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ANALYSIS, COST ESTIMATION AND OPTIMIZATION OF REINFORCED CONCRETE SLAB STRENGTHENING BY STEEL AND CFRP STRIPS

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ABSTRACT

As a result of the planned change of use, the imposed load on the existing reinforced concrete mezzanine slab will be significantly increased, wherefore a diagnostics and assessment of the current state of the structure has been carried out. The control calculation showed that the slab does not have sufficient bearing capacity for the increased load. After qualitative analysis of possible strengthening methods, two methods were selected for detailed analysis: strengthening with steel strips and strengthening with carbon fiber-reinforced polimer (CFRP) plates.

The criterion for choosing the optimal solution was the total cost of the material. It has been shown that the total price of materials for strengthening with steel strips is almost 40% lower than the price of strengthening with CFRP plates. It has also been observed that, when using steel strips, the contribution of the price of adhesive in the total cost of material is extremely high. When varying the level of strengthening, for imposed loads from 3 to 7.5 kN/m^2, the ratio of the total costs of materials for steel and CFRP strips ranges between 60 and 73% and shows a slight tendency to increase with the increasment of loads.

Keyword: *cost estimation, optimization, strengthening of reinforced concrete slab, CFRP strip, steel strip*

INTRODUCTION

The one storey residential building with atic was designed and built in the sixties of the last century in Subotica, Republic of Serbia. The current owner of the building intends to repurpose the ground floor and first floor from residential to office area, while the purpose of the attic, for housing, would remain unchanged. The change of purpose will significantly increase the imposed load, wherefore it is necessary to carry out an assessment of the bearing capacity of the existing structure and the possible need for its strengthening.

The design and technical documentation of the building was lost, so the condition of the structure was assessed based on information received from the owner, visual inspection, results of measurements and testings performed on site and results of laboratory testings on samples taken from the mezzanine slab. The bearing capacity of the existing mezzanine slab, calculated in accordance with current regulations, proved to be insufficient to sustain the increased imposed load, which is why the planning of its strengthening was started.

Three methods were considered: addition of a new steel reinforcement and a new layer of concrete, strengthening with externally bonded steel strips, and strengthening with externally bonded fiber-reinforced polymer (FRP) plates. Bearing in mind the requirements and limitations set by the investor, two methods were chosen that were analyzed in detail to find the optimal solution, which will provide the required bearing capacity at the minimum cost. Due to large fluctuations in the price of labor, the analysis was carried out only from the aspect of the price of materials, based on the market state on March 20, 2023. The price in euros is given according to the official middle exchange rate of the NBS (National Bank of Serbia) on April 7, 2023, according to which 1 EUR = 117.28 RSD.

A significant difference in the cost of materials was observed when strengthening with steel and CFRP strips. Since the required level of strengthening in this specific example was minimal, the authors wanted to investigate whether the price ratio for these two methods will change with the increasement of the level of strengthening. Therefore, the calculations of the strengthening and the cost of materials were carried out for imposed loads of 4, 5, 6 and 7.5 kN/m^2, for both considered methods. The results of the analysis are presented in this paper.

ASSESSMENT OF THE CONDITION AND BEARING CAPACITY OF THE EXISTING SLAB

Considering the time when it was built, it is assumed that the building meets the requirements of the Provisional Technical Regulations for Loads for Buildings from 1948 and the Provisional Technical Regulations for Concrete and Reinforced Concrete from 1947 [1], which means that the mezzanine slab is designed for the imposed load of 1.5 kN/m^2. After the change of purpose, the facility should meet the requirements of the SRPS EN 1990 [2,3], SRPS EN 1991**Greška! Nije pronađen izvor reference.** i SRPS EN 1992-1-1 [5,6]. The design value of the imposed load for the office area, which is classified as an area of category B [4], is 3.0 kN/m^2, which is an increase of 100% in relation to the load for which the existing slab was designed, so it is necessary to carry out an assessment of the condition of the existing structure and, if necessary, strengthen it.

Following the procedure presented in [7], an assesment plan was prepaired, and a detailed visual inspection of the building, with the necessary measurements, was carried out. A report was drawn up, after which field and laboratory testing was performed. The mezzanine slab under consideration is located inside the building and was not exposed to the actions of external environment or chemical agresion, so chemical analyzes of the embedded concrete and steel reinforcement were not carried out. Locating the reinforcement in the concrete was done using the magnetic method.

The compressive strength of concrete was determined by laboratory testing of the concrete cores drilled from the structure. A non-destructive ultrasonic method was used for confirmation of the compressive strength of concrete, for checking the uniformity of quality of concrete and to determine the slab thickness. In order to reveal possible concrete defects and the condition of the reinforcement, the mortar was removed from the lower surface of the slab. The results obtained by the conducted testings are presented in the following text.

The structure of the building is consisted of 38 cm thick brick load-bearing walls, placed around the perimeter of the building, with the clear distance of 5.2x12.0 m, supporting a solid rectangular reinforced concrete (RC) slab. The clear height of the ground floor and the first floor is 2.80 m.

The simply supported 20 cm thick RC slab is made of concrete whose strength corresponds to the class C16/20. The main steel reinforcement of class Č37 consists of 12 mm diameter bars at 10 cm spacing. The average thickness of the concrete cover is 1 cm. The floor consists of 5 cm thick cement screed and 2 cm of covering. The bottom surface of the slab is covered with a 2 cm thick mortar layer.

The calculated permanent load on the existing slab is 6.54 kN/m². Due to the repurpose, the imposed load increases from 1.50 kN/m² to 3.0 kN/m². The effective span of l_{eff} = 5.5 m was adopted.

The analysis of the slab using the above data, carried out in accordance with the Rulebook for Building Structures [8], showed that the moment capacity M_{Rd} of the unstrengthtened slab is smaller than the maximum bending moment M_{Ed} that occures under the increased load (figure 1):

$$M_{Rd} = 40.27 \text{ kNm/m} < M_{Ed} = 50.40 \text{ kNm/m},$$

wherefore the strengthening of the slab is necesery.

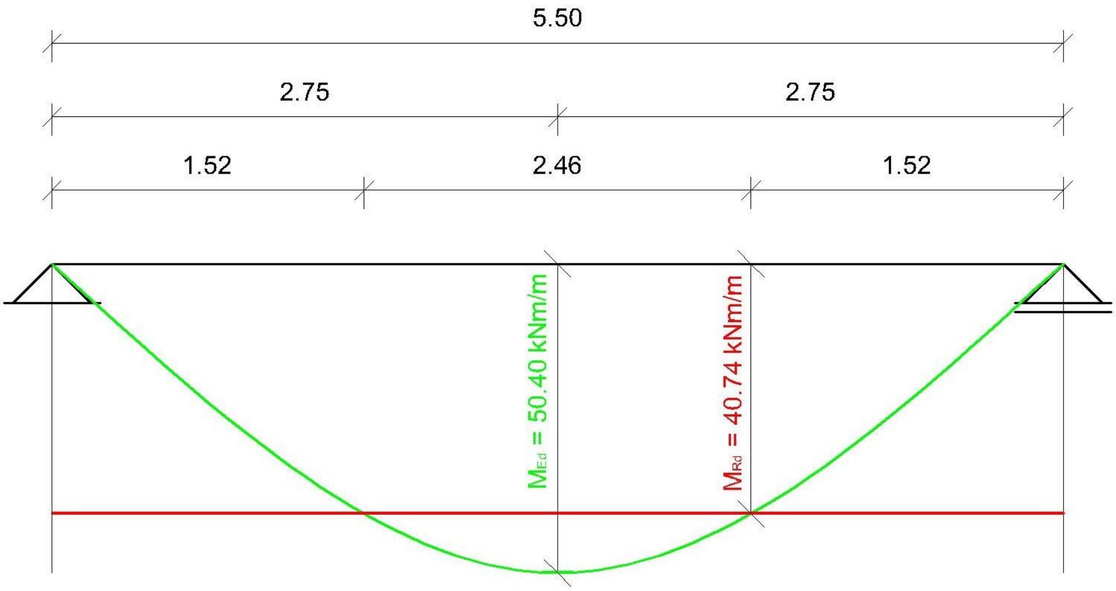

Figure 1. Moment capacity M_{Rd} of the existing slab and the bending moment M_{Ed} diagram after the change of purpose

CONSIDERATION OF POSSIBLE STRENGTHENING METHODS

The following requirements and limitations were considered when choosing a suitable method of strengthening of the existing reinforced concrete slab:

- Available space. The clear height of the rooms is currently 2.8 m. The investor requires that, after strengthening, the clear height should be at least 2.7 m, which leaves a space of 10 cm for the total height of the strengthening;
- Increasment of the load on the existing structure. It has been assessed that the existing walls and foundations have a sufficient capacity to bear the increased imposed load. Still the strengthening should not significantly increase the permanent load;
- Impact of construction works on the surrounding area. Strengthening should be carried out in such a way that the subsequent work on the surfaces of the surrounding walls and floors is reduced to the minimum possible extent;
- The impact of the works on the unhindered use of the facility. During the strengthening works, it is desirable to enable unhindered use of the atic, so the generation of noise, debris and dust should be reduced to a minimum;
- Availability of adequate labor and materials. The locally available materials and local labor should be preferred;
- Duration of works. The investor requires the works be completed in the shortest possible time;
- Price.

Based on these requirements and limitations, from all the possible solutions for strengthening the slab [9], strengthening by applying a new RC layer to the bottom surface of the slab, strengthening using steel strips and strengthening using FRP plates were taken into the further consideration.

Strengthening by applying a new RC layer to the bottom surface of the slab

Strengthening by addition of a new RC layer includes the local "exposing" of the existing tensile reinforcement and its connection with the new reinforcement by welding, after which a 3 cm thick layer of shotcrete is sprayed in a dry-mix process. This traditional method allows the hiring of local labor and the use of locally available materials, but at the same time it significantly increases the dead load on the structure and produces a lot of waste material, noise and dust, due to which it is necessary to suspend the use of the building during the works. The increase of the mezzanine structure's mass also affects the change in its behavior under seismic actions.

Strengthening by externally bonded steel strips

The slab strengthening with steel strips is performed by bonding the steel strips to the previously prepared concrete surface using epoxy adhesive. If planned, supporting the structure during execution must last at least 24 hours, depending on the type of adhesive used. The advantage of this strengthening method is its price, which is lower than the price of the most other RC slab strengthening methods. Also, the works can be carried out regardless of weather conditions, and the execution itself is relatively simple. When applying this type of strengthening, the cross-section dimensions remain almost unchanged, with minimal impact on other structural elements.

The method is used at temperatures no higher than 60 ^{o}C and relative humidity below 70%, without chemical aggression, which makes it applicable for strengthening mezzanine slabs of residential and commercial buildings. Since a layer of mortar was removed from the lower surface of the slab for the purposes of testing, it must be leveled with repair mortar before the strengthening. Steel strips are installed to a cleaned surface. It is necessary to ensure the optimal room temperature for bonding, which depends on the type of adhesive used, and most often ranges from +8 ^{o}C to +35 ^{o}C.

Strengthening by externally bonded FRP plates

By strengthening with polymer plates (strips) reinforced with carbon fibers, an increase in the load-bearing capacity of the structure is achieved without significan reduction of the clear volume of the building, since the thickness of the carbon fiber reinforced polymer strips is usually only 1 to 5 mm. The slab is strengthened by placing the CFRP strips in the zone of highest tensile stress, in the load-carrying direction. This strengthening system simultaneously increases the bearing capacity and stiffness of the structural member, limits deformations (deflection) and cracks, and increases fatigue resistance.

Compared to conventional strengthening systems, such as placement of steel strips, CFRP plates have the following advantages: they are lighter than steel strips, they are supplied in rolls and can be easily cut on site, the installation is simple and fast, they are durable and resistant to fatigue and corrosion, they are thin, easily covered with paint, have higher tensile strength and high stiffness of fibers. The bond between the existing slab and FRP strip depends on the quality of the preparation of the substrate. Installation of CFRP plates can only be performed on concrete substrates that will ensure a satisfactory degree of adhesion between concrete and adhesive during the exploitation of the building. Therefore, before installation, the substrate must be completely cleaned and dry. Surface humidity of concrete must not be higher than 4%.

The effective concrete pull-off strength after surface preparation must be verified by testing and should not be less than 1.5 MPa. To monitor the effectiveness of the strengthening, it is suggested to place one or two additional plates that will be tested by the pull-off method immediately after hardening. High temperatures, in case of fire, can seriously impair the effectiveness of the strengthening, so it is necessary to protect the CFRP plates externally with special coatings, gypsum panels, etc. Strengthening systems with CFRP plates must be protected from permanent exposure to direct sunlight, moisture and/or water. Maximum permissible continuous service temperature is approximately +50 °C. [10,11,12]

Selection of two methods for detailed analysis and their qualitative comparison

Strengthening the structure by placing a new layer of reinforced concrete, due to its disadvantages - a large amount of waste material, an increase in the weight of the structure and a decrease in the clear height of the room, will not be further analyzed. A detailed analysis and calculation will be carried out for the remaining two methods - strengthening of the RC slab by externally bonded steel strips and by externally bonded CFRP plates. Table 1 shows a qualitative comparison of the two selected strengthening methods, according to [13].

Table 1. Comparative analysis of steel and CFRP strips [13]

Criterion	Steel strips	CFRP strips
Self-weight	High	Low
Tensile strength	High	Very high
Thickness	Small	Very small
Corrosion	Possible	Not possible
Length	Limited	Practically unlimited
Processing	Complex	Easy
Behavior	Stiff	Flexible
Fatigue resistance	Significant	Sufficient
Price	Low	High
Installation cost	High	Low
Specific equipment for the installation	Supporting equipment	Not needed
Qualified labor needed	Yes	Yes

CALCULATION AND OPTIMIZATION OF STRENGTHENING WITH STEEL STRIPS

Steel strips made of construction sheet S 235 JR, installed to the bottom side of the slab in the load-carrying direction, were selected to strengthen the slab. Since the existing slab is able to carry the full permanent load, the strengthening can be done without supporting, and the steel strips are "activated" only when the imposed load is applied. By the ultimate limit state analysis of the cross-section with the maximum design bending moment, it was established that the required steel strips cross-section area is 2.90 cm^2/m. The analysis was carried out for steel strips with thicknesses of 1.5, 2.0 and 2.5 mm, and widths of 50, 100, 150, 200, 250 and 300 mm. The length of the individual strip of 3.5 m was determined by adding the anchoring length to both sides of the strengthening length (the length of 2.46 m in figure 1). The calculation results are shown in table 2. The axle distance of the strips is limited to 1 m, which is why some solutions are oversized (shaded fields in table 2).

Table 2. Geometric characteristics and arrangement of steel strips, and moment capacity of the strengthened slab

Serial number	Strip thickness [mm]	Strip width [mm]	Strip cross-section area [cm^2]	Required axle distance [cm]	Adopted axle distance [cm]	Total number of strips [kom]	Length of individual strip [m]	Total length of strips [m]	Moment capacity M_{Rd} [kNm/m]
1	1.5	50	0.75	25.86	25	48	3.50	168.00	50.70
2	1.5	100	1.50	51.72	51	24	3.50	82.35	50.50
3	1.5	150	2.25	77.59	77	16	3.50	54.55	50.43
4	1.5	200	3.00	103.45	100	12	3.50	42.00	50.70
5	1.5	250	3.75	129.31	100	12	3.50	42.00	53.25
6	1.5	300	4.50	155.17	100	12	3.50	42.00	55.77
7	2.0	50	1.00	34.48	34	35	3.50	123.53	50.51
8	2.0	100	2.00	68.97	68	18	3.50	61.76	50.51
9	2.0	150	3.00	103.45	100	12	3.50	42.00	50.71
10	2.0	200	4.00	137.93	100	12	3.50	42.00	54.11
11	2.0	250	5.00	172.41	100	12	3.50	42.00	57.46
12	2.0	300	6.00	206.90	100	12	3.50	42.00	60.76
13	2.5	50	1.25	43.10	43	28	3.50	97.67	50.41
14	**2.5**	**100**	**2.50**	**86.21**	**86**	**14**	**3.50**	**48.84**	**50.41**
15	2.5	150	3.75	129.31	100	12	3.50	42.00	53.28
16	2.5	200	5.00	172.41	100	12	3.50	42.00	57.48
17	2.5	250	6.25	215.52	100	12	3.50	42.00	61.61
18	2.5	300	7.50	258.62	100	12	3.50	42.00	65.66

For the calculation of the consumption and cost of the material, the use of "*Eporip Mapei*" adhesive is assumed, the consumption of which (from the technical sheet [14]) is 1.35 kg/m² for 1 mm of layer thickness. For a smooth substrate surface the consumption of 1.00 kg/m² can be adopted. The cost calculation also includes anti-corrosion protection of the strips by applying a one-component anticorrosive coating for steel sheets - "*Wash Primer*", whose consumption is 80-90 gr/m^2, before finishing the ceiling.

Based on a detailed analysis of the material cost for the selected steel strips, shown in table 3, the conclusion is that the optimal solution of strengthening can be accomplished with strips 2.5 mm thick, 100 mm wide, at a mutual axle distance of 86 cm (serial number 14 in tables 2 and 3). The total cost of material for this type of strengthening is 138.47 EUR, i.e. 16239.56 RSD.

Table 3. Analysis of cost of materials for strengthening with steel strips

Serial number	Total area of strips [m²]	Unit price of adhesive [rsd/m²]	Unit price of strips [rsd/m]	Total cost of adhesive [rsd]	Total cost of strips [rsd]	Unit price of coating [rsd/ m²]	Total cost of coating [rsd]	Total cost of material [rsd]	Total cost of material [EUR]
1	8.40	1868.35	37.00	21187.09	6216.00	142.97	1200.95	28604.04	243.90
2	8.24	1868.35	40.00	20771.66	3294.12	142.97	1177.40	25243.17	215.24
3	8.18	1868.35	43.00	20636.78	2345.45	142.97	1169.75	24151.98	205.93
4	8.40	1868.35	46.00	21187.09	1932.00	142.97	1200.95	24320.04	207.37
5	10.50	1868.35	48.00	26483.86	2016.00	142.97	1501.19	30001.05	255.81
6	12.60	1868.35	50.00	31780.63	2100.00	142.97	1801.42	35682.06	304.25
7	6.18	1868.35	52.00	15578.74	6423.53	142.97	883.05	22885.32	195.13
8	6.18	1868.35	54.00	15578.74	3335.29	142.97	883.05	19797.09	168.80
9	6.30	1868.35	56.00	15890.32	2352.00	142.97	900.71	19143.03	163.22
10	8.40	1868.35	58.00	21187.09	2436.00	142.97	1200.95	24824.04	211.66
11	10.50	1868.35	60.00	26483.86	2520.00	142.97	1501.19	30505.05	260.10
12	12.60	1868.35	62.00	31780.63	2604.00	142.97	1801.42	36186.06	308.54
13	4.88	1868.35	64.00	12318.08	6251.16	142.97	698.23	19267.46	164.29
14	**4.88**	**1868.35**	**66.00**	**12318.08**	**3223.26**	**142.97**	**698.23**	**16239.56**	**138.47**
15	6.30	1868.35	68.00	15890.32	2856.00	142.97	900.71	19647.03	167.52
16	8.40	1868.35	70.00	21187.09	2940.00	142.97	1200.95	25328.04	215.96
17	10.50	1868.35	72.00	26483.86	3024.00	142.97	1501.19	31009.05	264.40
18	12.60	1868.35	74.00	31780.63	3108.00	142.97	1801.42	36690.06	312.84

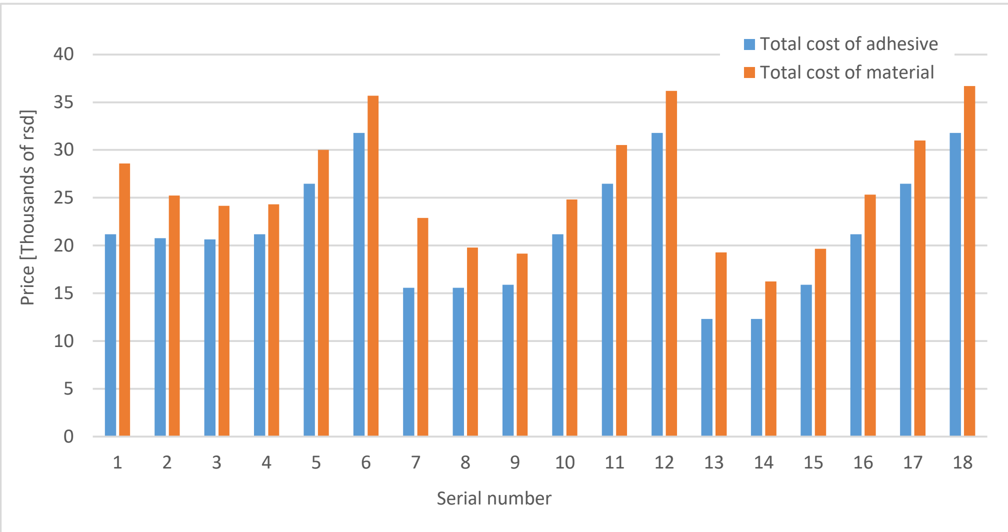

Figure 2. Total cost of material and total cost of adhesive for strengthening with steel strips

It should be noted that the contribution of the price of adhesive in the total cost of material is extremely high, in some cases even exceeding 80% (figures 2 and 3). The non-monotonic function of the total cost of material in figure 2 ("wavy" shape of the diagram) is a consequence of the fact that, due to the spacing limitation to 100 cm, in some cases was adopted a significantly larger area of steel than is necessary to achieve the design moment capacity (shaded fields in table 2). As will be shown later, this phenomenon is lost when strengthening is designed for higher imposed loads (figure 3).

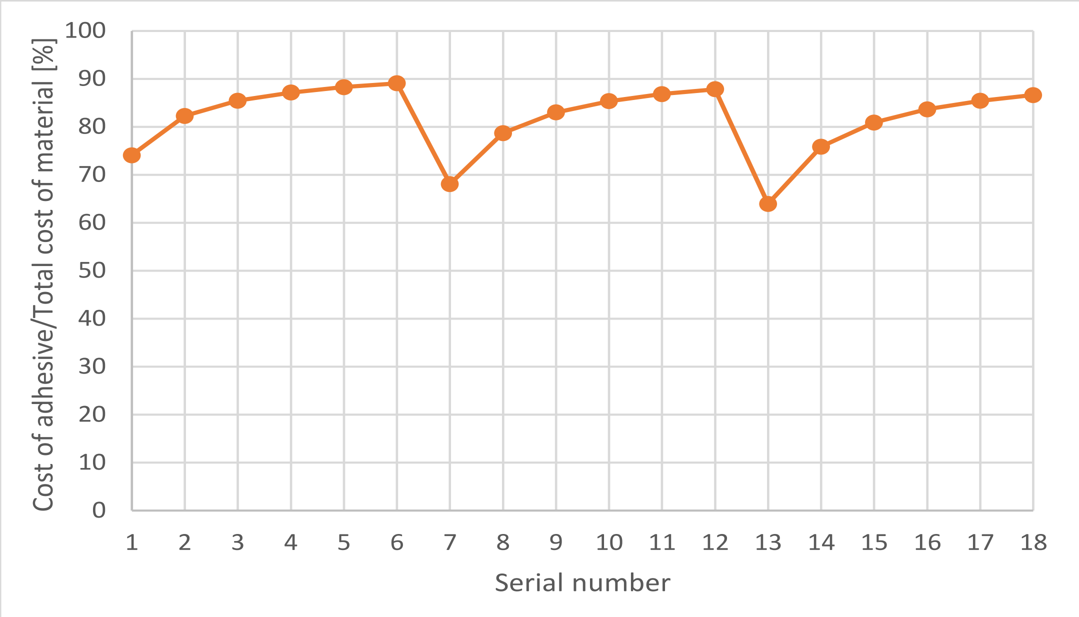

Figure 3. The ratio of the cost of adhesive and the total cost of material for strengthening with steel strips

CALCULATION AND OPTIMIZATION OF STRENGTHENING WITH CFRP PLATES

The Sika® CarboDur® system was chosen for the calculation and optimization of RC slab strengthening by FRP plates. The analysis was performed using Sika® CarboDur® FRP Design Software [15,16]. Three categories of CFRP lamellae were considered - S, M and E series [10,11], [12], which differ from each other in tensile strength (from 2300 to 3500 MPa) and elastic modulus (between 170 and 210 GPa).

Like in the strengthening by steel strips, FRP plates are applied to the bottom surface of the slab in the load-carrying direction, without supporting. The results of dimensioning according to the ultimate limit state are shown in table 4. The spacing of the strips is limited to 1 m, which is why some solutions are oversized (shaded fields in Table 4).

For the calculation of consumption and cost of materials, the use of *Sikadur®-30* adhesive [17] is assumed, whose consumption was adopted from the manufacturer's technical sheets [10,11,12], as a function of the type and width of CFRP plates.

Based on a detailed analysis of the material cost for the considered CFRP plates, shown in table 5, the conclusion is that the optimal solution is the strengthening with Sika® CarboDur® S 214 plates, placed at a mutual axle distance of 52 cm (row number 2 in tables 4 and 5). The total cost of material for this type of strengthening is 227.64 EUR, i.e. 26697.13 rsd, which is almost 65% higher than the cost of the material needed for the strengthening by steel strips.

The share of the price of adhesive in the total cost of material when strengthening with CFRP plates is much lower than in the case of strengthening by steel strips, and ranges between 27 and 51% (figures 4 and 5).

Table 4. Geometric characteristics and arrangement of Sika® CarboDur® FRP plates, and the moment capacity of the strengthened slab

Serial number	**Type of plate**	Plate width [mm]	Plate thickness [mm]	Required axle distance [m]	Length of individual plate [m]	Total length of plates [m]	Moment capacity M_{Rd} [kNm/m]
1	S 212	20	1.2	0.45	3.50	94.50	50.42
2	**S 214**	**20**	**1.4**	**0.52**	**3.50**	**84.00**	**50.53**
3	S 512	50	1.2	1.00	3.50	42.00	51.69
4	S 514	50	1.4	1.00	3.50	42.00	53.60
5	S 612	60	1.2	1.00	3.50	42.00	53.97
6	S 614	60	1.4	1.00	3.50	42.00	56.23
7	S 626	60	2.6	1.00	3.50	42.00	69.44
8	S 812	80	1.2	1.00	3.50	42.00	58.46
9	S 814	80	1.4	1.00	3.50	42.00	61.42
10	S 914	90	1.4	1.00	3.50	42.00	63.97
11	S 1012	100	1.2	1.00	3.50	42.00	62.86
12	S 1014	100	1.4	1.00	3.50	42.00	66.49
13	S 1212	120	1.2	1.00	3.50	42.00	67.19
14	S 1213	120	1.3	1.00	3.50	42.00	69.33
15	S 1214	120	1.4	1.00	3.50	42.00	70.90
16	S 1512	150	1.2	1.00	3.50	42.00	72.05
17	M 614	60	1.4	1.00	3.50	42.00	60.01
18	M 814	80	1.4	1.00	3.50	42.00	66.33
19	M 914	90	1.4	1.00	3.50	42.00	69.43
20	M 1014	100	1.4	1.00	3.50	42.00	71.49
21	M 1214	120	1.4	1.00	3.50	42.00	74.71
22	E 512	50	1.2	1.00	3.50	42.00	52.04
23	E 514	50	1.4	1.00	3.50	42.00	54.00
24	E 812	80	1.2	1.00	3.50	42.00	59.00
25	E 1014	100	1.4	1.00	3.50	42.00	67.25
26	E 1214	120	1.4	1.00	3.50	42.00	71.41

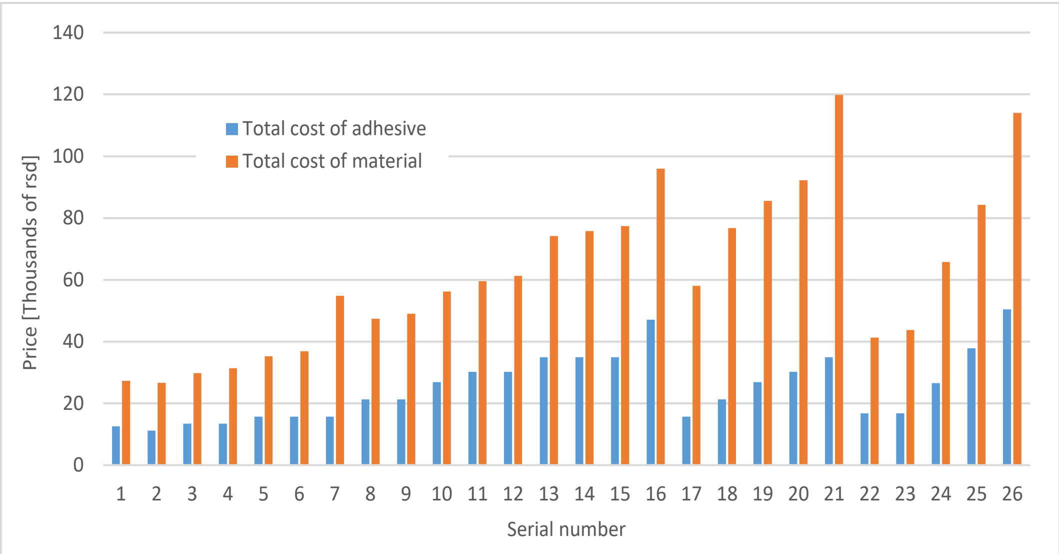

Figure 4. Total cost of material and total cost of adhesive for strengthening with CFRP plates

Table 5. Analysis of cost of materials for strengthening with CFRP plates

Serial number	**Type of plate**	Consumption of adhesive [kg/m]	Unit price of adhesive [rsd/kg]	Total cost of adhesive [rsd]	Unit price of plates [rsd/m]	Total cost of plates [rsd]	Total cost of material [rsd]	Total cost of material [EUR]
1	S 212	0.1	1333.33	12599.97	155.36	14681.52	27281.49	232.62
2	**S 214**	**0.1**	**1333.33**	**11199.97**	**184.49**	**15497.16**	**26697.13**	**227.64**
3	S 512	0.24	1333.33	13439.97	388.40	16312.80	29752.77	253.69
4	S 514	0.24	1333.33	13439.97	427.24	17944.08	31384.05	267.60
5	S 612	0.28	1333.33	15679.96	466.08	19575.36	35255.32	300.61
6	S 614	0.28	1333.33	15679.96	504.92	21206.64	36886.60	314.52
7	S 626	0.28	1333.33	15679.96	932.16	39150.72	54830.68	467.52
8	S 812	0.38	1333.33	21279.95	621.44	26100.48	47380.43	403.99
9	S 814	0.38	1333.33	21279.95	660.28	27731.76	49011.71	417.90
10	S 914	0.48	1333.33	26879.93	699.12	29363.04	56242.97	479.56
11	S 1012	0.54	1333.33	30239.92	699.12	29363.04	59602.96	508.21
12	S 1014	0.54	1333.33	30239.92	737.96	30994.32	61234.24	522.12
13	S 1212	0.625	1333.33	34999.91	932.16	39150.72	74150.63	632.25
14	S 1213	0.625	1333.33	34999.91	971.00	40782.00	75781.91	646.16
15	S 1214	0.625	1333.33	34999.91	1009.84	42413.28	77413.19	660.07
16	S 1512	0.84	1333.33	47039.88	1165.20	48938.40	95978.28	818.37
17	M 614	0.28	1333.33	15679.96	1009.84	42413.28	58093.24	495.34
18	M 814	0.38	1333.33	21279.95	1320.56	55463.52	76743.47	654.36
19	M 914	0.48	1333.33	26879.93	1398.24	58726.08	85606.01	729.93
20	M 1014	0.54	1333.33	30239.92	1475.92	61988.64	92228.56	786.40
21	M 1214	0.625	1333.33	34999.91	2019.68	84826.56	119826.47	1021.71
22	E 512	0.3	1333.33	16799.96	582.60	24469.20	41269.16	351.89
23	E 514	0.3	1333.33	16799.96	640.86	26916.12	43716.08	372.75
24	E 812	0.475	1333.33	26599.93	932.16	39150.72	65750.65	560.63
25	E 1014	0.675	1333.33	37799.91	1106.94	46491.48	84291.39	718.72
26	E 1214	0.9	1333.33	50399.87	1514.76	63619.92	114019.79	972.20

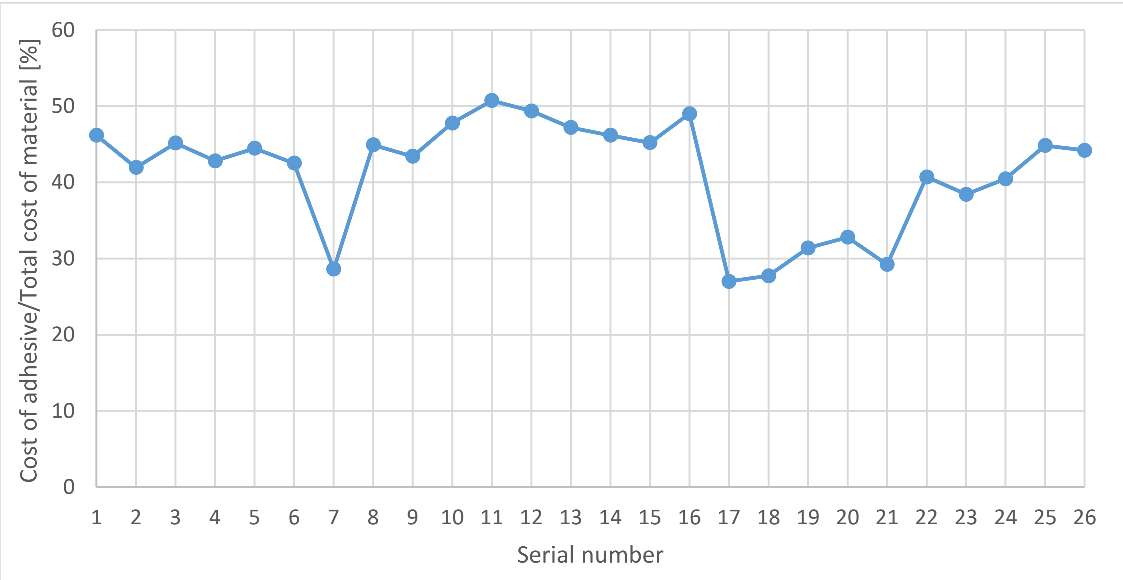

Figure 5. The ratio of the cost of adhesive and the total cost of material for strengthening with CFRP plates

COMPARATIVE ANALYSIS OF STRENGTHENING METHODS AND SELECTION OF THE MOST ECONOMICAL SOLUTION

The strengthening of the existing mezzanine slab includes the following activities:

- Visual inspection of the structure, measurement, registration of all visible defects and marking of places for further testings,
- Mechanical removal of mortar from the lower part of the slab for the purpose of assessing the condition of the reinforcement and possible defects and cracks in the concrete,
- Extraction of concrete cores by drilling and the laboratory testings of samples,
- Confirmation of concrete strength and slab thickness determination by ultrasonic method and locating the reinforcement using the magnetic method,
- Renovation of the lower part of the slab at the places of cores extraction and mortar removal,
- Installation of strips in places as provided by the design (steel strips/FRP plates),
- Plastering of the ceiling with lime plaster in two layers,
- Smoothing of finely plastered ceilings with dispersive putty,
- Painting walls and ceilings with a brush, with dissolved aged slaked lime and
- Cleaning the construction site after the completion of all works.

All listed activities are identical for both considered methods of strengthening, except for the execution of the strengthening itself. For this reason, the total cost of strengthening materials - adhesive, strips and, in the case of steel strips - anticorrosive coating, were used as the basis for comparison of the two methods.

As shown in the previous chapters, after analyzing the strengthening with steel and FRP strips of different geometric characteristics, for both methods was selected the solution with the lowest total material cost. When strengthening with steel strips, the lowest cost of EUR 138.47 is achieved by using strips 2.5 mm thick, 100 mm wide, placed at an axle distance of 86 cm. The lowest total material cost of 227.64 EUR for strengthening with CFRP plates is achieved by using strips S 214, on a mutual axle distance of 52 cm. Considering the criterion of the lowest cost of materials, the most economical solution for strengthening the existing RC slab is the installation of the above-mentioned steel strips.

It is interesting to note that the contribution of the cost of adhesive in the total cost of material when strengthening with steel strips ranges between 64 and 90%, while with the application of CFRP plates this share is significantly lower - between 27 and 51% (figure 6), depending on the plate type.

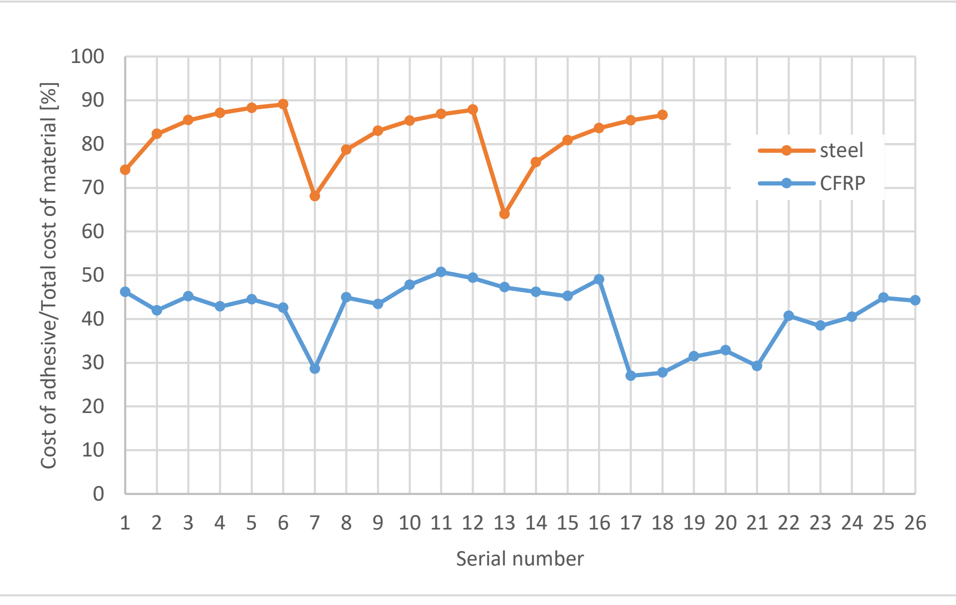

Figure 6. The ratio of the cost of adhesive and the total cost of material

ANALYSIS OF STRENGTHENING WITH STEEL AND CFRP STRIPS FOR VARIOUS INTENSITIES OF IMPOSED LOAD

In accordance with the task, the bending moment capacity of the existing RC slab had to be increased by only about 25%, which is achieved with minimal strengthening. In this specific example, the total cost of material for strengthening with steel strips was about 40% lower than the cost of material for strengthening with CFRP plates. The question is whether this price ratio remains unchanged in case that the strengthening is carried out for greater imposed loads.

To answer this question, an analysis was carried out for strengthening with steel and CFRP strips of the same types as in tables 2 to 5, but for imposed loads of 4, 5, 6 i 7.5 kN/m^2. The maximum value of the imposed load meets the criterion that the moment capacity of the strengthened section $M_{Rd,str}$ does not exceed twice the value of the moment capacity $M_{Rd,unstr}$ of the unstrengthened section, that is

$$M_{Rd,str} \leq 2 \cdot M_{Rd,unstr} = 2 \cdot 40.27 = 80.54 \text{ kNm/m.}$$

For each level of the imposed load, the same analysis was carried out as for q = 3.0 kN/m^2, both for steel and CFRP strips. The solution with the lowest material cost was selected for both methods. The total cost of materials and the cost of adhesive for the imposed load q = 6.0 kN/m^2, for different types of steel strips, is shown in figure 7, and for CFRP plates in figure 8.

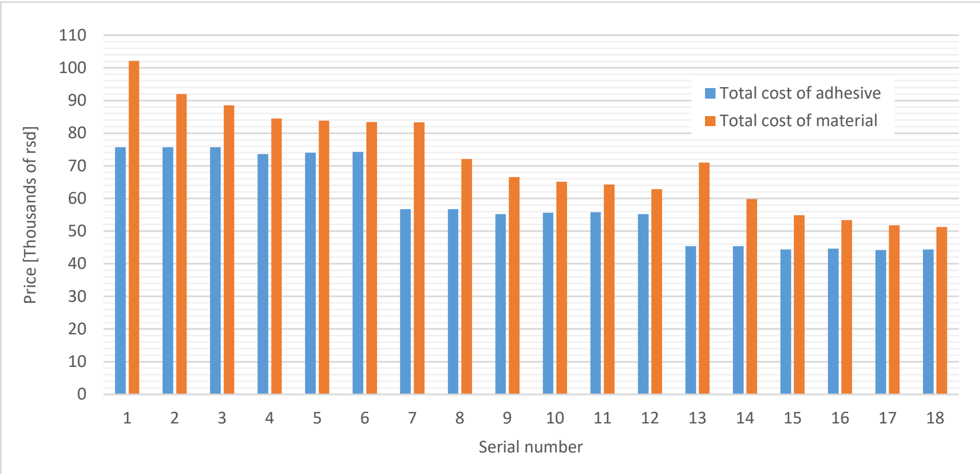

Figure 7. Total cost of material and total cost of adhesive for strengthening with steel strips, for imposed load of 6.0 kN/m^2

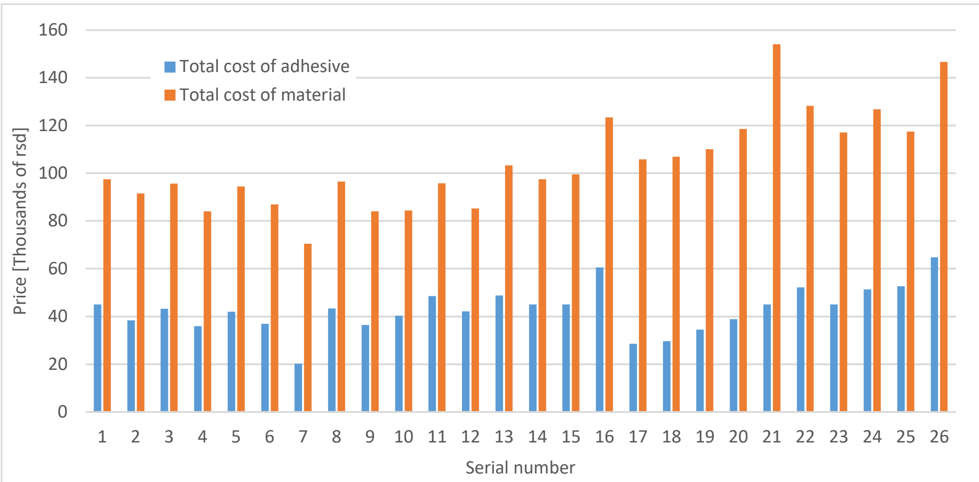

Figure 8. Total cost of material and total cost of adhesive for strengthening with CFRP strips, for imposed load of 6.0 kN/m^2

During the analysis, it was observed that when using steel strips, for all levels of imposed load, the lowest total material cost is achieved by using the thickest strips (2.5 mm). This is probably a consequence of the large share of the price of adhesive in the total price of material, because the consumption of adhesive depends only on the area covered by the strips, which is the smallest when the thickest strips are used.

When using CFRP plates, for all analyzed levels of imposed load, the most economical solutions were achieved with strips 60 mm wide. An exception is the imposed load of 3.0 kN/m^2, for which the lowest total cost of materials was obtained by using 20 mm wide strips. The most economical thickness of the plates up to the imposed load of 5.0 kN/m^2 is 1.4 mm, and for loads of 6.0 and 7.5 kN/m^2 the economical plate thickness is 2.6 mm.

Considering only the solutions that achieve the lowest material cost for each load level, figure 9 shows the total material cost and adhesive cost for steel and CFRP strips as a function of the intensity of imposed load.

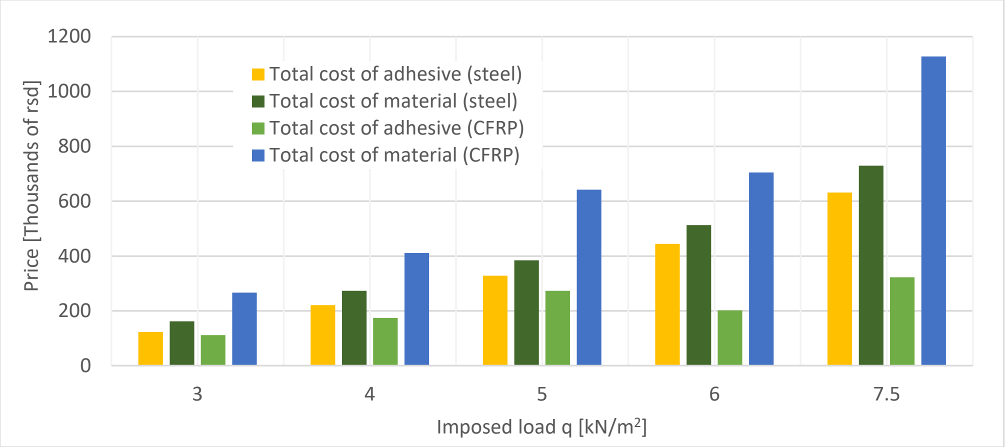

Figure 9. Total cost of material and total cost of adhesive for strengthening with steel and CFRP strips, for various intensities of imposed load

The increase of the total cost of materials with the increase of the imposed load for steel and CFRP strips, with their trendlines is shown in figure 10.

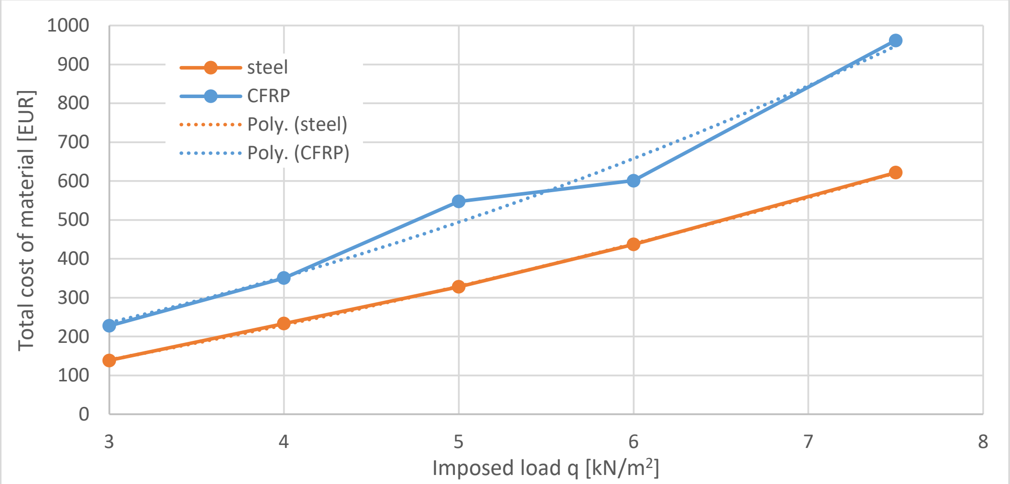

Figure 10. Total cost of material for various values of imposed load

The ratio of the total costs of materials for strengthening with steel and CFRP strips, for various values of the imposed load, is given in figure 11. Observing the trendline in figure 11, it can be concluded that the total cost of strengthening materials using steel strips is always lower than the cost of strengthening with CFRP plates. This price ratio is in a fairly narrow range between 60 and 73% and shows a slight increase with the increase of load. This practically means that, with the increase in the intensity of strengthening, the economy of the application of steel strips slightly decreases.

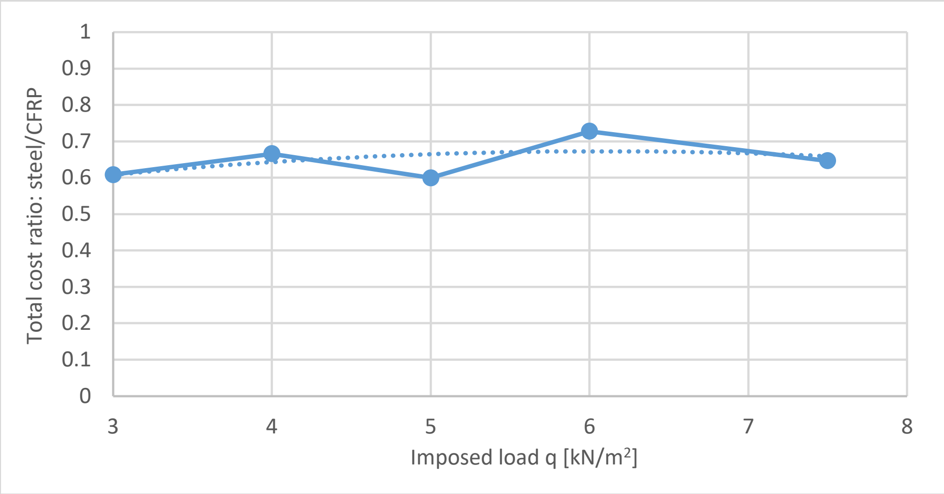

Figure 11. The ratio of the total costs of materials for steel and CFRP strips for various values of imposed load

CONCLUSION

When planning the strengthening of existing structural members, from many available methods, the one that optimally meets the set requirements and limitations is chosen. Universal requirements are contained in the technical regulations, but each project also contains a number of specific requirements set by the investor himself (e.g. maximum price, duration of works, overall dimensions, etc.) or imposed by the environment conditions, market conditions, etc. However, one of the most important criteria for choosing a strengthening method is its price, which has also been used as the final criterion for choosing a strengthening method for the existing solid RC slab with a span of 5.5 m.

After a qualitative analysis of three strengthening methods that potentially met the set requirements, two were selected for detailed analysis - strengthening by steel strips and by FRP plates installed to the underside of the slab. Further comparison of these two methods was carried out solely according to the criterion of cost of material. For each method, the types of strips were varied, and the one with the lowest total material cost was adopted. In this way, the most economical solution of strengthening was chosen - the use of steel strips S 235 JR, 2.5 mm thick, 100 mm wide, at a mutual axle distance of 86 cm, with a total cost of materials of 138.47 EUR.

The lowest material price of EUR 227.64 for strengthening with CFRP plates was obtained by using strips S 214 at a spacing of 52 cm, which is almost 65% higher than the price of strengthening with steel strips. A significant contribution of the cost of adhesive in the total cost of materials was observed when using steel strips (from 64 to 90%), while this share was between 27 and 51% when using CFRP plates.

The ratio of the total costs of material for strengthening with steel and CFRP strips did not change significantly even for higher strengthening levels, i.e. for imposed loads of 4, 5, 6 and 7.5 kN/m^2. The cost of material for strengthening with steel strips, for various levels of strengthening, ranges from 60 to 73% of the cost of material for strengthening with CFRP plates. A slight tendency of increasing of this ratio with the increase of load was observed.

Due to the large share of the cost of adhesive in the total cost of materials when strengthening with steel strips, the most economical solution for all levels of strengthening is obtained with strips of the largest considered thickness. The lowest cost of strengthening with CFRP plates for all load levels was achieved with strips of smaller width (20 mm for imposed load of 3.0 kN/m^2, i.e. 60 mm for all other load levels).

This research is based solely on the comparison of material prices for the two strengthening methods. In order to reach the optimal solution, all other advantages and disadvantages of the considered methods should be also taken into account.

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