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Analysis of Pre' Failure State of Historical Wooden Church

Piotr Berkowski, Grzegorz Dmochowski, Maciej Y. Minch and Jerzy P. Szołomicki
Wrocław University of Technology, Department of Civil Engineering, Wrocław, Poland

ABSTRACT: An example of pre'failure state of bearing wooden skeletal construction of building which is one of the most valuable historical churches of the Lower Silesia (western region of Poland) is presented in this paper. Constructional pre'failure state occurred as a result of execution, in area of church roof, an inappropriate strengthening works. In aim of supporting excessive deflected floor, located above main nave, the floor was suspended to roof girders by using steel rods. Statical model of bearing roof frames was changed. It caused a rise of excessive thrust on supported walls as well as an infringement of constructional nodes and "separation" of church walls. Each strengthening of construction by changing a statical model demands realization of detailed computational analysis, because assurance of safety of one element can cause failure of others. On the basis of gained calculation results the authors proposed a technical solution to protect existing pre'failure state of construction. The main idea was to strengthen roof construction by using steel rods which were hidden in the floor localized above main nave.

1 INTRODUCTION

Wooden evangelical–augsburg Church of Peace under the invocation of The Holy Ghost is located in Jawor (one of the Lower Silesia town) and is one of the most beautiful historical churches of this region. The church has a shape of basilica with galleries and polygonal finial of chorus without transverse nave. The three church naves has length of 43,30 m and width of 26,85 m. The width of main nave is about 14,23 m and an aisle is about 5,50 m. The height of main nave is 16,40 m when the measurement is executed to the bottom of floor beams. Originally only two galleries were in aisles, the first on height of 5,00 m and the second on height of 10,20 m above level of nave floor. In a later period between ground floor and the first main gallery as well as between the first and the second gallery additional inter-galleries were added with a half width of aisles. The balustrades of inter-galleries as well as balustrades of main galleries are located between pillars of nave walls. Adding additional inter-galleries enlarged stiffness of construction and also underlined basilican character of the church.

From southern and eastern sides of church there is visible from outside the skeletal construction (called also brick nogged timber wall). In the northern and western sides as well as in the eastern top there are board finishes which make protection from unfavourable atmospherical conditions. The skeletal construction of external walls is visible, only central field of external wall, on a large area above chorus, is finished by boards, and that place has painted skeletal construction. Besides that, main pillars, angle braces, bottom parts of floors, and turning to inside balustrades of galleries are finishing by boards. The roof of church is covered by wood shingle.

Figure 1 : View of the historical wooden church in Lower Silesia.

Near the southern wall of the church stands a bell tower which was built in 1707. The tower is placed in lower part on elevated stone base which is based on a square plane. Timber skeletal construction in upper part is realised on an octagon plane and has over-story.

In the year 2002 historic Lutheran church in Jawor was put onto the UNESCO list. General view of the church from the southern side is presented in Fig. 1.

2 SKETCHY DESCRIPTION OF CHURCH CONSTRUCTION

Originally, bed timbers were foundations of external walls in the church. In 1906 they were replaced by masonry plinth which surrounds the church.

Basic skeletal construction contains eleven transversal frames standing in a single file in direction of east-west which reach from bed timber to ridge. Distances between three last frames in the eastern and western sides are about 3,65 m. Distances among remaining frames are from 4,65 m to 4,87 m. The spaces between those frames are divided into three parts by lateral pillars.

The timber floors of gallery have classical open beam construction, meanwhile timber floor above main nave was realized as close beam floor. The beams of timber floor are formed in transversal direction and have about 1,16–1,22 m from center to center. Visible from inside the angle braces and struts were timbering. Most of surfaces of ceiling elements, walls, pillars, and struts have richly adorned valuable polychromies (see Fig. 2).

The roof above central nave has rafter and collar beam construction with lying king-post and longitudinal bracing of ridge posts above collar beams. The roof girders are divided on main and intermediate (solid and empty). Inclination of roof is about 46^0 and its span has about 14,40 m. The main girder consists of floor beam (on which rafters with the same inclination as roof are supported), upper collar beam, double lower collar beams braced with itself indirectly, and also angle brace which supports both collar beams as well as transmits forces onto rafter. Additionally, near to places were rafters are supported, there are short posts which connect rafter with floor beam. In the central part of girder there is a ridge post which at the same time is joint element for girder and longitudinal bracing which runs along the church. In the lower part that post is supported on collar beam by lower angle braces, while in upper part it takes over the forces from rafter and upper collar beam by means of upper angle braces. Generally, intermediate frames do not differ from main frames which were described above. Intermediate frames

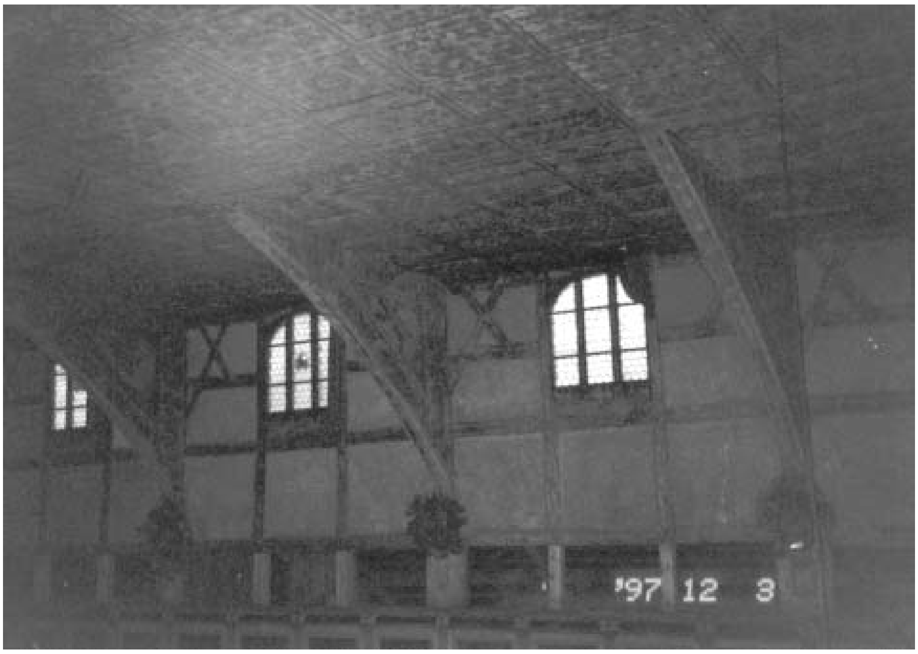

Figure 2 : View from inside the structure elements of main nave.

do not have rigid connections with longitudinal bracings which are supported on collar beam and bracing in the form of intersection of wind beams. Moreover, in intermediate frames there are no ridge posts and also double lower collar beams. Besides above mentioned differences, intermediate frames have the same arrangements of elements as main frames.

Transversal bracings of church construction are all truss-post systems of main nave as well as aisles and pillars. Main nave and aisles are structures which have constructional connection (extreme pillars of main nave are as well pillars of aisles). Extreme pillars have their end on height about 10 m. Pillars of main nave reach to the level of floor beam of that nave i.e. about 16,40 m. Direct connection of both naves is realized by layers of floor beams, collar beams and angle braces which are also construction of pent-roof of aisles.

Longitudinal bracings of church construction are main frames of central nave which are braced by two methods. The first method is a truss system that runs along the whole church in central plane of main frame with top chord placed under upper collar beam and bottom chord supported by lower collar beam. The second method uses lattices between side purlins and bed timbers. Additional longitudinal bracing of church is a lattice wall in the level of roof construction of aisle, between aisles and main nave as well as construction of brick nogged timber external wall.

Axonometric view of fragment of church skeletal construction from southern side is presented in Fig. 3 (in the first plane there is visible brick substructure of tower).

3 ROOF CONSTRUCTION DAMAGES AND COMPUTATIONAL ANALYSIS

Pre'failure state of church roof and walls stability was detected during executing of routine mycological opinion of elements of timber constructions. Description of biotic damages of rafter roof is typical and do not state here essence of problem, so it was omitted in this paper. In the time of inspection of rafter roof there was observed in its construction existence of secondary elements of steel hangers (steel rods), by means of which floor beams were suspended to roof girder above main nave. Suspensions were executed by two steel rods fixed to lowest (double) collar beam and symmetrically in relations to ridge post (Fig. 4) or one steel rod in axis of ridge post. Secondary elements of steel rods were built in roof construction in planes of main roof girder, only in the places where excessive deflection of floor beam of main nave occurred. Besides, suspension of floor beam to roof girder was not executed by any additional strengthening elements in roof construction. Specification of executed reinforcements is not preserve.

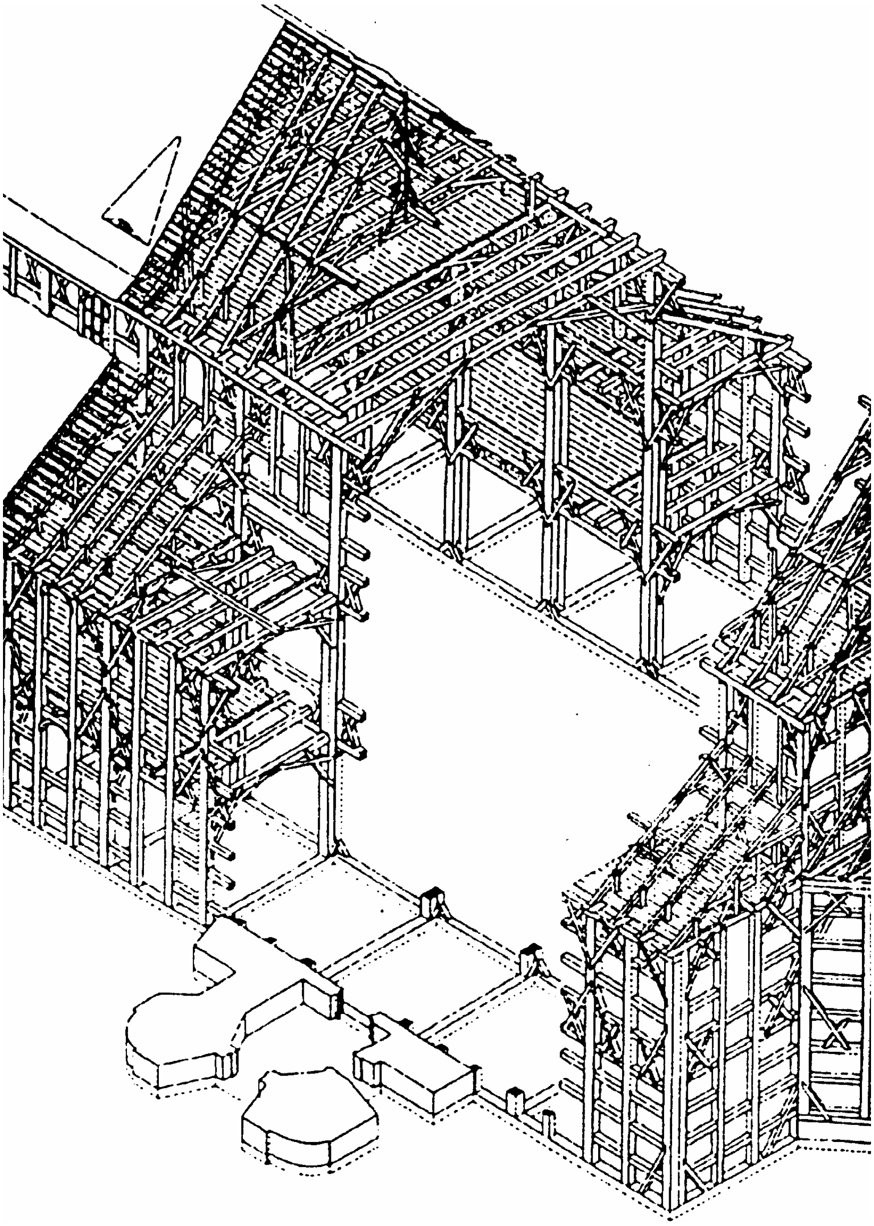

Figure 3 : Axonometric view of the fragment of church skeletal construction from southern side.

Without detailed analysis it is possible to state that application of suspensions which “save” floor beams above main nave can cause transfer of enlarged strut forces from rafter roof onto walls and in consequence theirs parting. It can end with loss of stability of the whole construction. Therefore in the time of inspection of building it a special attention was paid to the possibility of damage of timber bearing elements and timber lining elements caused by horizontal forces and enlarged horizontal deformation. In the Fig. 5 there is shown an exemplary effect of enlarged force struts of rafter roof as several centimeters separations between timber lining of angle braces under floor beam of main nave and walls construction. Damages with similar character occurred in all fields of floor beam of main nave where additional steel hangers were applied.

Change of statical schema of roof required checking calculations. In consideration of difficulty in estimating of real stiffness of spatial skeletal construction (compliance of nodes, biotic paralysis, damaged and strained carpenter joints etc.), values of internal forces in main girders were checked for different statical schemas. Geometry of roof girder and its loading were assumed on basis of cataloguing. Statical schema of roof girder is presented in Fig. 6 (forces P and P_1 denote loading due to weight of suspended floor beam of main nave).

Statical calculations (Table 1) were executed under the following assumptions:

1. Roof girder with steel rod and without suspended floor,
2. Roof girder without steel rod and suspended floor,
3. Roof girder with steel rod and suspended floor,
4. Roof girder without steel rod and with suspended floor.

Figure 4 : View of the construction of suspended floor beams to roof girder.

In Table 1 chosen results of calculations are presented. On the basis of assumed schemas of calculations it was noted that suspension of floor beam to roof girder caused almost double increase of displacements of construction (for variant without steel rod) and adequately two-three times increase of internal forces in bars. Floor beams above main nave were weaken by biotic corrosion on supports as well as in the bays and moreover performing function of braces which take over strut forces from roof girder. They were not in condition to transfer the whole of additional tensile forces. It caused excessive deformations of walls as well as timber lining and separation of walls of church building. Maximum horizontal displacements were calculated for assumption that in consequence of exceed of pressure stresses or shearing stresses in supported node of floor beam, steel rod break off carrying out tensile forces. Calculated values of displacements and damages of construction permitted to affirm, that it is in pre'failure state.

Figure 5 : Exemplary effect of enlarged force struts of rafter roof.

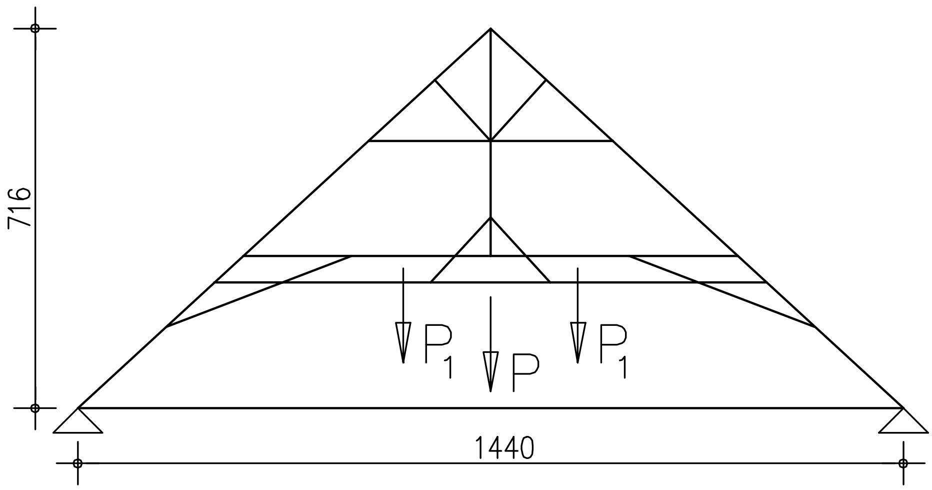

Figure 6 : Statical model of roof girder.

Table 1 : Chosen results of calculations of roof girder.

	Variant I	Variant II	Variant III	Variant IV
Supported reaction R_A (kN)	33,5	31,5	60,7	58,7
Force in steel rod H_A (kN)	28,7	0	56,3	0
Support node horizontal displacement u (mm)	1,3	279,0	2,5	528,9
Ridge node Vertical displacement v (mm)	1,8	142,9	4,6	272,2

4 CONCLUSIONS

Each strengthening of construction by changing a statical model demands realization of detailed computational analysis, because assurance of safety of one element can cause failure of others. In objective case it sufficed to assure self-equable schema of strengthening, i.e. take over additional strut forces from roof by, for example, steel rods what was recommended (for assumption that allowable stresses are not exceeded after increase of forces in rods from additional loads of floor beam). Besides the use of steel rods, the authors recommended also an inspection of all girder nodes and realization of strengthening for damage nodes. Applied methods of strengthening as well as fungicidal and insectidal impregnations of timber constructions were assumed as generally well known from technical literature. Therefore details of those solutions were omitted in this paper. Nowadays, there is being prepared a final design of repair, protection and strengthening of church building. At this stage there are also considering possibilities of strengthening of damage nodes by using of newer techniques, for example by means of sticking.

Not considering activity and inappropriate strengthening can cause a danger state of church building with appearance of pre’failure state or catastrophe of building.

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