Joints in wide-span Timber Trusses – Failures and Rehabilitations

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Summary

Following the Bad Reichenhall ice-arena collapse, numerous expertises on the structural safety of wide-span timber structures were carried out at the Chair of Timber Structures and Building Construction. It became evident that inadequate structural design and detailing as well as inadequate manufacturing principles were the main reasons for observed failures. The design and manufacture of connections in wide-span timber structures are still amongst the most challenging tasks for both the structural engineer as well as the executing company. This paper will, on the basis of an exemplary expertise, discuss specific issues in the structural reliability of connections in wide-span timber trusses and give recommendations towards a state-of-the art design of such connections.

Keywords: timber, truss, joint, failure, moisture, shrinkage, crack, block shear, tension perpendicular, rehabilitation

1. Examined Truss System

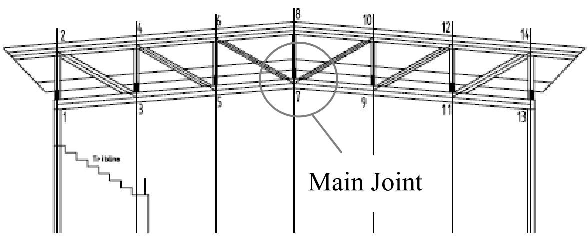

Fig. 1: Main Truss System

The truss system to be discussed supports the roof of a 3-field gymnasium (46 x 34 m). Three main glulam trusses at a distance of 15.5 m with girders running parallel with an inclination of 5° degrees span 34 m (see Fig. 1). They are resting on reinforced concrete columns. Due to reasons of transportation both girders, the lower as well as the upper, were delivered in two parts, giving the need for a main joint at mid-span of each glulam girder (nodes 7 an 8 in Fig. 1). The diagonals in the outmost field of the trusses, which are subjected to high stress, are reinforced with flat-bar steels.

The secondary system between the main trusses consists of triple span beams at a distance of 5.7 m. These are connected to the columns of the trusses respectively are resting on reinforced concrete structures. Additionally they are coupled by trusses with inclination of 45° degrees to the upper girder (see Fig. 2). All joints are realized by steel-plates and dowels.

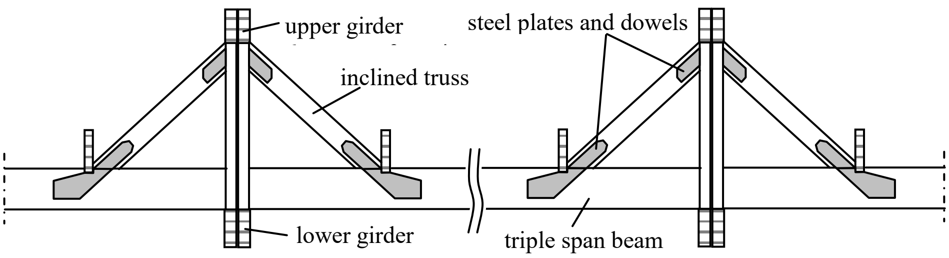

Fig. 2: Secondary System

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2. Failure Mechanisms

During the inspection, large cracks in the tension joints of the main trusses and the inclined trusses of the secondary system were identified. The main reason for the distinct crack pattern can be explained by the dry climate conditions of the gymnasium. The reduction of the moisture content from time of erection to time of measurement caused shrinkage in the wooden component parts. In the areas of the steel-plate connections, the shrinkage actions were constrained by the joints. This results in stress perpendicular to the grain which effects stress relief by the appearance of cracks.

Furthermore the analyses of the original design showed that only the verification for the lateral load-carrying capacity of metal dowel-type fasteners was controlled. But, according to Annex A of Eurocode 5 [1] the failure mechanisms of block shear respectively plug shear failure at multiple dowel-type steel-to-timber connections have to be verified additionally. Considering the state-of-the-art load and safety factors, the verification of block shear in the tension joints were exceeded significantly. It should be mentioned, that at the time of erection the verification of block shear was not included in the German design standard DIN 1052:1988-04 [2] in effect at time of design.

The strength of the resorcinol glue lines were verified by testing core samples according to DIN EN 392 [3]. Analysis of the test results according to DIN EN 386 [4] confirmed the strength of the glue line.

3. Reinforcements

To reduce the tensile forces in the lower girder of the main truss system each of the three main truss systems was pre-stressed by external tensile bars. These were placed on each side of the lower girders. The pre-stressing of the bars was designed so that the tensile stress could be reduced to a value, which enables the verification of block shear in the main tension joint. Additionally cracks in the area of the main tension joints in the lower girder were grouted under pressure with epoxy-glue to recover the strength of the glue line.

Due to organisational reasons it was decided to reinforce the secondary structure temporarily for one winter period while only allowing a reduced snow load. More information about this approach is given in the additional paper of Philipp Dietsch and Stefan Winter [5]. For this first step, the joints of the inclined trusses were reinforced by screws with continuous threads, positioned perpendicular to the grain and the axe of the fasteners [6]. The strength of the reinforced connection was verified by experimental investigations.

In the course of extensive rehabilitation in the following summer period further reinforcements of the components were carried out to enable the structure to bear the total snow load. Therefore external pre-stressed tensile steel bars were applied next to the inclined trusses. These steel bars were designed to cover in combination with the existing system the snow load, while the original inclined trusses have to carry the dead load.

4. Conclusion

The truss, an optimized system for bearing loads, is highly dependent on its connections. The expertise has shown the high sensitivity of connections under tensile forces in truss systems in timber. The brittle failure mechanisms in shear (block shear) and tension perpendicular to grain failure, oftentimes superimposed by stresses through moisture effects, govern the robustness of such systems. This paper aims at facilitating the identification of these important failure mechanisms as they are exemplary for a multitude of structures.

Considering the development of codes and design principles, the authors present some considerations for discussion towards an increased robustness of such systems:

- Regulations towards a more ductile behaviour of connections
- Reducing timber grades within connections with e.g. slotted-in steel plates
- Design principles towards an increased redundancy of such systems
- The clear definition of factors (e.g. k_{crack}, k_{volume},…) for design formulas in codes