TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

2-B/2013

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METHODS OF REINFORCING HISTORICAL WOODEN CEILINGS ON THE EXAMPLE OF THE PALACE COMPLEX IN GORZANÓW

METODY WZMACNIANIA ZABYTKOWYCH STROPÓW DREWNIANYCH NA PRZYKŁADZIE ZESPOŁU PAŁACOWEGO W GORZANOWIE

A b s t r a c t

Modern design and implementation does not only concern newly created and designed buildings, but also buildings that already exist, including historical buildings. The necessity of maintaining their authenticity with minimum interference in the historical substance of the building requires the application of modern design and materials solutions. This problem pertains to most renovated and modernized historical buildings, including the palace complex in Gorzanów, which is located in Lower Silesia in the Kłodzko Valley. Within the framework of adapting the building to modern requirements while maintaining its historic nature, solutions making it possible to preserve richly decorated wooden ceilings, despite the increase of operational loads in palace rooms, are sought after. For this purpose, analysis of the load-bearing capacity of wooden ceilings has been conducted, including architectural and construction inventory, material studies, and the modeling of various possible ceiling reinforcement solutions. The work presents the results of the conducted analysis, and methods of reinforcing wooden structures by means of modern materials and technological solutions have also been discussed.

Keywords: wooden structures, ceiling reinforcement, historical wooden ceilings, CFRP composites

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

Nowoczesne projektowanie i realizacje dotyczą nie tylko nowo powstałych i projektowanych obiektów budowlanych, ale również obiektów już istniejących, w tym obiektów zabytkowych. Konieczność zachowania ich autentyzmu przy minimalnej ingerencji w zabytkową tkankę obiektu wymusza zastosowanie nowoczesnych rozwiązań projektowych i materiałowych. Problem ten dotyka większości remontowanych i modernizowanych obiektów zabytkowych, w tym również zespołu pałacowego w Gorzanowie, który zlokalizowany jest na Dolnym Śląsku w Kotlinie Kłodzkiej. W ramach dostosowania obiektu do współczesnych wymagań, przy jednoczesnym zachowaniu jego zabytkowego charakteru, poszukuje się rozwiązań pozwalających na zachowanie bogato zdobionych drewnianych stropów mimo zwiększenia obciążeń użytkowych w pałacowych pomieszczeniach. W tym celu przeprowadzono analizę nośności drewnianych stropów, która objęła inwentaryzację architektoniczno-budowlaną, badania materiałowe oraz modelowanie różnych możliwych rozwiązań wzmocnienia stropów. W pracy przedstawiono wyniki przeprowadzonej analizy, a także omówiono metody wzmacnianie konstrukcji drewnianych przy pomocy nowoczesnych materiałów i rozwiązań technologicznych.

Słowa kluczowe: konstrukcje drewniane, wzmacnianie stropów, zabytkowe stropy drewniane, kompozyty CFRP

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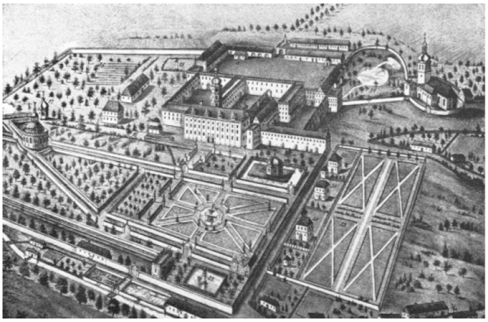
1. Introduction

The reinforcement of building structures, including historic buildings, currently constitutes an important problem for both renovators and designers. The development of technologies results in the application of newer solutions and materials which allow for the fulfillment of the requirements posed during conservational renovations. They make it possible to maintain authenticity with minimum interference to the historic substance of the building. It should be remembered, however, that the application of modern technologies carries risks relating to lack of experience in the design of structures with their use.

Historical palace complexes are an essential part of the landscape of Lower Silesia, however, the last decades have been a time of slow degradation for many of them. This is often the result of a lack of clear property rights as well as the necessity of performing large modernizing work in order to achieve a useful state.

Gorzanów is a picturesque town, situated in the center of the Kłodzko lands. In 1573, a renaissance palace and park complex was built there. During the XVII century, the monumental palace was partially rebuilt in the baroque style. Currently, the palace consists of four wings surrounding an inside courtyard, and its representative body can be seen from the Palace rooms in the basement have been covered with barrel vaults with lunettes with sharp vault seams. The upstairs rooms had renaissance polychrome beam-framed floors, which were remodeled in the XVIII century in the central wing to plafonds with polychrome with antique and contemporary themes [4, 8].

a)



b)

Fig. 1. Palace and park complex in Gorzanów [10]: a) urban layout from the XVII century, b) archival photograph from the beginning of the XX century

After the Second World War, the settled populace from the eastern borderlands stopped caring for the building, and in extreme cases, even used valuable elements of palace furniture for its own purposes. After 60 years of neglect, the current state of the palace can be best described as a ruin [3]. In 2010, one of the owners made an attempt to secure the roof structure. However, badly performed renovation work caused further devastation of the building. Currently, the palace is subject to protective works, and revitalization of the entire area of the palace and park complex is planned in the future. One of its elements will be the adaptation of the main palace body for commercial purposes.

a) b)

Fig. 2. Palace and park complex in Gorzanów – state as of the year 2012: a) exterior eastern facade [10], b) interior eastern facade

2. Analysis of registered damage

In order to determine the current technical state of the building, an inventory of present damage was taken. The most damage was registered in the central part of the palace – the east wing, in which part of the roof was destroyed as a result of badly performed renovation works (Fig. 2b). Also in the west part, in which residential rooms could still be found up to 2011, much damage resulting from a lack of roofing was observed. The north and south wings were kept in a much better state, due to the good state of the roofing.

The main cause of most of the registered damage was the harmful impact of water on structural elements, including, above all, on the historical wooden ceilings. This was caused by many gaps in the roofing and by the complete lack of a roof on the central part of the palace. The absence of a roof is as a consequence of badly performed renovation work. Originally, the palace roofing was made from stone roofing tiles, however, these were replaced with ceramic roofing tiles during renovation work. During renovation, the rafter framing structure was not reinforced despite the biological corrosion present in it. Excessive loading of the rafter framing with material with a greater weight caused this part of the roof to collapse. This, in turn, caused the destruction of ceilings of lower floors found below the collapsed part of the roof (Fig. 5a).

The lack of maintenance work on roof flashing at the point of contact of valley rafters and dormers has resulted in local but intensive impact of water on the structure of the wooden ceilings. As a result of the total degradation of the ceiling of the highest floor, the above impact was transferred in a straight line to the ceilings of successive floors causing their destruction, as illustrated on Fig. 3a and 3b.

Furthermore, it was observed that a significant part of wooden ceiling elements exhibits local damage caused by biological corrosion. This was caused by many years of use, the absence of the appropriate climatic conditions and of ceiling maintenance, as well as by the direct impact of water. The greatest damage to ceilings is present in areas where elements are supported, e.g. points of support of ceiling beams on walls (lack of the appropriate anti-moisture insulation), and also in other areas, locally. This was confirmed by sagging measurements of selected ceilings.

a)

b)

Fig. 3. Damage to ceilings of successive floors caused by the local impact of water: a) damage on the II floor, b) damage on the I floor

a)

b)

Fig. 4. Biological corrosion of ceilings: a) corrosion caused by a lack of the appropriate atmospheric conditions, b) corrosion caused by the direct impact of water

a)

b)

Fig. 5. Ceiling damage: a) absence of ceilings that collapsed along with the roofing, b) fire damage

Sagging measurements of wooden ceiling beams were performed for rooms in which ceilings were preserved in their entirety or were not damaged for the most part. 12 wooden beams located in 6 rooms were subject to measurement. Sagging measurement was conducted using laser rangefinders and a leveled geodetic staff. The results of measurements are presented in graphic form on Fig. 6–7. The X axis shows the distance between successive measuring points, and the Y axis shows vertical distance between measuring points located underside of the beam and reference level. Measuring points are located at an interval of every 50 cm over the entire span of the beam, assuming shifting of extreme measuring points from the wall face by approx. 30–50 cm. Conducted sagging measurements and macroscopic assessment made it possible to determine the nature of the operation of beams and places of their deterioration. Based on measurements, two characteristic types of dislocations can be distinguished – sagging in the center of the beam span resulting from own weight and static load, a natural phenomenon for such a structural system, as well as depressions in areas near supports (e.g. seatings of ceiling beams) that may result from deterioration of the wooden element and significant deflections of walls from verticality. The following charts present results of measurements for two ceilings with varying degrees of sagging.

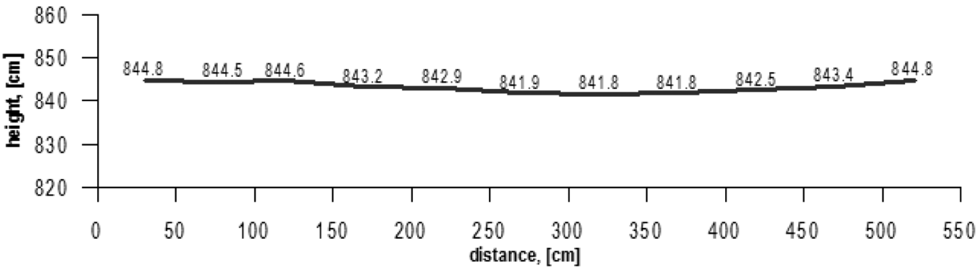


Fig. 6. Exemplary beam sagging at the center of its span

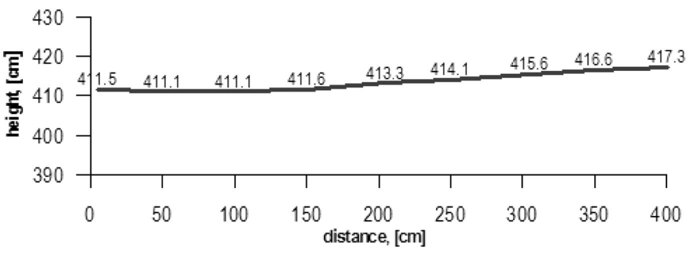


Fig. 7. Exemplary depression in the area near a support

Many years of the absence of protection against water has also caused significant dampness of both interior and exterior walls. This has caused detachment and loosening of plasters, destruction of wall surfaces, and destruction of wall elements themselves.

Table 1

Results of destructive and non-destructive tests

Parameter		Number of samples [pcs.]	Shape and dimensions of sample [mm]	Average value	Standard deviation	Value for 12% moisture content	Characteristic value
Moisture	%	12	20 × 20 × 30	9.33	0.28	12	–
Density	kg/m^3	18	20 × 20 × 30	407.72	28.77	–	–
Compressive strength along fibers	MPa	10	20 × 20 × 30	42.99	5.30	38.41	30.62
Compressive strength transverse to fibers	MPa	8	20 × 20 × 30	9.25	3.1	8.26	3.72
Flexural strength	MPa	3	20 × 20 × 300	74.61	12.97	66.92	47.64
Modulus of elasticity along fibers	GPa	3	–	8.86	–	7.92	–

3. Material studies

In order to assess the technical state of structural wooden elements and the load-bearing capacity of existing ceilings, material samples were collected for non-destructive and destructive laboratory tests.

Destructive tests were conducted according to standards PN-77/D-04227, PN-77/D-04229, PN-79/D-04102, PN-79/D-04103; and the following parameters were determined on their basis: dampness, density, compressive strength along fibers, compressive strength transverse to fibers, flexural strength. In the case of the modulus of elasticity, tests on small samples without flaws were abandoned in favor of tests on full-dimensional elements. Obtained values of individual parameters are presented in table 1. Based on obtained results, the class of wood was determined according to standard PN-B-03150:2000 as C18. The decisive parameter that classified the tested material in a given class of wood proved to be the modulus of elasticity.

Fig. 8. Elements collected for tests

The bending test was conducted as a non-destructive laboratory test on ceiling elements at their actual size. The maximum concentrated force for which studied elements fulfilled the limit use state condition (max $u = L/167$) was determined. The method of conducting tests has been presented on Fig. 9, and obtained results are listed in Table 2. The results of the test show a dependency between the state of the wood and its load-bearing capacity. However, results should not be compared directly, because the tested elements had differing cross-sections.

Fig. 9. Testing of beams in technical scale – view of test apparatus

Table 2

Results of non-destructive material tests

Series	Shape and dimensions of beam [mm]	Macroscopic assessment of state	Sagging [mm]	Force [kN]
Beam I	165 × 155 × 2000	Good	12.08	28.13
Beam II	169 × 150 × 2000	Very good	12.14	33.08
Beam III	159 × 156 × 2000	Biological corrosion	12.35	22.10
Beam IV	130 × 115 × 2000	Good	12.26	13.52
Beam V	164 × 129 × 2000	Very good	12.02	26.24

4. Methods of reinforcing wooden structures

Methods of structure reinforcement can be divided in terms of the nature of their work into:

- a new system of load-bearing elements, in the case where the existing structure is capable of carrying its own load (Fig. 10),

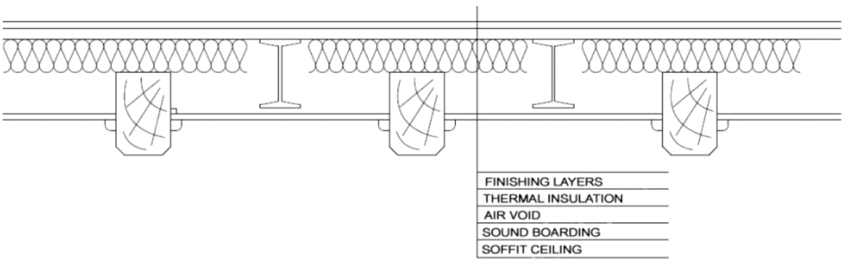


Fig. 10. Exemplary solution of independent reinforcement of a wooden ceiling

- a suspended system, which is simultaneously responsible for carrying useful loads as well as the weight of the historical wooden structure itself (Fig. 11),

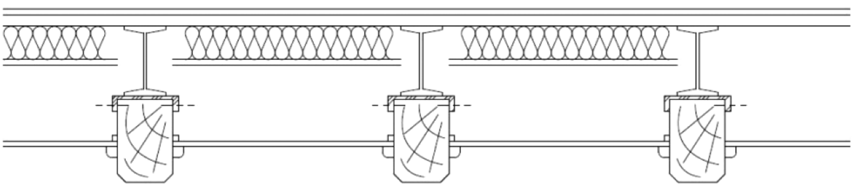


Fig. 11. Exemplary solution of suspended reinforcement of a wooden ceiling

• systems based on cooperation of the reinforcement with the existing structure (Fig. 12),

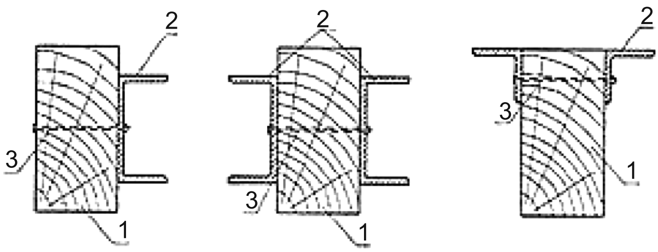


Fig. 12. Exemplary solution of systems based on cooperation of the reinforcement with the existing structure; 1 – Ceiling beam, 2 – Rolled section, 3 – Steal connection

These last systems are most often used due to technological and material diversity as well as due to the exploitation of the existing load-bearing capacity of the structure [1].

Over the years, a series of solutions for reinforcement of wooden structures using conventional construction materials has been developed. The material most often used for reinforcement is steel elements – from steel rods glued in specially prepared grooves in the beam, through substitute rod lattices, steel shackles and cover plates, to brackets made from rolled sections and replacement of part of the element. Such reinforcements are usually visible in the structure, which significantly limits the capability of applying them in historical elements. In certain cases, it is possible to create a coupled structure, e.g. ceiling on wooden beams coupled with a reinforced concrete slab. Such a solution is possible for application when wooden beams are capable of carrying tensile stress, compressive stress will then be carried by the reinforced concrete slab. Conventional solutions also include structural reinforcement based on hydrophobization of elements, which leads to general improvement of the technical parameters of wood [1, 2, 9].

The development of technologies makes it possible to fashion new solutions, with the application of composite materials, among others. These are plastics that most often consist of two phases: a continuous phase (called the matrix) and a dispersed phase, constituting the reinforcement. Currently, fibrous composites with polymer matrices (thermoplastic and thermally hardened resins) reinforced with carbon fibers (CFRP), glass fibers (GFRP) or aramid fibers (AFRP) are most often used. Composites are joined with wood using glues, mainly resin-based glues. The main advantage of composites is the ratio of their weight and dimension to the achieved strength. They can protect a structure very well while essentially not creating any additional load. For example, the gluing of tape to the upper and lower surface of a beam may improve its load-bearing capacity by 100% and rigidity by 40% [6]. CFRP tapes are easy to "conceal" in the cross-section so that the original appearance and shape of the element is preserved. Fig. 13 shows an example of reinforcement of an historical wooden beam with tapes. Pre-stressed composite tapes give new capabilities for reinforcing existing structures. They take part in carrying loads immediately after being glued on and reduce stresses in the existing cross-section. Improvement of the load-bearing capacity of elements therefore takes place through the introduction of a stress state contrary to the stress expected during exploitation as well as through elimination of the influence of wood flaws on its strength [1, 6].

Fig. 13. Reinforcement of ceiling beams in the palace in Gorzanów

5. Analysis of reinforcement of selected structures

Within the framework of the adaptation of the palace in Gorzanów to modern requirements, solutions making it possible to preserve the richly decorated wooden ceilings while improving their useful loads are sought after. For this purpose, analysis of the capability of reinforcing selected wooden ceiling structures was conducted. The ceiling over the “Fireplace” room was analyzed in detail, and its current state has been presented on Fig. 14. Solutions that do not raise doubts concerning aesthetics and that are technologically possible for implementation have been accepted for analysis. The following methods of reinforcement were considered:

- replacement of selected wooden ceiling beams with steel elements,
- gluing of CFRP tapes into selected ceiling beams,
- direct coupling of the wooden ceiling structure with a reinforced concrete slab,
- construction of an independent reinforced concrete slab – suspended system.

a) b)

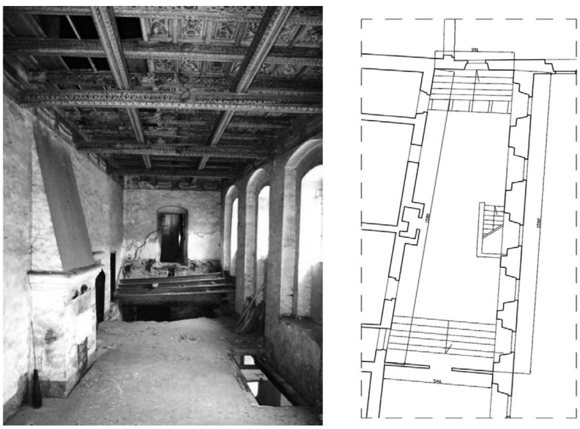


Fig. 14. „Fireplace” room: a) current state, b) projection

Calculations of the load-bearing capacity of the ceiling were carried out using Autodesk Robot Structural Analysis 2012 software. The accepted model of calculations has been presented on Fig. 15.

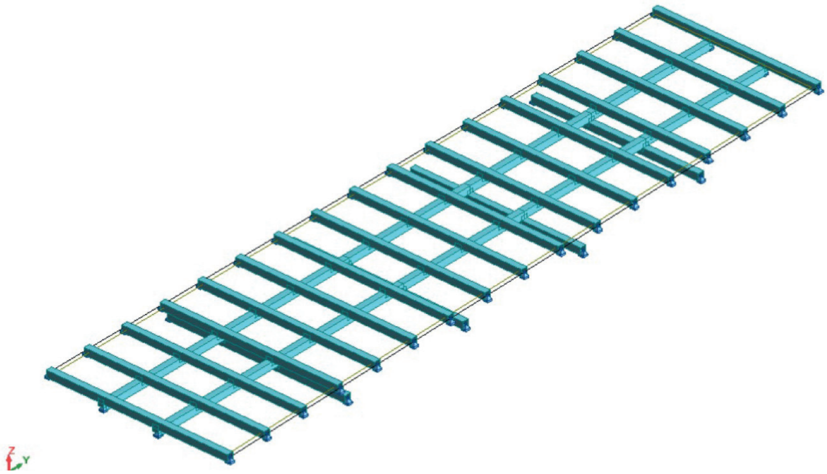


Fig. 15. Calculated model of the ceiling in the “Fireplace” room

For calculations, dimensions of wooden beams of 14.0 × 16.0 cm and a wood class of C18 were accepted based on conducted material tests. In the analyzed ceiling, 3 characteristic groups of beams were distinguished, which were subjected to effort analysis (Fig. 15). Performed calculations of the current ceiling load state (own weight and constant loads from the weight of finishing elements) showed that the efforts of the elements subjected to the greatest load from individual groups of beams do not exceed 100.0%, although the effort of beam no. 2 was as high as 99.0% (Fig. 16).

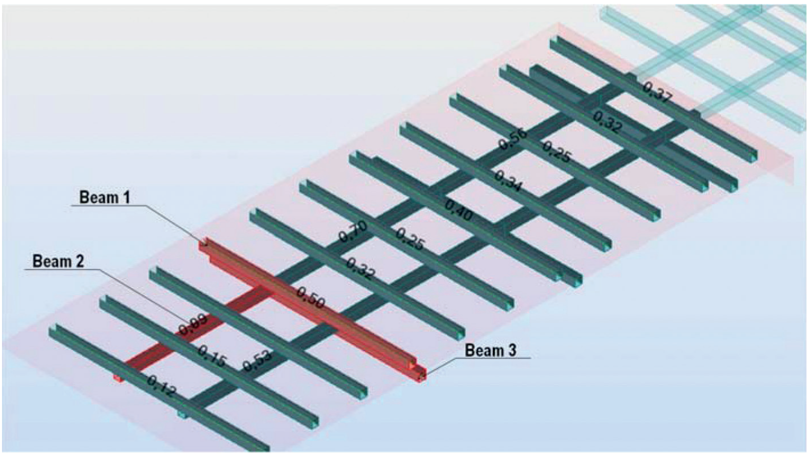


Fig. 16. Efforts of wooden structural elements of the “Fireplace” room ceiling

In the case of the application of additional load to the existing structure, resulting from among other things, the capability of adapting the rooms over the “Fireplace” room as useful rooms, the efforts of the elements carrying the greatest loads were respectively, 77.0% for beam 1, 189.0% for beam 2, and 78.0% for beam 3. This proves that the current technical state of the ceiling does not make it possible for it to carry the additional load relating to the change of use. Furthermore, the current level of effort of certain ceiling beams indicates the necessity of performing additional reinforcing works for the purpose of adapting the analyzed ceiling to modern requirements.

Analysis of ceiling reinforcement through replacement of longitudinal wooden ceiling beams (beam 2) with IPE 100 steel elements indicates (Fig. 17) that this type of structure would be capable of carrying both constant loads as well as operational loads acting on the ceiling. However, at the same time, it must be emphasized that this type of reinforcement would have to be carried out by making special grooves in existing beams into which steel sections would have to be inserted in order to maintain the existing decorations of wooden beams.

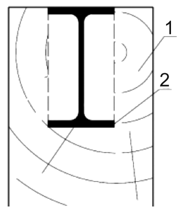


Fig. 17. Replacement of selected wooden ceiling beams with steel elements; 1 – Ceiling beam, 2 – Rolled section (IPE 100)

The application of the method of reinforcement of wooden ceiling beams with CFRP tape makes it possible to accept a higher class of wood in calculations of limit states due to the significant improvement of their strain properties. This is confirmed by the results of studies presented in paper [6] and by the author’s own studies, which were conducted on ceiling beam elements acquired from the palace in Gorzanów (Fig. 8). Studies were conducted on beams into which individual CFRP carbon tapes were glued (Fig. 18), and load was applied to these beams to check the fulfillment of limit bending state requirements. Obtained results were related to tests of these same beams without reinforcement.

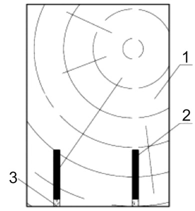


Fig. 18. Gluing of CFRP tapes into ceiling beams; 1 – Ceiling beam, 2 – CFRP tapes; 3 – Structural glue

Analysis of reinforcement of the ceiling above the “Fireplace” room through gluing of CFRP tape into individual ceiling beams indicates that this type of structure would be capable of carrying both constant loads as well as operational loads acting on the ceiling. It is to be emphasized that the improvement of the load-bearing capacity of reinforced beams is directly dependent on the method of gluing CFRP tapes. It can therefore be accepted that the level of reinforcement can be appropriately shaped in this way with the preservation of the same elements in the ceiling.

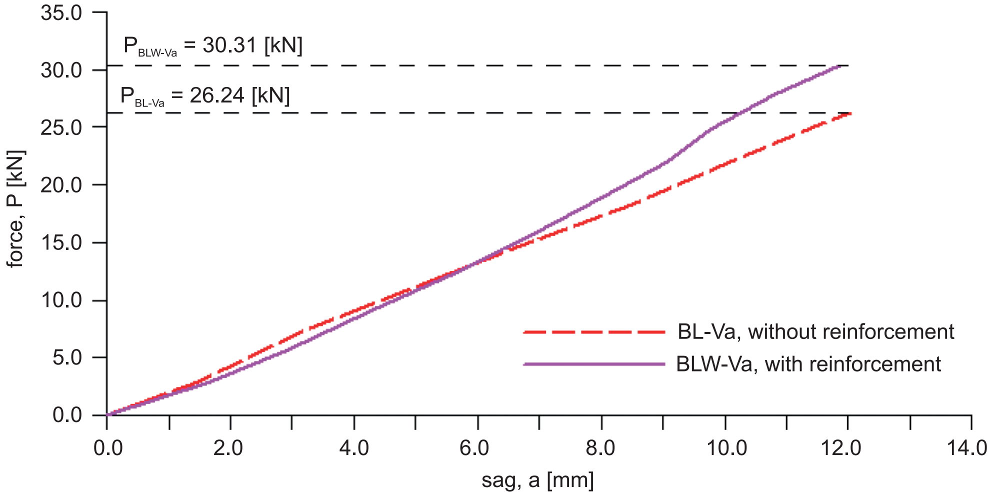


Fig. 19. Improvement of the load-bearing capacity of BL-VA beam in the scope of SGU reinforced with CFRP tape

The application of reinforcement of the analyzed ceiling through coupling of its wooden structure with a reinforced concrete slab (Fig. 20) causes excessive load on it, particularly in beam 2, in which effort rose to above 250%. Above all, this is related to a significant rise in the weight of the entire ceiling structure. In such a case, a suspended system should be implemented by resting the reinforced concrete slab on an independent structure e.g. steel (Fig. 10). The efforts of individual wooden elements in this solution are very small and arise only from carrying loads related to their own weight. It must be remembered that the implementation of reinforcement through direct coupling of a wooden structure with a reinforced concrete slab or the construction of an independent reinforced concrete slab in a suspended system causes significant loading of building walls can cannot *can or cannot?* always be used.

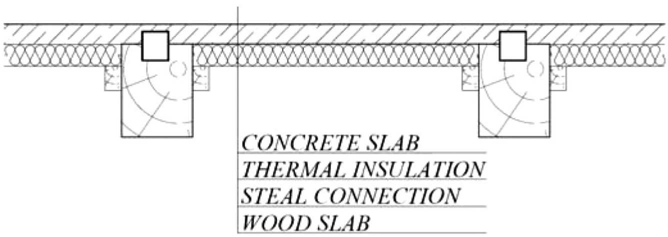


Fig. 20. Direct coupling of the wooden ceiling structure with a reinforced concrete slab

A combined list of obtained results of calculations for individual technical solutions has been presented in Fig. 21.

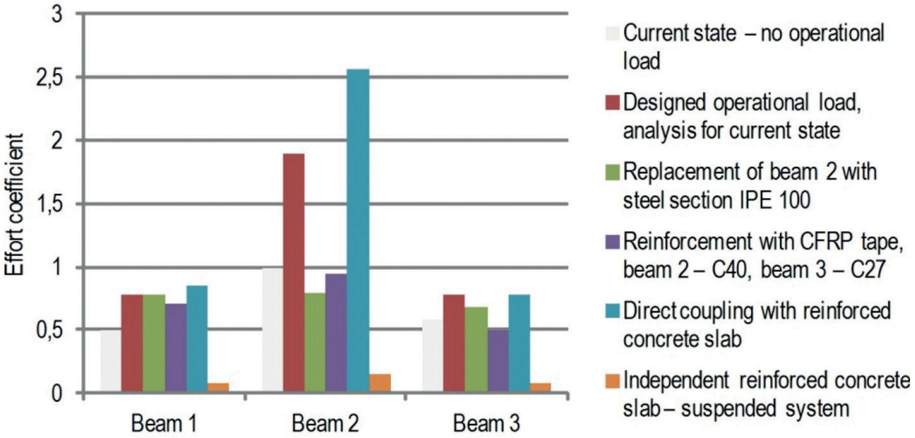


Fig. 21. Results of load-bearing capacity analysis of selected structural elements of the ceiling above the "Fireplace" room depending on the method of reinforcement

6. Conclusions

The damage inventory and conducted tests made it possible to determine the current technical state of selected ceilings found in the historical palace in Gorzanów. Based on performed calculations, it can be stated that selected wooden ceilings that have been preserved in a good state due to their historical value can be reinforced by implementing CFRP carbon fiber tapes or other technical solutions. Reinforced structures would be capable of carrying both constant loads as well as operational loads acting on the ceiling. Before the introduction of new operational loads however, load-bearing capacity analysis must be conducted individually for each ceiling – if load-bearing capacity is too low, coupling of wooden ceilings with a modern reinforced concrete slab may be considered. It should be remembered, that the implementation of certain solutions that reinforce the structure of ceilings may result in excessive loading of building walls and cause additional cracking.

Deteriorated ceilings that do not present historical value may be replaced with new ceilings by using existing seatings as support points for new beams e.g. wood or steel.

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