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Structural failure in large-span timber structures: A comprehensive analysis of 230 cases

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ABSTRACT

This paper presents a comprehensive statistical analysis of structural failure in 230 large-span timber structures. The objective is to identify typical failures and their causes to enable structural engineers in charge of comparable structures to initiate necessary measures to avoid similar failures. The analysis shows the wide range of use of large-span timber structures such as buildings of public assembly, sports halls and storage facilities. More than two thirds of the structures were realized with glued-laminated timber. The most frequently observed failure is cracking along the grain (46%). The causes for such failure are low or frequently changing wood moisture content as well as systematic tensile stresses perpendicular to the grain resulting from the geometry of the structural elements. Almost half of the timber components featured low moisture contents of 10% or less. The majority of failures can be linked to planning errors. Timber products, manufactured and installed according to the state-of-the-art, are rarely the cause for failure. The same applies to high snow loads, which could partly be identified as the triggering event but not the cause for failure. Proposals to decrease errors and thereby the occurrence of failures are given.

1. Introduction

The winter 2005/2006 was amongst the most snowy of the last decades in southern Germany, Austria and the Czech Republic. It was characterized by heavy snowfall and an unusually long cold season from the end of November to the end of March. Areas in these regions at altitudes above 500 m experienced a closed snow cover throughout the specified period [1]. The maximum snow depth measured outside the alpine regions was 1080 mm, whereby the precipitation measured during this period was 155 mm [2]. During this period, numerous failures on large-span roof structures were observed. One of the most tragic and publicly discussed cases was the progressive collapse of the roof of the Bad Reichenhall ice arena on January 2nd 2006, during which 15 people died and 34 were injured [3]. Triggered by these events, building owners, facility managers and authorities became concerned with the question of assessing the structural safety of the buildings under their responsibility. Amongst experts, the discussion focused on underlying causes and triggering events of these failures as well as necessary measures to avoid comparable failures. The objective of the project presented in the following, is to collect information on failed timber structures and to use the data for statistical analysis. The results of such an analysis are, strictly speaking, only valid for the analyzed sample, however they can help to identify certain tendencies.

2. Review – existing knowledge

A material independent review of failures in large-span structures is only feasible if limited to an overview of the sources of error due to the very different material properties and the different areas of application and construction methods.

Ellingwood [4] consolidates the results of twelve studies, including 800 cases discussed by Matousek & Schneider [5]. According to these studies an average of 45% of the errors in building can be attributed to the planning and design phase, 38% to execution and 17% of the utilization (including maintenance). Highlighted sources for design errors are erroneous assumptions regarding structural behavior as well as lack of attention to boundary conditions. Construction errors can often be attributed to the organizational separation as well as unclear responsibilities between planning and execution. Several measures to reduce human error are encouraged, including independent design reviews as well as the importance of written documentation to reduce ambiguities at interfaces, are mentioned.

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Early publications on failures in timber structures focus on historical timber constructions [6] and timber houses [7]. From the 31 cases described by Dröge & Dröge [8], 25 can be related to large-span timber structures. Erroneous design of connections and insufficient consideration of climatic boundary conditions are the most frequently mentioned causes for failure. Grouping the cases without weighting them, an average of 50% of the errors can be attributed to the planning and design phase, 38% to execution and 12% of the utilization (including maintenance). Frühwald et al. [9] report on 127 cases of failure with focus on Scandinavia, whereby 84% of the structures featured free spans $\geq$10 m. 53% of the errors are attributed to the planning and design phase, 26% to execution and on-site alterations, the rest to manufacturing and other causes. It is underlined that the majority of failures is due to human error and not due to wood as structural material. Frese & Blaβ [10] evaluate damages in 428 timber structures, mostly featuring large spans. 73% of the errors are attributed to the planning and design phase (including building construction), 23% to execution and 4% to operation and maintenance. As a consequence of the reported damages (e.g. 70% cracking in grain direction), Frese & Blaβ suggest to avoid systematic tensile stresses perpendicular to the grain and to give special attention to timber moisture content in connection with climatic boundary conditions.

3. Methods – data collection and classification

The database currently covers failures in 230 large-span timber structures from southern Germany and Austria. Two successive factors justify the accumulation of events in this area: the weather conditions, described in Section 1, which triggered an increase in structural failures. Following that, authorities and building owners increasingly carried out or authorized assessments of large-span structures. Only inspected and/or visibly damaged structures can be noticed, i.e. can become part of such a database.

Basis was information from authorities, professional institutions and experts, but mainly results from own investigations on-site. As a result, very accurate information can be analyzed for the majority of the structures, e.g. in the form of an experts report (63%) or an inspection report (15%) For the remaining structures (22%), relevant information could be obtained, yet leaving blank spots in the data collection. Data from previous publications (e.g. [8–10]) is not included, since a repeated use of the same data is seen detrimental with respect to an objective analysis.

Since one structure can feature several damaged components, multiple entries per building are possible, however, repetitive damage to identical components is counted only once. The possibility of weighting several damages in one structure for the purpose of maintaining constant total sums is dispensed since this would necessitate a (subjective) intervention of the authors in the analysis. This lead to a total of 307 damages in 230 large-span timber structures. Only structural failures, i.e. damages impairing the ultimate limit state (and not the serviceability limit state) are included in the database.

The classification of data is, if appropriate, based on the thematically related publications [9] and [10]. However, the population of the analyzed cases differs from these publications.

The following general classification is applied:

- General information (e.g. data source, quality of information)
- Building information (e.g. location, age, use, climate, structural system)
- Component information (e.g. service class, dimensions, timber moisture content)
- Failure information (e.g. type of failure, cause, sources of error, consequences, rehabilitation)

All data available for one object is classified into the four groups and their respective substructure via keywords. The full list of keywords and detailed classification is given in [11]. In the case that no data is available for a certain keyword, this is marked as "not defined" in the database. For reasons of clarity, this fraction is excluded from the analysis, explaining the different total sums in the following diagrams.

4. Results – data analysis

4.1. Building information

The majority of buildings was built in the 1970s (24%) and 1980s (31%), the oldest building dates from 1900, the average age at time of data acquisition was 27,5 years. Fig. 1 shows the multitude of uses for large-span timber structures, e.g. sports halls, halls for public assembly or storage facilities. The large proportion of indoor ice rinks is due to the collapse of the roof of the Bad Reichenhall ice arena [3] after which the building authorities ordered an assessments of all timber roof structures of ice rinks in Germany. A comparison with the frequency distribution of all built large-span timber structures and their respective use could not be realized since, despite intensive research, no related data could be found. Closely correlated to the building use are the climatic boundary conditions within respectively around the building. 87% of the structures are within a closed building envelope (62% heated, e.g. gymnasiums; 25% unheated, e.g. storage facilities), 8% are in external climate but covered, e.g. stables/livestock; 5% are directly exposed to weather, e.g. bridges.

4.2. Load information

One advantage of timber as structural material is its good ratio between self-weight and load-bearing capacity. The average characteristic self-weight of the analyzed roofs, including load-bearing components, and based on the ground area (to enable comparison with snow loads), is 1,26 kN/m^2, see Fig. 2, while the average self-weight of the primary structural system in the roof is 0,26 kN/m^2. Due to the comparatively low self-weight of timber roofs, the potential impact of variable loads such as snow loads is increased, see Fig. 3 for an analysis of the snow loads. Fig. 4 shows the ratio between characteristic self-weight of the roof and characteristic snow-load on the roof, the average ratio being $g_k/s_k = 1{,}44$. This value does not correspond with the average values indicated in Figs. 2 and 3 due to the reduced set of buildings available to deter-

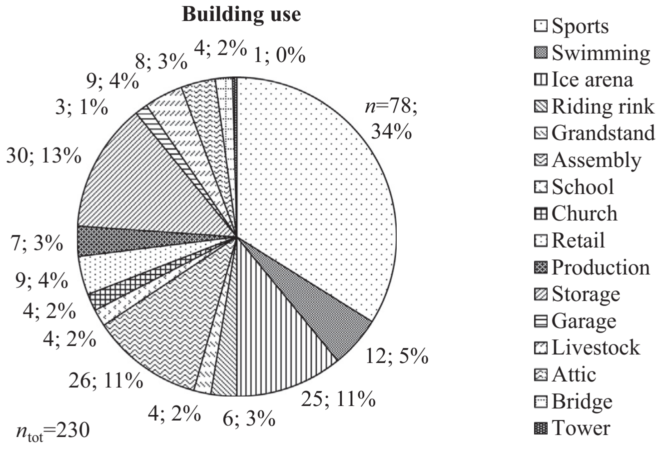

Fig. 1. Distribution of building use (sequence of entries in legend clockwise, starting at the twelve o'clock position).