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Multi-criteria Analysis of the Selection of Secondary Anchors for the Modernization of Multi-layer External Walls in Existing Large-panel Buildings

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Abstract. Prefabricated, large-story, large-panel buildings constitute the basic housing stock in the countries of Central and Eastern Europe (Germany, Poland, Czech Republic, Bulgaria, Romania, Ukraine), which are still used by 10 to 30% of their inhabitants. The program established in the EU to achieve energy based on renewable energy sources by 2050 requires a complex of activities covering both the buildings themselves and their sources of electricity and heat supply. Multi-family, multi-story buildings, commonly constructed after 1960 using the technology of prefabricated concrete construction, constitute a special subject of analysis in the context of the expected changes. One of the necessary ways to implement such a program is the thermal modernization of external walls, including their structural reinforcement. The problem is of a mass nature (in Poland there are 60,000 large-panel buildings covered by modernization programs), so an optimization approach is required, the outline of which is presented in this publication **.**

Keywords: Large-panel buildings; secondary anchors; multi-criteria analysis

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INTRODUCTION

The analysis covered three-layer external walls of large-panel buildings with the following layers:

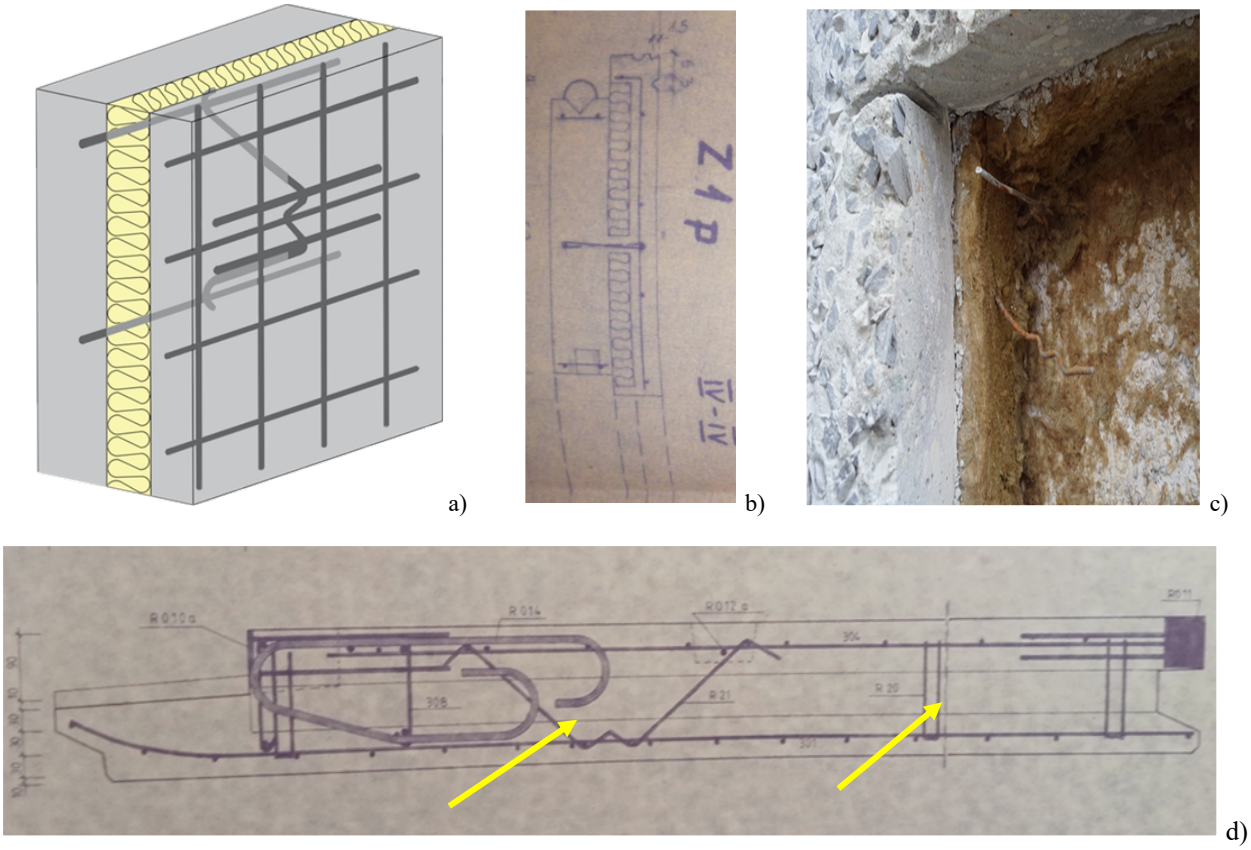
- from the outside, a 6-8 cm layer of gravel concrete (so-called textured), reinforced with a mesh of Ø 10 mm rods, most often with a ready-made texture made in the factory (glass mosaic, white grit, etc.),
- in the middle, an 6 cm layer of mineral wool (often damp),
- from the side of the room, a structural layer, reinforced with two steel meshes, made of gravel concrete with a minimum thickness of 15 cm, or made of lightweight concrete (e.g., expanded clay concrete).

The external, textured layer is attached to the structural layer either with steel hangers - connectors made of ordinary steel Ø8 mm or stainless steel, and with pins made of stainless steel with a diameter of 3 mm. Common solutions for anchoring the texture layer to the structural layer are shown in **FIGURE 1 a–d.**

The expert assessments of existing buildings revealed numerous irregularities that occurred at the stage of production of elements and their operation over a period of several decades. First of all, numerous deviations from the system assumptions were found. They concern both the type of steel from which the anchors were made (often instead of the declared stainless steel, ordinary steel was used; the number of anchors - hangers made of stainless steel was also limited) and the thickness of the individual layers. Often, the facade layer made of gravel concrete, instead

of the designed thickness of 6-8 cm, showed a thickness in the range of 10-12 cm, while the load-bearing capacity calculations of the hangers were performed for thinner layers. The deviations in thickness were caused by the technology of production of these elements. The slabs were made in horizontal stand molds starting from the structural layer. The structural layers always have the designed thickness, while the thermal insulation and texture layer - do not.

The problem results from the natural compression of the mineral wool under the load of the texture layer. Leveling the surface with textured concrete up to the upper edge of the mold caused numerous deformations of the mineral wool and thus different thicknesses of the external layer. Taking into account the above aspects, as well as additional insulating and architectural layers related to thermal modernization processes, it is necessary to additionally - secondary anchor the old texture layer to the load-bearing structural layer [1,2,3].



a) b) c) d)

FIGURE 1. Common solutions for anchoring the texture layer to the structural layer: a) diagram of a three-layer wall showing the connector and reinforcement of the textured layer, b) example of a wall with a connector made of a Ø8 mm rod, c) wall exposure with Ø3 mm stainless steel connectors, d) view of the reinforcement of a three-layer wall; on the left a Ø8 mm connector, on the right two U-type connectors made of stainless steel Ø3 mm

SOLVING THE OPTIMIZATION PROBLEM

In the case of secondary connectors (most often in the form of perpendicularly attached anchors – **FIGURE 2** and **3**), the calculation verification of the connection should include the following destruction patterns:

- checking the load-bearing capacity of the connector: shear on eccentricity and possibly tension;
- concrete destruction: cone failure (including combined with connector pull-out – tear-out), splitting, pry-out failure;
- checking the connector deflection (determining the permissible δ).

Due to the arrangement of layers in a three-layer wall and thus the "suspension" of the textured layer (its entire weight) specific to this wall, it is necessary to check the load-bearing capacity of the concrete of the textured layer (above the connector) under pressure F_{Rdu}.

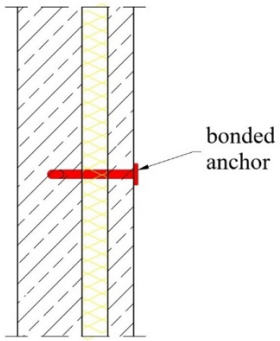


FIGURE 2. Secondary attachment workflow diagram

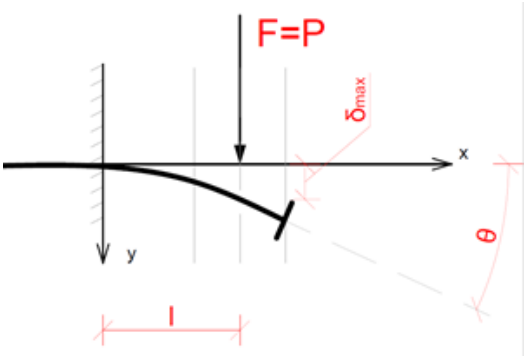


FIGURE 3. Anchor deflection diagram

In order to select secondary anchors, a solution to a multi-criteria optimization problem was proposed, assuming two criteria for the anchor:

a) minimum anchor deflection δ;
b) minimum diameter d (which corresponds to mass) of the anchor – taking into account the range of 12-50 mm;

and variables related to the wall element:

c) characteristic compressive strength of concrete in the range of 11.6-18.8 MPa;
d) thickness of the textured layer h_f in the range of 40-120 mm;
e) thickness of the insulating layer h_i in the range of 47-105 mm.

The above values and ranges were established based on our own research and the inventory of several large-panel buildings. At the same time, the load-bearing capacity of concrete under pressure F_{Rdu} cannot be exceeded, taking into account the variable surface area of the pressure and the load from its own weight (Fd = P). The constant parameters include: steel density and Young's modulus.

The optimization problem has the following calculation model [4]:

1) **decision variables :**
d [mm]
f_{ck} [MPa], P [kN], h_f [mm], h_i [mm] (partly dependent on each other)

2) **parameters**: surface area A = 15.36 m^2 (example wall element); steel density ρ_s = 7800 [kg/m^3]; concrete density ρ_c = 2500 [kg/m^3]; thermal insulation density ρ_i = 50 [kg/m^3]; Young's modulus of steel E = 200 [GPa]; values: k_l= 1.0; γ_c= 1.4; $\propto_{cc}$= 1.0 , load from new thermal insulation F_{izol} = 0.28 kN/m^2; γ_G=1.35; δ_{dop}= 3 mm.
;

3) **limitations:**

f) pressure strength condition:

$$F_{Rdu} = A_{c0} \cdot \sigma_{Rd,max} = A_{c0} \cdot k_1 \cdot \nu' \cdot f_{cd} \geq P = F_d \quad (1)$$

g) stiffness condition :

$$\delta_{max} = \frac{Pl^3}{3EI} = \frac{Pl^3}{3E\frac{\pi d^4}{64}} = \frac{64Pl^3}{3E\pi d^4} \leq \delta_{dop} \quad (2)$$

h) material and geometric conditions:

I. $12 \leq d \leq 50$ [mm];
II. $11{,}6 \leq f_{ck} \leq 18{,}8$ [MPa];
III. $40 \leq h_f \leq 120$ [mm];

IV. $47 \leq h_i \leq 105$ [mm];

V. $l = h_i + 0{,}5\ h_f$ [mm] [1];

VI. $P = F_d = [(h_i \cdot \rho_i + h_f \cdot \rho_c + F_{isol}) \cdot A \cdot \gamma_G]/2$ [kN] [2];

VII. $A_{c0} = \pi \cdot r \cdot hf = \pi \cdot \frac{d}{2} \cdot hf$ [m^2];

VIII. $f_{cd} = \propto_{cc} \frac{f_{ck}}{\gamma_c} = 1{,}0\ \frac{f_{ck}}{1{,}4} = \frac{f_{ck}}{1{,}4}$ [MPa];

IX. $\nu' = 1 - \frac{f_{ck}}{250\ MPa}$;

4) **optimization criteria**

– anchor mass:

$$f_1(d, l) = (\frac{\pi d^2}{4} \cdot L) \cdot \rho_s > \text{minimum}, \text{ [kg]} \quad (3)$$

– anchor end deflection:

$$f_2(d, l, P) = \frac{64Pl^3}{3E\pi d^4} > \text{minimum}, \text{ [mm]} \quad (4)$$

Due to the excessive number of variables for the calculations, the variables for which we can determine the most unfavourable variant by default were selected – these are: f_{ck} [MPa] and h_i [mm]. For h_f, this is no longer so obvious, because the greater thickness of the textured layer causes an increase in loads (which affects both the strength and stiffness conditions), but at the same time the value of A_{c0}, i.e. the pressure resistance $F_{Rdu,}$ increases.

In the case of f_{ck}, we know that the most unfavourable value is the value tending to the minimum, i.e. in our case 11.6 MPa. For h_i, the most unfavourable value should be assumed to be the maximum, i.e. 105 mm.

Thus, we limit ourselves to two decision variables: d [mm] and h_f [mm]. Of course, when starting the calculations, we can freely modify f_{ck} and hi, which are treated as constant parameters in the following.

Given two conflicting objective functions f_1 and f_2, the task can be solved using the vector scalarization of the objective function and the concept of the Pareto minimum, using the notation according to [4].

$$\bar{f}(d, h_f) = (1 - WEIGHT) \cdot f_1(d, h_f) + WEIGHT \cdot f_2(d, h_f) \quad (5)$$

For WEIGHT = 0 only the anchor mass criterion is important, while for WEIGHT = 1 the deflection criterion is important. WEIGHT values from the range ⟨0, 1⟩ the task takes the form of multi-criteria optimization with a compromise between the criteria.

ANALYSIS OF ACCEPTABLE SOLUTIONS

TABLE 1 and **FIGURE 4** present Pareto optimal, compromise solutions for different weight values. The Pareto optimal solution means that it is not possible to find a better solution with respect to at least one criterion - for another solution at least one objective function will achieve a worse value [5]. The calculations were performed using the Excel Solver module and prepared spreadsheets.

TABLE 2 and the following **FIGURES 5, 6 and 7** present the area of permissible solutions and graphic designation of characteristic points (with the calculation). Point 12 represents the ideal solution, which, however, does not meet the constraints and boundary conditions - in accordance with the specificity of the ideal solution. Particular attention should be paid to the red field (**FIGURE 6**), which is the area of unacceptable solutions due to the load-bearing capacity of concrete under pressure. This area is in a very characteristic range for both the thickness of the textured layer (40-60 mm) and the diameters of the anchors (22-28 mm). As can be seen, when using two anchors for a slab with a selected surface area (15.36 m^2), with a reduced thickness of the textured layer (compared to the most commonly assumed 60 mm), there is a significant risk of unknowingly exceeding the load-bearing capacity of the concrete (while meeting the other conditions).

[1] The anchor length for which the deflection is measured was taken into account, in accordance with **FIGURE 3**.

[2] For the stiffness condition the γ_G coefficient is not taken into account. Additionally, the value is divided by 2, due to the assumed minimum of two anchors.

TABLE 1. Set of Pareto optimal solutions

WEIGHT	d (mm)	h_f (mm)	L (mm)	f_1 (kg)	f_2 (mm)	F_{Rdu} (kN)	f (d,L)
0	27,828	40,00	125,00	0,593	1,132	13,82	0,593017
0,1	27,828	40,00	125,00	0,593	1,132	13,82	0,646875
0,2	27,828	40,00	125,00	0,593	1,132	13,82	0,700733
0,3	30,206	40,00	125,00	0,699	0,815	15,00	0,733639
0,4	32,515	40,00	125,00	0,810	0,607	16,14	0,728614
0,5	34,788	40,00	125,00	0,927	0,463	17,27	0,695046
0,6	37,220	40,00	125,00	1,061	0,354	18,48	0,636503
0,7	40,064	40,00	125,00	1,229	0,263	19,89	0,553125
0,8	43,830	40,00	125,00	1,471	0,184	21,76	0,441327
0,9	50,000	40,00	125,00	1,914	0,109	24,82	0,289164
1	50,000	40,00	125,00	1,914	0,109	24,82	0,108582

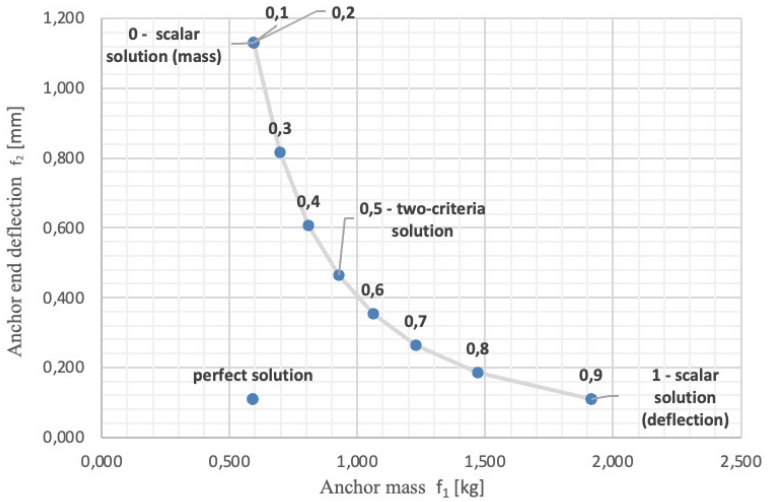


FIGURE 4. Set of Pareto optimal solutions

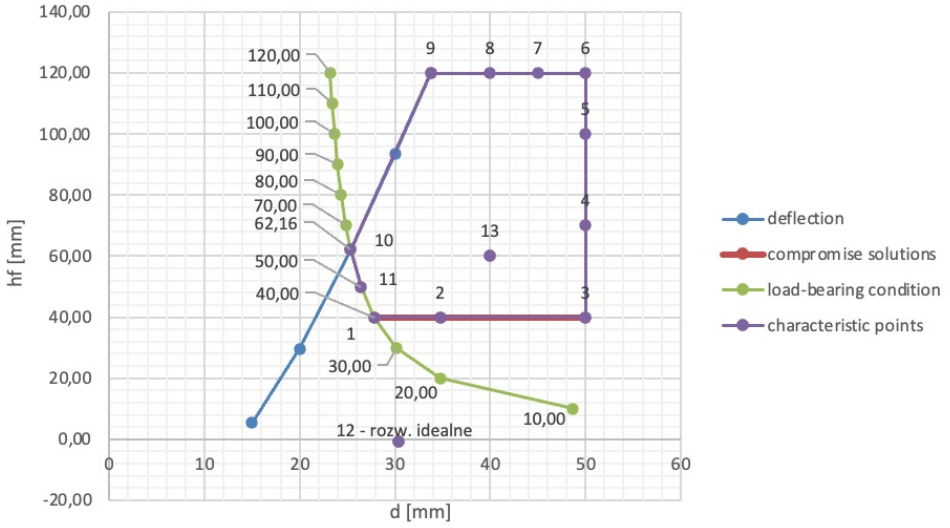


FIGURE 5. The space of decision variables and the area of feasible solutions

TABLE 2. Characteristic points of the decision variable space

No.	d (mm)	h_f (mm)	L (mm)	f_1 (kg)	P (for defl. condition) (kN)	P (for load-bearing condition) (kN)	f_2 (mm)	F_{Rdu} (kN)
1	27,828	40,00	125,00	0,593	10,234	13,82	1,132	13,82
2	34,788	40,00	125,00	0,927	10,234	13,82	0,463	17,27
3	50,000	40,00	125,00	1,914	10,234	13,82	0,109	24,82
4	50,000	70,00	140,00	2,144	15,994	21,59	0,238	43,44
5	50,000	100,00	155,00	2,374	21,754	29,37	0,440	62,06
6	50,000	120,00	165,00	2,527	25,594	34,55	0,625	74,47
7	45,000	120,00	165,00	2,047	25,594	34,55	0,952	67,02
8	40,000	120,00	165,00	1,617	25,594	34,55	1,525	59,57
9	33,774	120,00	165,00	1,153	25,594	34,55	3,000	50,30
10	25,353	62,16	136,08	0,536	14,488	19,56	3,000	19,56
11	26,439	50,00	130,00	0,557	12,154	16,41	1,855	16,41
12	30,420	-0,79	104,60	0,593	2,402	3,24	0,109	-0,30
13	40,000	60,00	135,00	1,323	14,074	19,00	0,459	29,79

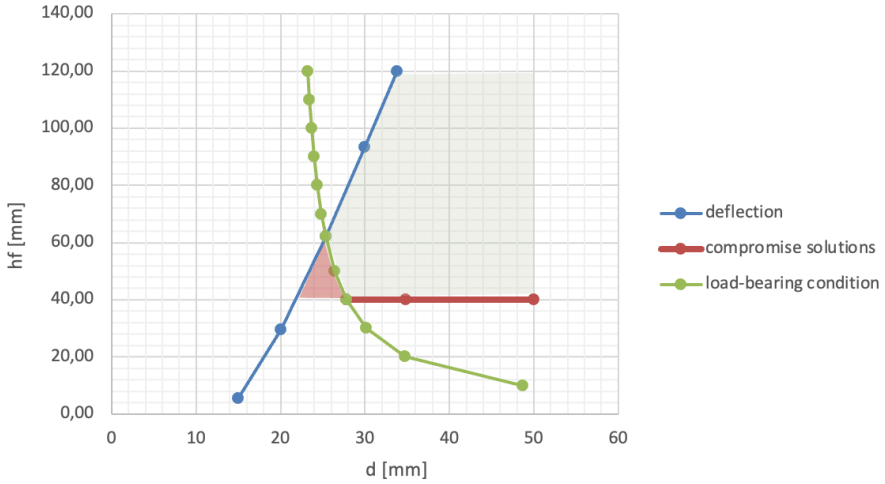


FIGURE 6. Solution areas: green - acceptable, red - unacceptable due to the concrete's load-bearing capacity

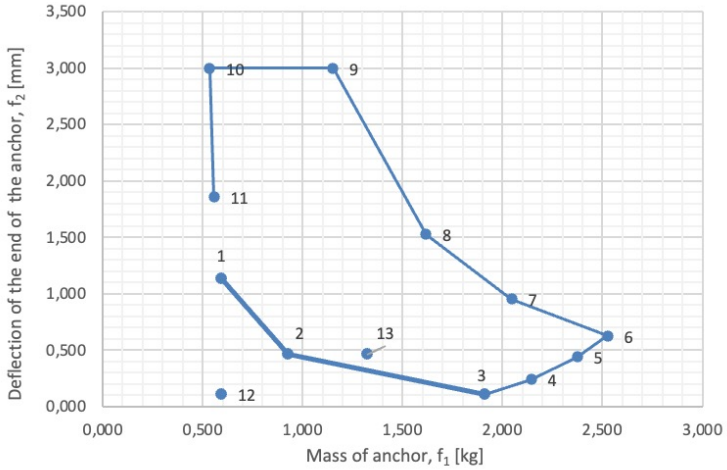


FIGURE 7. Criteria space (quality). The range of points 1-3 contains the set of Pareto optimal solutions

Of course, the calculations can be modified by the initially assumed parameters, including primarily f_{ck} and hi. Below (**FIGURE 8 and 9**), for example, the area of allowable solutions is graphically presented in the case of f_{ck} = 18.8 MPa (max.) and a typical value of h_i = 60 mm .

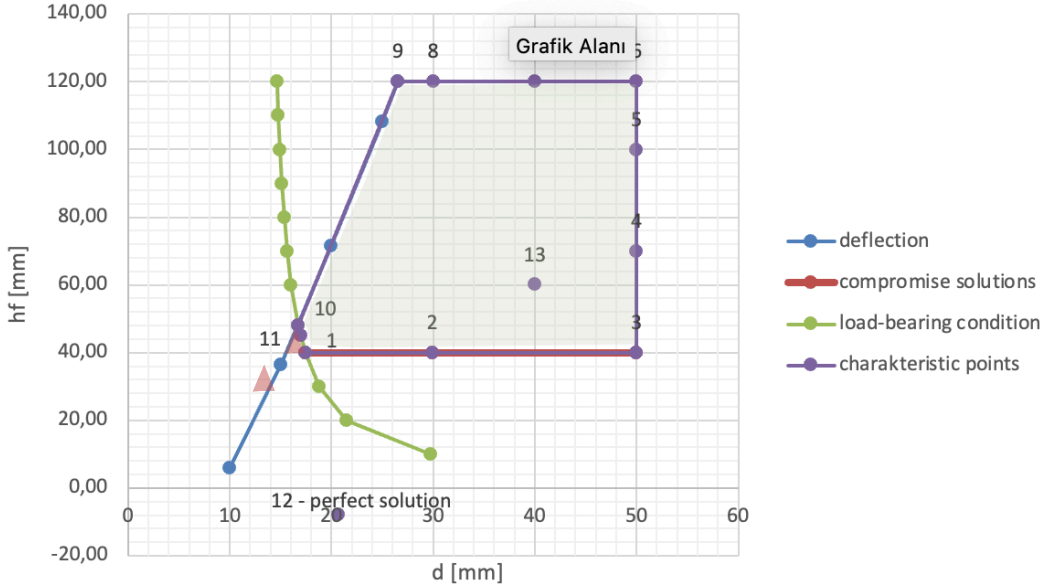


FIGURE 8. Solution areas for f_{ck} = 18.8 MPa and h_i = 60 mm: green - permissible, red - inadmissible due to the concrete's bearing capacity under pressure

It is clearly visible that the area of solutions meeting geometric and material constraints but not meeting the load-bearing capacity requirement has significantly decreased. This confirms the significant importance of the concrete strength of the textured layer for the selection of secondary anchors.

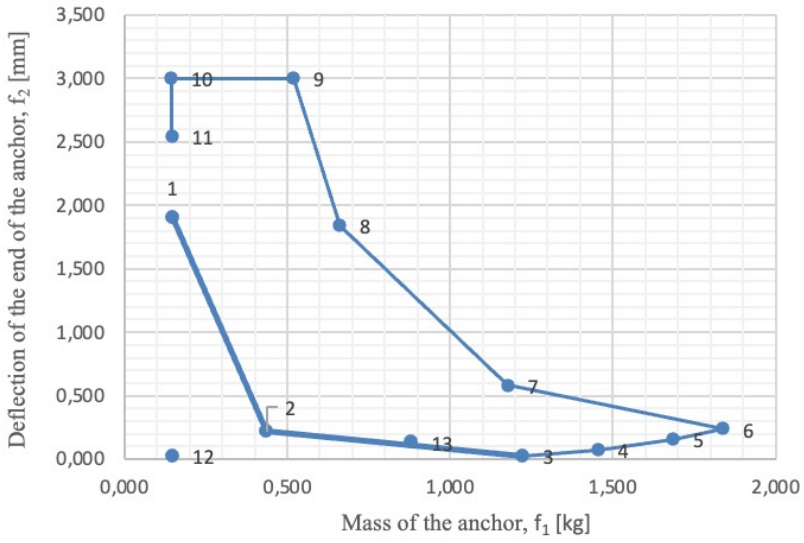


FIGURE 9. Criteria space for f_{ck} = 18,8 MPa and h_i = 60 mm

The methodology of optimal anchor selection presented in the article was used in the thermal modernization of 16-storey large-panel buildings in Poznań. As a result of calculations - depending on the mass and size of the texture layer - 2, 3 or 4 steel anchors Ø22 type R-STUDS-A2 (A4) - FL were used. The solution is shown in **FIGURE 10.**

FIGURE 10. Anchoring of a three-layer wall. A single steel bonded anchor and a pull-out device for checking the effectiveness of the bonding of the anchor into the concrete are shown (according to RAWLPLUG)

CONCLUSIONS

In this paper multi-criteria analysis of the selection of secondary anchors for the modernization of multi-layer external walls in existing large-panel buildings is proposed.

Determining the secondary fixing of the façade layer by solving the optimization problem is a purposeful and effective undertaking. After determining the space of permissible solutions, meeting the condition of the concrete load-bearing capacity for pressure, a system solution should be selected according to the established minimum anchor diameter and the established deflection (recommended maximum 3 mm). If necessary, additional restrictions are introduced for the use of stainless steel (due to durability > 60 years), anchorage depth ≥ 40 mm and the aim is to use two horizontal anchors per plate in order to limit the stiffening of the element. Finally, a system solution should be selected from the space of permissible solutions or the standard conditions should be checked [6,7,8].

There is a significant risk of unknowingly exceeding the load-bearing capacity of the concrete of the textured layer if the wrong concrete class and layer thickness are used. In the case of the minimum measured compressive strength f_{ck} = 11.6 MPa and the maximum thickness of the insulating layer hi = 105 mm, this risk applies to cases with a thickness of the textured layer hf = 40÷60 mm and anchors with a diameter of 22 to 28 mm. For f_{ck} = 18.8 MPa (maximum value) and hi = 60 mm (typical value), the area of inadmissible solutions is significantly limited – to h_f values from the range of 40÷48 mm and a diameter of < 17.4 mm, i.e. the risk is minimized. Therefore, both the thickness of the textured layer and the strength of the concrete have a significant effect on the load-bearing capacity of the secondary fastening.

In summary, it should be noted that when solving the optimization task, it was not possible to take into account all criteria related to the test results of the wall element. Qualitative criteria, such as primary cracking of concrete reducing the load-bearing capacity, but also the results of carbonation are not measurable in the scope of the objective function and decision variables. In this case, it would be necessary to use, for example, fuzzy reasoning, which can be a support for estimating non-quantitative criteria.

ACKNOWLEDGMENTS

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REFERENCES

1. J. Jasiczak and K. Girus, *Maintenance and Durability of the Concrete External Layer of Curtain Walls in Prefabricated Technological Poznan Large Panel System* IOP Conference Series: Materials Science and Engineering, vol. 245 / 3 , 10 2017.
2. J. Krentowski, P. Knyziak, M. Mackiewicz, *Durability of interlayer connections inexternal walls in precast residential buildings*, Engineering Failure Analysis, vol. 121 3 2021.
3. M. Wójtowicz , T. Możaryn, *Technical condition of joints and prefabricated elements of a large-panel building after 40 years of use*, in: Building failures: prevention, diagnostics, repairs, reconstructions. XXVI Scientific and Technical Conference, Szczecin-Miedzyzdroje, 2013 (in Polish).
4. M. Ostwald, *Fundamentals of structure optimization in system design*, Poznań: Poznań University of Technology Publishing House, 2016 (in Polish).
5. E. Szlachcic, *Multi-criteria optimization* (teaching materials), Institute of Computer Science, Automatics and Robotics of the Wroclaw University of Science and Technology, Wroclaw, accessed 2022 (in Polish).
6. A. Cholewicki, T. Chyży i J. Szulc, *New openings in the structural walls of large-panel buildings*, Warsaw: ITB, 2003 (in Polish).
7. Technical Report TR 029, *Design of Bonded Anchors*, EOTA (European Organisation for Technical Approvals), 2007.
8. European Technical Assessment ETA-21/0242 of 11/03/2021*: Bonded fasteners for use in concrete - RAWPLUG, R-KER-II, R-KER-II-S and R-KER-II W*, Warsaw: Building Research Institute, 2021 (in Polish).