The Bad Reichenhall Ice-Arena Collapse

A contribution to COST action E55

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The third chapter “Considerations on Robustness” was added to suit the specific purpose of this publication.

1. Introduction

The year 2006 starts in Europe with some heavy building collapses. Due to an uncommon heavy winter season with snow e.g. in Bavaria from 18th of November until mid of April 2006 without interruption several types of buildings collapsed – from ordinary barns to wide span structures. Germany was mainly affected by the Bad Reichenhall ice-arena collapse (timber structure), but also in Poland a fair pavilion (steel structure) collapsed and people died. Austria and other neighbour countries were also affected, but without injured or killed people.

The reasons for the collapse of the Bad Reichenhall ice-arena structure, which was not an ordinary glulam structure but a special box girder, are detailed below.

2. The collapse of the Bad Reichenhall ice-arena structure

After editing of the final reports, a common press text was settled among the two expert teams (TU München and TÜV Süd) and the public prosecutor. In view of the ongoing legal proceedings this text is given below with some additional and explanatory pictures and some explanatory text given in [brackets].

“Assessments of the experts:

The reports submitted by both of the main experts from the Technical University of Munich and TÜV-Süd are based on extensive investigations on site, directly following the occurrence of the damage, as well as follow-up inspections on secured building sections. The experts have, among others, extracted parts from the undamaged remaining structure and determined the characteristic strength properties of the individual components used.

In doing so, both main experts have largely reached the same results. In particular, it was consistently determined that the collapse of the roof structure of the Bad Reichenhall ice-arena is not due to a single cause, but rather, a series of several defects and damages.

In detail, the experts have reached the following findings:

a) Mode of construction

The Bad Reichenhall ice-arena, built in 1971/1972, was a structure of approx. 75 m in length and approx. 48 m in width. The roof was supported by 2.87 m high main girders, which were produced in timber construction as box-girders. It was a special type of construction. The box-girders were produced with upper girders and lower girders made of glulam and lateral web boards made from a so-called “Kämpf web board” [a type of X-lam], whereby the 48 m long girders were produced out of three 16 m long sections, which were joined with general finger joints. For the “Kämpf web-girder” type of construction, a general technical approval was available, which, however, limited the building height of the web-girders produced in this manner to 1.20 m.

Figure 1: Ice-arena in Bad Reichenhall

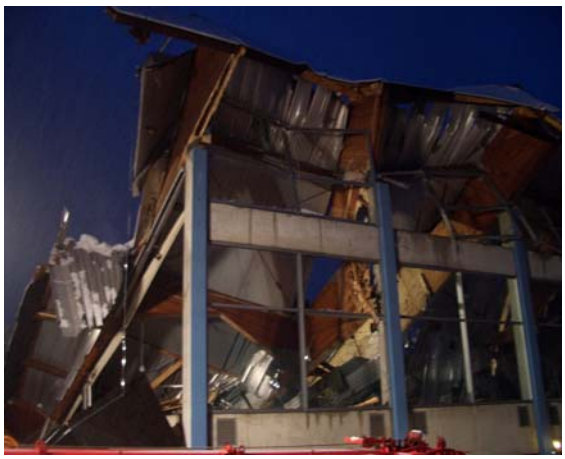

Figure 2: Partial view of the collapsed roof structure

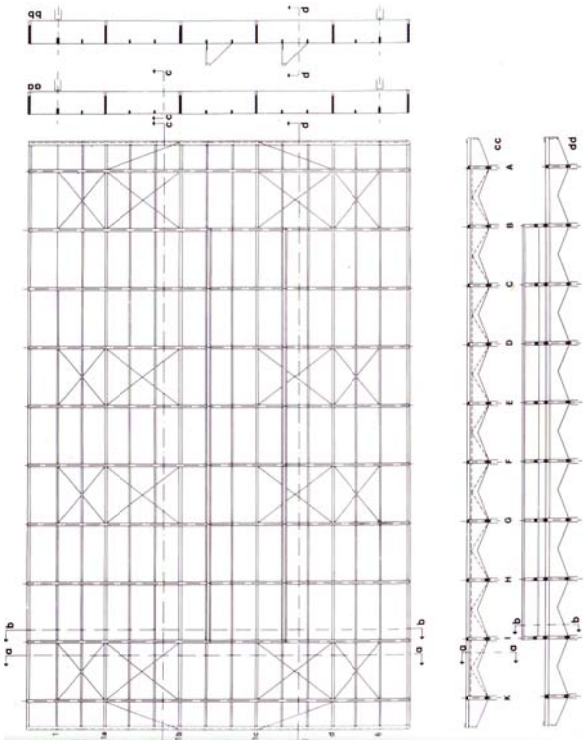

Figure 3: Layout of the arena and side view of the girders (extracted from [1])

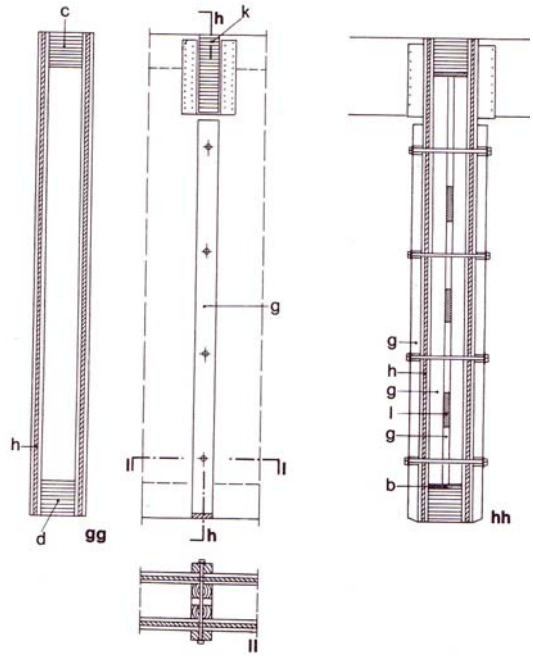

Figure 4: Cross-section of the box-girders in the ice-arena (from [1]); c-upper girder, d-lower-girder, h – Kämpf web-board, k-purlin, g-reinforcement (to avoid buckling)

b) Deviation from the technical approval

With the ice-arena in Bad Reichenhall, significant regulations in the technical approval for the Kämpf web-girder construction were violated and the scope of experience at that time was abandoned. In particular, the maximum girder height of 1.20 m according to the approval was far exceeded in the construction of the Bad Reichenhall ice-arena, with a girder height of 2.87 m. An applied-for extension of the approval to the planned type of construction with box-girders without a height limit was not granted by the German Institute for Building Technology in 1971. Therefore, a so-called “Approval for an individual case” by the Supreme Building Authority of the Free State of Bavaria for executing the special structure would have been necessary. According to the findings to date, such an approval was not applied for by those involved in construction and was not available.

c) No checking of the static calculation

A static calculation for the roof of the ice-arena examined by a check engineer was not able to be found so far, despite intensive research. Without such an examined static calculation, the structure should not have been built. [In Germany the “four-eye-principle” is obligatory for the static calculation of special buildings, e.g. assembly or sport halls. The additional examination is done by so called “check-engineers”, experienced structural civil engineers which are appointed by the building authorities.]

d) No unusual snow load

The maximum snow load of 150 kg/sqm applied in the static calculation was not exceeded at the time of the accident. A calculatory excess stress on the basis of external load at the time of the collapse therefore did not exist, under the assumption of conventional structural safety margin and the building should therefore not have collapsed on the basis of the existing snow load.

e) Errors in the static calculation

The review of the static calculation that had not been examined, according to findings to date, resulted in two errors/omissions worth mentioning being present. The tensile strength in the centre of gravity of the glulam girders was not verified. Due to this, the load-bearing behaviour of the upper and lower girder was over-assessed. The weakening of the structure as a result of the finger-joints of girders and web-boards with general finger joints was also not taken into account in the static calculation. These errors and omissions resulted in a significant over-assessment of the static load-bearing behaviour of the roof box-girders. With this, the necessary structural safety margin of at least 2.0 did not exist. The structural safety margin incorporates a possible exceeding of the load, the structural ageing and the negligible deviations in planning and production. Comparative calculations of the experts, based on the applicable technical rules at the time of the Bad Reichenhall ice-arena being built, have shown that the calculated safety factor at the time of building the arena, taking into account all general conditions and verifications, was only in the magnitude of around 1.5.

f) Use of urea-formaldehyde (UF) – glue

The main box-girders of the roof structure were mainly produced using a urea-formaldehyde glue. The use of this glue for load-bearing components was also only admissible in a dry ambient climate, according to the existing technical rules at that time.

According to the current state of knowledge, urea-formaldehyde glues are not suitable for bonding load-bearing components in ice-arenas, as they are not permanently moisture-proof. Unheated and non-air-conditioned ice-arenas represent a particularly critical climate for moisture-sensitive components. The relative humidity in such arenas is generally very high. Furthermore, the heat emission as a result of the thermal radiation between the roof structure and the ice surface leads to

supercooling and therefore to increased formation of condensation on the underside of the roof structure facing the ice.

In Bad Reichenhall, there were also repeated cases of water penetration as a result of leaks in the roof membrane and in the area of the roof drainage. In contrasts, the experts agree that there were no disadvantageous effects from the subsequent enclosure of the arena, which was initially open on two sides.

The current findings regarding the critical humidity conditions in ice-arenas did not exist in 1972, so that the use of urea-resin glue for bonding the load-bearing components did not generally violate the state-of-the-art of technology at that time. However, even according to the technical rules at the time of construction, for the connections between the glulam-girders and Kämpf web-boards, instead of the brittle urea-formaldehyde glue, significantly more elastic resorcinol glue (RF) should have been used, due to the thick bonding gaps.

Through the humidity exposure over the years in the Bad Reichenhall ice-arena, the glue-lines carried out with urea-formaldehyde glues cause significant damage to the roof structure. This primarily affected the general finger joints on the lower girders and the bonding between the girders and the web-boards. On the general finger joint of the lower girders, there was so much damage to the glue in some cases, that it no longer had an adhesive effect to a depth of 50 mm to 80 mm.

The humidity-related damage to the glue lines in the roof structure represents a significant cause for the collapse of the Bad Reichenhall ice-arena.

g) Defects in the structure of the main supports

The production process for the box-girder cross sections of the main girders by means of block gluing between girders and web-boards did not correspond to the recognised rules of technology at the time [gluing secured by nails was and is limited to a board thickness of max. 35 – 50 mm]. The production of the vertical general finger joints of the web-boards must also be regarded as difficult and not very robust. The quality of the glue lines in these finger joints of the webs differed. Added to this was prior damage to the large-format web-boards due to changing humidity exposure. These structural defects were involved in causing the collapse of the arena.

h) Concrete support structure

In contrast, the existing subsidence of the concrete support structure of the ice-arena, which amounts to approx. 100 mm along the southern row of foundations on from the east-to-west side, is not regarded as being relevant to the damage. The resulting deformation of the roof structure itself is so minor that on the basis of plausibility comparisons and comparative calculations, additional forced stress on the roof structure could not be concluded.

i) Maintenance

With respect to the maintenance of the building, it is determined that the causes of repeated water penetration into the ice-arena (leaks in the roof membrane) were not permanently rectified and the wooden roof structure did not receive renovation paint during the use of the arena.

Whether such measures would have significantly delayed the damage to the glue lines of the roof structure, cannot be answered at this time with sufficient certainty.

A professional examination of the structural integrity of the roof structure is not documented. With this, it should have been taken into account that it involved a special structure. Furthermore, even

years ago, indications must already have existed for damage to the glue lines between glulam-girders and web-boards, as well as to the general finger joints of the lower girders and the general finger joints of the web-boards. For a professional, this should have given rise to a more detailed examination of the condition of the roof structure and the related technical documentation.

Summary

In summary, the causes of the collapse are to be described as follows:

The structural safety margin at significantly below 2.0, which was too low anyway, as a result of errors in the static calculation and structural defects, was constantly further reduced over the period of the building's service life due to external influences, particularly the deterioration of the general finger joints and glue lines on the lower girders, until the collapse of the arena took place on 2nd January 2006, triggered by the snow load.

According to the findings of the experts, one of the three main box-girders on the east side failed first. Due to the stiff cross girders, the loads were shifted from the box-girder that failed first to the neighbouring girders. These box-girders, which were already pre-damaged were also overloaded, due to which the entire roof collapsed like a zipper."

3. Considerations towards Robustness

Robustness has not been considered, neither during design nor during the lifetime of the building. However, in principle the roof structure was partly robust as described in the following.

The members of the secondary system (purlins) were planned to carry vertical loads and act as lateral bracing (K-bracing) for the main box-girders (see Figure 3). This resulted in very strong and stiff cross girders as well as very stiff connections between these members and the main box-girders. This enables the roof structure to redistribute loads between the girders. A random local failure would therefore not have caused collapse. This also means that the box-girders are not key elements in the usual meaning of the term.

The given roof structure was composed of repetitive elements which were connected by analogical construction principles. This systematic implies that the above-mentioned mistakes, made during the planning and construction phase, were most likely repeated in all identical elements. Thereby, the load-carrying capacity of all girders was reduced significantly, compared to the code requirements. These systematic mistakes imply, that the girders adjacent to the girder that first failed were unable to resist the increased load, causing a progressive collapse of the entire roof.

Since the secondary structure was not only strong but also very stiff, there was no possibility of warning from deformations. This means that e.g. some general finger joints could have lost their strength long ago, transferring their load to the adjacent girders and their finger joints.

A more robust system could have been achieved in various ways:

- A strong but softer secondary system could give warning about redistribution of load taking place due to increasing deformations. Since the secondary structure also had to fulfil the purpose of bracing against lateral-torsional buckling of the main girders, it needed to be stiff. If both requirements should have been fulfilled, a different bracing system would have been needed.

- A statically determinate secondary system with connections, which would allow one girder to fall down, without increasing the load on the adjacent girders.

- The joints between the 16 m long girder sections could have been staggered, meaning that every second girder would have been executed with three general finger joints instead of two. Since stiffer parts of a structure will attract more loads, the stiffer, continuous parts of the girders would have attracted the loads, thereby reducing the loads on the general finger joints.

References

[1] Schmidt, H.J. et al., 1974: „Überdachung der Eislaufhalle Bad – Reichenhall“. Ausstellung Holzbau Konstruktionen der Arbeitsgemeinschaft Holz e.V. Düsseldorf als Sonderdruck aus Zeitschrift detail 6/1974

[2] Winter, S., Kreuzinger, H., 2008: “The Bad Reichenhall ice-arena collapse and the necessary consequences for wide span timber structures”. Proceedings WCTE 2008 Conference 2008, Miyazaki, Japan