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Evaluation of wide-span timber structures - results and recommendations

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Summary

Following the Bad Reichenhall ice-arena collapse, the Chair of Timber Structures and Building Construction conducted two large-scale projects to evaluate existing wide-span timber structures

The paper discusses the most frequent failure modes and reasons for observed failures and will give recommendations on how to assess wide-span timber structures as well as on intervals of future evaluations to maintain the intended level of safety.

1. Introduction

Two large-scale projects to evaluate existing wide-span timber structures were conducted at the Chair of Timber Structures and Building Construction. Both were started in March 2006, two months after the Bad Reichenhall ice-arena collapse.

The objective of the first project was to gather information on large timber structures that had shown weaknesses from partly failure to total collapse. The results should permit to identify failure patterns. These could enable the engineer in charge of comparable structures to initiate necessary measures to avoid similar failures. 109 failure cases from Bavaria and neighbouring countries were included in this evaluation. Basis was information from authorities and professional institutions and experts, but mainly results from own investigations on-site.

The objective of the second project was to assess the structural reliability of all 152 wide span timber structures under the responsibility of the City of Munich. The assessment of the current state of these structures should result in specifications on potentially necessary reinforcement/repair measures as well as the preparation of procedures and intervals for future assessments. This approach should secure a reliable safety level for the future.

2. Evaluation of failed Timber Structures

2.1 Initial Situation

The beginning of 2006 was marked by numerous failures and collapses of wide-span structures, especially in southern Germany and neighbouring countries. Many of them were timber structures. The collapses occurred mostly under high snow loads which however exceeded the design snow load in only 13% of the classified cases. Therefore snow load was certainly the actuator but rarely the reason for the collapses.

2.2 Classification of Data

2.2.1 All Structures

In total, 109 structures were included in the evaluation. The majority of information was received for structures in Bavaria. This can be explained by strong snowfall and administrative divisions, both leading to an accumulation of structural investigations. Only investigated (or visibly failed) structures can become noticeable. All failures were classified into total collapse, partly collapse, closure (also temporary) and rehabilitation (see Fig. 1). 71% of the reported buildings included structural elements from timber (77 in total), the reason partly being the high sensitivity of authorities towards timber structures after the Bad Reichenhall ice-arena collapse, having lead to increased investigations on timber structures. In 54% of all collapsed structures, structural members in timber were the main reason for failure. 62% of the classified timber structures were glulam structures (see Fig. 2), mirroring the prevalent utilization of glulam for wide-span timber structures but also indicating problems associated with this building material (e.g. reinforcement of curved and pitch cambered glulam beams), which are nowadays mainly covered by the new code generation. Since information received was partly scarce, all diagrams include a partition “not defined”. For reasons of failure, multiple answers could be given, which explains the variation in total numbers in these diagrams.

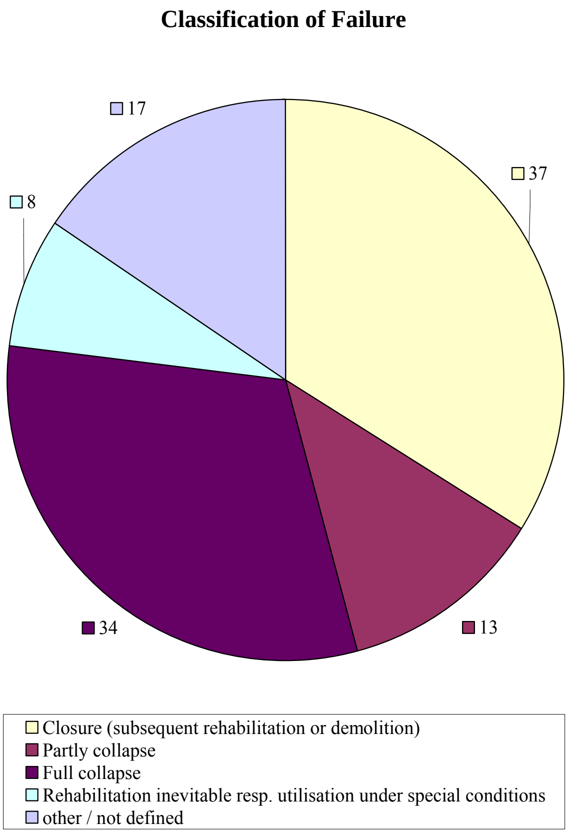

Fig. 1: Classification of Failure

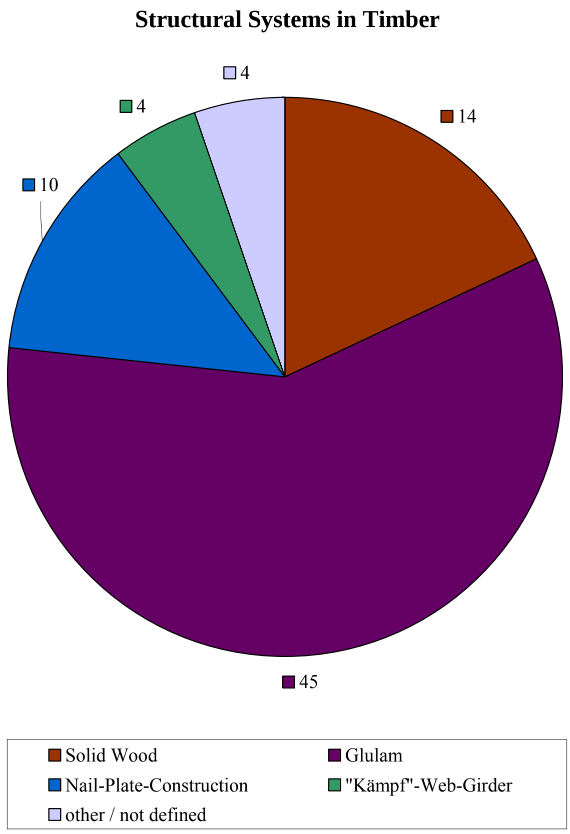

Fig. 2: Structural Systems in Timber

2.3 Failure in Timber

The causes for failure do not vary extensively between timbers structures and glulam structures in particular.

2.3.1 Errors in Design, Construction and Maintenance

The most common cause of failure are errors in design, construction and maintenance due to human error (incorrect structural calculations, deficient construction engineering, inadequate execution, on-site alterations), accounting for 33%, (resp. 43% for glulam structures) of failures (see Fig. 3 and Fig. 4). The quota of failed structures in which the execution differed considerably from checked construction plans and calculations was remarkable. Another noteworthy cause of failure were conversions (e.g. the addition of a green roof without supplemental structural calculations), leading to e.g. increased loads or changed climatic conditions. Failures in older structures could sometimes be linked to a gap of knowledge in the state-of-the-art at time of planning (e.g. block shear or tension perp. to grain stresses in curved and pitch cambered beams).

The Bad Reichenhall ice-arena collapse made it clear that the owner / authorized person is responsible for the maintenance and safety of the building. Correct and timely maintenance of the building is an essential prerequisite towards a consistent structural performance over its lifetime. In many cases, this requirement was not followed, leading to increasing risk of failure and decreasing reliability of the structure.

2.3.2 Climatic Effects

Environmental conditions, leading to low or high moisture content (and eventually to decay) were in 21% (20%) of the cases the cause for failure. Human error is again the main reason for the occurrence of these failures due to a lack of consideration of environmental effects during planning or conversions during the lifetime of the building (e.g. open structures being converted into closed exhibition halls). Structures with large cross-sections are especially at risk if they, due to the respective use (e.g. ice-rink arenas, riding rinks), are exposed to high changes in moisture content (MC). The changing moisture gradient leads to a progressive crack formation, especially when free shrinkage is hindered by e.g. highly offset fasteners.

2.3.3 Material

Material weakness, including tension perpendicular to grain failure accounted for 21% (23%) of the causes of failure, again being influenced by human error. For example, the reinforcement against tension perp. to grain stresses is state of the art since 1980 but was not always applied. Further examples include the use of inappropriate glue (e.g. the use of urea formaldehyde glue in moist climates) or the use of inappropriate finger joints or cup shake.

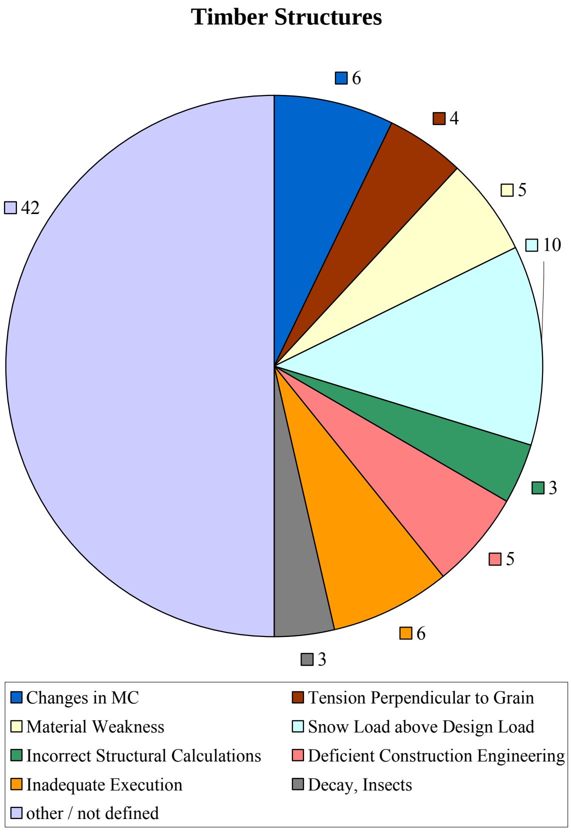

Fig. 3: Timber Structures

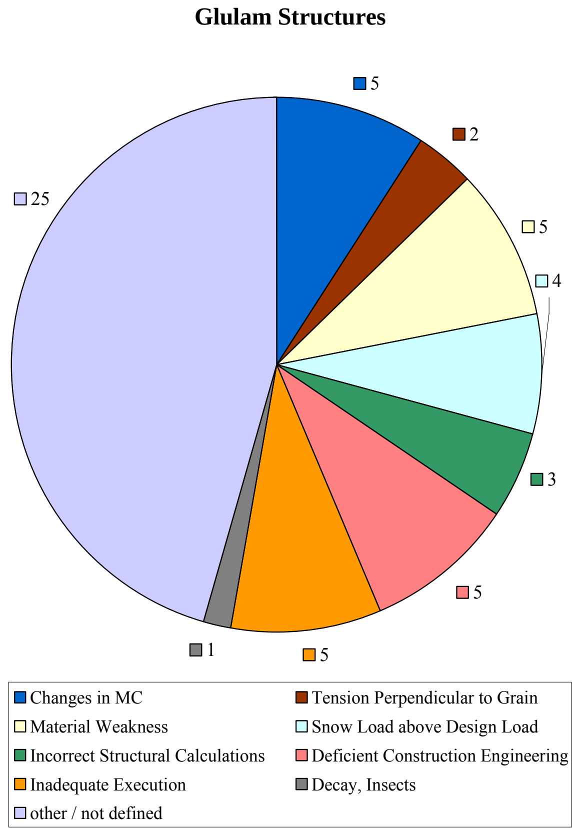

Fig. 4: Glulam Structures

2.4 Summary

It can be concluded that failures connected to human error represent the vast majority of classified cases. Timber, if manufactured and used with the right principles, was in very rare cases the cause for failure. The same applies for high snow loads which can be seen as the actuator but rarely the reason for classified failures. Another large and detailed analysis of failed timber structures in Germany by Frese and Blaß [1] comes to a matchable conclusion. A Nordic project by Frühwald et al. [2] emphasizes as well the connection of failures in timber structures to human error. Comparable evaluations for other materials [3] indicate the same.

3. Assessment of the Structural Reliability of Timber Structures

3.1 Initial Situation

Prompted by the events in winter 2006, the City of Munich decided to systematically assess the structural reliability of all structures under its responsibility, starting with timber structures. The Chair of Timber Structures and Building Construction was asked to categorize the structures into priorities for easier scheduling, to prepare a guideline for the assessment of these structures, to evaluate on the results and to advise on future inspection intervals. The assessment of all structures itself was conducted in collaboration with five check engineers.

3.2 Initial categorization of Structures into Priorities

The categorization of the Munich timber structures was undertaken with special emphasis on two aspects: Structural system and consequence of failure. Three priorities were set up (see Tab. 1).

Tab. 1: Classification of the Munich Timber Structures into Priority of Assessment

Priority	Timeframe	Examples
I	Assessment and potential rehabilitation before next snowfall	Buildings: assembly halls and sports facilities Structural Elements: truss systems, nail-plate and “Kämpf”-web girders as well as curved or pitched-cambered glulam beams
II; III	Assessment before next snowfall; rehabilitation upon necessity	Structures of shorter span, steep roof trusses, secondary structures in timber

The highest priority had to be assessed in short timeframe to enable potential rehabilitation measures to be carried out before the next snowfall. Therefore, the assessment of the Priority I structures was linked directly to a categorization of these structures for further rehabilitation measures (see Fig. 5).

3.3 Guideline for the Assessment of Timber Structures

The guideline prepared for the assessment of these structures is comparable to the “Guideline for a first evaluation of large-span timber structures” [4], established by five experts (Blaß, Brüninghoff, Kreuzinger, Radovic and Winter) and published by the CTT. It incorporates the following steps:

Tab. 2: Excerpt from” Guideline for a first Evaluation of wide-span Timber Structures”

Step	Description	Tasks (excerpt)
1	Review of technical documentation	plausibility of structural design and construction drawings inspection reports conformity of main structural parts with standards and technical approvals (certificates of conformity) compliance of existing structure with construction drawings information about the bonding process and erection

2	Identification of the use of the building	use of the building / change of use allocation to a service class with regard to climatic exposure within the building assumed actions like dead and live load with regard to the use of the building
3	Detection of constructional alterations	comparison of planning with present condition alterations (green roof, ventilation, heat insulation…) closure of a formerly open building additional openings in beams, additional loads
4	Verification of the geometry of the building	visual inspection to detect cambers and deformations laser measurement to determine deflections and deformations measurement of warping and inclinations
5	Hands-on visual inspection	connections (close- fitting, number of fasteners) water stains (source of moisture; examination of timber and glue lines; measurement of moisture gradient) drainage (heating of pipes; blocked drains; emergency drains) fungi; corrosion of metal parts changes of colour; changes of sound while tapping the timber components located in moist conditions (effectiveness of finish)
6	Detection of cracks	recording of depth, width, length, number and distribution of cracks; documentation consultation of an expert, when cracks are more than 90 mm deep or exceed 1/6 resp. 1/8 of the member width (without resp. with stresses perpendicular to the grain) measurement of timber moisture content with sufficiently long insulated electrodes; documentation
7	Boundary conditions in terms of building physics	air-tightness of the building envelope facade connections building climate

In the given project, the first problem arose from the frequent absence of planning documents and structural calculations, necessitating own measurements on-site and the recalculation of important structural members. The inspections on-site were oftentimes performed in two parts since a first site visit was needed to obtain an overview and to establish procedures for necessary inspection as well as tools, instruments and personnel needed. If necessary, the inspections were combined with materials testing, e.g. shear tests on core samples to investigate the quality of the bonding line or drill resistance measurement to identify the depth of decay.

For each building assessed, an expertise had to be prepared, including the following chapters:

- short description of building and structure
- available documentation
- on-site inspections (incl. photo documentation)
- diagnosis and conclusions (relevance of failure for structural reliability)
- guidelines for reinforcement / rehabilitation measures
- recommendations for future inspection and inspection intervals

3.4 Results and Guidelines for Rehabilitation

From 45 buildings, classified priority I, two structures had to be closed until the completion of rehabilitation measures. In both cases, the bracing system was insufficient or inexistent. 19

structures (= 42%) could remain open but had to be rehabilitated before the next snowfall (see Fig. 5). Structures in this category had shown various failures, prevalently in the structural calculations or execution of bracing systems, joints or large glulam beams.

Buildings in Priorities II and III revealed better results. Of all 152 classified buildings, the majority of buildings (76 %) fell into categories III and IV, leaving 24 % of buildings which had shown structural failures (see Fig. 6).

3.4.1 Snow Load Register

For the case that necessary rehabilitation measures could not be completed until the next snowfall, a snow-load-register was established. This register listed all relevant structures and their maximum allowable snow load before the completion of rehabilitation measures. "Reference-roofs" on which the snow load would be measured at particular times were designated. They had to be evenly distributed over the city surface and featured a variety of roof-systems. If the snow load on a reference roof reached 80% of the allowable snow load, the respective building would be closed and the snow possibly be removed from its roof. A person responsible for these tasks was assigned to each building.

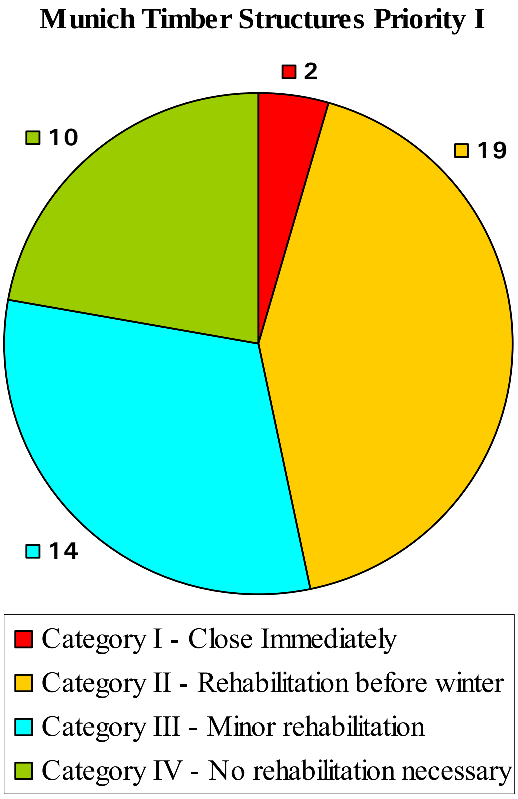

Fig. 5: Munich Timber Structures - Priority I

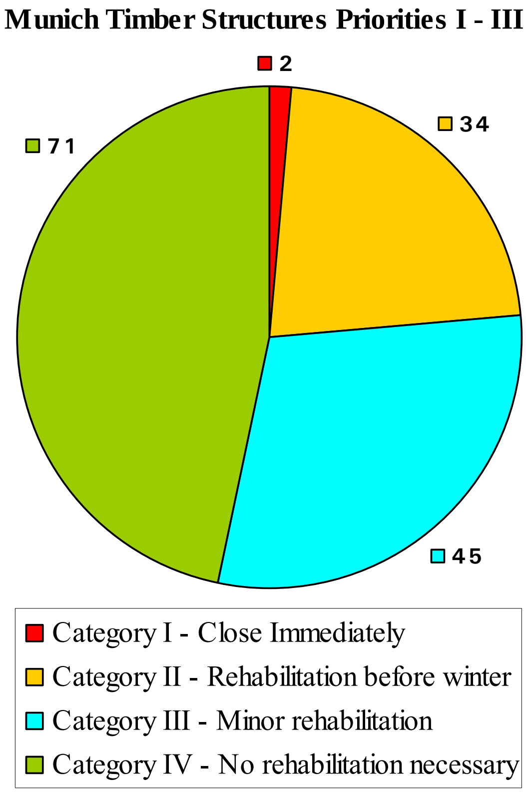

Fig. 6: Munich Timber Structures - Priorities I-III

3.5 Recommendations for future Inspection

To guarantee a reliable continuation of initiated project, recommendations for further inspections were established for each building (see Tab. 4). These were prepared according to abovementioned guidelines with special emphasis on critical elements detected during performed assessment (declaration of elements to be monitored, measurements to be verified…). The establishment of inspection intervals and required qualification to carry out the inspection was performed on the basis of a paper prepared in the same winter with the Bavarian Building Authorities. The "Instructions for the assessment of the Structural Reliability of Buildings by the owner/authorized person" ("Hinweise für die Überprüfung der Standsicherheit von baulichen Anlagen durch den Eigentümer/Verfügungsbereichtigten", only available in German) [5] classify buildings of all materials by the potential for danger and the consequences of failure (see Tab. 3). Papers including similar instructions have been set up in other countries [6].

Tab. 3: Categorization of Buildings according to the “Instructions for the Assessment of the Structural Reliability of Buildings by the owner/authorized person” [5]

Potential for danger / consequences of failure	Type of building and exposed structural elements	Examples
Category I	Places of public assembly with more than 5000 spectators	Stadiums
Category II	buildings with heights > 60 m	Television towers, Skyscrapers
	buildings or structural elements with spans > 12 m or cantilevers > 6 m	Shopping centres, sports halls, production halls, schools, theatres…
	exposed structural elements with particular potential for danger	Large projecting roofs, balconies, cupolas…

Based on this classification, recommendations for inspection intervals are established.

Tab. 4: Inspection Intervals according to [5]

Category	Inspection (Interval in years)	Visual Inspection (extended inspection)	Detailed Inspection
I	1-2	2-3	6-9
II	2-3	4-5	12-15
To be carried out by:	Owner/authorized person	Competent person	Expert

This enables the owner to carry out the frequently recurring inspections by himself. For the visual and detailed inspections, he should call upon competent persons and experts. Competent persons are e.g. civil engineers or architects with more than 5 years experience in related field (structural calculations, technical construction management). Experts are e.g. check engineers, officially appointed experts, and civil engineers with > 10 years experience in related field (here: timber structures).

To facilitate future inspections and to guarantee a consistent documentation, the concept of a building book was introduced.

3.6 Building Book

The building book should contain all necessary information for the person in charge of the building and future inspectors. It can have the following structure:

Tab. 5: Exemplary Structure of a Building Book

1	Preface
2	Setup data (architect, specialist engineers, check engineer, construction firms…)
3	Building sheet (building type, structural system, main dimensions, foundations…)
4	Description and sketches of building (position plan, structural materials and dimensions)
5	Superstructures / Loads / Live loads (e.g. snow loads)
6	Structural calculations (codes used (edition), programs applied, assumptions…)
7	Foundation / Subsoil (e.g. water table)
8	Materials / Structural Elements (material characteristics, technical approvals...)

9	Changes / Modifications / Renovations (e.g. openings, green roof, ventilation, heat insulation…)
10	Rehabilitation measures / Instructions for inspection (instructions and intervals)
11	Inspections performed (participants, tools utilised, particularities)
12	Planning documents (documents available, date of document)
13	Copies (set-up information, copies received by…)
14	Table of Contents

For existing buildings, the building book is a good means to facilitate future inspections and to guarantee a consistent documentation, even with the change of authorized personnel. It should be set up in conjunction with a detailed inspection and should include all available information. If necessary information (e.g. planning documents) is lost, an agreement with the owner should be found, which information shall be newly acquired/created. For new buildings, it is advised that the structural engineer prepares the building book. The aspect of maintainability and crucial elements to be inspected should also be included in the planning phase. The building book is only fully beneficial, if continued by the owner and future inspectors.

4. Discussion and Conclusions

Human error has shown to be still the prevalent cause of failure of timber structures.

Human error is virtually always connected to knowledge and quality of work. Knowledge is a quality for itself and quality needs time.

To decrease errors and the occurrence of failures, it has proven very beneficial to introduce guidelines and schedules for assessing and inspecting a structure. The building book, accompanying a structure over its lifetime, customizes these and is therefore a good resource to accomplish abovementioned objectives for each individual structure.

5. Acknowledgements

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6. References

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