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STRUCTURAL ANALYSIS OF A FAILURED RC BEAM WITH OPENINGS IN A BUILDING UNDER CONSTRUCTION

ANALIZA STANU AWARYJNEGO BELKI ŻELBETOWEJ Z OTWORAMI W NOWO WZNOSZONYM BUDYNKU

A b s t r a c t

Examples of defectively constructed-designed and constructed openings in RC beams in a building under construction were presented in the paper. As a result of errors in the design and construction-construction phases, the beams could not fulfil their function. The state of the considered beam with openings was defined as critical (a failure). The results of an analysis of the designed and constructed-constructed state showed differences in the static performance of the structure. However, the redistribution of internal forces is not significant because of the relatively stiff floor slab which takes over the loads from beams. This paper can also provide a background for a more general discussion about the present quality of coordination between design and construction of building structures.

Keywords: beam openings, failure, construction-construction errors, RC structures

S t r e s z c z e n i e

W artykule przestawiono przykłady błędnie wykonanych otworów w belkach żelbetowych nowo wznoszonego budynku. Na skutek błędów projektowo-wykonawczych belki nie mogły spełniać swojej funkcji. Stan analizowanej belki z otworami określono jako awaryjny. Wyniki obliczeń stanu projektowanego i istniejącego wykazały różnice w pracy statycznej konstrukcji. Redystrybucja sił wewnętrznych nie jest jednak znacząca z powodu zastosowanej względnie sztywnej płyty stropowej, która przejmuje na siebie obciążenia z belek.

Słowa kluczowe: otwory w belce, awaria, błędy wykonawcze, konstrukcje żelbetowe

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1. Introduction

Reinforced concrete floor beams are often an element of monolithic structures of buildings. Openings are made due to a necessity of equipping objects in various ceiling installations through these beams (and also floor slabs, walls etc.). The location and size of these openings should not influence the capacity and stability of the load-bearing element.

The subject of the analysis is a structure in which openings in load-bearing elements were defectively designed and constructed. The author of this paper has the design documentation and his own documentation in the form of photographs. Examples of incorrectly designed and constructed openings in reinforced concrete beams and other load-bearing elements (floor slabs, walls) in the public building under construction were presented in the paper. As a result of significant defects of construction, a question appeared as to whether load-bearing elements (mostly beams) can perform their function during new, changed static conditions of a structure. The aim of this analysis is an attempt to answer such a question based on the performed analysis. The condition of reinforced concrete beams was described as critical (i.e. a failure).

2. The building specification

2.1. Geometry and materials

The described building is a monolithic reinforced concrete structure of mixed type – flat slab dominates and slab-beam floor appears in several rooms, in addition, there are some columns and load-bearing walls. In considered part of the building, there are five above-ground stores (the height at the attic: +22.60 m) without basement; main dimensions in plane 54 × 16 m (Fig. 1). The building is dilated at G-G' (44 m/10 m), which is why two separate parts can be considered.

Full, flat floor slabs of 22 cm thickness made of concrete C25/30 (the same concrete grade as for floor slabs and beams), supported on columns (dimensions of cross-sections were diversified, concrete grade C25/30), were designed and constructed. In the considered area,

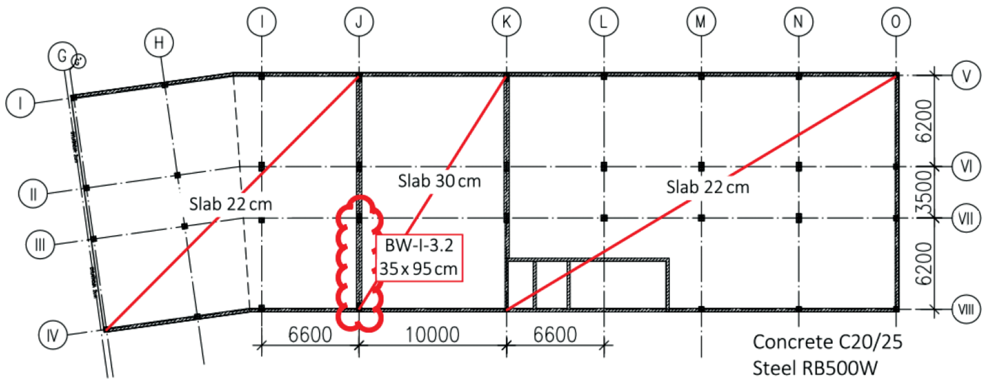

Fig. 1. The considered Floor Plan (defective beam marked)

a slab-beam floor with increased thickness (to 30 cm) occurs between axes J-K/V-VIII on level +9.35 m. The main beams supporting floor slab in this area have dimensions of cross-section 35 × 95 m, concrete C20/25, steel tensile reinforcement 3ϕ25 mm A-IIIN (RB500W), a concrete cover of main reinforcement equal to 6 cm.

2.2. Actions on the structure

Designer [1] predicted typical actions on the load-bearing elements (only the loads affecting the considered area of floor slabs are specified here):

1. Self-weight of load-bearing elements:
   a. floor slab $g_{k.s}$ = 5.5/7.5 kN/m^2 (for thickness 0.22 m and 0.30 m, respectively),
   b. beams $g_{k.b}$ = 6.39/5.69 kN/mb (without slab),
   c. where γ_f = 1.10 (0.90). Self-weight of elements was considered automatically by computer software.
2. Dead loads: g_k = 2.4 kN/m^2, where γ_f = 1.30 (0.80),
3. Live service loads: q_k = 2.5 kN/m^2 (including 0.5 kN/m^2 from weight of installations), where γ_f = 1.4.

This analysis follows the national standards PN-B.

2.3. Failure of a floor beam

A lot of holes for installations were made in the load-bearing elements during the construction of the building. They were made in slab floors, beams and walls (see Fig. 2a–Fig. 2g). The majority of these holes were made defectively, causing unexpected structural response.

Fig. 2a. Openings in load-bearing elements

Fig. 2b."Random" openings in a floor slab

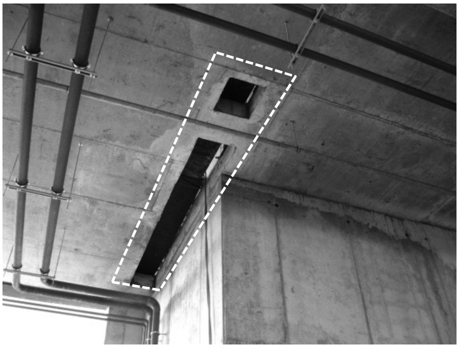

Fig. 2c. Openings designed in floor slab (marked by dashed line)

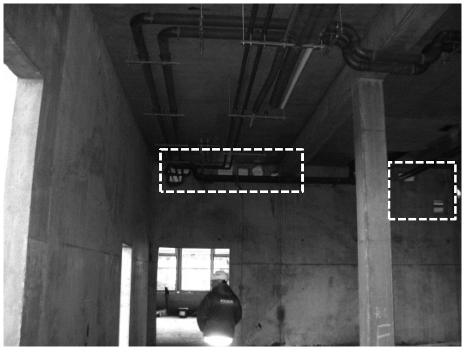

Fig. 2d. Uncontrolled openings in a load-bearing wall

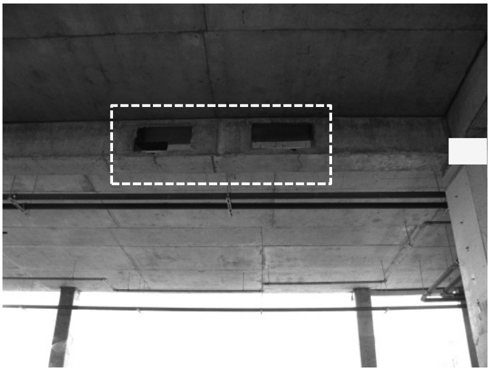

Fig. 2e. Defectively designed openings in beam (cracked lower strip)

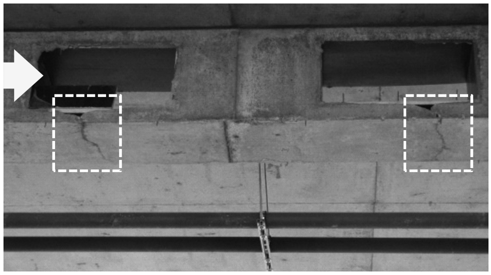

Fig. 2f. Detail of Fig. 2e

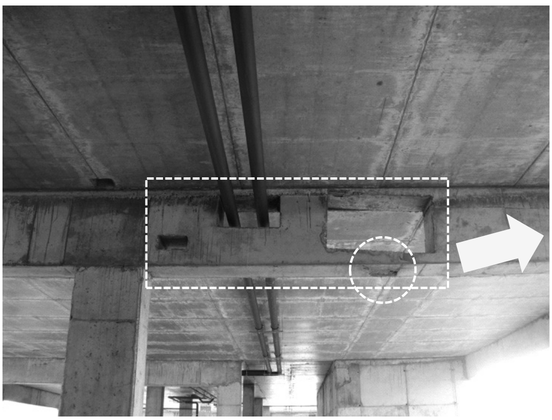

Fig. 2g. Failed beam

Fig. 2h. Detail of Fig. 2g (concrete decrement in lower strip)

Moreover, numerous design-construction mistakes were noticed (cf. Fig. 3a to 3d).

Fig. 3a. Demaged column

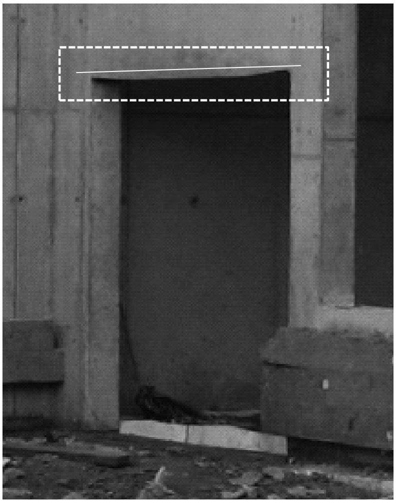

Fig. 3b. Deflection of doorhead due to wrong shoring procedure

Fig. 3c. Defective concrete placement

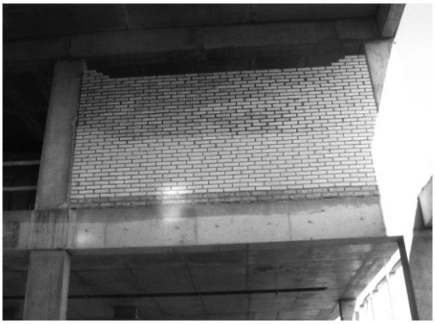

Fig. 3d. Internal wall made of solid bricks (is it needed?)

3. Structural analysis

3.1. Assumptions

An analysis was performed of selected, critical area of the structure (beam with openings and a floor slab in section J/VII-VIII – Fig. 2g and 4; element number BW-I-3.2, construction drawing no. IP026_PW_DR_2542_RC). Two models were developed:

1) plate model of a floor slab with load-bearing beams and
2) disk model (plane stress state – PSS) of the selected, critical beam.

The “ABC Płyta” and “ABC Tarcza” software was used for analysis. The results of calculations for the model representing the constructed structure (E) (existing state) were compared to corresponding results for the as designed structural model (D).

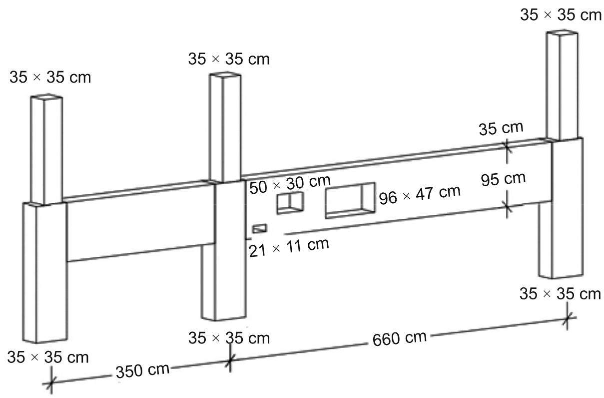

Fig. 4. Designed geometry of beam BW-I-3.2

3.2. Plate model

The differences between constructed state (E) and the designed situation (D) are presented below. Results show an expected modified distribution of displacements (and therefore modified internal forces) and support reactions for slab and analysed beam. Table 1 shows the results for:

– the ultimate limit state (ULS) of moment in fixed support (cf. Fig. 5a and 5b),
– the serviceability limit state (SLS) of displacement of the beam caused by quasi-static actions (confer Fig. 6a and 6b).

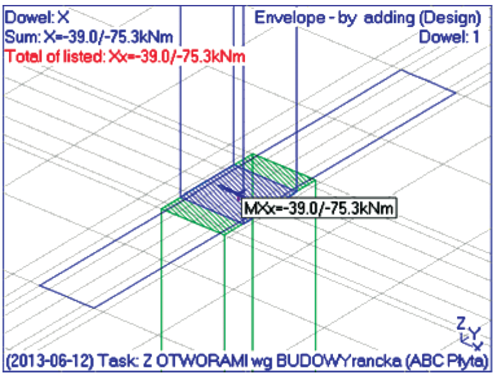

Fig. 5a. Moment in fixed support of beam with constructed openings (E)

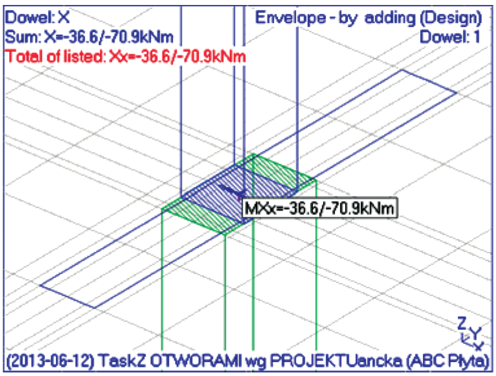

Fig. 5b. Moment in fixed support of beam with designed openings (D)

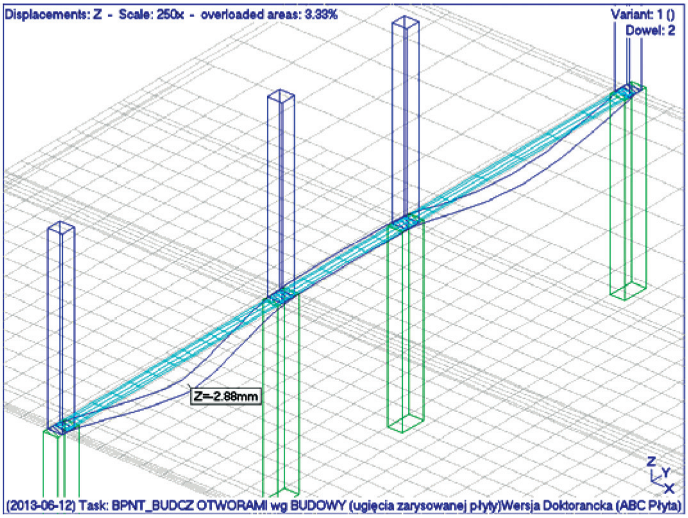

Fig. 6a. Deflection of beam with constructed openings (E)

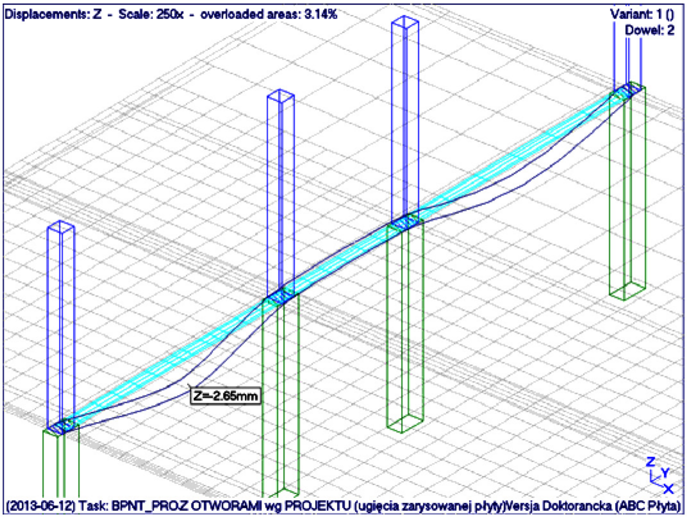

Fig. 6b. Deflection beam with designed openings (D)

The results indicate that the maximum beam deflections in (E) state are larger than deflection in (D) state, and the difference is approximately $\delta_f = 9\%$. In the beam without openings, the deflection equals $f_Z = 1.70$ mm ($\delta_f = -36\%$ in comparison to (D), with a significant observation that this point is not a point of the maximum deflection, which in reality is located in another area of the beam and is equal to $f_{max} = 2.16$ mm). It is caused by a change of the static system of the structure, where a redistribution of internal forces occurs as a result of local stiffness variation. The reduction of bending stiffness of cracked beams is not significantly different between (E) and (P) models – ca. 4%.

Table 1

Values of deflections and moments in fixed support for plate model

Model	Deflection of beam			Deflection of plate		Moment in fixed support		Remark
	f_Z [mm]	δ_f	β	$f_{Z.s}$ [mm]	$\delta_{f.s}$	M_X [kNm]	δ_M	
Constructed beams (E)	2.88	**+9%**	260%	18.08	–1%	–75.3	**6%**	$f_Z = f_{max}$
Designed beams (D)	2.65	–	270%	18.30	–	–70.9	–	$f_Z = f_{max}$
Beams without openings	1.70	–36%	240%	17.57	–4%	–58.4	18%	$f_Z \neq f_{max}$

where: δ_f and δ_M were defined in relevance to (D) state; β – stiffness reduction of cracked section in comparison to (D) state in elastic phase, defined according to equation $\beta = f_Z/f_e$, where f_e – elastic beam deflection from quasi-static loads.

Such relatively slight variations of deflections (and internal forces in analogy) between (E) and (D) models are as a result of the assumed large slab thickness (i.e. 30 cm). This slab takes over the majority of loads and transfers them to the columns without any distinctly visible contribution of the beams.

The maximum deflections of the floor slab do not show any significant variation between (E), (D) and "Beam without openings" models ($\delta_{f.s}$ < 5%; places of maximum deflections are covered for all three models) – again, a considerable influence of floor slab thickness in bearing the loads is observable here.

It is worth paying attention to variation of the moment in fixed support along the beam M_X, (cf. Fig. 4a and 4b) – the value of increment is equal to δ_M = 6% (in comparison with model of beams without openings δ_M = 18%).

3.3. Disk model (plane state of stress)

The disk model allows for the consideration of the shape and scale of deformations of the beam caused by openings (Fig. 7a and 7b). The tensile reinforcement at of the bottom of beam was modelled as an equivalent of 325 mm (cf. point 2.1).

The openings in the beam caused considerable changes in element curvature in the area of reduced stiffness of a section (area around the openings). It leads to a redistribution of internal forces which was not anticipated in the design phase. In the figures below, the principal stresses (σ_1, σ_2) from self-weight loads for beams (Fig. 8a and 8b) with and without openings (Fig. 9a and 9b) models are shown.

The beam openings significantly disturb the distribution of stresses in the considered cross-sections. A particular concentration of stress occurs along the edges of openings and around the corners of openings. The horizontal tension stress σ_X in an area of the largest

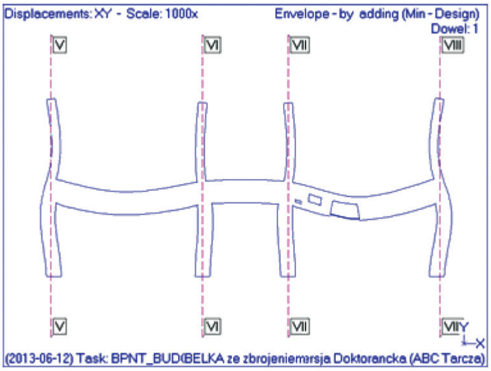

Fig. 7a. Deformation of beam in disk model

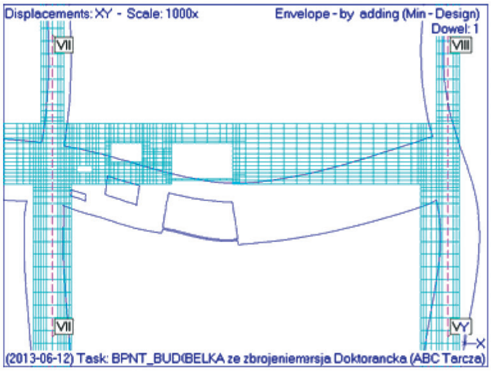

Fig. 7b. Deformation of beam (zoom of Fig. 7a)

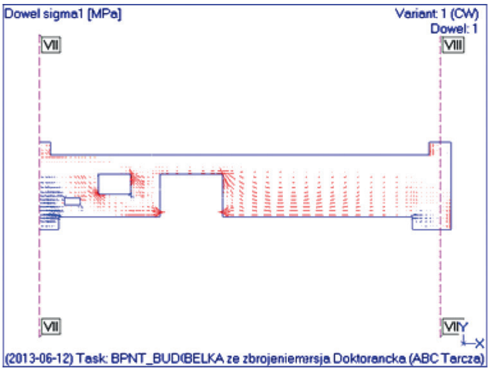

Fig. 8a. Principle stress σ_1 of beam with openings

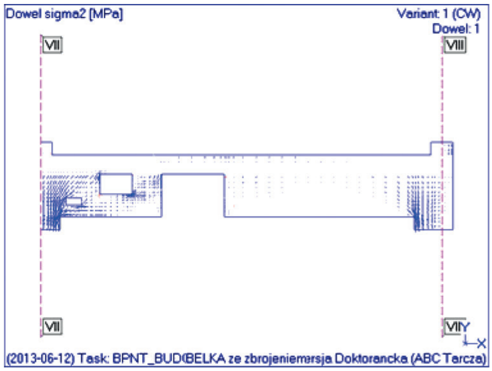

Fig. 8b. Principle stress σ_2 of beam with openings

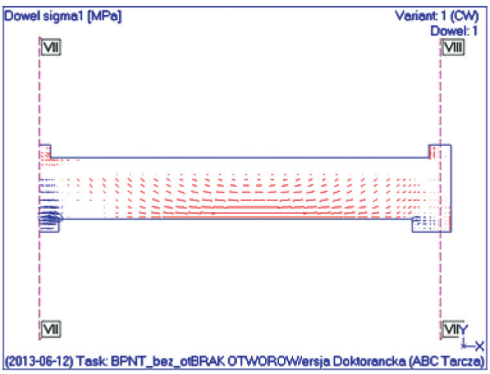

Fig. 9a. Principle stress σ_1 of beam without openings

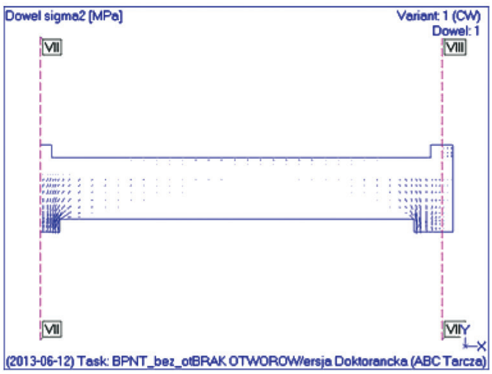

Fig. 9b. Principle stress σ_2 of beam without openings

opening is concentrated at the bottom (represented by steel reinforcement). Simultaneously, the small part of these stresses is taken over by the slab, where the σ_X stress distribution is linear – as shown in Fig. 10. The stress σ_X in the area of the openings (but beyond the slab) is nonlinear (σ_X stress between the openings, Fig. 10). The visible move of the beam neutral axis in top direction (σ_X stress beyond the area of openings) is caused by interaction between the beam and the floor slab, which are monolithically connected. The distribution of vertical stress σ_Y (similar to σ_X) is nonlinear, especially in the corner area of openings where there is a considerable variation of σ_Y (Fig. 11).

Fig. 10–11 show the distribution of σ_X and σ_Y stresses in particular sections of the beam.

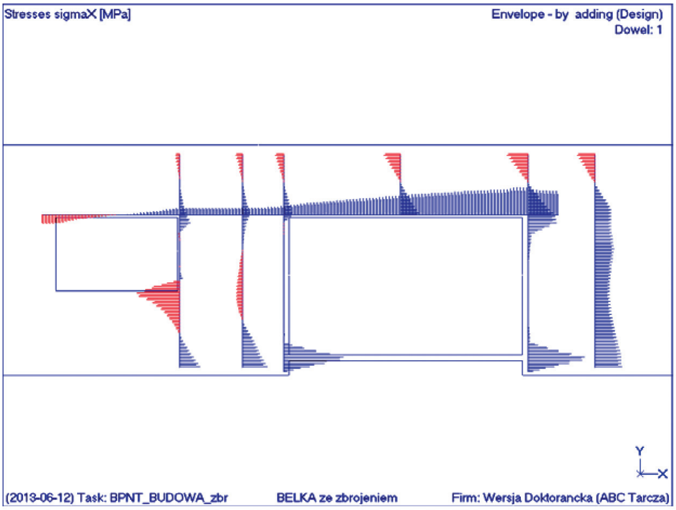

Fig. 10. Stress σ_X

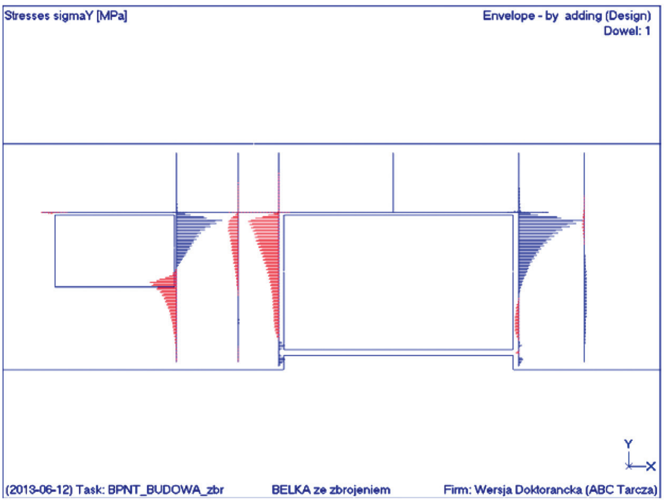

Fig. 11. Stress σ_Y

4. Conclusions from the analysis

The analysis above implies that defectively constructed openings have an impact on the behaviour of load-bearing elements. A structure under loads adapts to a "new" geometry through, among other things, a redistribution of internal forces (confer variations of displacements for slab and beam). However, it causes the risk of unexpected response of a structure due to changed static system. The redistribution is not significant in this case because of the relatively stiff floor slab, which takes over the majority of loads (beam is out of work in the structure) and transfers these loads, to a large extent, directly onto the columns. The recommendation from Designer in point 5.3.3 of the construction project "in the places with insufficient stiffness, reinforced concrete beams connected with floor slabs and columns should be constructed" was not fulfilled, and even missed both during the design and the construction phase – the analysed beams do not have sufficient stiffness.

5. Conclusions

The intention for the presented observations was to voice an opinion about a still timely problem of communication between Designer and Contractor in building projects, and in particular related to supervision, coordination and quality of these works. Despite more and more advanced tools used in engineering, up to now, nothing can replace the human factor (which usually is an adequate experience) [6]. Providing required level of structural reliability does not depend on the use of modern tools – it depends not less on good habits, experience and integrity during everybody's own work. Let the figure below (Fig. 12) be the punchline, which quite clearly illustrates the problem of quality and coordination in the building process.

Fig. 12. „Well-founded" construction of the opening in beams

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