkowska[1*]

[1] Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

[2] Czestochowa University of Technology, ul. J.H. Dąbrowskiego 69, 42-201 Częstochowa, Poland

* Corresponding author's e-mail: a_czajkowska@o2.pl

ABSTRACT

The article presents an analysis of the results obtained from the testing of simply supported reinforced concrete beams subjected to four-point bending. The beams, with two levels of steel reinforcement (ρ_{s1} = 1.26%, $\rho_{s\,2}$= 0.71%), and dimensions of 0.12×0.30×3.30 m, were subjected to loading involving a sudden increase in force with multiple unloading cycles to zero. The study included comparative analysis of deflection results obtained from experimental tests (calculated based on the curvature of the element and readings from measurement devices) with deflection values obtained through calculations based on two selected standards. Real values of ultimate bending moments were also compared with theoretical values. Additionally, compressive strength tests were conducted on eight cubic concrete specimens with a side length of b = 150 mm, obtained for each concrete batch. They constitute accompanying studies. Using standard procedures, strength and statistical parameters were estimated and evaluated, taking into account the assessment of the quality of the concrete production used to make the reinforced concrete beams. Ensuring compliance with the process of producing full-sized reinforced concrete beams with existing standard procedures, as well as attention to the quality of concrete production, contributed to achieving satisfactory results in the experimental tests. Knowledge about the impact of loading on mechanical properties enables effective management of factors shaping quality to obtain a construction material with optimal parameters.

Keywords: special processes; reinforced concrete beams; ultimate bending moment; deflection; compressive strength of concrete.

INTRODUCTION

Special processes, in the context of quality management, constitute a critical element in the production of high-quality products. They are characterized by the fact that their outcomes cannot be easily and unequivocally verified using standard methods of control or testing. Consequently, it becomes necessary to implement special procedures and actions to ensure that these processes are executed correctly and meet specified quality standards. Special processes are defined in ISO 9000:2015. In accordance with ISO 9000:2015(E) 3.4.1 Process, Note 5: A process where the conformity of the resulting output cannot be readily or economically validated is frequently referred to as a "special process" [1]. Special Processes are referenced in ISO 9001 8.5.1.f as "the validation, and periodic revalidation, of the ability to achieve planned results of the processes for production and service provision, where the resulting output cannot be verified by subsequent monitoring or measurement".

These processes are distinguished by the fact that their results cannot be unequivocally controlled. This means that these special processes must be verified under controlled conditions, and it is impossible to determine whether the product is compliant (OK) or non-compliant (NOK) without destroying the outcome of this special process

[2, 3]. Special processes encompass various activities such as welding, soldering, heat treatment, painting, and non-destructive testing. Due to their specific nature and the difficulty of directly assessing the outcome, they require special supervision and control. For example, in the case of welding, it is not possible to definitively determine whether a weld is correct or incorrect solely based on visual inspection. Often, specialized non-destructive tests such as radiographic or ultrasonic testing are required to assess the quality of the weld.

In quality management of special processes, validation of these processes is crucial. This means that these processes must be qualitatively confirmed and systematically controlled to ensure they achieve the intended results. The implementation of procedures, standardization of methods, proper personnel training, and regular inspections and audits are essential for effective management of special processes.

The key objective of managing special processes is to achieve high product quality, minimize the risk of defects, and meet customer expectations. These processes often play a significant role in the safety, reliability, and compliance of products with specific standards and regulations. Therefore, proper management of special processes contributes to strengthening an organization's position in the market and building customer trust in the products and services offered.

To ensure products are free from significant manufacturing and handling difficulties, it is necessary to implement supervision from the design stage through material selection, the production process, and subsequent testing phases [4, 5].

A specialized procedure involves a scenario in which the outcome of a process remains unverifiable without degrading the product. In a general sense, if the assessment or validation of the process outcome – which includes the resulting product or service – is unattainable through the use of precisely calibrated tools or instruments, preventing the evaluation of its compliance with pre-defined specifications, this indicates the existence of a specialized procedure that requires rigorous validation protocols.

The dynamic advancement of technology in the context of digitization and process automation, economic developments, unemployment rates, wage levels, societal mobility, increasing environmental awareness, as well as changing demographics, significantly contribute to the growing need for the construction of new buildings for production, public utility, residential, and other purposes.

Boadu, Wang and Sunindijo in their research study [6] focus on the impact of characteristics that define the construction industry in developing countries on health and safety issues. These researchers analyze dynamic changes in the construction sector, particularly in the context of countries such as Ghana. While Anaman and Osei-Amponsah in research [7] emphasize the significant relationships between the pace of growth in the construction industry and the rate of macroeconomic development in developing countries. They point out that progress in the construction sector influences macroeconomic growth, highlighting the substantial role of this sector in the economic development process.

In addition, the construction industry has a significant impact on the development of other sectors of the economy. For example, the construction of manufacturing facilities, office buildings, roads, infrastructure, water supply systems, and power lines contributes to increased production of goods and services and becomes a significant source of creating new job opportunities. Therefore, the construction sector plays a crucial role in supporting economic development. The comprehensive influence of socio-economic, technological, and ecological factors on the construction sector makes its development not only essential but also a strategy to promote growth and economic stability in developing countries.

An essential aspect of management in the construction industry is the prudent allocation of resources to complete a project in accordance with the approved budget, allocated time, and established quality standards [8]. This will not only enable effective construction organization but also ensure the timely completion of contracts and the construction of structures in accordance with project specifications.

Every construction, every building is exposed to various influences during its operation. As a result, various defects and damages to these elements occur, which affect their safe functioning [9, 10]. Often, human errors during construction, repairs, modernization, or the execution of structural elements of buildings are also a cause of defects and damages [11, 12]. That's why the quality of materials used in construction is so crucial. Many authors emphasize that the quality of materials used in production is a factor that can have the most significant impact on the final result [13–15]. The use of appropriate solutions and materials in this field not only accelerates the construction process but also enhances the durability of the constructed buildings. The development of technology, including in the construction industry, leads to the search for new solutions or the improvement of existing ones [16, 17].

Reinforced concrete beams, also known as concrete beam structures, are a common and effective technique used in construction. Reinforced concrete beams consist of concrete and steel reinforcement, combining the advantages of both materials. They are used in various types of structures, such as residential buildings, office buildings, bridges, parking lots, industrial halls, and many others.

A reinforced concrete beam is a horizontal or slanting structural element used in construction. Its primary purpose is to bear vertical loads, typically originating from horizontal ribs and floor slabs, and then transfer these loads to supports, such as walls, columns, piers, or columns. Reinforced concrete beams are usually made of reinforced concrete and contain embedded steel reinforcing bars, making them strong enough to carry heavy loads.

It's important to emphasize that the use of reinforced concrete beams has its limitations and requires appropriate technical knowledge and experience. In every case of designing and constructing structures, it is essential to adhere to applicable standards and regulations to ensure the safety and durability of the final structure.

The design of reinforced concrete beams must consider numerous technical factors to ensure they can perform their function and protect the structure for many years. At the absolute minimum, one must consider the selection of appropriate loads, materials, and geometry. Additionally, depending on the building's location, designers must account for climatic conditions to ensure the beam's and the entire structure's durability. It's also worth considering aesthetic aspects to ensure the beam matches the style and color of the building.

Reinforced concrete beams are a vital structural component in construction, serving to carry loads, provide stability, and ensure the durability of structures. Reinforced concrete beams are composed of concrete and steel reinforcement and are designed to transfer both vertical and horizontal loads. There are various types of beams, including simple and composite ones, with different cross-sectional shapes like rectangular, "T," or "I" shapes. Designing beams involves selecting the appropriate cross-section, reinforcement, and concrete while adhering to construction standards. Steel reinforcement is used to strengthen the structure, and beams are calculated for load-bearing capacity considering factors such as bending, shear, deflection, and cracking [18, 19]. The installation of beams is often prefabricated in factories and then transported to the construction site, where they are assembled with other structural elements. Quality control includes the assessment of concrete, reinforcement, welds, and connections. Reinforced concrete beams require regular maintenance and inspection to ensure long-term durability and reliability. In practice, reinforced concrete beams are an integral component of various types of structures, from bridges and residential buildings to industrial and commercial facilities. Proper design and construction are crucial for ensuring the stability and safety of the entire structure.

All the mentioned stages of the technological process are classified as special processes according to the definition. The only way to manage the process is by controlling the variability of individual parameters. Therefore, it is essential to conduct a series of specialized tests, including destructive tests such as the bending test. All mechanical tests are part of statistical quality control, which is the foundation of managing special processes. This underscores the need for conducting scientific research in this area.

Since the beginning of the use of reinforced concrete structures in the construction industry, studies of the behaviour of individual structural elements under the influence of loads have been carried out. In addition to numerous processes and phenomena occurring in materials, deformability is one of the factors that determines the usability of a reinforced concrete element. Therefore, on the basis of the results obtained from the research carried out so far, various theories describing deflections and cracking of elements have been developed. Some theories are still used today. In this work, the theoretical values of deflections were determined in the light of selected standards. Theoretical results were compared with the results obtained through experimental research.

The paper provides a comprehensive analysis of the outcomes derived from the examination of simply supported reinforced concrete beams exposed to four-point bending. The beams, featuring dual levels of steel reinforcement (ρ_{s1} = 1.26%, ρ_{s2} = 0.71%), and dimensions measuring

0.12×0.30×3.30 m, underwent loading scenarios involving sudden force increments with multiple subsequent unloading cycles to zero. The investigation encompassed a comparative assessment of deflection results obtained from experimental tests, calculated based on element curvature and measurements from precision instruments, juxtaposed with deflection values computed according to two specified standards. Furthermore, actual ultimate bending moments were contrasted with theoretical counterparts. In addition to these analyses, compressive strength tests were executed on eight cubic concrete specimens with a side length of b=150mm, procured for each concrete batch. Employing established protocols, strength and statistical parameters were meticulously estimated and evaluated, incorporating an assessment of the concrete production quality integral to the creation of the reinforced concrete beams. The meticulous adherence to established procedures for the production of full-sized reinforced concrete beams, coupled with a keen focus on the quality of concrete manufacturing, significantly contributed to the attainment of commendable results in the course of experimental trials.

The popularity of concrete as a construction material is as vast as the possibilities of its modification, both in terms of composition (mix design) and the manufacturing process (curing conditions), leading to the optimization of mechanical properties to best fulfil its purpose. Research on understanding its mechanical properties based on various variables is extensive. This is primarily due to the specificity of this material and the significant lack of result repeatability. The goal of laboratory research was to analyse the behaviour of reinforced concrete beams with varying degrees of steel reinforcement under the sudden increase in force during multiple unloading cycles to zero. This contributes to the field of concrete knowledge and facilitates the conscious management of known variables in the future.

MATERIALS AND METHODS

The article presents the results of studies on two series of reinforced concrete beams with cross-sectional dimensions of 120×300 and a span of 3300 mm. Each series consisted of four research elements, differing in the type of reinforcement. The beams were subjected to four-point bending with a stepwise variable force until the elements were destroyed. The research was conducted in the laboratory of the Department of Strength of Materials and Building Structures at the Kielce University of Technology, Poland.

Materials

The concrete mixture was made using basalt aggregate in the range of 8–16 mm and sand in the range of 4–8 mm.The mass of the individual components of the mixture was calculated to obtain concrete of class C20/25. The mixture recipe for 1 batch (370 dm^3) was is presented in Table 1.

The procedure for preparing the material for the study was as follows: to measure the mass of ingredients, an electronic Zup-type scale with a reading accuracy of 0.5 kg was used. The concrete mix was thoroughly mixed using a THZ 355 concrete mixer with a capacity of 375 dm^3. Two beams were concreted in a rigid, demountable, steel form. The concrete mix was laid in layers and compacted on a vibrating table with a vibration frequency of 50 Hz. Rectangular concrete samples (8 for each beam) with dimensions of 150×150×150 mm were vibrated on the vibrating table described above. On the first day after concreting the elements, concrete curing was started in order to prevent shrinkage cracks from appearing and to avoid excessive drying. The maturing of the beams took place in the conditions prevailing in the laboratory hall and included: constant ambient temperature, concrete care in the molds, removing the elements from the mold, and lasted 28 days. Reinforcement of elements in beams of series 1 in the tension zone was used for

Table 1. Composition of the concrete mixture

Composition of the concrete mixture	Quantity	Unit
Sand	362.8	kg
Cement 32.5 R (Nowiny deposit)	98.7	kg
Basalt aggregate (Graczy deposit)	380.4	kg
Water	64.4	dm^3

longitudinal reinforcement 2 bars of ribbed steel class A IIIN, grade RB 500 W, diameter 16 mm. In the compressed zone of the element, reinforcement of the same class and grade, with a diameter of 8 mm, was used. The stirrups were made of class A I steel, grade St3S, with a diameter of 6 mm. The spacing of the stirrups in the section between the support axis and the concentrated force (section length 1000 mm) was 100 mm. In the section between the two concentrated forces, the stirrups were spaced every 225 mm. In the beams of the 2 series, in the tension and compression zones, 2 bars of ribbed steel class A IIIN (RB 500 W) with a diameter of 12 mm were used for longitudinal reinforcement. The same steel was used for the stirrups as for the Series 1 beams, with the same diameter and spacing. Tie wire with a diameter of 1 mm was used to bind the reinforcement. In order to ensure proper coverage of the reinforcement bars during concreting, spacer inserts in the amount of 6 pieces and 20 mm high were used. They are distributed evenly along the entire length of the element. The applied reinforcement for beams in series 1 and 2 is summarized in Table 2 and illustrated in Figure 1.

METHODS

In order to facilitate the measurement of deformations and the observation of the formation of cracks during loading of the elements, a grid of squares with a side of 10 cm was drawn on both sides of the beams. At a distance of 3 cm (for series 1 beams) and 2.5 cm (for series 2 beams) from the lower edge of the beams.

A line has also been marked that corresponds to the position of the theoretical center of gravity of the reinforcement in tension. A similar line was drawn from the upper edge of the beams at a distance of 25 mm. The upper line corresponds to the theoretical location of the center of gravity of the compression reinforcement. In this way, 13 measurement bases were drawn, each 200 mm wide, on both sides of the beam (Fig. 2). At the ends of the measurement bases, at the height of the theoretical centers of gravity of both reinforcements, pins were placed. The dowels were attached to the external surface of the beams using epoxy resin and were used to measure concrete deformations. Deformation measurements were conducted using a extensometer of the MERCER type with a constant of 0.79×10^{-5} and an accuracy of 0.0052 mm.

In the middle of the span of the tested sample and at a distance of 1 meter from each axis of the support, under concentrated forces, three deflection clocks with a scale of 0.01 mm were placed. The clocks were attached with magnets to a steel rail placed between the pillars of the measurement system.

The test stand was adapted for testing single-span simply supported beams. It consists of a steel structure composed of two columns. The columns, which acted as supports for the research elements, were connected with each other by two steel beams. Hydraulic actuators were attached to the upper beam, resting on two steel cylinders, and clocks for measuring deflections were attached to the lower beam with magnets. The actuators were

Table 2. Tangiers of the reinforced concrete beams in series 1 and 2

No of series	Tensile reinforcement	Compressive reinforcement	Steel (longitudinal reinforcement)	Stirrups	Steel (stirrups)
Series 1	2 ø 16	2 ø 8	AIIIN RB 500 W	27 ø 6 at a spacing of 100 mm and 225 mm	AI St3S
Series 2	2 ø 12	2 ø 12			

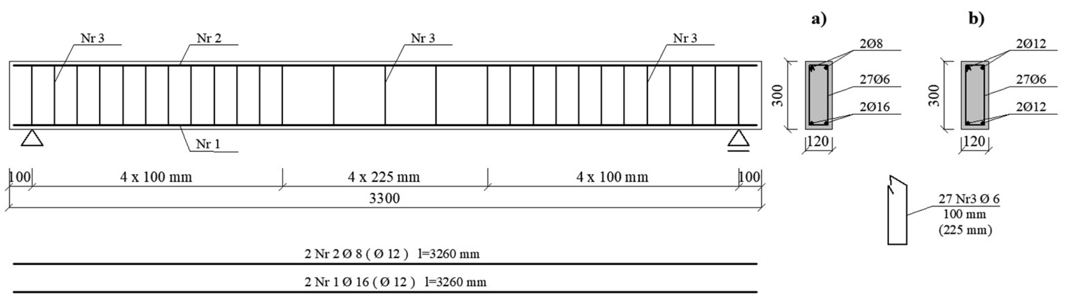


Figure 1. Reinforcement design for reinforced concrete beams: (a) series 1, (b) series 2; where: ø represents the diameter of the steel reinforcement

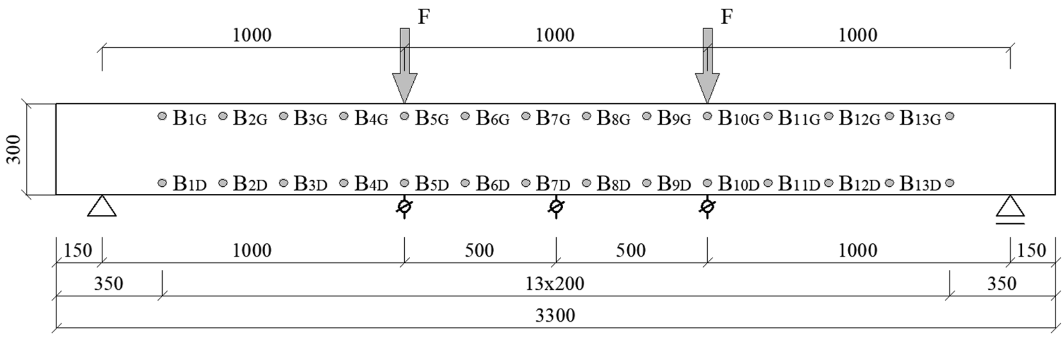


Figure 2. Scheme of the arrangement of places for the deflections measurements and the arrangement of bases for the deformations measurements; where: F – the load force acting on the element, $B_{1G\div13G}$ – designation of the upper reference points for deformation measurement, $B_{1D\div13D}$ – designation of the lower reference points for deformation measurement

connected in parallel, which made it possible to transfer the load in the form of two equal concentrated forces to the tested elements. The cylinders were powered by a hydraulic press. The maximum pressure generated by it was 200 kN. The value of the applied load was controlled by: a manometer on a hydraulic press, force gauges placed under the heads of hydraulic cylinders with a range of 160 kN for the ETP 7920 model - 16t and 100kN for the CT model, located at equal distances from the axis of the supports, equal to 1 m.

The tested beams were supported on rigid steel washers, and then on steel cylinders placed between the columns of the measuring system. Before starting the tests, the position of the actuators in the axis of the element was checked and the beam was secured against torsional buckling. For this purpose, wooden wedges were used, which were placed between the test elements and the columns of the steel measuring system. A static scheme (Fig. 3) of a single-span beam, simply supported, with spans in the support axes – l_{eff} equal to 3000 mm, was adopted for the tests. A beam with a cross-section of 120×300 mm was loaded with two concentrated forces F, distant from the axis of the supports at a certain distance of the span (l_{eff}).

Beams of both series were subjected to a load involving a step increase in force F with several unloads to zero. The unloading of each beam always started above the determined theoretical cracking moment. For beams of series 1 and 2, it was M_{cr} = 3.96 kNm. Both series were subjected to the same loading program. Up to the force value of 10 kN, the load was increased by 2.5 kN, and above by 5 kN. When unloading, the force was reduced every 5 kN. The loading pattern was as follows: 0 » 2.5 » 5 » 7.5 » 10 » 5 » 0 » 5 » 10 » 15 » 10 » 5 » 0 » 5 » 10 » 15 » 20 » 15 » 10 » 5 » 0 – further load and unload every 5 kN until failure. The load-implementation diagram isshown in Figure 4. The compressive strength of concrete were also tested 8 samples (150×150×150 mm) from each test

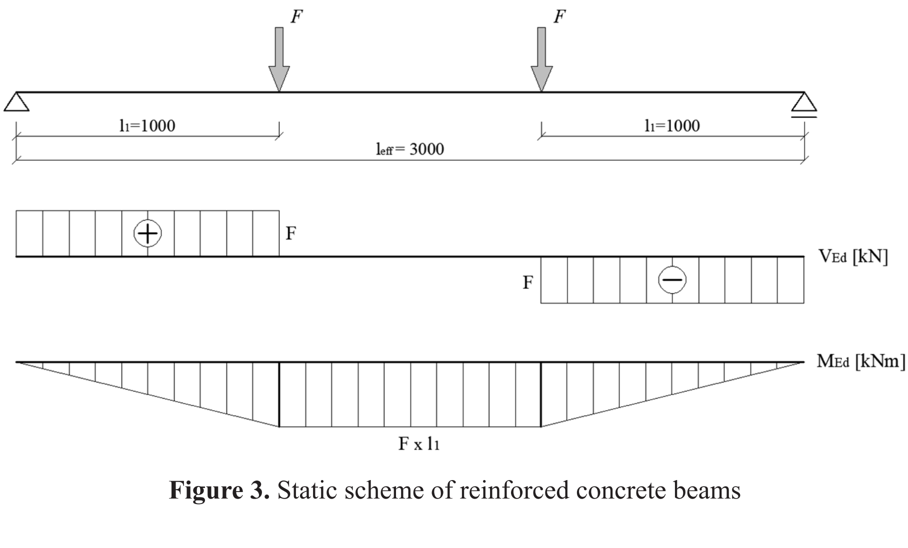


Figure 3. Static scheme of reinforced concrete beams

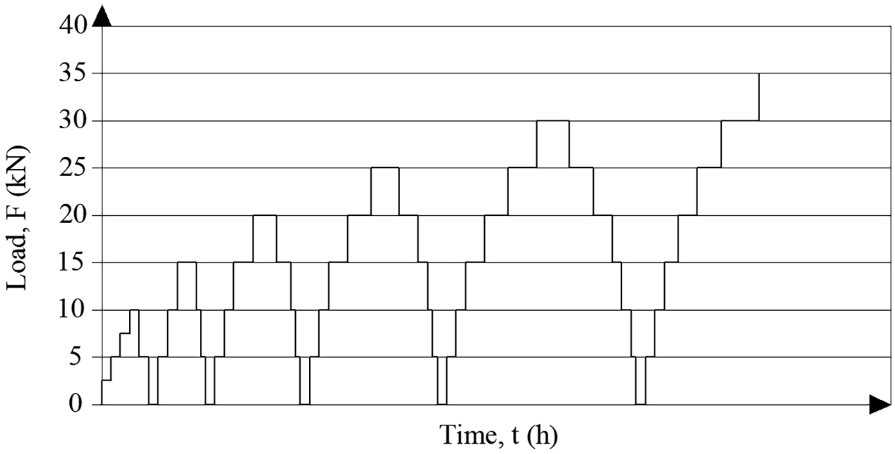


Figure 4. Load change diagram for series 1 and 2 beams

beams were subjected to destruction. The research was conducted using a strength-testing machine in accordance with [21]. When examining the samples, one of the three scales of the machine (scale B) was used, the range of which was from 0 to 1.5 MN. The accuracy of the given range was equal to 0.005 MN. The samples, placed in the center of the lower pressure plate, were loaded continuously until failure. The recorded measurements of the destructive force allowed for the estimation of strength and statistical parameters, in accordance with [22, 23, 24, 25]. For the determination of compressive strength (f_c) of individual cubic concrete samples, formula 1 was used:

$$f_c = \frac{F}{A} \text{ [MPa]} \tag{1}$$

where: F – force destroying the sample [N], A – surface area of the compressed cross-section of the sample [mm].

The average compressive strength was determined on the basis of formula:

$$f_{cm} = \frac{1}{n}\sum_{i=1}^{n} f_{ci} \text{ [MPa]} \tag{2}$$

where: n – number of tested samples from one series, f_{ci} – compressive strength of i-th samples from one series.

Standard deviation:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(f_{ci} - f_{cm})^2} \text{ [MPa]} \tag{3}$$

where: n – number of tested samples from one series, f_{ci} – compressive strength of i-th samples from one series, f_{cm} – average compressive strength.

Guaranteed strength of concrete:

$$f^G_{c,cube} = f_{cm} - 1.64s \text{ [MPa]} \tag{4}$$

where: f_{cm} – average compressive strength, s – standard deviation.

Characteristic concrete compressive strength:

$$f_{ck} = 0.8 f^G_{c,cube} \text{ [MPa]} \tag{5}$$

where: $f^G_{c,cube}$ – guaranteed strength of concrete.

On the basis of the recorded measurements of the destructive force (in tensile test), the value of the tensile strength f_{ctm} of the tested samples has been calculated according formula (6). Average tensile strength of concrete:

$$f_{ctm} = 0.3\sqrt[3]{f_{ck}^2} \text{ [MPa]} \tag{6}$$

where: f_{ck} – characteristic concrete compressive strength.

And to obtain full information about material durability also other parameters have been determined: characteristic tensile strength of concrete (7), design concrete tensile strength (8), design tensile strength of concrete (9), the modulus of elasticity of concrete – according formulas as follows.

Characteristic tensile strength of concrete:

$$f_{ctk} = 0.7 f_{ctm} \text{ [MPa]} \tag{7}$$

where: f_{ctm} – average tensile strength of concrete.

Design concrete compressive strength:

$$f_{cd} = \frac{f_{ck}}{\gamma_c}\ [\text{MPa}] \tag{8}$$

where: γ_c – partial safety factor of concrete; in reinforced concrete and prestressed structures, in permanent and transient design situationsγ_c =1.5, f_{ck}- characteristic concrete compressive strength.

Design tensile strength of concrete:

$$f_{ctd} = \frac{f_{ctk}}{\gamma_c}\ [\text{MPa}] \tag{9}$$

where: γ_c – partial safety factor of concrete; in reinforced concrete and prestressed structures, in permanent and transient design situations γ_c =1.5, f_{ctk}- characteristic tensile strength of concrete.

The modulus of elasticity of concrete:

$$E_{cm} = 11000(f_{ck} + 8)^{0,3}\ [\text{MPa}] \tag{10}$$

where: f_{ck} – characteristic concrete compressive strength.

The relative standard deviation, also known as the coefficient of variation, calculated using formula (11), was used to estimate the quality of concrete production.

$$\nu = \frac{s}{f_{cm}} \tag{11}$$

where: f_{cm} – average compressive strength, s – standard deviation.

RESULTS

The deflections of the element were determined using the Mohr integral method. In this method, the load of the real system is replaced by a continuous load equal to the values of the previously determined curvatures. On the basis of such a load, it is possible to determine the value of moments – deflections in a given section of the element. The span and scheme of the element are left unchanged (Fig. 5). In the Figures 6–15 exemplary graphs from the results of calculations based on the measurements of the research element were presented. In the Figures 16–17 exemplary view of the test stand is

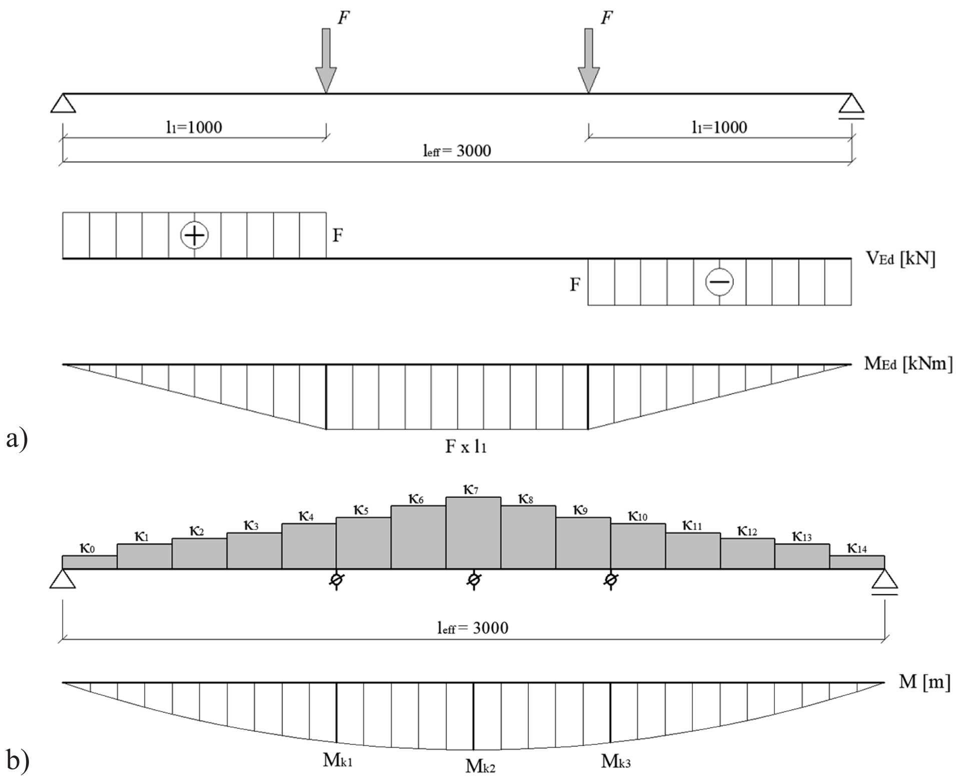


Figure 5. Scheme of a simply supported beam: (a) real scheme; (b) curvature-loaded diagram; where: F – the load force acting on the element, l_{eff}–the span of the beam between support axes, l_1 – the distance of the compressive force from the support axis, κ – representation of the curvature at each measuring base, $M_{k1\div k3}$ representation of the bending moment magnitude at the location of measuring gauges

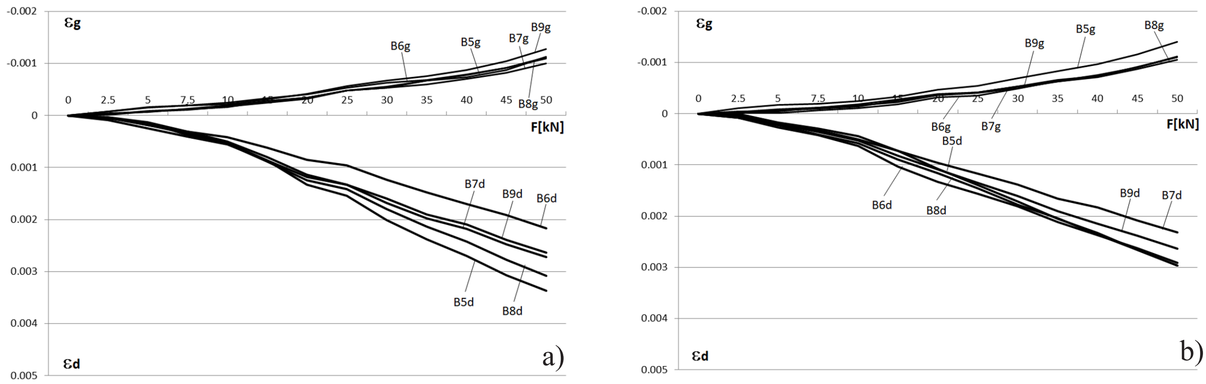


Figure 6. Deformation increase: (a) left side: beam series 1: B3; (b) right side: beam series 1: B3; where: ε_g – deformations at the center of gravity of the compressive reinforcement, ε_d– deformations at the center of gravity of the tensile reinforcement, $B_{5g\div 9g}$ – designation of the upper measuring bases, $B_{5d\div 9d}$ – designation of the lower measuring bases

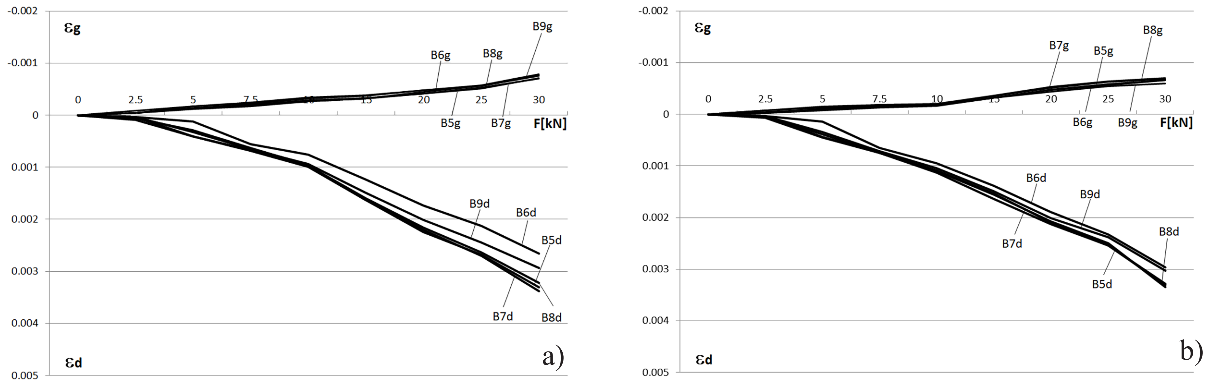


Figure 7. Deformation increase: (a) left side: beam series 2: B8; (b) right side: beam series 2: B8; where: ε_g – deformations at the center of gravity of the compressive reinforcement, ε_d– deformations at the center of gravity of the tensile reinforcement, $B_{5g\div 9g}$ – designation of the upper measuring bases, $B_{5d\div 9d}$ – designation of the lower measuring bases

presented, as well as a sample (beam) during and after strength testing. The characteristics of the tested material was also carried out on the basis of a compression test. The measurement results presented in the Table 1 were obtained on the basis of the uniaxial compression test of concrete rectangular samples with the dimension of each side equal to 150 mm. Date presented in Table 3 were the basis for the calculations and determination of the set of parameters presented in Tables 4–5.

DISCUSSION

Obtained during the tests, the results for 2 series of samples were compared with the failure moments calculated in accordance with the PN-B-03264:2002 standard. The concrete used to make the test elements was of good quality. The average guaranteed strengths obtained as a result of accompanying tests for individual mixtures range from 31.34 MPa to 35.15 MPa (for series 1 beams) and from 35.23 MPa to 37.87 MPa (for series 2 beams).After calculating the relative standard deviation, it was determined that the quality of the tested concrete production was very good [28]. The coefficient of variation for the manufactured concrete mixtures did not exceed 7% ($\nu \leq$ 7%). Only beam B7 (series 2) deviates from the overall trend, with a coefficient of variation of $\nu =$ 9.1%. In this case, the quality of concrete production was categorized as good ($\nu \in$<8 to 10>).

The elastic modulus of concrete, E_{cm}, determined on the basis of measured compressive strengths, ranges from 31.422 GPa to 32.150 GPa (for series 1 beams) and from 32.280 GPa to 32.836 GPa (for series 2 beams). Based on the determined compressive strengths and concrete

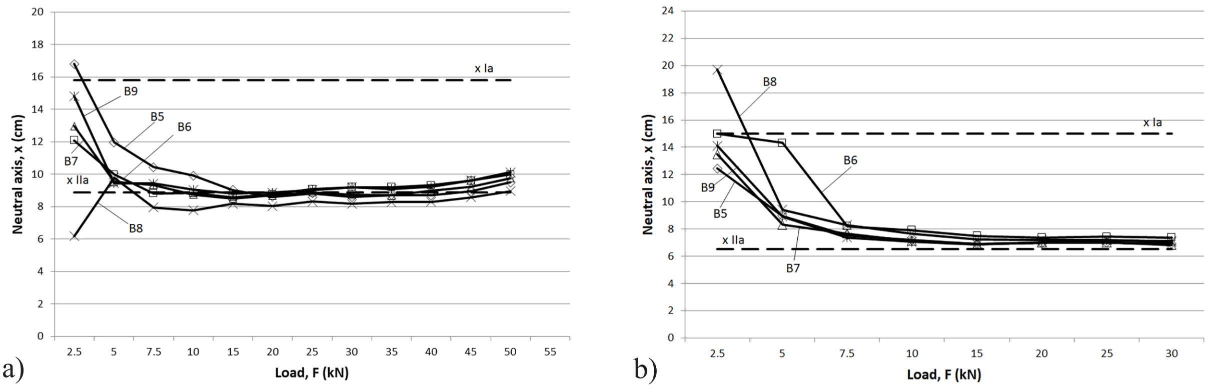


Figure 8. Location of the neutral axis: (a) beam series 1: B3; (b) beam series 2: B8; where: x_{Ia} – the position of the neutral axis in phase Ia of the concrete element's operation, x_{IIa} – the position of the neutral axis in phase IIa of the concrete element's operation, $B_{5g\div9g}$ – designation of the upper measuring bases, $B_{5d\div9d}$ – designation of the lower measuring bases

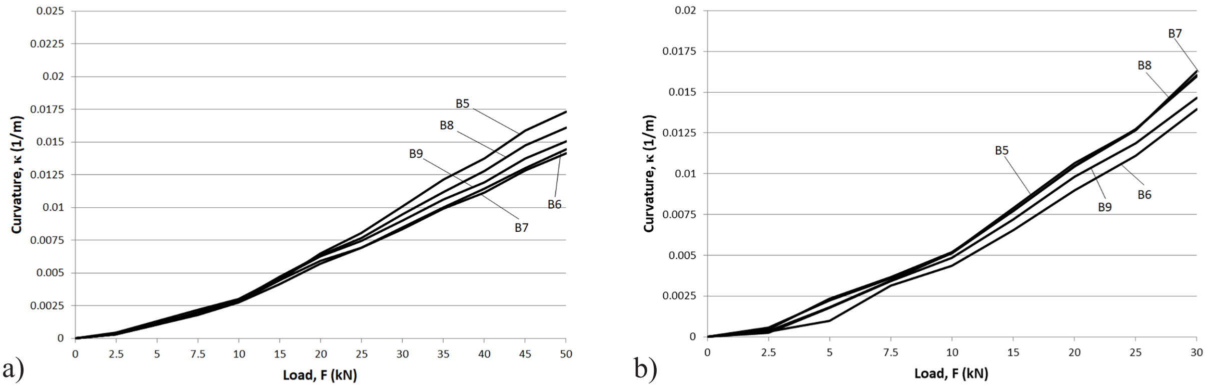


Figure 9. Curvature increase: (a) beam series 1: B3; (b) beam series 2: B8; where: $B_{5\div9}$ – designation of the measuring bases

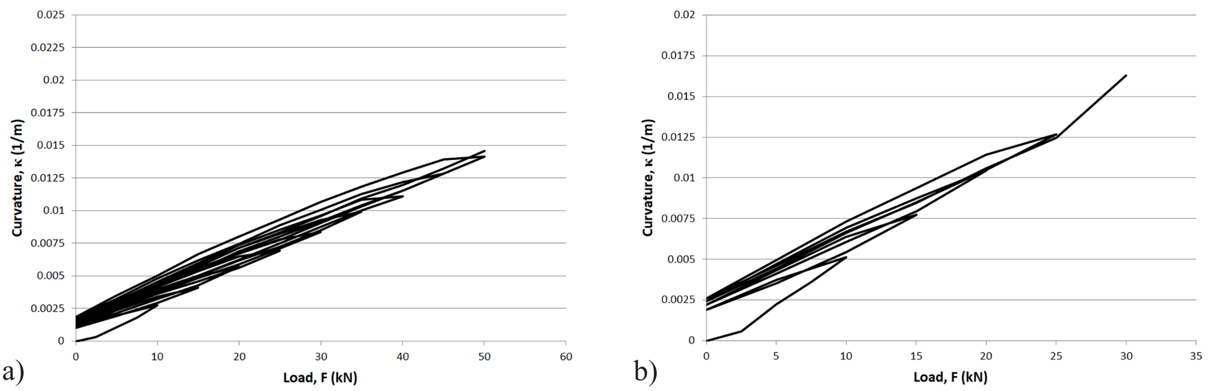


Figure 10. Variability of curvatures: (a) beam series 1: B3, base 7; (b) beam series 2: B8, base 7

elastic moduli E_{cm}, the concrete used to make the test elements can be classified as class C30/37. This class is higher than that of designed concrete that meets the requirements of class C20/25. Before the first crack appears, the neutral axis charts determined by experiment in all beams are similar to the neutral axis chart determined on the basis of the PN-B-03264:2002 standard. The values of the neutral axes determined in accordance with the above-mentioned standard for beams of series 1 and 2 are 15.80 cm and 15.00 cm, respectively. After reaching the drawing moment, the neutral axis charts determined from experimental tests in all beams are similar to the neutral axis chart

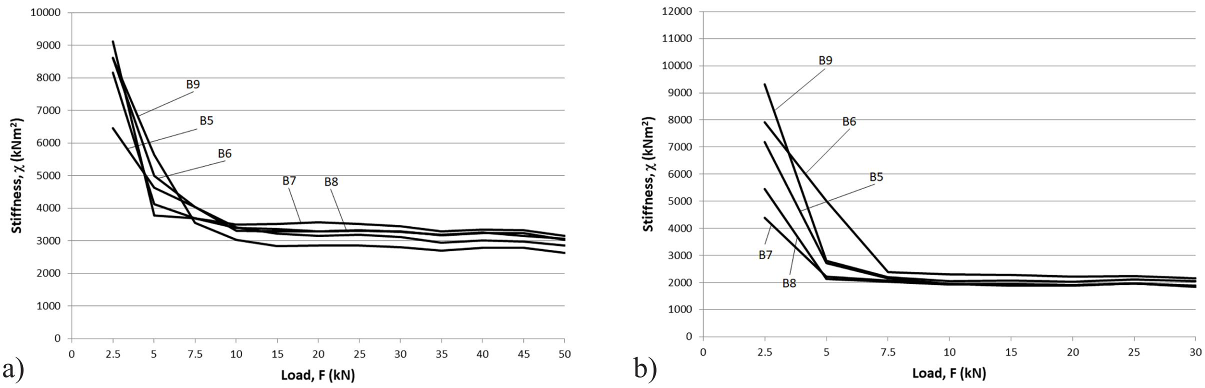


Figure 11. Stiffness variability: (a) beam series 1: B4; (b) beam series 2: B8; where: $B_{5\div9}$ – designation of the measuring bases

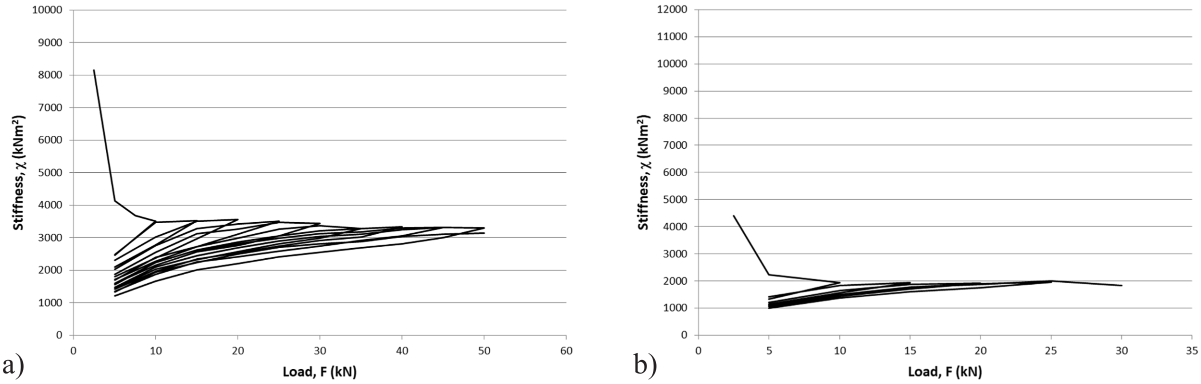


Figure 12. Stiffness variability: (a) beam series 2: B4, base 7; (b) beam series 2: B8, base 7

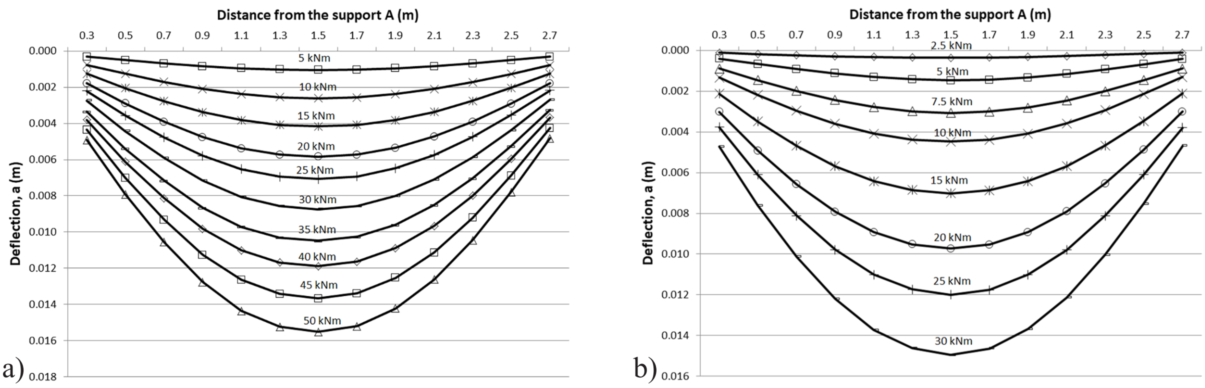


Figure 13. Deflection chart: (a) beam series 1: B3; (b) beam series 2: B8

determined in accordance with PN-B-03264:2002. The values of the neutral axes determined on the basis of the above-mentioned standard for beams of series 1 and 2 are 8.89 cm and 6.52 cm, respectively. The actual values of destructive moments for beams of both series (presented in tables 4, 5) are higher than the theoretical values determined on the basis of the PN-B-03264:2002 standard, which amount to M_{Rd} = 35.98 for beams of series 1 and 2, respectively M_{Rd} = 35.98 kNm, M_{Rd} = 22.40 kNm. As the bending moment increases, the stiffness of the tested element decreases. Its faster decline is noticeable after reaching the moment cracking. The value of the theoretical cracking moment M_{cr} = 3.96 kNm is lower than that obtained by experiment, where the values of cracking moments range from 5.0 kNm to 7.5 kNm. As the bending moment increases, the curvature of the element increases. The average curvature at the midspan for beams of series 1 and 2 equal to 0.00734 and 0.00618,

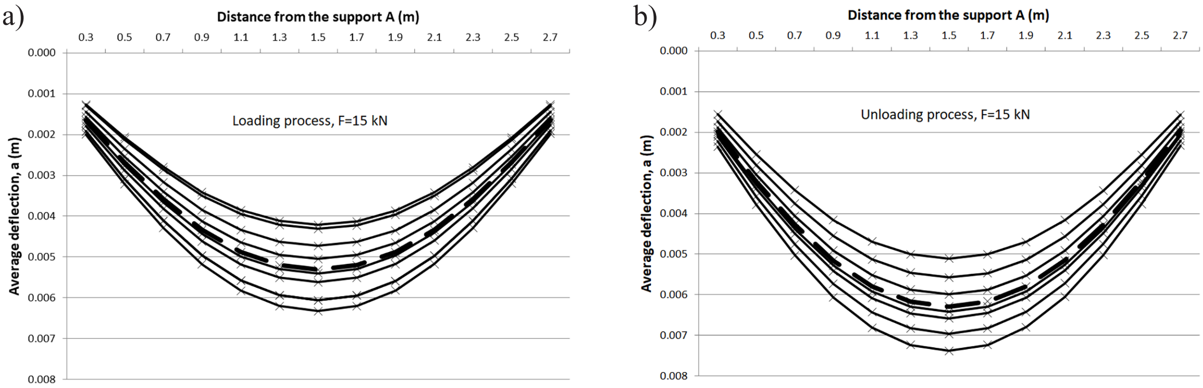


Figure 14. Chart of average deflections for beams of series 1 (a) during the loading process - load value 15 kN; (b) during the unloading process- load value 15 kN

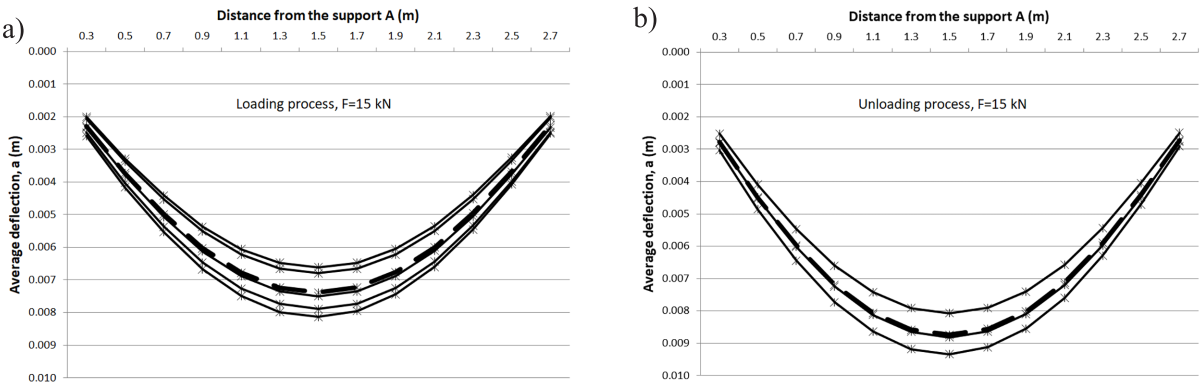
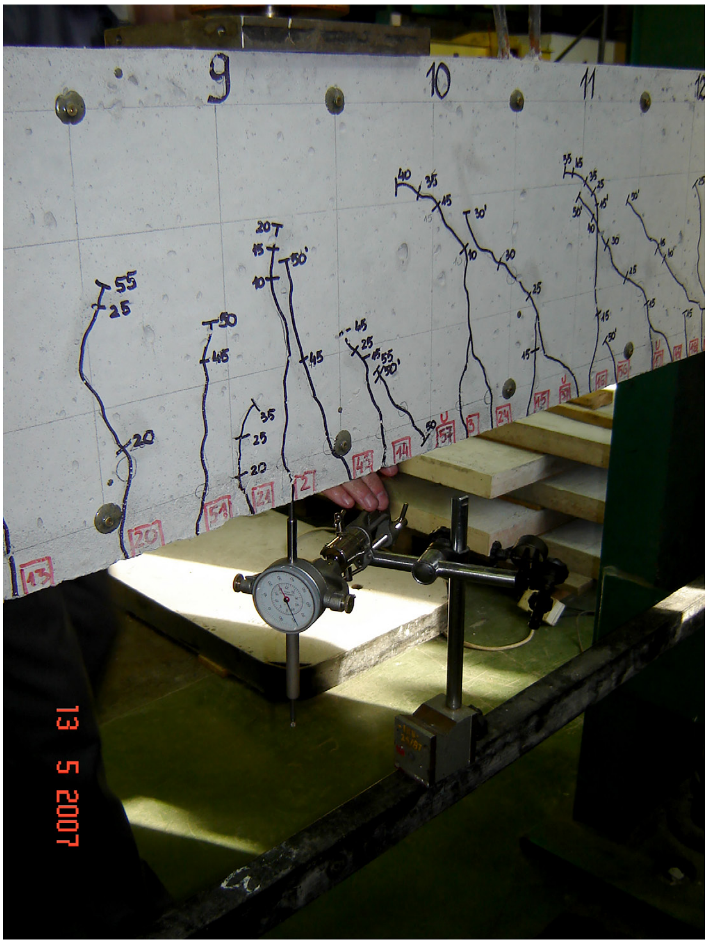
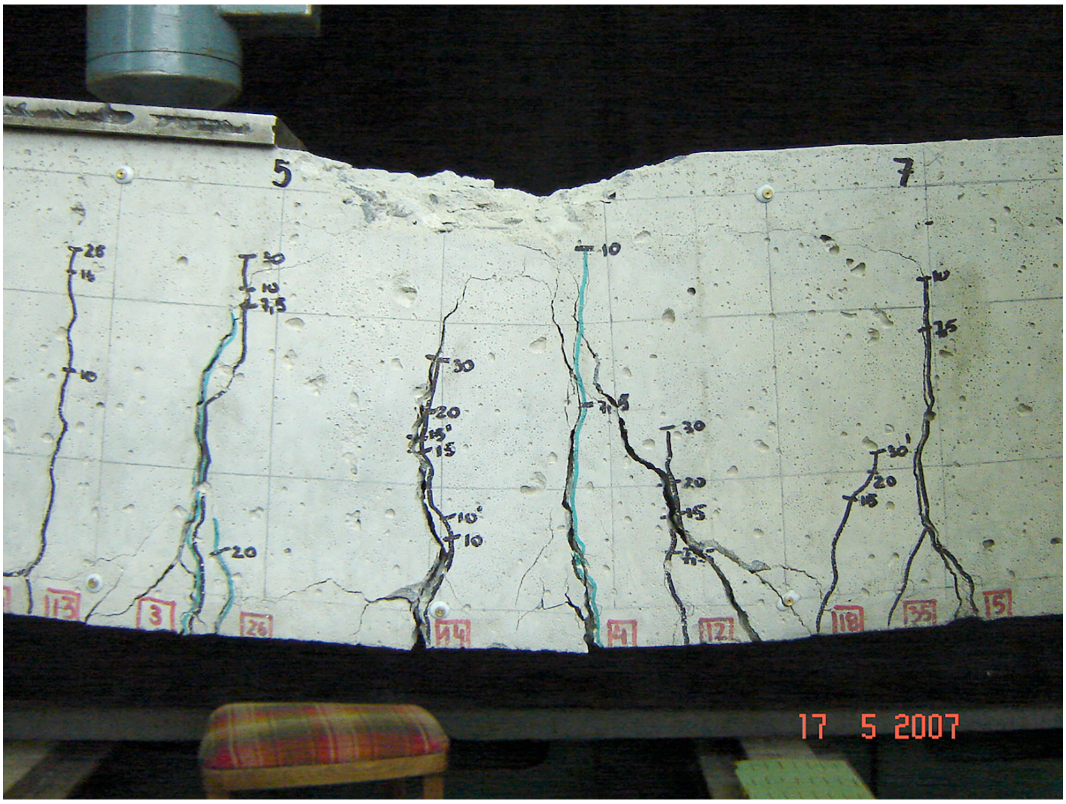


Figure 15. Chart of average deflections for beams of series 2 (a) during the loading process - load value 15 kN; (b) during the unloading process - load value 15 kN

Figure 16. View of the test stand with the tested element



a)



b)

Figure 17. View of the set for measuring element deflections (a) example image of failure of a bending reinforced concrete beam - measurement base 5, 6 and 7 (b)

Table 3. Tabular summary of the results of measurements of the destructive force of concrete samples

Beam designation/ sample number	Destructive force [MN]							
	B1	B2	B3	B4	B5	B6	B7	B8
1	0.800	0.955	0.725	0.850	0.865	0.870	0.790	0.875
2	0.865	0.960	0.860	0.855	0.815	0.895	0.920	0.885
3	0.860	0.905	0.850	0.910	0.820	0.925	0.945	0.900
4	0.805	0.905	0.780	0.815	0.855	0.845	0.890	0.975
5	0.870	0.910	0.725	0.815	0.865	0.910	0.860	0.865
6	0.850	0.960	0.795	0.830	0.810	0.900	0.990	0.955
7	0.810	0.860	0.805	0.835	0.775	0.925	1.015	0.925
8	0.935	0.870	0.765	0.825	0.840	0.915	1.045	0.915

Table 4. Strength characteristics of concrete from which series 1 of beams were prepared

Beam designation/material characteristics	B1	B3	B4	B5
Average compressive strength f_{cm} [MPa]	37.75	35.03	37.42	36.92
Standard deviation s [MPa]	1.99	2.25	1.38	1.40
Coefficient of variation v [%]	5.27	6.42	3.69	3.79
Guaranteed strength $f^{G}_{c,cube}$ [MPa]	34.48	31.34	35.15	34.62
Characteristic strength for compression f_{ck} [MPa]	27.59	25.07	28.12	27.70
Average tensile strength f_{ctm} [MPa]	2.74	2.57	2.77	2.75
Characteristic tensile strength f_{ctk}[MPa]	1.92	1.80	1.94	1.92
Calculated compressive strength f_{cd}[MPa]	18.39	16.72	18.74	18.47
Calculated tensile strength f_{ctd}[MPa]	1.28	1.20	1.29	1.28
Modulus of elasticity E_{cm} [GPa]	32.12	31.42	32.62	32.15
Concrete class	C30/37	C25/30	C30/37	C30/37

Table 5. Strength characteristics of concrete from which series 2 of beams were prepared

Beam designation/material characteristics	B2	B6	B7	B8
Average compressive strength f_{cm} [MPa]	40.69	39.92	41.42	40.53
Standard deviations s [MPa]	1.76	1.25	3.77	1.72
Coefficient of variation v[%]	4.33	3.13	9.10	4.23
Guaranteed strength $f^{G}_{c,cube}$ [MPa]	37.82	37.87	35.23	37.71
Characteristic strength for compression f_{ck} [MPa]	30.25	30.30	28.18	30.17
Average tensile strength f_{ctm} [MPa]	2.91	2.92	2.78	2.91
Characteristic tensile strength f_{ctk} [MPa]	2.04	2.04	1.94	2.04
Calculated compressive strength f_{cd} [MPa]	20.17	20.20	18.79	20.11
Calculated tensile strength f_{ctd} [MPa]	1.36	1.36	1.30	1.36
Modulus of elasticity E_{cm} [GPa]	32.82	32.84	32.28	32.80
Concrete class	C30/37	C30/37	C30/37	C30/37

respectively. Experimental tests of bending reinforced concrete beams. Deflection of beams does not exceed the average theoretical value calculated according to the PN-B-03264:2002 standard, equal to 0.0078 and 0.00762, respectively. The actual deflections determined experimentally based on the curvatures are smaller than the actual deflections read from the clocks during the tests. The average deflections obtained through experiments based on curvature measurements are smaller than the average deflections recorded from the gauges during the conducted tests for each load level. Considering the ultimate loading, the average deflections for beams in series 1 and 2 are 17.30 mm and 14.56

Table 6. Comparison of failure moments obtained from experimental and theoretical tests for series 2 beams

Beam designation	Reinforcement	Failure moment M_{Rd} calculated [kNm]	Failure moment M_{Rd} empirical [kNm]
B1	- tension reinforcement 2 ø16 RB 500 W - compression reinforcement 2 ø 8 RB 500 W - stirrup ø6 St3S	35.98	55.0
B3			53.5
B4			53.0
B5			53.5

Table 7. Comparison of failure moments obtained from experimental and theoretical tests for series 2 beams

Beamdesignation	Reinforcement	Failure moment M_{Rd} calculated [kNm]	Failure moment M_{Rd} empirical [kNm]
B2	- tension reinforcement 2 ø12 RB 500 W - compression reinforcement 2 ø 12 RB 500 W - stirrup ø6 St3S	22.40	33.5
B6			30.5
B7			30.0
B8			30.0

Table 8. Comparison of element deflections obtained from experimental and theoretical tests for series 2 beams

List of empirical deflection values for beams of series 1					
No	Force [kN]	No		No	
		Deflection a calculated according to PN-B-03264:2002 [mm]	Deflection fk calculated according to ACI (318-71) [mm]	Average deflections determined on the basis of curvatures [mm]	Average deflections a determined on the basis of strain gauges [mm]
1	0	0.00	0.00	0.00	0.00
2	2.5	0.26	0.29	0.33	0.27
3	5	1.16	0.83	1.01	1.08
4	7.5	1.98	1.74	1.79	2.06
5	10	2.75	2.56	2.68	3.05
6	15	4.25	4.06	4.21	4.73
7	20	5.73	5.51	5.78	6.43
8	25	7.20	6.89	7.28	7.93
9	30	8.66	8.33	8.86	10.10
10	35	10.12	9.72	10.69	12.41
11	40	11.58	11.11	12.08	14.17
12	45	13.03	12.50	13.79	16.38
13	50	14.49	13.89	15.74	18.38
14	55	15.94	15.28	17.30	22.80

mm (deflection based on curvature measurements), respectively, and 22.80 mm and 17.87 mm (deflection based on gauges), respectively.

The design deflections determined on the basis of the PN-B-03264:2002 standard are larger than the deflections determined on the basis of the ACI standard (318–71). The actual deflections read during experimental tests from clocks mounted on the rail under the tested elements, as well as calculated on the basis of the curvatures of the tested elements, are greater than the deflections determined from both standards mentioned above. At the same load level, the deflection values of elements during the unloading process are greater than during the loading process.

Based on the analysis performed, it can be concluded that the theoretical values calculated in accordance with the PN-B-03264:2002 and ACI (318–71) standards are larger than those obtained as a result of experimental tests. This is due to the fact that the concrete produced is of a higher class than the concrete used for calculations (C20/25), as well as the omission of compressive reinforcement with a diameter of less than 12 mm in the theoretical calculations.

Table 9. Comparison of element deflections obtained from experimental and theoretical tests for series 2 beams

LIST OF EMPIRICAL DEFLECTION VALUES FOR BEAMS OF SERIES 2					
No	Force [kN]	No		No	
		Deflection a calculated according to PN-B-03264:2002 [mm]	Deflection fk calculated according to ACI (318-71) [mm]	Average deflections determined on the basis of curvatures [mm]	Average deflections a determined on the basis of strain gauges [mm]
1	0	0.00	0.00	0.00	0.00
2	2.5	0.25	0.29	0.35	1.06
3	5	1.72	0.94	1.31	2.27
4	7.5	3.05	2.33	2.69	3.78
5	10	4.28	3.67	4.06	5.23
6	15	6.66	6.07	6.61	7.96
7	20	8.98	8.30	9.26	10.77
8	25	11.29	10.51	11.52	13.20
9	30	13.59	12.78	14.56	17.87

CONCLUSIONS

In light of the conducted experiments and analyses, several key conclusions can be drawn regarding the investigated concrete beams:

1. Concrete quality:
   - the concrete used in the test elements demonstrated good quality, with average guaranteed strengths falling within the range of 31.34 MPa to 37.87 MPa for different mixtures;
   - the relative standard deviation for the tested concrete production was very good, not exceeding 7%, except for beam B7 in series 2, where it was 9.1%.
2. Elastic modulus of concrete:
   - the elastic modulus of concrete (Ecm), determined based on measured compressive strengths, ranged from 31.422 GPa to 32.836 GPa.
3. Concrete classification:
   - based on compressive strengths and elastic moduli, the concrete used was classified as class C30/37, surpassing the designed concrete class C20/25.
4. Neutral axis charts:
   - before the appearance of the first crack, neutral axis charts determined experimentally aligned with the PN-B-03264:2002 standard;
   - after reaching the drawing moment, the experimental neutral axis charts remained consistent with the standard.
5. Destructive moments:
   - actual destructive moments for both series exceeded the theoretical values prescribed by the PN-B-03264:2002 standard.
6. Stiffness and cracking:
   - the stiffness of the tested elements decreased as the bending moment increased, notably after reaching the drawing moment;
   - the theoretical cracking moment (Mcr) was lower than the experimentally obtained values, indicating a conservative design approach.
7. Curvature and deflection:
   - as the bending moment increased, the curvature of the elements also increased;
   - experimental deflections based on curvature measurements were smaller than those read from gauges during tests.
8. Comparison with standards:
   - deflections determined based on the PN-B-03264:2002 standard were larger than those calculated using the ACI (318–71) standard;
   - theoretical values from both standards were larger than experimental values, attributed to the higher concrete class than the designed one and the exclusion of compressive reinforcement with a diameter less than 12 mm in theoretical calculations.

The experimental tests revealed the robustness and superior performance of the concrete beams, surpassing the theoretical expectations based on standard calculations. The discrepancy can be attributed to the higher concrete class used in the experiments and the omission of certain factors in theoretical calculations. These findings emphasize the importance of considering concrete quality and updated standards in structural design and analysis. Reinforced concrete beams are an integral part of many structures, from bridges and residential buildings to industrial and commercial buildings. Properly designed and constructed beams play a key role in maintaining safe and stable structures.

The conducted research on two series of full-sized reinforced concrete beams, manufactured under laboratory conditions, confirmed that ensuring compliance with the process of beam production with applicable standard procedures, as well as attention to the quality of concrete production, sample preparation, and proper curing, contributes to achieving satisfactory results in both the ultimate load-carrying capacity and serviceability states.

In both series of reinforced concrete beams, the actual values of the ultimate bending moments were found to be greater than the theoretical values. This serves as confirmation of the correct adoption of normative assumptions and the meticulousness in the manufacturing process of the tested elements. A similar trend is also observed when considering serviceability limit states. Real deflections, as measured based on gauges, as well as those determined based on curvature measurements of the tested beams, are greater than the theoretical deflections calculated based on two selected standards.

The accompanying tests conducted on the hardened concrete mixture allowed for the estimation of the concrete's class and the assessment of both its strength and statistical parameters.These tests revealed a concrete class higher than the design specification C20/25. The quality of concrete production for the reinforced concrete beams from both series of tests (excluding beam B7) turned out to be very good. This is evidenced by obtaining a relative standard deviation below 7%.

When estimating the compressive strength of hardened concrete, which is a primary material used in construction projects, and evaluating its quality, it's crucial to remember that material properties play a significant role in the durability of existing structures or those under construction, ensuring their intended service life. Insufficient quality and strength of materials used can be a cause of various damages, failures, or even construction disasters.

Procedures and instructions prepared with due care play an important role in strengthening supplier supervision, improving resource management, ensuring compliance with customer requirements and effective monitoring of product quality, which ultimately contributes to reducing production costs. In a number of purposefully selected organizations, efforts are being made to integrate welding quality management systems with other standard management systems. It is worth emphasizing that as part of this integration, an important aspect is the skillful management of specialized processes in which quality is particularly important. Ensuring compliance with the required standards is mainly based on the implementation of a comprehensive quality management system, especially important in the case of complex processes, such as the production of reinforced concrete beams.

The research conducted on reinforced concrete beams highlights the critical role of specialized processes in construction. By adhering to stringent production procedures and maintaining concrete quality, the study achieved satisfactory results in terms of load-carrying capacity and serviceability. The findings also underscore the importance of correctly implementing normative guidelines and meticulous manufacturing processes, resulting in greater actual bending moments and deflections compared to theoretical values. Additionally, the assessment of concrete quality and strength, exemplified by a higher concrete class than initially specified, emphasizes the significance of material properties in ensuring structural durability. Effective quality management systems, particularly for specialized processes like reinforced concrete beam production, are essential for maintaining compliance with standards and reducing production costs within the construction industry.

The conducted research allowed for the assessment of the behavior of reinforced concrete beams subjected to loading in the form of two step-variable forces until failure, with multiple unloading to 0 kN. In the future, research is planned to study the behaviour of reinforced concrete beams under the influence of cyclically variable loading for different levels of reinforcement and the quantity of applied forces. An unquestionable limitation in further research lies in the properties of the tested material, which, as a composite, is a highly demanding material, arising from factors such as the curing time of the concrete mixture, appropriate vibration, or the curing time of the hardened concrete.

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