Effectiveness of strengthening pre-loaded RC beams with CFRP strips in conventional and accelerated strengthening procedures

Dorota Michałowska-Maziejuk[1,*], *Barbara* Goszczyńska[1], and *Wiesław* Trąmpczyński[1]

[1]Kielce University of Technology, Faculty of Civil Engineering and Architecture, Poland

Abstract. This paper analyses the results obtained from the testing of reinforced concrete beams additionally strengthened with composite materials pressed into the concrete cover using the near-surface-mounted reinforcement (NSMR) method. The testing program comprised two series of beams with cross-sectional dimensions of 0.12 x 0.30 x 3.30 m. The series differed in the amount of longitudinal steel reinforcement, 0.51% and 1.00%. Three beams were cast in each series. One beam was assigned as the control beam, while two other beams were strengthened with carbon fibre strips. A two-component thixotropic epoxy resin was used as a bonding agent. One of the two beams was cured for 7 days (to the product information document). The bonding process in the other beam was accelerated to last 1.5 hours by heating the strip up to 70°C. As the strengthening of "new" elements is not an accepted practice in engineering, the beams were pre-loaded. The load was maintained during the strengthening procedure and curing period (for 7 days and 1.5 hours) and then the beams were monotonically loaded to failure. The comparison of load capacity results for the CFRP strengthened and control beams revealed the effectiveness of the strengthening method. The paper also presents the strengthening technique in the NSMR application with the prototype heating device.

1 Introduction

In many countries worldwide, including Poland, new construction projects are becoming limited both in scale and scope. Over the last several years, retrofitting, structural upgrades, modernization works and strengthening procedures have been on the rise in relation to the decreasing number of newly constructed buildings. The need to strengthen may originate from poor workmanship, design errors, misuse of the building, wear-out of its structural components used beyond their design service life, or increased user requirements. Strengthening can also be performed when a building changes its function. The required increase in usable loads will create the need for adequate increase in the load capacity of structural elements of the building.

Traditional strengthening techniques [1], such as increasing the cross-section of the member, adding internal or external reinforcement, gluing steel flat bars or reducing internal

* Corresponding author: d.michalowska@tu.kielce.pl

forces by changing the static scheme of the member, usually generate high deconstruction costs. However, load-bearing capacity improvement can be achieved through the use of innovative solutions employing externally-bonded composite materials in place of more conventional techniques. Composites are lightweight, corrosion-resistant, high-quality, and alkali-resistant materials easy to transport and mount [2, 3]. Any lengths of the composite strips are manufactured and applied thus eliminating the need for joints. A high modulus of elasticity makes them suitable for strengthening the existing reinforced concrete structures. New techniques and methods of increasing load carrying capacity of members in bending, shear or compression are being developed.

Composite laminate strips and flexible sheets are widely used in carbon fibre reinforced polymer (CFRP) strengthening of reinforced concrete (RC) components (beams and slabs) in bending. Bonded on the external surface of the reinforced element (*externally bonded reinforcement,* EBR), they act as external tensile reinforcement. Many researchers have confirmed the effectiveness of this type of strengthening [4-7]. An alternative method, NSMR (*near surface mounted reinforcement*) [8-11] is one of the latest techniques and involves embedding CFRP materials in the resin grout-filled grooves in the concrete cover of the reinforced component. In addition to protecting the composite against mechanical damage, this solution provides better anchoring capacity and improved tensile strength of the material without changing the dimensions or aesthetics of the structure. The method can be used only in cases where the thickness of the concrete cover is sufficient. The techniques of load-bearing capacity enhancement have been used in Europe since the 1940s. The pioneering method consisted in pressing steel reinforcing bars into a groove cut in a concrete cover and filled with cement grout [12]. The NSMR method with the use of composite materials was first applied at the beginning of the 21st century.

The aim of this article was to evaluate the effectiveness of strengthening pre-loaded RC beams with CFRP strips in the NSMR method. The strengthening was carried out from the bottom surface of the components under the load that corresponded to static load.

The paper analyses the results from testing RC beams with a CFRP strip embedded in the concrete cover (NSMR) for flexural strength. As the duration of the strengthening process is of key importance (the structure needs to be temporarily put out of operation, which generates high costs), this paper proposes an accelerated strengthening procedure in which CFRP strips are heated using the prototype heating device [13, 14]. This method reduces the adhesive grout bonding time even to 1.5 hours and, consequently, shortens the entire strengthening process.

The effectiveness of strengthening the RC beams with the use of the accelerated method was compared with the effectiveness of the 7-day bonding process conducted in compliance with the guidelines [15].

2 Research program

2.1 Test set up

The test stand used in this study was designed for testing single span beams with a clear span length of 3.0 m. It consists of a stiff steel frame fixed to the stand base plate. The frame system enables the installation of the supports (bridge bearings) and actuators powered by the controller for programming the load. Any combination of concentrated forces is possible.

Simply supported reinforced concrete beams with a 3000 mm clear span and the cross-sectional area of 120x300 mm were tested in a four-point loading scheme. The load was applied with a spacing of 1000 mm between the two concentrated forces at a 1000 mm distance from the axis of the supports. The HBM measuring set and the optical measuring

system were used to register the load and deflection of the specimens. The optical measuring system allowed the analysis of failure modes. Figure 1 shows the test stand with the RC beam being tested.

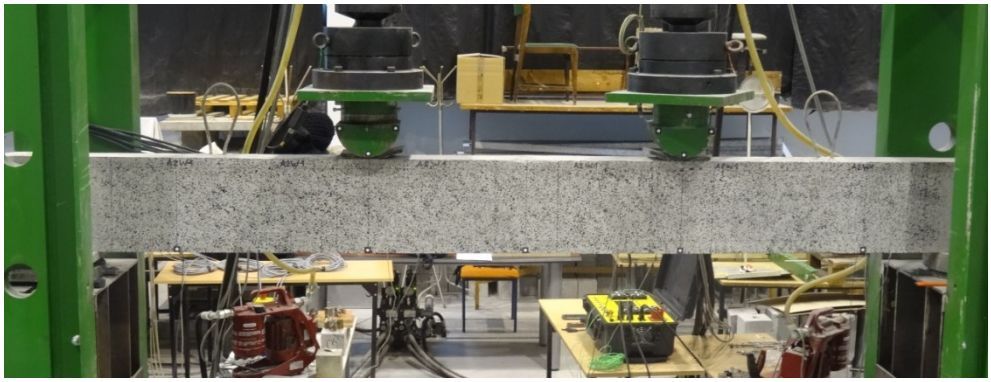

Fig. 1. View of the test stand with a reinforced concrete beam.

2.2 Test specimens

Six reinforced concrete beams in two series (I and II, three beams in each series) were prepared and tested in this study. The series differed from each other in the amount of steel reinforcement used, 0.51% and 1.00%, respectively. Each series consisted of one unstrengthened reference beam (denoted by **R**) and two strengthened beams. One of the two beams (denoted by **A)** was strengthened using the heating device [13, 14] and the adhesive bonding time was 1.5 hours. In the case of other strengthened beam (beam **C)**, the adhesive bonding process took 7 days under normal temperature conditions (23°C), as recommended in the product data sheet [15].

Table 1 summarizes the details of the tested beams, bonding time and glue hardening temperature.

Table 1. Details of tested beams.

Series	Beam	Compressed / tension rods	CFRP strip n x t_f x b_f	Bonding time (temperature)
I	R1	2#8 / 2#10	-	-
	A1W1		1x10x30 [mm]	1.5 hours (70°C)
	C1.1W1			7 days (23°C)
II	R2	2#8 / 2#14	-	-
	A2W1		1x10x30 [mm]	1.5 hours (70°C)
	C2W1			7 days (23°C)

The RC beams were cast in the laboratory with C20/25 concrete. Steel reinforcement A-IIIN and BST500S was used. Two steel bars with diameter of 8 mm were used in the compression zone of the beam. The steel reinforcement in the tension zone consisted of the bars with diameter of 10 mm (series I) and 14 mm (series II). The shear reinforcement comprised steel stirrups 6 mm in diameter spaced at 100 mm (in the shear span) and 225 mm (in the constant moment region) and made with the same class and type of steel as the longitudinal reinforcement.

To ensure the suitable concrete cover for embedding the composite strips, 30 mm distance inserts were used during casting. The reinforcement scheme for beams series I and II is shown in Figure 2.

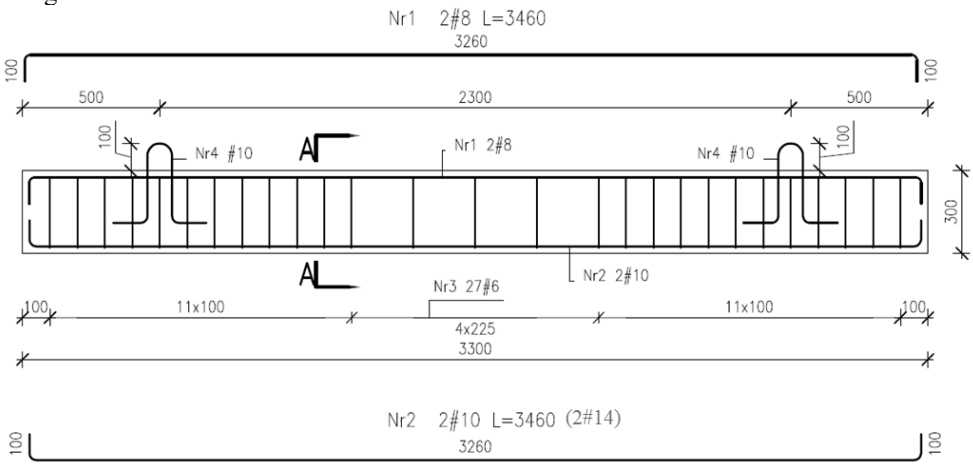

Fig. 2. Details of two series of tested beams – steel reinforcement.

All the RC beams were strengthened in bending with a single CFRP strip Sika®CarboDur® S NSM 1.030 having material characteristics as in [16]. The 10 mm wide, 3 mm thick and 2360 mm long strip was embedded in the longitudinal pre-cut grooves filled with two-component, thixotropic epoxy resin as an adhesive.

2.3 Beam loading and strengthening

2.3.1 Loading

To simulate the process of strengthening RC beams in real conditions, the strengthening was performed on the bottom surface of the pre-loaded specimens. The values of applied forces corresponded to actual loads on the beam in the RC beam-framed floor.

The values of the loading forces were assumed to reach 30% of the load bearing capacity of the beam and were 8 kN and 13 kN for the beams with lower and higher content of steel reinforcement, respectively. Since the strengthening should be performed at the minimum stress on the structure [17], the pre-loading was reduced in the beams with a longitudinal steel $\rho s = 0.51\%$ to the value of 3.9 kN, and in the beams with $\rho s = 1.00\%$ to the value of 6.6 kN. The load was maintained throughout the strengthening, both in the accelerated method and in the 7-day adhesive hardening period. After strengthening, all the beams were loaded monotonically to failure. The specimens were loaded and unloaded with concentrated forces (F) at an increment of 0.4 kN/min.

Figure 3 illustrates the loading scheme. The horizontal line shows the bonding process of 1.5 h duration (accelerated adhesive bonding) and 7 days duration (adhesive bonding at ambient temperature).

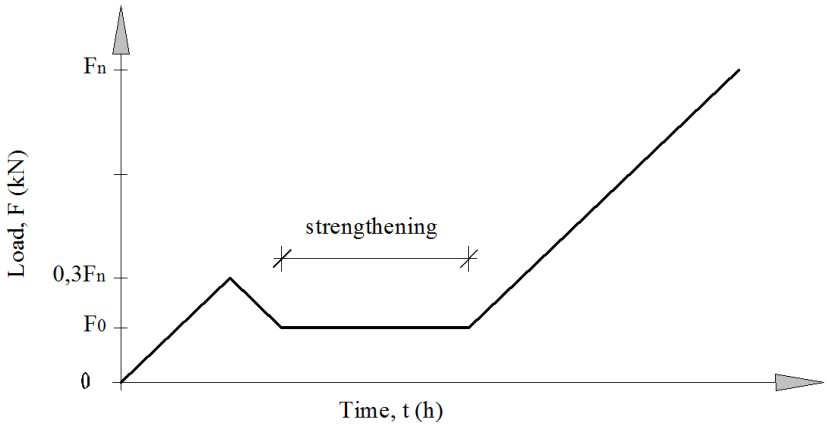

Fig. 3. The loading program for beam strengthening.

2.3.2 Strengthening

The beam supports on the test stand, Figure 1, were raised up to the maximum for strengthening by pressing the composite material into the concrete cover during the loading process. The strengthening process in the NSMR method started with the preparation for CFRP strip embedment. The grooves were opened in the concrete cover using a diamond blade concrete saw. Groove dimensions, 7x14 mm, followed the requirements set forth by the manufacturer of the strips and grout [18]. The cut was made at a distance of 60 mm from the side surface of the test member. Before the strip was embedded, compressed air was used to thoroughly clean the groove of concrete pieces and dust. In the next step, the CFRP strip was pressed into the concrete cover with the use of adhesive grout mixed as recommended [15], maintaining the proportions by weight. In order to prevent the strip from slipping out of the adhesive grout, steel clamps were used in the mid-span of the beam at the distance of 350 mm from the axis of each support. The beam was left under constant load for the bonding time, which was 7 days under laboratory conditions.

In the accelerated procedure, before the strips were embedded, special flat copper clamps were applied at the tape ends to allow the correct current flow between the heating device and carbon fibre strip. The RC beam with the groove, flat copper bar and the heating device cables is shown in Figure 4.

Fig. 4. Reinforced concrete beam with the groove and copper flat bar.

The CFRP strip with the copper flat bars was pressed into the glue-filled groove and secured against slipping out. In the next step the adhesive bonding process was accelerated with the heating device prototype. The flow of electric current through the carbon fibre strips heated them to the desired temperature (t = 70°C), increased the temperature of the adhesive, and as a result reduced the bonding time.

The electric current was carried through the wires with special clips at the ends clamped to the flat copper bars. The copper flat bars stuck out of the testing element (Fig. 4). The thermocouple cable with thermocouple gauge, embedded in the adhesive grout in the hottest place (in the middle of the heated carbon strip) measured the temperature. An increase in temperature over the assumed value was prevented with a PID controller, which was installed in the heating device [19]. The accelerated adhesive bonding process took 1.5 hours. The scheme of the accelerated strengthening process is shown in Figure 5.

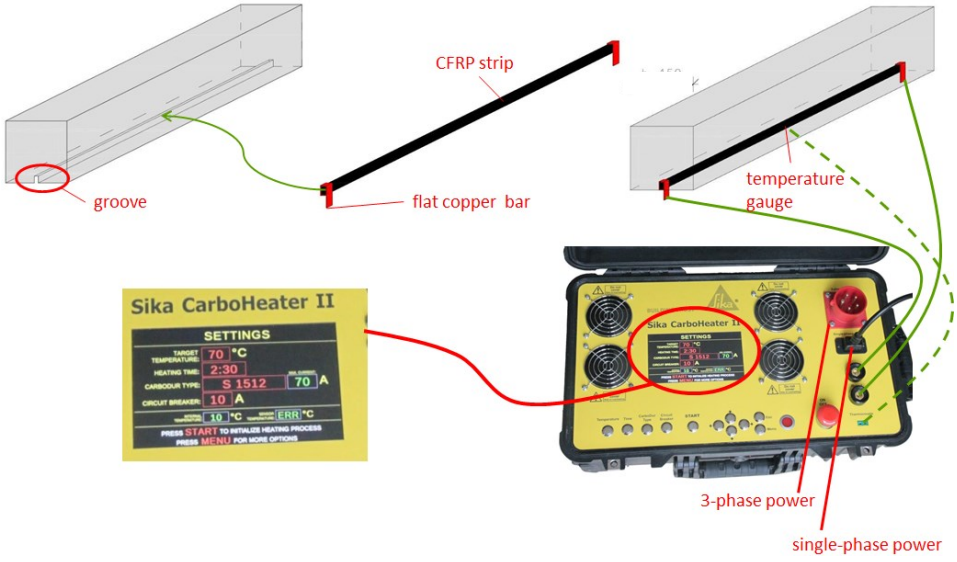

Fig. 5. Accelerated strengthening process.

3 Experimental results and discussion

The amount of steel reinforcement (ρ_s) and adhesive bonding time (t) were the variables in the strengthening evaluation. The amount of composite reinforcement (ρ_f) was the constant parameter. The amount of steel and composite reinforcement was determined from formulas 1 and 2:

$$\rho_s = \frac{A_s}{bd_s} \tag{1}$$

$$\rho_f = \frac{A_f}{bd_f} \tag{2}$$

where A_s is the surface area of the steel reinforcement; d_s is the usable height from the beam compression face to the centroid of the steel reinforcement; A_f is the surface area of the composite reinforcement; d_f is the usable height from the beam compression face to the centroid of the composite reinforcement; b is the width of the beam.

The recorded results of force measurements at failure (F_n) were used to obtain the strengthening ratio of the tested reinforced concrete beams from formula 3:

$$\eta = \frac{M_u - M_0}{M_0} \tag{3}$$

where M_u and M_0 are breaking moments of strengthened and unstrengthened specimens.

The beam strengthening effectiveness was determined by comparing the strengthening ratio to the load capacity of the unstrengthened specimens (η).

The results are compiled in Table 2.

Table 2. Results for the beams under test

Series	Beam	ρ_s [%]	ρ_f[%]	F_n [kN]	M_n [kNm]	η
I	R1	0.51	-	26.0	26.0	-
	A1W1		0.08	41.6	41.6	0.60
	C1.1W1			35.0	35.0	0.35
II	R2	1.00	-	42.8	42.8	-
	A2W1		0.08	56.5	56.5	0.32
	C2W1			50.0	50.0	0.17

In general, the strengthening effectiveness in the NSMR method without heating the adhesive was found to be lower than expected.

It seems that the effectiveness of 35% (C1.1W1 beam – steel reinforcement of 0.51%) is comparable to that of the EBR method. The accelerated adhesive bonding process seems to have a positive effect on the strengthening efficacy, which is 60% for a beam with the same quantity of steel reinforcement.

The test results show that the strengthening ratio decreases with increasing steel reinforcement quantity. The specimens with ρs = 0.51% exhibit higher strengthening ratio (η = 0.35) than elements with ρs = 1.00% (η = 0.17).

The same decreasing trend is observed for the beams to which the accelerated strengthening process was applied. The strengthening ratio of the beams with ρs = 0.51% is higher (η = 0.60) than that of the beams with ρs = 1.00% (η = 0.32). The double increase of the steel reinforcement amount in the tested beams (ρs = 0.51% to ρs = 1.00%) results in a nearly 50% reduction in the strengthening ratio, regardless of whether the bonding time was 7 days or 90 minutes.

A higher decrease in the strengthening ratio is observed in the case of a longer adhesive bonding time (decrease by 51.4%). In the case of the accelerated strengthening process, the decrease is 46.7%.

It can be concluded that the use of hardening of the adhesive grout at high temperature has a beneficial effect on the effectiveness of beam strengthening. When we compare the strengthening ratios of "heated" and "non-heated" beams with the same amount of steel reinforcement - it can be seen that the strengthening ratio is higher for beams after the accelerated adhesive bonding. For beams from series I (ρs = 0.51%) the increase in the strengthening ratio was 71%, with 88% increase for beams of series II (ρs = 1.00%). The graphic representation of the effect of the steel reinforcement quantity (ρ_s) on the strengthening ratio (η) is shown in Figure 6.

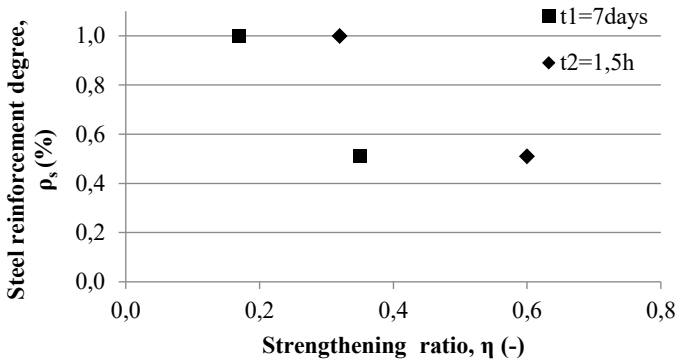

Fig. 6. Effect of the percentage of steel reinforcement (ρs) on the strengthening ratio (η)

Analysis of the mechanism of failure in the test specimens indicates three failure modes.

Unstrengthened beams (R1, R2) failed in a typical way for reinforced concrete elements by exhausting the load capacity of reinforcement in the tension zone.

Reinforced beams after the accelerated strengthening process (A1W1, A2W1) failed due to the debonding of the composite reinforcement together with the concrete cover, exposing the steel reinforcement (ICD - *intermediate crack debonding*). The failure was rapid, and the debonded area covered the region within the concentrated force located closer to the articulated-sliding support that partially extended over the zone of pure bending.

On the other hand, at the connection of the strips with flat copper bars, which allow the electric current to flow through the composite, the concrete cover remained well-integrated with the strip, and the composite was not debonded from the tested element. The failure mode of the beams after accelerated strengthening process is shown in Figure 7.

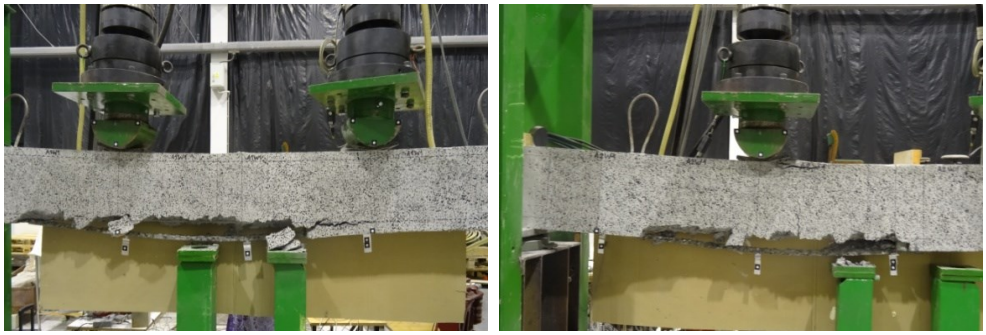

Fig. 7. The failure of beams (from left) A1W1, A2W1.

Strengthened beams after the 7-day bonding process (C1.1W1, C2W1) failed by concrete crushing in the compression zone (CC), which indicates the insufficient use of composite reinforcement.

The influence of bonding time (*t*) on the value of beam deflection (a_n) at failure was also analysed. The results of deflection measurements performed with the ARAMIS optical system in the mid-span of the test specimens after the strengthening process (a_0) and at failure (a_n) are shown in Table 3.

Table 3. Deflections of beams after strengthening process and at the moment of failure.

Series	Beam	F_0 [kN]	F_n [kN]	a_0 [mm]	a_n [mm]	Δa[mm]	Bonding time (t)
I	A1W1	3.96	41.6	0.84	49.40	48.6	1.5 hours
II	A2W1	6.62	56.5	2.50	46.00	43.5	
I	C11W1	3.83	35.0	1.14	31.70	30.6	7 days
II	C2W1	6.54	50.0	3.41	26.90	23.5	

It can be seen that the increase in deflection is higher in the case of beams to which the accelerated bonding process was applied. In both cases, within the same adhesive bonding time a smaller deflection increase is observed in the beams with higher percentage of steel reinforcement, ρs = 1.00%, being lower by 10% and 23% for the bonding time of 1.5 h and 7 days, respectively. The relationship between the deflection (a_n) and force at failure (F_n) is shown in Figure 8.

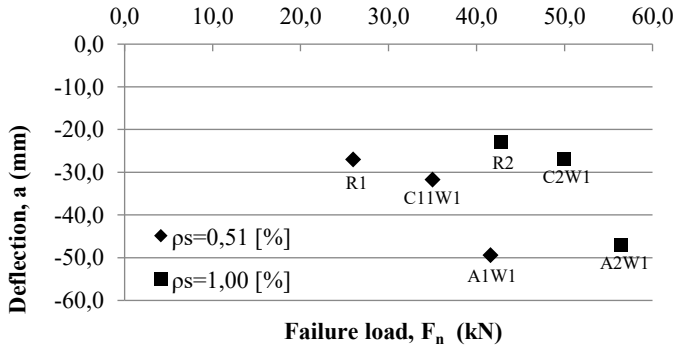

Fig. 8. Relationship between deflection (a_n) and force at failure (F_n).

4 Conclusions

The paper presents preliminary results of research on the effectiveness of strengthening of preloaded (by modelling the service load) reinforced concrete beams using the NSMR method and composite materials. CFRP strips were embedded in the concrete cover from the bottom surface of the elements under constant load. The 7-day adhesive bonding took place at ambient temperature and when heating was applied the bonding time was 1.5 hours. From the test and analysis results it follows that the effectiveness of the method depends on the percentage of steel reinforcement used in the beams. The results obtained in the study show that:

- strengthening effectiveness (η), defined as the strengthening ratio, referred to the load capacity of unstrengthened elements in the so-called "cold method", depends on the steel reinforcement amount in the beams;
    - 35% for the beams with 0.51% steel reinforcement;
    - 17% for the beams with 1.00% steel reinforcement,
- a similar tendency is observed when the accelerated method of strengthening is used,
- the strengthening ratio in the case of accelerated bonding by heating increases as compared to the strengthening ratio for the ambient temperature bonding. For the same steel reinforcement percentage, the strengthening ratio (η) increased by 88%. A significant increase is also evident when we compare the deflections of the tested beams. The results of deflections at the level of breaking force in the accelerated method increase to 71% relative to the beams where the bonding time was 7 days,
- the use of heating process reduces the bonding time and increases the strength properties of the reinforced elements. The strengthening effectiveness related to the load capacity of unstrengthened beams was as follows:
    - 60% for the beams with steel reinforcement of 0.51%,
    - 35% for the beams with steel reinforcement of 1.00%,
- the technique is able to shorten the time and reduce the costs of strengthening existing structures, especially structures such as bridges or viaducts.

References

1. T. Urban, *Strengthening reinforced concrete structures with traditional methods* (PWN, Warsaw, 2016) [in Polish]
2. Guidelines: CNR DT 200, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures* (National Research Council, Advisory Committee on Technical Recommendations for Construction, Rome, 2004)
3. Report: *FIB 14: Externally bonded FRP reinforcement for RC structures* (2001)
4. M.E. Kamińska, R. Kotynia, *Experimental research on RC beams strengthened with CFRP strips*, *Report No. 9* (Lodz University of Technology, Lodz, 2000) [in Polish]
5. R. Kotynia, *Debonding failures of RC beams strengthened with externally bonded strip,* (Proceedings of the International Symposium on Bond Behaviour of FRP in Structures , Hong-Kong, 2005)
6. H. Rahimi, A. Hutchinson*,* J. Compos. Constr. **5(1)**, (2001)
7. A. Khalifa, T. Alkhrdaji, A. Nanni, S. Lansburg*,* Conc. Int.: Design Constr., **21(10)**, (1999)
8. R. Kotynia, Arch. Civ. Eng. **LII (2)**, pp. 305-317 (2006)
9. J. Barros, S. Dias, J. Lima, Cem. Concr. Compos., **29**, pp. 203-217 (2007)
10. J. Sena-Crus, S. Dias, D. Ferriera, A. Fortes, J. Baros, *Near surface mounted CFRP – based technique for the strengthening of concrete structures* (Proceedings of the Jornada Técnica en Honor a Ravindra Gettu, Barcelona, 2004)
11. A.S. Kalayci, B. Yalim, A. Mirmiran, Constr. Build. Mater, **24(10)**, pp. 1821-1829 (2010)
12. S.Q. Asplund, , ACI J. Proc., **45(1)**, (1949)
13. D. Michałowska-Maziejuk, B. Goszczyńska, W. Trąmpczyński, *Accelerated method of reinforced concrete component strengthening with carbon fibre strips* (Proceedings of the IABSE Conference - Creativity and Collaboration, Switzerland, pp. 212-213)
14. D. Michałowska-Maziejuk, B. Goszczyńska, W. Trąmpczyński, *Acceleration of strengthening reinforced concrete with carbon fiber strips in NSMR method*, (Proceedings of XXIII Scientific-Technical Conference on Structural Failures, Szczecin-Międzyzdroje, pp. 805-814, 2017) [in Polish]
15. Document: Sikadur®– 330, *Two-component impregnating epoxy resin*, 2016, version 01.01 [in Polish]
16. Document: Sika®CarboDur® S NSM, *Carbon fibre strips for structural reinforcements, a component of the Sika Carbodur® system,* 2016, version 03.02 [in Polish]
17. M. Łagoda, *Recommendations for strengthening bridge structures by gluing external reinforcement* (IBDM, Warsaw, pp 1-62, 2002) [in Polish]
18. A. Baier, *Recommendations for the use of the Sika® CarboDur® NSM system for structures with near-surface reinforcement* (*Sika Services AG*, pp. 1-13, 2011, version 850 41 07) [in Polish]
19. *CarboDur Heating Device 2 user manual* (PEPE.AG, pp 1-15, 2016, version 1.0) [in Polish]