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Analysis of design solutions for strengthening the load-bearing structure of a building for further safe use

R. Chmielewski [a], A. Baryłka [b,*], J. Obolewicz [b]
[a] Military Technical Academy, ul. gen. Sylwestra Kaliskiego 2, 00-908 Warszawa 46, Poland
[b] Scientific Institute of Engineering of The Safety of Anthropogenic Objects, ul. Obozowa 82A/19, 01-434 Warszawa, Poland
* Corresponding e-mail address: biuro@crb.com.pl
ORCID identifier: https://orcid.org/0000-0001-5662-9180 (R.C); https://orcid.org/0000-0002-0181-6226 (A.B); https://orcid.org/0000-0002-7866-0039 (J.O.)

ABSTRACT

Purpose: The article present issues related to strengthening the supporting structure of swimming pool in a primary school building paying special attention to the damaged reinforced concrete pillars of supports.

Design/methodology/approach: Analysis of design solutions strengthening the supporting structure of the building for further safe use.

Findings: Engineers noticed multiple cracks and deformations in rebar while performing on-site verification. Three posts (pillars) were damaged in the basement rooms and needed repair.

Research limitations/implications: Structural elements of building structures wear out over time and cause damage that requires repair. The scope of repair works should be designed and carried out in accordance with applicable law.

Practical implications: The solution, which has been designed in great detail, allows the building to continue working without the risk of damaging the structure.

Originality/value: Due to the scale of damage to the reinforced concrete columns in the basement of the building, it was necessary to protect the facility against a construction failure.

Keywords: Construction, Construction elements, Design, Structural reinforcements

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ANALYSIS AND MODELLING

1. Introduction

The most common cause of construction disaster are chance events that occur in nature and around human activity. The second cause in terms of occurrence are errors in upkeep of buildings. Building malfunctions that are a consequence of executive errors are on the third place on the list and are relatively rare (4.1% in 2017, 5.05% in 2014-2017 [1]). The main reason behind these errors is non-conformity with technological requirements (76.9 in 2017, 64.8% in 2014-2017 [1]). Case of the newly built swimming pool building is not a case of construction disaster but is an example of a construction disaster risk brought by not following method of implementation was specified in the design.

Emergence of the damage to the pillars of the load bearing structure was sudden and building manager responded to it in a correct way by treating is an emergency putting in place a protection structure around affected objects. Reinforced concrete pillars in a room underneath the swimming pool were a subject to the damage. The binders resting on columns were made of steel cylinder sections. The following process was adopted [2-4]:

- Technical review of damaged construction elements of the building,
- Construction and geometric inventory,
- Analysis of building load per single construction elements
- Decision on extent and technology for necessary construction works [3, 5-9]. Currently, engineers have a choice of many technologies that can be used to strengthen reinforced concrete structures based on the use of high-strength materials, for example reinforcement with carbon fibre tapes [3, 5-9].

When designing the reinforcement of the damaged concrete column structure, engineers sought to ensure that both the load-bearing structure and the damaged building structure were reinforced and resistant to deformation.

2. Description of the building structure

The building that contains the indoor swimming pool and a room for corrective exercise is based in primary school in Międzyrzec Podlaski town. The building was arranged in a wireframe technology construction. Roof of the building is made of plates CN 180 made of steel St3SX supported by pre-tensioned prestressed concrete beams of the span of 18.0 m The cover is made of corrugated sheet steel TR40 that is 0.75 mm thick and based on steel purlins. Steel roof sheets carry insulation on both sides of the insulating Styrofoam panels and shingle roofing felt. Intermediate floors are made of channel floor slabs type II, reinforced concrete elements of the roof were poured of B12 (C12/15) concrete and reinforced with class A III steel. Interior and exterior walls at the level of the first floor are made of solid ceramic class 7.5 brick on cement and lime mortar of brand 3. Interior and exterior basements walls are made of solid ceramic class 10 brick on cement and lime mortar of grain size 5. Basement walls additionally overburdened with the forces of ground pressure thrust were additionally strengthened with reinforcement wreaths and columns made of B12 (C12/15) concrete reinforced with class A III steel. Steel underlining's are made of two connected rolled I sections NP 260 or NP 220 from St3SX of combined rolled steel sections. I sections are connected by welding top and bottom belts with 10 cm joints every 10.5 m. Reinforced concrete pillars were poured of B15 (C12/15) concrete reinforced with class A III steel. The damaged pillars that are identified at the 5.4 position in the project documentation have square cross-section 25 centimetres x 25 centimetres and are reinforced with four steel A III bars with a diameter of 14 millimetres. The building's pool has a separate supporting structure. During an on-site verification that involved visual inspection of all the elements of the supporting construction described above engineers found it in being in a good technical condition, apart from the damaged supporting beams in the building's basement – Figure 1. The pillars were secured with a temporary steel supporting construction that was completed by the building supervisor.

3. Analysis of causes of the observed abnormalities

That state of the damaged reinforced supporting beams in the swimming pool basement was described as emergency condition. Engineers carrying an on-site inspection noticed multiple cracks and appearance of bends and notches. There were three pillars that got damaged in the basement rooms – after cracks appeared on the first column (Figure 1a, column no 1) it took a short period of time (about a week) for two more columns to follow (Figure 1a, columns 2 and 3). After the first post lost its load bearing capacity the weight transferred onto two neighbouring pillars that got overloaded as a result. The project contractor immediately undertook construction work that involved assembling a temporary steel supporting structure that prevented construction disaster.

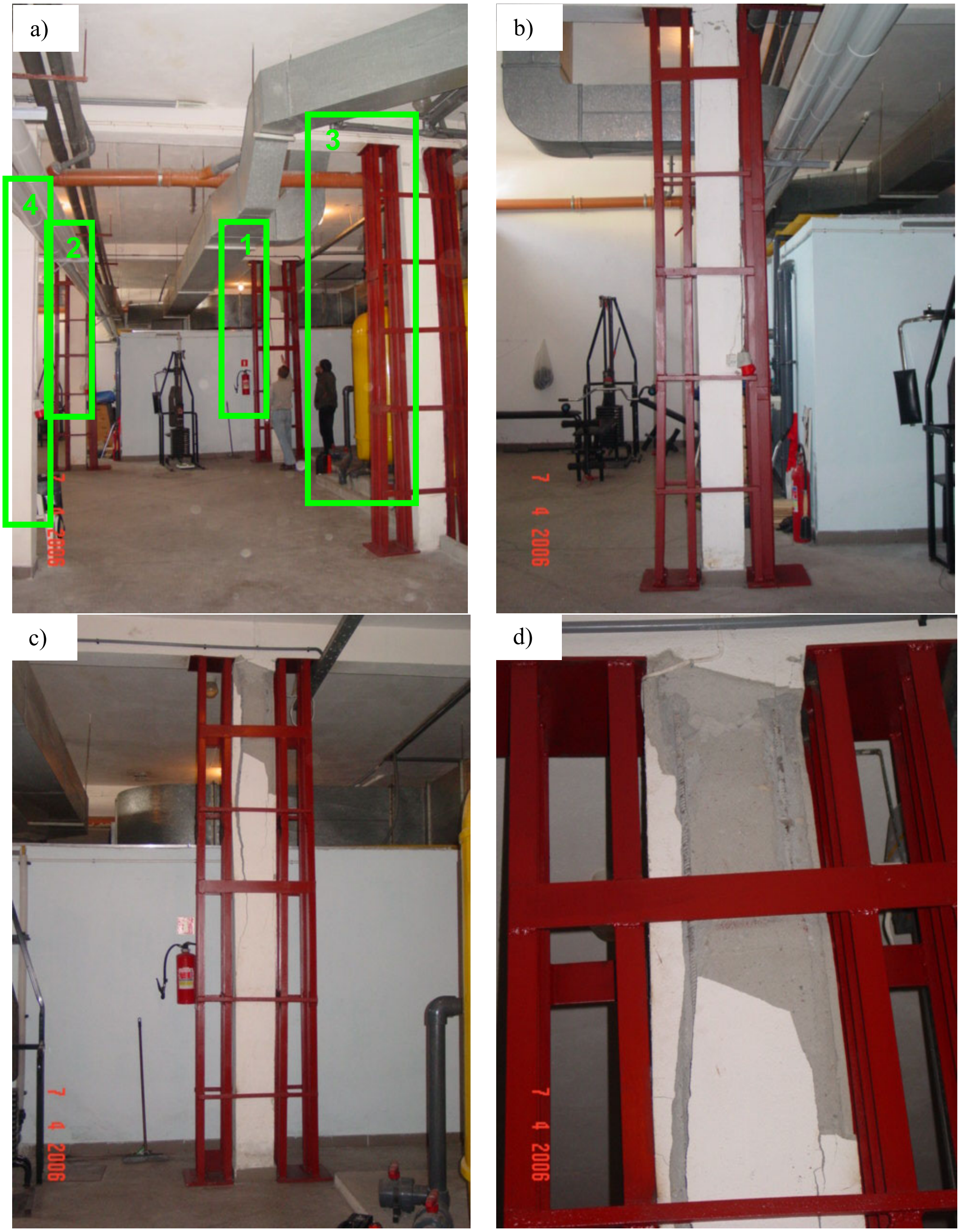

Fig. 1. Overall view of the damaged reinforced concrete pillars in the basement rooms, damaged pillars are marked with 1, 2, 3 numbers

The concrete in the damaged pillars was 10 years old. Reinforcement concrete pillars were operated in dry conditions. Concrete in the pillars was made of gravel of up to 4 mm grain size. Assessment of concrete grade in the damaged pillars was conducted with a use of a Schmidt hammer type N following ITB Technical Recommendation no. 210. The assessment was carried on side surfaces of all the pillars in under the sub-basin basement (position 5.4 in the project documents). It was concluded that all the pillars were made of the same class concrete with a good material uniformity (ν_R = 11%). The average number of hammer reflection was L=22. Due to lack of possibility to drill wells on the pillar cores, it was not possible to verify hypothetical curve, that would be based on the material samples.

Concrete class is determined by the strength of the mortar in a form of so called "composite matrix". Concrete in the damaged pillars was assessed in air-dried state. With a use of hypothetical curve from ITB Technical Recommendation no. 210:

$$f_{\mathrm{cm}} = 0.04094\mathrm{L}^2 - 0.91425\mathrm{L} + 7.4 \quad (1)$$

concrete's strength was estimated as 7.1 MPa. Its uniformity was good. Using formula eigen curve in the form:

$$f_{\mathrm{cm}} = 0.076L^2 - 2.36\mathrm{L} + 25.7 \quad (2)$$

that was developed for concrete in the 1980's it was estimated as 10.6 MPa.

The average concrete strength in the damaged pillars was concluded as corresponding with class B10 (C8/10 according to PN-EN 206-1:2002). This concrete did not meet standard requirements of construction material for use in reinforced concrete constructions.

Engineers carried calculation tests of the strength of the pillars taking into account the incorrect class of the concrete material. The total factor load per damaged pillar was estimated as 450.86 kN.

According to Figure 2 the following geometrical data for damaged reinforced concrete pillar were accepted:

$$A_{s2} = 6.16\ \mathrm{cm}^2,\ \alpha = 0.85,\ f_{yd}=350\ \mathrm{MPa} \quad (3)$$

$$A_{s1} = 0.28\ \mathrm{cm}^2,\ A_{core} = 441\ \mathrm{cm}^2,\ f^{yd*} = 190\ \mathrm{MPa} \quad (4)$$

For class B15 (C10/15) concrete that should have been used in accordance with a design project, the design compressive strength is fcd = 8 MPa.

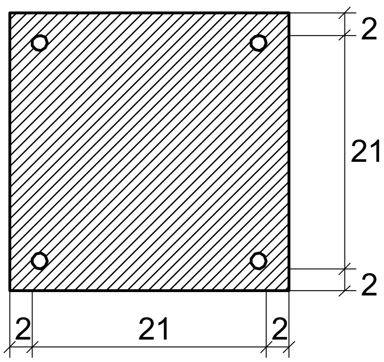

Fig. 2. Pillar cross-section

The beam design resistance for a correct class of concrete is:

$$N_{\mathrm{Rd}} = 0.9\alpha f_{\mathrm{cd}} A_{\mathrm{core}} + f_{\mathrm{yd}} A_{\mathrm{S2}} + 2.5 \mathrm{f}^*_{\mathrm{yd}} A_{\mathrm{S1}} = 498.79\ kN \quad (5)$$

N_{Rd} = 498.79 kN – ultimate limit state (ULS) condition is met

If we take into account the actual design resistance for class C8/10 concrete that was found in the damaged pillars as fcd = 5.2 MPa, then beam resistance is:
N_{Rd} = 404.33 kN – ultimate limit state (ULS) condition is not met.

4. Discussion and proposal of repair works

The next logical step was to designing a reinforcement for the above structure. The new supporting structure was designed in a form of four-arm equal-angled cross-sections. Due to constructional damage an additional safety factor was added in order to increase the total load exerted on a single pillar by 50%. This approach enables weight redistribution of the weight within the building structure that occurred as a result of the earlier damage.

The new construction of the reinforced concrete pillars was designed as a four-arm equal-angled cross-sections of L 80 x 80 x 10 made of 18G2A steel where f_{yd}=295 MPa. The load per pillar is equal to Q = 450.86 kN, additional safety factor (adopted do to the damage) is equal to γ_{dod} = 1.5, therefore total calculated load imposed per pillar is Q(r) = 676.29 kN.

Engineers first checked the resistance of the steel rods and established that the damaged reinforced concrete pillars do not transmit the load imposed on them. The total load will be taken on by the new supporting steel construction and the reinforced concrete elements will remain as non-structural components.

Engineers calculated substitute loadbearing capacity/ slenderness of the angled cross-sections The equivalent slenderness of the multi-branch section was determined that was 29.70. Comparative loadbearing capacity of the cross-section is:

$$\lambda_p = 84\sqrt{\frac{215}{f_d}} = 71.71 \quad (6)$$

Relative slenderness is:

- for the single ros:

$$\bar{\lambda}_1 = \frac{\lambda_v}{\lambda_p} = \frac{20.747}{71.71} = 0.289 \quad (7)$$

- the whole angled cross-section:

$$\bar{\lambda}_p = \frac{\lambda_m}{\lambda_p} = \frac{29.70}{71.71} = 0.414 \quad (8)$$

Because slenderness is < 250, the load bearing capacity of the cross-section was taken from:

$$N_{Rc} = \psi A f_d \quad (9)$$

where:
ψ – the reduction factor of the design resistance of the cross-section, equal to min (φ_1, φ_p),
A – cross-sectional area – 60.4 cm^2,
φ_1 – buckling factor for a single branch – 0.956,
φ_p – the buckling coefficient of the cross-section – 0.899.

$$\text{so: } N_{Rc} = 0.899 \cdot 60.4\ cm^2 \cdot 295\ MPa \quad (10)$$

$$N_{Rc} = 1602\ kN < Q(r) = 676.29\ \text{kN} \quad (11)$$

Calculated condition of ultimate limit state (ULS) of the design of the pillar was met.

The next step was to check load-bearing capacity of pillar battens. Column battens were designed in a form of flat bars of cross-sectional dimension 6 x 100 mm and stem trait W = 6 cm^3, cross-section area of $A_v = 6\ cm^2$.

The transverse force in the beams is:

$$V_Q = \frac{0.012 Q^{(r)} l_1}{2a} \quad (12)$$

where:
a – pole branch spacing – 213.2 mm.

$$V_Q = \frac{0.012 \cdot 676.29\ kN \cdot 500\ mm}{2 \cdot 213.2\ mm} = 9.52\ kN \quad (13)$$

The bending moment in the battens is:

$$M_Q = \frac{0.012 Q^{(r)} l_1}{4} \quad (14)$$

$$M_Q = \frac{0.012 \cdot 676.29\ kN \cdot 500\ mm}{4} = 1.01\ kNm \quad (15)$$

The design resistance of the cross-section for bending with simultaneous transverse force is:

$$M_{R,V} = M_R\left(1 - \left(\frac{V_Q}{V_R}\right)^2\right) \quad (16)$$

where:
M_R – design resistance of the cross-section for unidirectional bending,
V_R – design resistance of the cross-section in shear.

$$M_R = W f_d = 6\ cm^3 \cdot 295\ MPa = 1.77\ kNm \quad (17)$$

$$V_R = 0.58 A_v f_d = 0.58 \cdot 6\ cm^2 \cdot 295\ MPa = 102.66\ kN \quad (18)$$

from here we have:

$$M_{R,V} = 1.77\ kNm\left(1 - \left(\frac{9.52\ kN}{102.66\ kN}\right)^2\right) = 1.755\ kNm \quad (19)$$

$M_{R,V} > M_Q$ – the load capacity condition of the battens has been met.

The last designed element were column baseplates. The total design load carried by the pillars onto foundational footings is 676.29 kN. The total computed strength of the B15 concrete in terms of pressure is equal to 8 MPa, the floor concrete was crosschecked with the sclerometric method. The required baseplate surface area is:

$$F_b = \frac{676.29\ kN}{8\ MPa} = 845.36\ cm^2 \quad (20)$$

The baseplate dimensions are 42 cm x 42 cm with a hole 22 cm x 22 cm and total surface of 1280 cm^2.

It is always very important to pay special attention to establishing what if the correct technology to use for construction works after a reported incident. Construction works should be carried in such a way that when the damaged construction elements are reinforced, they should not be further damaged as a result of the work. In the case of the damaged supporting pillars of the swimming pool building engineers advised the following plan of activities:

- Preparatory work (gathering construction products, equipment and devices),
- Moving the support structure 0.5 m away from each side of the damaged columns,
- Taking off damaged wall plaster and cracked concrete from the damaged pillars,
- Making holes in the basement floor to the upper surface of foundational footings and removal of plaster on transfer beams in order to directly base the steel beams, the minimum dimensions of the holes in a wall are 60 cm x 60 cm,
- Hacking off the coating of the reinforcement bars at the top and bottom part of the reinforced concrete columns for plates at the head and base of the pillar,
- Assembly of steel elements for reinforcing concrete pillars in previously prepared places,
- Filling of the spaces between steel elements of the construction's reinforcement and the damaged reinforced concrete ceiling using non-shrining repair cement mortar:
  - Corrosion protection of the built-in steel elements,
  - Plastering of the pillars – plaster on Rabitz steel net,
  - Filling in the floor around the reinforced pillars.

The construction work should be carried in an order for the pillars listed above. The removal of the existing steel supporting structures can only be done after all four damaged pillars are reinforced.

5. Conclusions

The technical state of the building's supporting structure is described as good, apart from the damaged reinforced concrete pillars in the basement of this building object. The supporting pillars are currently supported by temporary protective structure. Because of the quick reaction of the building's supervisor and user of the facility, making steel supporting structure of the damaged pillars and construction of Steel downstand beams, the damage in this part of the basement didn't spread onto the remaining elements of the supporting structure of the described building object. The cause of the damage to three reinforced concrete supporting beams is incorrect structural concrete at the strength class experimentally established as C8/10 that was used. The fourth reinforced concrete beam that did not get damaged is also made of understated concrete class C8/10.

Due to the damage to reinforced concrete pillars in a building's basement, securing renovation work involved getting a construction permit. This permit was obtained on the basis of design project compiled by the authors of this paper [10, 12-14]. Construction works were carried under a constant author's supervision. Temporary steel protective structures raised in order to strengthen the damaged pillars were removed only after the planned reinforcement of all the pillars in basement rooms was completed.

Normal use of building facilities resumed after the planned construction works were completed and handed over for use. Currently, few years after the renovation work was finished, the building object is fully functioning without any limitations.

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