Assessment of all wide span Timber Structures owned by the City Munich

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Summary

Following the Bad Reichenhall ice-arena collapse, the Chair of Timber Structures and Building Construction at the Technische Universität München conducted a large-scale project to assess the structural reliability of all 152 wide-span timber structures under the responsibility of the City of Munich.

The paper presents the chosen approach and gives recommendations on how to assess wide-span timber structures as well as on intervals of future evaluations to maintain a designated level of safety. The concept of a Building Book will be introduced. The paper will conclude with a discussion of the observed types of failure, causes for failure and accountabilities for failures, referring to our database of 214 failed timber structures.

Keywords: timber; wide-span structures; structural reliability; assessment; rehabilitation; failures; failure mechanisms

1. Introduction

The objective of the 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 potential necessary reinforcement/repair measures as well as the preparation of procedures and intervals for future assessments. This information, combined with further essential structural information, was collected in a Building Book to enable a quick and reliable overview of the structure and its current condition. This approach should secure the designated safety level and its future adherence.

All expertises, accomplished in collaboration with five check engineers, were evaluated against the background of possible failure mechanisms. Structures exhibiting a failure were included into our database of 214 failed timber structures. An evaluation of this database will be given in Chapter 3.

2. Assessment of the Structural Reliability of Timber Structures

2.1 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. With the objectives to keep the impact on the owner and the users of the building as low as possible, to satisfy the right of continuance while still maintaining the required level of safety, our Chair was asked to categorize the structures into priorities, to prepare a guideline for the assessment of these structures, to evaluate on the results of the assessments and to advise on future inspections. The assessment of all structures itself was conducted in collaboration with five check engineers.

2.2 Categorization of Structures into Priorities

Since the most critical structures had to be assessed in short timeframe to enable necessary rehabilitation measures to be carried out before the next snowfall, all structures were categorized into priorities of assessment. This categorization was undertaken with special emphasis on two aspects: structural system and consequence of failure. Three priorities were set up (see Table 1).

Table 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, curved or pitched-cambered beams
II; III	Assessment before next snowfall; rehabilitation upon necessity	Structures of shorter span, steep roof trusses, secondary structures in timber

2.3 Guideline for the Assessment of Timber Structures

The guideline prepared for the assessment of these structures is related to the “Guideline for a first evaluation of large-span timber structures” [1], established by five experts (Blaß, Brüninghoff, Kreuzinger, Radovic and Winter) and published by the German Council for Timber Technology (CTT). Table 2 lists the essential steps.

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 glue line or drill resistance measurement to identify the depth of decay.

For each building assessed, an expertise was prepared, including the following chapters:

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

2.4 Results and Guidelines for Rehabilitation

The assessment of each structure was directly linked to a categorization of this structure for further rehabilitation measures. Four categories were set up:

- Category I: Immediate closure until the completion of rehabilitation measures
- Category II: Utilization under special conditions and rehabilitation before winter
- Category III: Minor rehabilitation without structural relevance
- Category IV: No rehabilitation necessary

Table 2: Excerpts from the" Guideline for a first Evaluation of wide-span Timber Structures" [1]

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, if 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

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 Figure 1).

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 featuring structural failures (see Figure 2).

A comparison of Figure 1 and Figure 2 shows the benefit of prioritising the buildings beforehand, since the majority of structures to be rehabilitated was classified Priority I. The failures and reasons for failure for structures in Category I and II were included in our database of failed timber structures, which is evaluated in chapter 3.

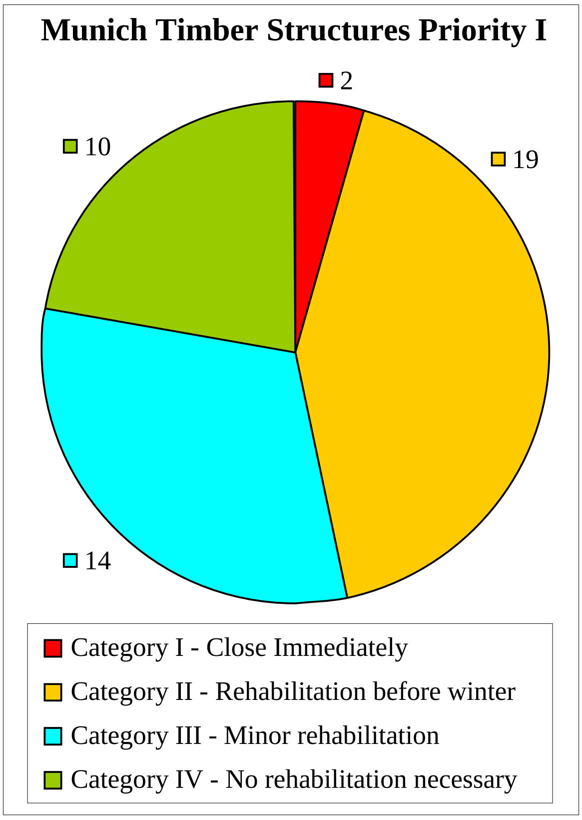

Figure 1: Munich Timber Structures – Prior. I

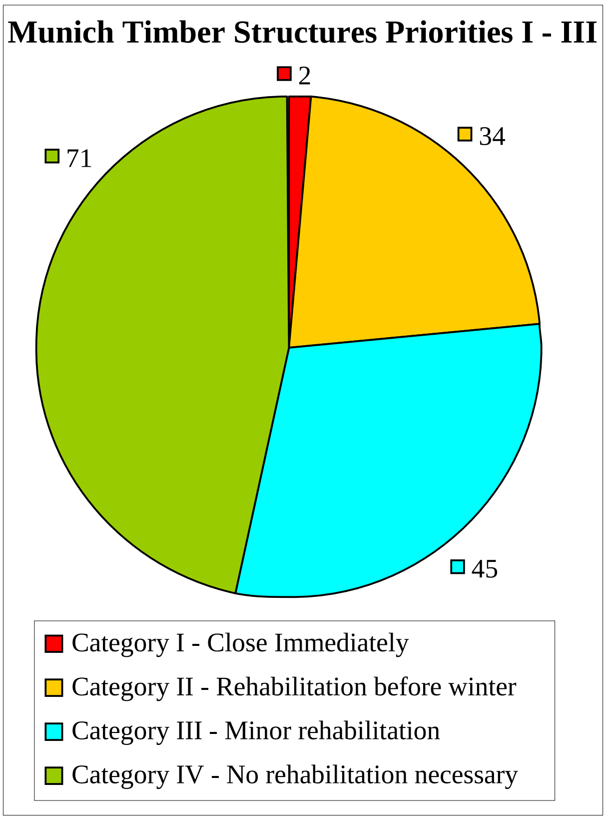

Figure 2: Munich Timber Structures – Prior. I-III

2.5 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, featuring 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. One person was assigned to each building that was responsible for the supervision and implementation of these tasks.

2.6 Recommendations for future Inspection

To guarantee a reliable continuation of initiated project, recommendations for further inspections were established for each building (see Table 3). These were prepared according to abovementioned guidelines [1] with special emphasis on critical elements detected during the assessments (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 in collaboration 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) [2] classify buildings of all materials by the potential for danger and the consequences of failure (see Table 3). Papers including similar instructions have been set up in other countries [3].

Table 3: Categorization of Buildings according to the "Instructions for the Assessment of the Structural Reliability of Buildings by the owner/authorized person" [2]

Potential 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 danger	Large projecting roofs, balconies, cupolas…

Based on this classification, recommendations for inspection intervals and necessary qualification of the assessor were established, see Table 4. The given approach enables the building owner to carry out the frequently recurring inspections by himself. For the visual and detailed inspections, he has to call upon more competent persons or experts.

Table 4: Inspection Intervals and necessary Qualification according to [2]

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 (e.g. civil engineers or architects with more than 5 years experience in related field)	Expert (e.g. civil engineers with > 10 years experience in related field, check engineers, officially appointed experts)

2.7 Building Book

To facilitate future inspections and to guarantee a consistent documentation, the concept of a building book was introduced. It should contain all necessary information for the person in charge of the building and future inspectors. Table 5 lists its possible structure.

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 on which information shall be newly acquired/created. For new buildings, it is advised that the building book is prepared by the structural engineer. In addition, he should already include the aspect of maintainability and crucial elements to be inspected in the planning phase.

The building book is only fully beneficial, if it is utilized as a "Building Diary", meaning it is continued by the owner and future inspectors.

Table 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

3. Evaluation of failed Timber Structures

3.1 Classification of Data

In conjunction with the assessment of the Munich timber structures, another research project was carried out at our Chair, dealing with failures in wide-span timber structures. The objective of this project was to gather information on large timber structures that had shown weaknesses from damaged structural elements to total collapse. The results should permit the identification of failure patterns. These could enable the engineer in charge of comparable structures to initiate necessary measures to avoid similar failures. To date, the evaluation includes 214 cases of failed timber structures, mainly from Bavaria and neighbouring countries. Basis is information from experts, professional institutions and authorities as well as results from own investigations on-site. For the majority of structures (62%), very detailed information could be evaluated. Sufficient information for evaluation could be obtained for 14% of the structures. For the remaining structures, the received information enabled evaluation, yet leaving some blank spots in the data collection. Since a building can contain more than one failed structural element, multiple answers are possible.

3.2 Structural Information

Figure 3 shows the range of utilization of evaluated structures. It indicates the wide application of timber structures, e.g. for sports facilities, assembly halls and storage spaces. The large number of ice-skating facilities is due to the Bad Reichenhall ice-arena collapse which resulted in the assessment of all ice-skating arenas featuring timber roofs.

3.3 Types of Failure, Causes for Failure and Accountabilities for Failures

Figure 4 shows the most common types of failure while Figure 5 highlights their causes. The main type of failure is intense cracking along the grain (46%). The major cause is low or changing moisture content, the second cause being the low tension perpendicular to grain strength of timber, resulting in cracking of e.g. unreinforced curved or pitch cambered beams. The immense influence of moisture (regulated by the environmental conditions) on the performance of timber structures is also highlighted by the considerable amount of failures due to a high moisture content, e.g due to decay and fungi (14%). But the most frequent influence is by far the drying out and/or intensive change of moisture content of structural timber elements in use.

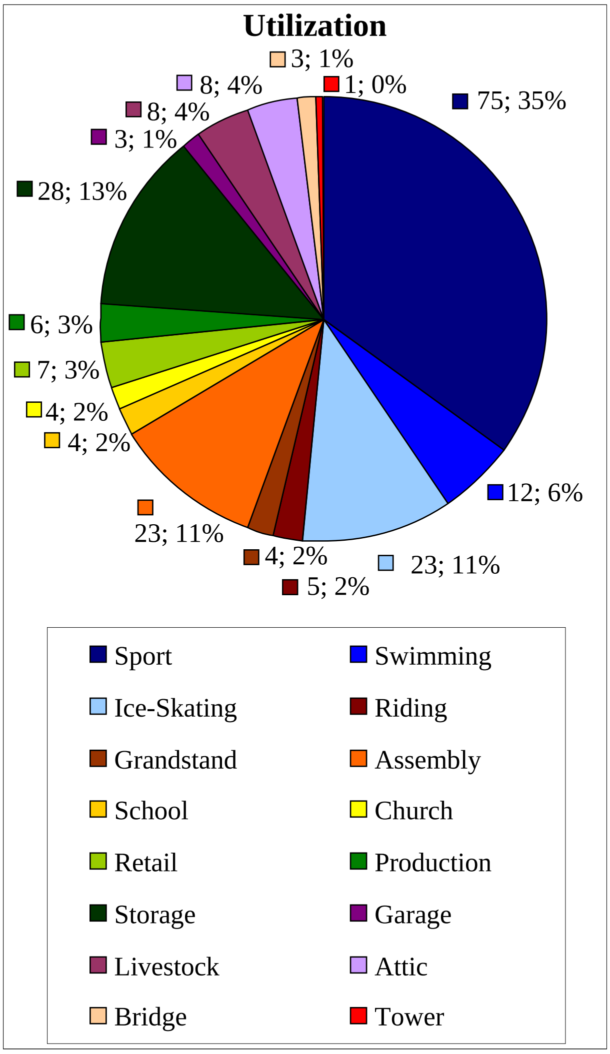

Figure 3: Utilization

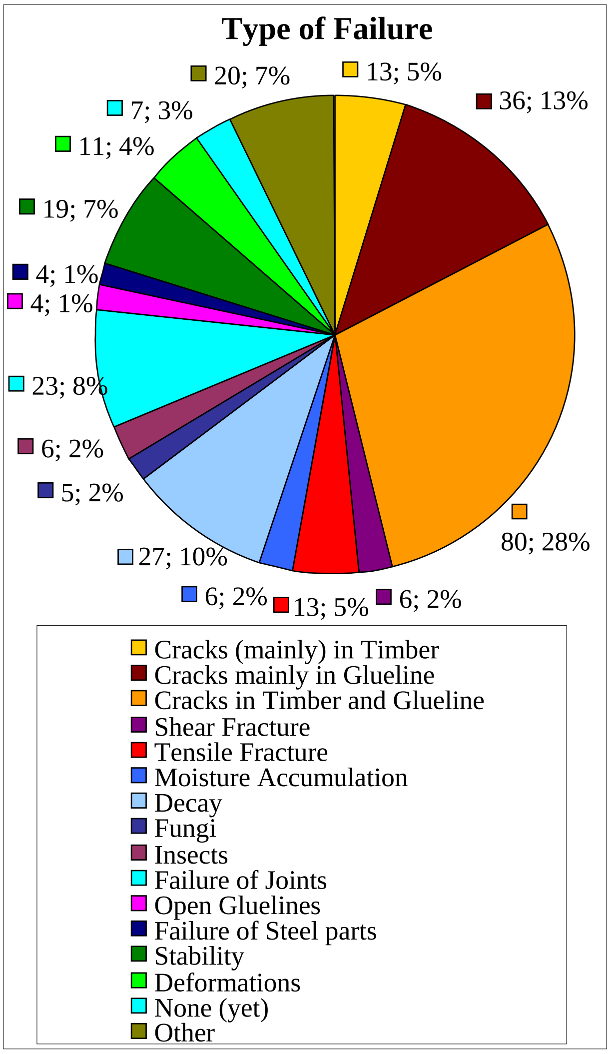

Figure 4: Type of Failure

Figure 6 displays the accountabilities/responsibilities for failures. It indicates that the majority of failures result from errors in the planning phase, whereby the wrong estimation of the prospective environmental conditions (28%) accounts for a large portion of future damages. Failures in structural design could oftentimes be linked to missing knowledge or the neglection of the state-of-the-art in timber design at time of planning (e.g. stresses perpendicular to the grain in curved and pitch cambered beams). The quota of failed structures in which the execution differed considerably from checked construction plans and calculations was remarkable.

The given evaluation illustrates clearly, that high snow loads, oftentimes cited as the reason for failure, should in this context be seen as the actuator but rarely the cause for failure.

4. Summary

It can be concluded that failures connected to human error represent the vast majority of classified cases. Another large and detailed analysis of failed timber structures in Germany by Blaß and Frese [4] and a Nordic project by Frühwald et al. [5] both come to a matchable conclusion.

Human error is virtually always connected to knowledge and quality of work. 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. In the long term, this can result in an extended lifetime, thereby achieving a higher sustainability of these structures.

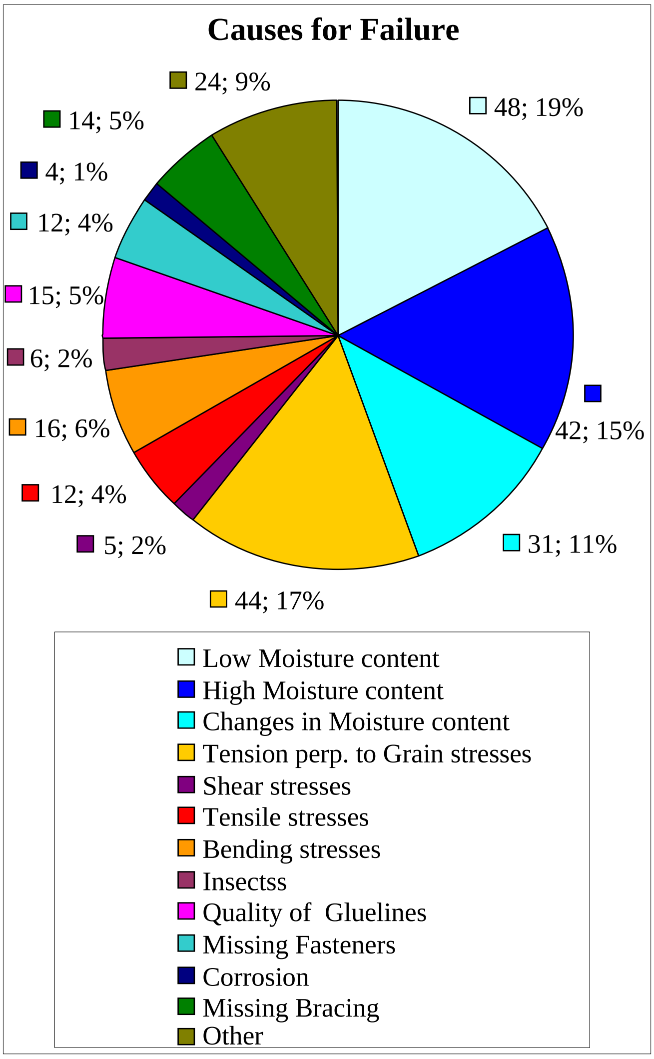

Figure 5: Mechanisms leading to Failure

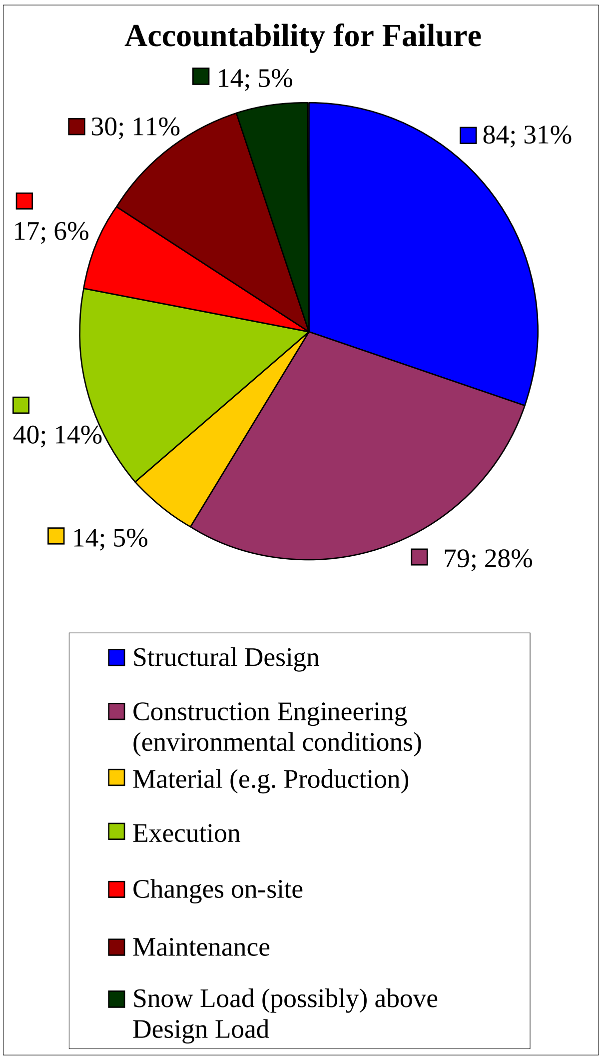

Figure 6: Accountability for Failure

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6. References

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