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Design and execution risks of safety of the structure made from glued laminated timber

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Abstract: In this paper safety risks of an existing structure made from glued laminated timber were presented. The hazard of safety comes from an inappropriate design and a structural approach as well as from the changes in design assumptions. Design approach for timber structures differs from design approach for reinforced-concrete and steel structures in the material aspect, which is often neglected by designers.

Keywords: glued laminated timber structures, timber beams, safety risk.

GENERAL DESCRIPTION OF THE STRUCTURE

The structure was designed and executed from glued laminated timber in form of the open shed with dimensions 35 × 62 m in plan, served as the public ice skating rink. The structure is made from eleven girders curved lengthwise – in the shape of the letter "S" in vertical plane. The view of the structure is shown in Fig. 1.

Figure 1. View of the roof of the public ice skating rink

The cross section of the girders is prismatic lengthwise and equals 0.20 × 2,0 m. The axial span of the girders made from glued laminated timber is equal to 33.5 m in plan, and the spacing of the girders is equal to 6.0 m. The bottom part of the girders is supported on steel corbels embedded in the RC columns, rigidly joined with the pad foundation. In the top part, the girders are supported with use of steel plates on RC-arch cantilevers which form the auditorium frame. In the top steel plates the elliptical holes were made to allow displacements axial-wise. Due to abovementioned fact, the girder was designed as a beam with the curved axis and as simple supported.

The roofing of the shed is made as bituminous on full boarding (25 mm thick). The boarding is supported by the rafters 0.08 × 0.12 m made with glued laminated timber, spaced at 1.0 m. The rafters are placed parallel to the main girders and they are supported by the purlins made with glued laminated timber. The purlins differ in cross sectional dimensions: 0.12 × 0.28 m at the mid-span of the girder and the dimensions: 0.14 × 0.28 m; 0.16 × 0.28 m; 0.20 × 0.28 m; 0.24 × 0.28 m within the curved parts of the girder. The spacing of the purlins equals 2.5 m. The purlins are joined to the side edge of the main girder. The whole timber structure is stiffened in the top part of the girders, directly below the purlins, with use of the ∅20 mm steel bars and with use of timber purlins as struts. Roof stiffeners were made within two central areas (Fig. 2) and within two side areas. Lengthwise the shed four stiffeners were used in the plane perpendicular to the surface of the roof and the girders. They were made with glued laminated timber (K-type) and spaced at 7.5 m (visible in the Fig. 1 and Fig. 2). Also, alongside the shed, between the side purlins, the roof stiffeners were made with use of ∅20 mm steel bars (Fig. 2) placed lengthwise the whole roof.

Figure 2. View of the roof stiffenings

TECHNICAL CONDITION OF THE TIMBER STRUCTURE

During the on-site visits in November and December 2014, the inspection of the whole glued laminated timber structure was done and the following remarks were made:

a) roofing, rafters and purlins are in good condition, but with visible stains and the mould fungi appearance on the surface; the timber moisture was registered with use of the wood moisture meter WRD-100 with needle head and varied from 23.6 to 28.2 %,
b) main girders are in good condition; there were observed, like in all timber elements, visible stains and the mould fungi appearance on the surface; the moisture content in timber varied from 23.5 to 28.0 %,
c) on the side edges of a few girders, the longitudinal cracks were observed; the examples of the main cracks are shown in the Fig. 3; in many cases, the cracks were observed nearby the top support of the girder and the top arch (marked No. 3 in Fig. 3); the cracks appear approximately at mid height of the girders and extend to the longitudinal stiffener of the structure. Similar cracks were present also in the place where the rectilinear part of the girder changes into bottom arch (marked No. 1 in Fig. 3) also in the area of the longitudinal stiffeners. In a few girders they were observed longitudinal cracks also in the rectilinear part of the girders, in the area of the longitudinal stiffeners (marked No. 2 in Fig. 3).
d) permanent displacements of the girders were registered on the top, sliding support (under assumption that the bolts were mounted centrically in the elliptical hole with a length equal to 150 mm); the value of displacements varies and for the side girders equals between 1-2 cm and increases to the 5-6 cm for the girders in the central part, where displacement is the highest (Fig. 4).

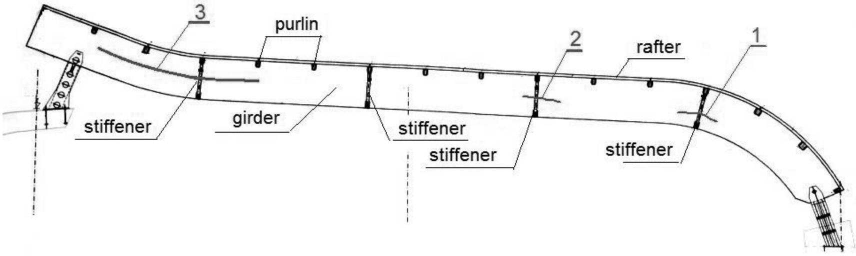

Figure 3. View of the exemplary longitudinal cracks with their localization

Figure 4. Displacement of the central girders on the top support

INVESTIGATION OF DESIGN DOCUMENTATION

The following design documentation was received for further investigation:

a) building permit design, made in 2003, which consists of the architectural part (description and 6 drawings), the light design and the structural part which include: technical description, static calculations and four drawings,
b) execution design of the roof (from 2004) which consists of the following parts: technical description, specification of steel profiles, specification of timber elements and 15 drawings. The static calculations were missed, although they were declared in the design table of contents.

For static calculations of those elements of the roof which were made with glued laminated timber, in the building permit design timber grade GL35 was provided, with accordance to then current Standard PN-B-03159:2000 [1], whereas in the technical description and on the drawings of the execution design, design timber grade KL33 (GL30) was described. Indication KL33 refers to the standards before 2000, whereas timber grade GL30 implicates a choice of the timber grade lower than in the building permit design (GL35). Declarations of conformity append to design documentation prove the use of the glued laminated timber grade KL33 (GL30) in the roof structure. Regardless abovementioned change in design timber grade from GL35 to lower GL30, any static calculations were not provided in design documentation. Therefore only building permit design was used for the analysis of design loads as well as for the static and strength calculations.

During analysis of the static and strength calculations of the girders the following omissions were found in the loads specification:

- not all roofing layers were provided for calculations: roofing specification lacks a layer of roofing felt laid underneath the roofing made from the bitumen roof shingle (tile-like felt), chosen due to small roof slope equal to 3.5 degree. Albeit, on the sectional drawing, the heavy bitumen felt glued to the base for bitumen roof shingle was recommended. In addition, in the specification of permanent loads, average safety coefficient $\gamma_f = 1.17$ (according to [2] and [3]) was calculated on basis of the loads specification, whereas in the computer program the lower safety coefficient $\gamma_f = 1.00$ was applied.

- in the calculations the potential snow drift [4] occurrence is neglected in the area where the roof slope increase.

Disregarding disagreement between the assumed and provided timber grades, in the scope of design data as well as static and strength calculations, the following faults were noticed:

- service class 2 was provided (which is valid for an average moisture content in wood does not exceeded 20%). For the structure localized in the open air, the increase in moisture content in wood shall be taken into account. As mentioned here above, in the assessed structure the moisture content varies from 24% to 28%, which imply assumption of the service class 3;
- in consequence of the foregoing, in analyzed design $k_{mod} = 0.8$ was provided (which is valid for the service class 2 and for the load-duration class – medium-term: snow). Whilst, the correct value is $k_{mod} = 0.7$ (which is valid for the service class 3 and for the load-duration class – short-term: wind);
- regardless static calculations of the girders as curved in plane – in strength calculations, the curvilinear shape was not taken into consideration to check surplus stresses in the curvature of the arch. Strength calculations were limited only to checking stresses in the rectilinear part of the girder;
- the influence of the longitudinal stiffener on tensional stresses acting perpendicular to the grains of the main girders was neglected; this omission is especially faulty in case of the excessive snow cover on the roof.

MAIN CONCLUSIONS FROM CHECKOUT CALCULATIONS

Due to lack of the complete static and strength calculations both in building permit design and execution design, independent checkout calculations of the roof structure were made with use of a few variants. The checkout calculations were done, among the others, also with the assumption of the applied in the structure timber grade GL30 and for the working conditions which correspond to the load-duration class: short-term, the service class 3 and the potential snow drift occurrence.

As a result of the above mentioned design assumptions, it was found out that:

a) in the main girders: the permissible normal design stresses were exceeded of about 10%,
b) in the main girders: the limit deflection was exceeded of about 20% (with assumption that the limit value for purlins is equal to $l/200$ – this is conservative approach, because the Standard [1] does not define the limit values for the curvilinear elements),
c) multiple (equal to 7.34) excess of the limit design tensile stresses acting perpendicular to the grains in the curved (bottom) part of the girders,
d) limit design bending stresses in the rafters in areas of the potential snow drift occurrence excess of about 46%, with subsequent excess of the limit deflection of 67%.
e) unfavorable for the girder solution of the stiffener made as a K-type lattice (Fig. 2), which results in the transfer of the considerable high forces from the stiffener (2 × of approx. 11 kN) to the bottom part of the girder. This results in the excessive tension perpendicular to the wood grains; these stresses sum up with tensional stresses perpendicular to the grains in the curvatures of the girder.

SUMMARY AND CONCLUSIONS

The conclusions which come from the in-situ tests and comprehensive evaluation of technical condition of the structure, in particular: in regard to the main elements of the structure and design documentation are listed below.

1. Regardless errors found in design, the excess of design carrying capacity due to normal stresses of the main girders and purlins (except the area of the potential snow drift occurrence) could be considered as satisfied within the margin of safety of the design

calculations – nevertheless the building owner is obliged to maintain the roof girders with special care during the snow cover occurrence. In emergency, excessive snow cover shall be removed from the roof. Alternatively, but expensive solution is strengthening of the girders, e.g. with use of CFRP strips.

2. Assumption of the service class 2 (timber moisture limited to 20%), instead of service class 2 represents an inappropriate approach in design of timber structures influenced by environmental impact, even though they are covered by the roof. It is proved by the tests of the timber in which the moisture content varies from 23.5 to 28.0%. This inappropriate design approach results in the stresses above the limit values and underestimation of deflections in building permit design. This is crucial due to maintenance of the indoor ice skating rink, which in winter season may lead to increase in moisture content in the timber structure.
3. Simplification of the curvilinear timber elements as rectilinear results in underestimation in specification of loads, as well as in endangerment of the structural safety due to verification of limit design stresses in timber due to both: the element curvature and the anisotropy of the material. This inappropriate design approach results in the necessity of the strengthening which decreases tensional stresses acting perpendicular to the grains in the curvilinear parts of the element.
4. Stiffening of the structure with use of the K-type lattice is faulty. This inappropriate solution has a negative influence on the main girders and results in the excessive tensile stresses perpendicular to grains. To prevent this phenomenon, suspension of the bottom chord of the K-type lattice stiffener to the purlin is necessary.

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Streszczenie: *Zagrożenie projektowe i realizacyjne obiektu z drewna klejonego warstwowo*. W artykule przedstawiono zagrożenia istniejącej konstrukcji z drewna klejonego warstwowo, wynikające z niewłaściwego podejścia obliczeniowego i konstrukcyjnego oraz zmian założeń projektowych. Specyfika projektowania konstrukcji drewnianych różni się od projektowania konstrukcji żelbetowych lub stalowych z uwagi na podejście materiałowe o czym często zapominają projektanci.

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