Contractor errors as the cause of emergency conditions of a timber roof rafter framing

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Abstract. The paper presents results of an analysis conducted in order to determine a cause of an emergency state of a timber roof rafter framing of a central nave ceiling in a church. The article showed an assessment of the current technical conditions, a description of the diagnostic tests performed and the results of the static strength analysis. Based on that information, the causes of this emergency state are described as the consequence of contractor's errors during the execution and significant derogations from the construction design. Moreover, an implementation of a repair programme in order to restore the full value in use of the building is recommended.

1 Introduction

Religious buildings are classified as public buildings. They are supposed to be maintained in a proper technical condition and aesthetics that provide efficient and safe performance. Unfortunately, as experience shows, religious buildings are often subjected to construction breakdowns or failures [1-3]. Given their function and useful life, such facilities should be characterized by greater durability and load bearing. This paper presents a rather different example of an execution of a roof construction in the central nave of a church. The executor's errors that occurred in that structure significantly decreased its load bearing and serviceability. The roof construction has been a direct cover of the central nave for decades and that has led to a collapse hazard. Indeed, a number of errors during the execution of the roof and many years of negligence have eventually led to a failure. At a time of intense snowfall, a substantial deflection of the central nave ceiling was observed in the church. Immediately after a determination of emergency conditions, the shoring of the central nave ceiling was applied by supporting joists in the area of the greatest deflections. The executed support was not overly interfering with the construction system and it allowed a continuing use of the building. Moreover, it made it possible to keep the original construction for a later repair. The results of examinations and analyses enabled determining the factors that caused the emergency state. Furthermore, they allowed formulating recommendations that concerned an implementation of a repair programme in order to restore the full value in use of the building.

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2 Description of the building

The subject of this paper is a church of the Nativity of the Blessed Virgin Mary parish located in Marklowice, Poland. The building was built in the 1980s. It is composed of three parts separated by movement joints: a tower, a central nave and a presbytery (Fig. 1). The article discusses an issue with the central nave of the church. The floor plan of the central nave is rectangular with dimensions of 9.68x9.08 m. The external walls are made of masonry – solid bricks. The load bearing system of the central nave is regular, symmetric and with little changes in stiffness. The structure is protected against an impact of mining activity with steel ties arranged in wall grooves that end with anchor plates in the corners of the building. This strengthening was adopted at the top of the external masonry walls. The central nave is separated from the rest of the building by movement joints having a width of 50 mm.

Fig. 1. A general view of the church in Marklowice.

The completion of the central nave is a pent roof with a pitch of approximately 7° and covered with asphalt roofing. The location of the central nave roof, between the higher parts of the church (the tower and the presbytery), creates a possibility of a snowdrift formation on the slope.

A major deflection of a middle section of the central nave ceiling occurred at a period of intense snowfall. The property manager performed a temporary strengthening by shoring the joists of the ceiling (Fig. 2). The visible and permanent deflection of the ceiling appeared before the emergency state according to the information provided by the manager.

Fig. 2. The temporary strengthening of the central nave ceiling.

3 Technical conditions of the roof structure

An on-site verification of structures of the roof and the central nave ceiling of the church was conducted in order to find the cause of the emergency conditions. The observations, the analysis of the construction system and the measurement of the geometric dimensions of structural components allowed assessing the current technical conditions of the structure.

In the first stage of the studies, an inspection of the dimensions of roof elements was performed. Moreover, a detailed visual examination of the destruction extent was taken on each element. Among the present timber defects, knots as well as longitudinal and torsional cracks should be mentioned. The occurrence of local areas of biological corrosion was identified. This resulted from a flooding and dampness of timber around the damaged roofing and insect feeding. It should be noted that the damage of timber parts occurred on a minor scale. Furthermore, the on-site verification demonstrated an existence of overload effects on timber structural components.

Fig. 3. A photography from the on-site verification. A description is given in the text.

In the next stage of the studies, an analysis of the existing construction systems was conducted. The construction system of the central nave ceiling is a pent roof (mono-pitch) with a pitch of 12%. The rafters, 100x120 mm in cross-section, lean on a high wall (without angle braces) that is adjacent to a gable wall (Fig. 3c), an intermediate purlin and a knee wall. Without the continuity in the linking point, the rafters work as a single-span simply-supported beam (Fig. 3a). Moreover, it was observed that the rafters were characterized by reduced cross-sections in the form of a triangular cut located in the middle of the span (Fig. 3d) and the support point on the outer purlin (Fig. 3c). It can be assumed that the roof components came from the wrecking of another construction system. The load impact from the roof construction is transferred on the external walls of the building and on the intermediate purlin. The intermediate purlin consists of a two-beam system of a 120x180 mm cross-section connected with batten plates (Fig. 3b). During the on-site verification, a substantial deflection of the intermediate purlin as well as rafter was observed. The purlin deflection was estimated for around 90 mm and the rafter deflection for approximately 35 mm. Because of the excessed deflection of the intermediate purlin, the load from the roof construction was transferred on the central nave ceiling construction.

Fig. 4. A schematic view of the existing roof construction.

The central nave ceiling of the church is a system of single-span timber beams (having a span of 8.3 m) that lean on structural walls of the building. The joists with dimensions of 200x200 mm are arranged with a 1440 mm spacing. The ceiling was temporarily strengthened with shoring of the joists in the area of the greatest deflections. In that state, the deflections of the joists were comparable to the intermediate purlin deflection.

It should be noted that the on-site verification revealed a lack of due diligence of the execution of the roof construction as well as of the connections of the construction components. Taking into account the highlighted contractor's errors (the lack of high wall bracing, the application of the elements coming from building wrecking), it might be assumed that existing roof was meant to be a temporary construction.

4 Timber diagnostics

Following the assumption of a demolition origin of the structural components, laboratory tests were conducted to establish the wood species, its hardness and mechanical properties, such as the flexural strength and elasticity modulus that allow determining its class.

In order to determine the homogeneity of the timber and detect potential internal damage, resistographic tests were performed. The drilling resistance is the ratio of the homogeneity and performance state of timber elements. Moreover, there is a strong correlation with the density in the air-dry conditions. The measurement consists in recording the drilling resistance of the 3-mm-diameter drill in the wood analysed. The course of the record is used to assess the homogeneity of the material. The quotient of the surface area under the diagram and the diagram's length is used to determine the hardness and the density of the wood [4-5]. Characteristic peaks in the drilling resistance diagram symbolize changes of the subsequent annual growth rings (Fig. 5).

Fig. 5. A drilling resistance diagram of a rafter.

All of the accessible elements were tested using the drilling resistance method. The results suggest that all the elements are made of the same soft wood species. The timber used in the roof construction is characterized by a high level of homogeneity and an absence of lower density areas in its inner structure.

In order to estimate the timber class and to confirm that the elements are made of the same wood species, samples with a volume of 1 cm³ each were collected from the selected elements. The wood species was identified as the spruce. A smooth transition of the vessel wall thickness between an early and late annual growth, as well as an occurrence of epithelial cells in a thick-walled resin canal was observed in the cross-section (Fig. 6). On the tangential section, a presence of short and single-row medullary rays was observed. When observed with a magnification factor of 400, the radial section revealed a single-line arrangement of pits in tracheids, smooth walls of tracheids and pits in the crossing area of tracheids and medullary rays that are piceoid in shape [6].

Fig. 6. Microscopic photographs of the wood analysed, from left: cross-section, tangential section and radial section.

Given the necessity of a precise determination of the mechanical parameters of the wood, three cuboidal samples with dimensions of approximately 20x20x300 mm were tested. The flexural strength and elasticity modulus along fibres were tested in the specimens (Fig. 7). The samples were collected from the area of the least limiting stress ratio. Gaps created in the process were filled. The flexural strength was determined according to the guidelines [7]. The average destructive strength was 1.23 kN, the average flexural strength – 44.04 MPa and the average elasticity modulus was 9.75 GPa, which pointed towards timber class C20.

Fig. 7. The flexural strength test, from left: sample before and during the test.

5 Analysis of the emergency state causes

One of the causes of the excessed deflections of the structural components should be linked with applying a wrong roof design approach. The insufficient stiffness of the intermediate purlin resulted in transferring loads from the roof to the structural ceiling. The transfer led to visible excessed deflections of joists, especially when there was a snow load on the pitch. Furthermore, an additional permanent increase of deflection in time appeared due to the rheological properties of the timber. It is caused by a combination of creep and humidity changes of timber members.

The analysis of the plans and specifications of the building revealed that the adopted construction system is inconsistent with the building design. The roof construction design recommended a use of two steel purlins of double C300-section located in second and forth axis.

The emergency state of the structure was a consequence of a change of the original static diagram, a change of the intermediate purlin's material, a lack of due diligence of the roof construction execution and the negligence of experts performing an inspection of the technical condition.

6 Static strength analysis

The data that was collected during the on-site verification of the timber roof construction of the central nave allowed building a 3D model of the roof and performing a static strength analysis. The calculation model was made in Autodesk Robot Structural Analysis Professional 2013 (Fig. 8).

Fig. 8. The calculation 3D model of the roof construction.

The aim of numerical calculations is an unambiguous determination of the limiting stress state of each structural component of the roof. The analysis includes the geometrical characteristics of each element and their connections. Moreover, the locally reduced cross-sections are taken into account. The calculation model involves transferring dead (timber elements, roofing, ceiling members) and climatic (wind, snow, snowdrifts) loads on the roof construction. The timber class of C20 was estimated in the laboratory tests of samples collected from the structure. The analysis takes into consideration the ultimate limit state (ULS) and serviceability limit state (SLS) according to the guidelines [8]. The design of the timber members was performed according to the guidelines [9].

The static strength analysis showed that the majority of structural elements exceeded both of the limit states. In the case of the analysis of the dead and climatic loads configuration, the bearing conditions were overrun, exceeding 224% for the intermediate purlin. Moreover, the verification calculations revealed that taking the reduced cross-sections of the rafters into consideration significantly influence their load bearing (Table 1). The results of the calculations confirmed that the substantial deflections of the structural components are similar to the observed ones during the on-site verification (Fig. 9).

Fig. 9. Ad-hoc displacement during serviceability limit state combination.

Thus, it should be noted that in this state the roof construction could only bear the dead loads. The analysed construction is now in the emergency conditions. The additional loads, such as climatic loads and mining activity, endanger the stability of the construction.

Table 1. List of limiting stress ratio in the analysed structural components.

Element	Cross-section (mm)	Limiting stress ratio of ULS	Limiting stress ratio of SLS
Rafters	100x120	0.63÷1.93	1.25÷3.86
Intermediate purlin	120x180	2.24	3.92
Joists	200x200	0.41÷1.99	0.16÷2.68

7 The proposed strengthening

The results of the static strength analysis revealed that a modification of the current structural state is required. In order to eliminate the transfer from the roof to joists, a replacement of timber intermediate purlin with a steel HEA300 profile supported on structural walls is proposed. Moreover, a suspension of the joists to steel purlin with bolts and its rectification is suggested. Taking into consideration the technical determinants of the steel purlin installation and the technical conditions of the roof structure, dismantling all timber elements and replacing them with new ones is recommended. The proposed strengthening require to prepare a different construction design of considered roof.

8 Conclusions

An execution of even a potentially simple construction system should be absolutely conducted under a surveillance of experts with proper experience and relevant building licence. Moreover, it is necessary to execute construction based on the building design and in compliance with the principles of technical knowledge. A derogation of those procedures could led to shortcuts in the execution. They are a danger for the construction and could be a potential reason of a failure. In the timber roof of the central nave, an insufficient supervision of its execution resulted in the several executor's errors. The main errors, which were related to the derogation of the designed static diagram and the material design of the intermediate purlin, led to an emergency state of the construction. The results of conducted diagnostic tests of the timber and the static-strength calculations allowed formulating recommendations that concerned an implementation of a repair programme in order to restore the full value in use of the building. Given the necessity of a modification of the existing structural system and the current technical conditions of the construction, a preparation of the new construction design of the central nave roof is recommended.

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