Failure and documentation of building structures

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Abstract

In recent years, a number of structural failures have occurred in buildings in Denmark, trigging a debate on safety and reliability in the built environment in general. In this context, the quality of the documentation of the capacity and functionality of building structures has been criticised and a common understanding of content and quality assurance of the documentation of load-bearing building structures has been identified.

Based on experience from the Danish building industry as well as guidelines published by the Danish Building Research Institute, the paper discusses the outline and control of documentation of load-bearing building structures. The qualitative analysis includes the content of individual parts of the documentation. A distinction between the documentation of the physical structures and the documentation of the design process is introduced. Furthermore, the organisation of the design process and tasks related to the individual parts of the documentation are discussed both regarding the engineer in charge of the main design and for the individual engineering tasks for all elements of the structure, including drawings and structural calculations.

Finally, the paper discusses a set of information and document management issues of critical importance for the resulting safety of the documented load-bearing structures; e.g. how to administer, document, identify and draw up the individual parts of the documentation; especially how to incorporate results from digital modelling and simulation of structural behaviour into the documentation. It is concluded that an industry standard is necessary in order to maintain the safety levels of load-bearing building structures in the future.

Keywords: Structural failure, defects, safety, quality assurance, documentation

1. Introduction

1.1 Recent incidents

In recent years, a number of structural failures have occurred in buildings in Denmark. In 1999, a storm caused severe damage for approximately 2 billion euros (Andersen & Buhelt, 2000). In 2003, a relatively light snowfall caused the roof of a Sports Arena in Ballerup, Copenhagen, to collapse in 3 sections (Nielsen, 2004a), Figure 1. In 2007, a heavy snowfall

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in central Jutland caused damage to a large number of warehouses, stadiums and commercial buildings (Nielsen & Pedersen, 2008).

In early 2009, a steel-concrete structure of a new skating arena in Copenhagen, collapsed during construction (Pedersen et al. 2009), Figure 2. In February and March 2010, snow accumulating over a period of 2 months caused damage to some 5000 buildings mainly located in northern Jutland, around 300 of which suffered damage of structural significance; they were mainly agricultural buildings (Hansen & Tølløse, 2010). Later the same year, the apse of ‘Club Denmark Sports Center’ in Valby, Copenhagen, with a span of approx. 80 m. collapsed under the weight of local snowdrifts in what was expected to have been a harmless light snowfall (Pedersen et al. 2011), Figure 3.

Figure 1 Sports Arena, Ballerup, (Nielsen, 2004), Photo: Jørgen Munch Andersen

Figure 2 Skating Arena, Rødovre, (Pedersen et al. 2009), Photo: Niels-Jørgen Aagaard

Figure 3 Agricultural building (Hansen & Tølløse 2010), Photo: John Dalsgaard Sørensen

Figure 4 Club Denmark Sports Centre, (Pedersen et al. 2010)), Photo: Erik Steen Pedersen

In most of the reported cases, failures were caused by defects or omissions in the design phase or in the construction execution. In a small number of cases, failures where caused by unexpected natural loads or load-combinations as prescribed in applying design codes (CEN 2002a, 2003, 2005). In none of the reported cases, failures where caused by unexpected imposed loads on the buildings (CEN 2002b).

1.2 Causalities

Based on an analysis made in (Nielsen, de Place Hansen, & Aagaard, 2009), the following terminology for causality of failures is used: Situation → Cause → Defect → Failure, being a simplified version of the schematic pathway from defects to rework suggested by (Sommerville 2007).

Failure is regarded as the physical loss of functionality; e.g. collapse or major deflection. Defect is the physical relation(s) in the structure that might lead to a failure; e.g. an omission, wrong dimensions or placements of structural elements or unintended modes of operation. Cause is the underlying incident(s) leading to the defect(s); e.g. miscalculations, design errors, gaps in rules of actions, execution errors or inappropriate maintenance. Finally, the situation as such may imply the cause(s) in the first hand. The situation might refer to circumstances in the project, e.g. contracts, organisational matters or staffs competences, or circumstances in the industry in a broader sense, e.g. building regulation, strong competition or 'safety culture' in general.

In a significant number of the reported instances, several circumstances in combination leads to a set of causes that leads to one or more defects that eventually – if the structure is tested by loads at limit level – may cause failure. Consequently, we very seldom observe deterministic relationships between causes and failure; usually a mix of circumstances creates causes that act together, se discussion below.

Causes of defects leading to failures in the above mentioned incidents are grouped into Basis (e.g. regulation and requirements), Design (e.g. inconsistencies and mis-calculations), Construction (e.g. omissions and non-compliance with design) and Maintenance (e.g. deterioration and misuse) in Table 1 corresponding to the generic phases of almost any construction projects. Causes are mainly rooted in design and construction activities and initiatives should respond to this pattern.

Table 1. Causes for defects leading to failures in 6 reported incidents

Incident of failure	Causes for defects			
	Basis	Design	Construction	Maintenance
1. Wind storm 1999		x	X	
2. Sports Arena, Ballerup 2003		x		
3. Snow fall 2007		x	x	x
4. Skating Arena, Rødovre 2009			x	
5. Snow fall 2010	x	x	x	x
6. Club Denmark Sports Centre, 2010	(x)	x		

The reported incidents have triggered a debate on safety and reliability in the built environment in general, and focus has turned towards the culture of quality management in engineering design companies as well as contractors' handling of errors, omissions and rework. It is assumed that the incidents are only 'the top of the iceberg', since many defects will only emerge and show up when loads in rare cases approach the design limit loads. Consequently, the building stock may in general have a lower safety level than intended in codes and regulations (Nielsen, de Place Hansen, & Aagaard, 2009).

1.3 Cost of defects

Analysis indicates that costs correlated to rework due to defects in construction are at a magnitude of 10% of the production value for Danish conditions, not including costs due to delays and rework during construction, (Nielsen, 2004b), (Reenberg et al., 2010), (Erhvervs- og Byggestyrelsen 2011). Research in the English construction industry indicates a magnitude of costs for rework during construction at 15-16% (Barber, Graves, Hall, Sheath, & Tomkins, 2000), while similar case studies in the Swedish construction industry (Josephson & Hammarlund, 1999) indicate some 2-6% of the production value. Reports from Australian case studies indicate costs for rework during construction at a level of 2-3% (Love & Heng, 2000). It is difficult, if not impossible, to compare these figures as the referred investigations define defects in different ways and consequently may include different magnitudes of costs. Nevertheless, it seems obvious that an effort to reduce defects and failures may be necessary both in terms of reducing costs for rework and to ensure the safety level in the built environment.

1.4 Causes of defects

Many causes may contribute to defects and a strict classification scheme for defects is needed in order to analyse the underlying circumstances and causes. Defects are rooted in an array of causes that may act interdependently. A State of the art for classification of design errors are given in (Lopez et al. 2010).

Through seminars and network-based discussions, a handful of possible causes has emerged as being important in a Danish context:

- New ways of organising construction projects
- Fewer competent structural engineers available in the construction industry
- Use of new and advanced structures
- Use of new and advanced materials
- Uncertain or inexperienced use of Engineering Information and Communication Tools (EICT)
- Missing or weak control of design basis and documentation
- Missing or weak supervision of construction execution
- Loss of good workmanship
- Constant demand for productivity enhancements, i.e. reduced costs for design and execution

Each one of these factors, or several of them in combination, may cause defects, which in the end trigger a structural failure. Evidently, the listed causes are not independent of one another, and it one cause might trigger one or more other causes. Obviously, it would be an interesting and important but immense scientific task to reveal the inner causalities and correlations of causes behind defects in general, but some causes seem particularly important for the Danish construction industry: Project organisation, use of ICT and quality assurance, i.e. control of design and supervision of execution.

1.5 Project organisation

For some years, the organisation in the construction industry in Denmark has been undergoing significant changes, and new models for the organisation of a construction project have been tried out. In many cases, structural elements are delivered and documented by many different manufacturers, and the delivery system becomes very complex. Consequently, the design and documentation activities as such are distributed on many subcontractors; and manufacturers leaving the coordination task to the main contractor or consulting engineers (Busby, 2001).

1.6 Use of ICT

The use of Information and Communication Technology (ICT) for static calculations has enabled the construction of more sophisticated and complex structures and made it difficult to ensure the correctness of calculations and documentation. It is often due to the fact that content and formats of output from various ICT systems are defined by the system vendors, who are rarely familiar with the building regulations in specific countries and the design process. ICT systems are seldom fitted to suit the phases of a construction project and the demands for documentation from building authorities.

1.7 Quality assurance

Today management systems for quality assurance or their elements are common in the construction industry and among design companies as well as manufacturers and contractors. In Denmark, the Danish Society of Engineers runs - on behalf of the Danish Energy Agency - a certification scheme for structural engineers that aims to ensure the quality of the design and execution process for load-bearing structures, and allows only certified engineers to perform design and documentation of structures where the consequences of failure would be severe. Unfortunately, these elements of quality assurance differ in structure and content, and expectations to their use may be somewhat uneven among actors in the construction industry. It has been suggested that a major cause of defects has to do with the quality of design documentation produced by consultants and that higher fees would result in improved quality of contract documentation. However, no such significant relationship could be established (Love, Edwards, & Smith, 2006).

Traditionally, designers have browsed or checked each other's calculations and drawings and made notes on the documents directly. Only in rare circumstances do they distinguish between 'control' and 'acceptance' and generally, separate documentation of the control and findings has not been prepared. As the above-mentioned changes have taken place in the construction industry's delivering system, this means that the documentation of load-bearing structures is distributed among many parties, and such ways of control becomes inadequate and insufficient.

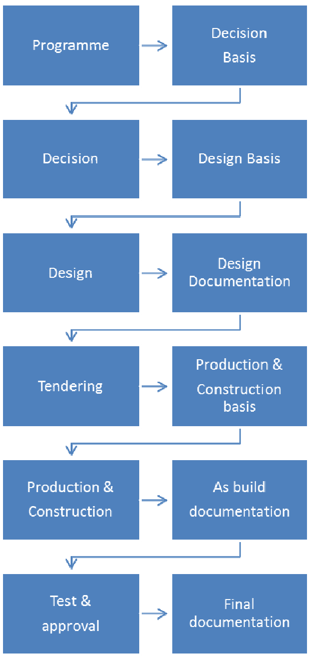
Furthermore, in the traditional way of controlling the execution and ensuring that the construction work is in accordance with the design and intention of designers, designers have supervised the construction work on site. The supervision has often been documented in minutes of meeting or separate memos. Following the more fragmented design processes as mentioned above, each manufacturer has to some extent supervised his own deliveries. Consequently, the extent and level of supervision has faded.

1.8 Structural Documentation

The common focal point for distributed responsibility for quality assurance, uncertain or inexperienced use of ICT and weak quality assurance is the documentation of load-bearing structures, or 'structural documentation' for short. Consequently, building authorities, trade organisations, major design companies and technical universities have joined efforts to develop a common understanding of form and content of structural documentation.

2. Basics on Structural Documentation

It is claimed that a common understanding of form and content of documentation of load-bearing structures may increase the level of safety in the built environment. The assumption is that demands from building authorities concerning documentation will force designers to more careful preparation and calculation of building structures, manufacturers of building parts to document their product in a project-specific way and finally contractors to follow prescriptions more carefully in the execution of the project.



The design, production and execution of building structures may be understood as an ideally serial process; an interpretation of this is illustrated in Figure 5. In the real world, there will be lots of loops and feedbacks that make the picture a lot more complicated, and the process will probably have its unique character for each construction project.

Figure 5 Activities (left column) and documentation (right column). From each activity in the left column, a part of the total documentation is produced.

Internationally, an early attempt to guide the structuring of building related documents is presented in (CIB 1972) and (CIB 1993), while later, the guidelines has bifurcated into separate systems for industrial systems and technical documentation of products, e.g. (CENELEC 2001), and principles for structuring BIM, leaving us today with no international standard for documentation of buildings.

In several countries, national attempts have been made to enhance the project documentation in general. In Spain, an XML-based system has been developed including a new set of taxonomies to support the processes of elaboration, control, verification, digital stamping and compulsory registration and storage of the project documentation by public authorities (Mena, Lopez, Framinan, Flores, & Gallego, 2010). In the UK, benefits and elements of a process documentation system for industrialised housing has been suggested (Roy, Low, & Waller, 2005), and through case studies (Laryea, 2011) shows that the quality of tender documentation is still a problem in construction in the UK despite newly developed standards and best practices. Based on the assumption that there has been a decrease in the level of quality of design and documentation to or from contractors in Australia (Tilley, McFallen, & Tucker, 1999), (Tilley, Wyatt, & Mohamed, 2004) analyse the 'Request for Information' (RFI) process with focus on deficiencies in the overall project performance.

In Denmark, several initiatives address the matter of structural documentation like textbooks outlining design methodology and engineering reporting in general (Mosegaard & Broch, 2008), (Behnke, 2009) as well as methods for structural calculations (Jensen & Hansen, 2012; Jensen, 2003). Specific textbooks address structural calculations of structural elements of specific construction materials like concrete (Jensen, 2012) or steel (Jensen, Bonnerup, & Plum, 2009).

bips (translated from Danish: Construction, Information Technology, Productivity and Corporation), is a non-profit trade organisation specialising in tools for productivity improvements in the construction industry. bips has prepared several systems and best practices on digital description of building components classification systems and BIM, but none of them covered technical calculations and documentation.

The above mentioned works cover general aspects of information and documentation in the construction industry. Only little research has been reported internationally on the importance of quality of documentation for structural safety, although it seems obvious that preparation and control will inevitably catch errors. (Kangari, 1995) reports the importance of having updated and full documentation on arbitration. (Lopez, Love, Edwards, & Davis, 2010) find that no single strategy may handle the problem of design errors, but rather a multitude of strategies needs to be adopted (abstract, p. 399) in construction engineering. They distinguish between three categories of design error: (1) Skill- or performance-based errors, e.g., the plan is acceptable, yet the actions are not performed as planned, (2) Rule- or knowledge-based errors, e.g., the actions are performed as planned, yet the plan did not achieve the outcome intended; and (3) Violations or non-compliances, e.g., to industry or organisation imposed norms and standards." (p.400).

The following proposed framework deals with all 3 types of errors, in the sense that the framework outlines both the planning of the documentation and the preparation of the documentation.

3. Framework

3.1 Documentation of objects and processes

In (Aagaard & Feddersen, 2009), a distinction is introduced between documenting the physical objects/structures and documenting the design process as such. The documentation of the physical objects/structures may be regarded as product documentation, while documentation of the design and execution process may be regarded as documentation of legal responsibilities of the involved parties.

The enhanced framework in Table 2a and Table 2b is proposed for the documentation of load-bearing building structures and design and execution process respectively, and is by the Danish Building Regulation implemented as mandatory structure for documentation of any load-bearing building structures; except those with low consequences of failure according to (CEN 1990).

Table 2a: Documentation of structure

Document	Part	Issues
A1 Design basis	Building	Building type and use; Type of structure and main elements; Structural sections; Execution, descriptions, models and drawings
	Basics	Codes and Standards; Safety level and factors; ICT-tools, references
	Pre-investigations	Site, soil and local conditions, geotechnical parameters, environmental parameters, environmental and climate conditions on site
	Structures	Structural system and models, functional requirements, service life, robustness, fire, execution
	Materials	Soil, concrete, steel …
	Actions	Combination of actions; Loads: permanent, imposed, climatic, accidental, seismic
A2 Structural analysis	A2.1 Structural analysis of the building	Main structural system; Robustness;, General structural analysis and calculations
	A2.2 Structural Analysis of sections	Design basis for structural sections; Main structural system for sections, verification of structural components
A3 Drawings and models	A3.1 Drawings and models for the building	Plans, sections, elevations, details and 3D models of the building
	A3.2 Drawings and models for the sections	Plans, sections, elevations, details and 3D models of structural sections
A4 Design changes	A4.1 Design changes to the building	Description and verification of design changes to the building
	A4.2 Design changes to the sections	Description and verification of design changes to the structural sections

Table 2b: Documentation of design process

Document	**Part**	**Issues**
B1 Report on design process	Building	Type and use of building, situation and context; Overall layout of the building, definition of structural sections
	Organisation	Organisational layout, parties involved, distribution and responsibilities for tasks
	Quality assurance, design	Plan for quality control of design documentation, Documentation of design review Coordination of design review
	Quality assurance, execution	Plan for supervision Documentation of supervision Coordination of supervision
	Design changes	Plan for handling design changes
	Content of documentation	Required list of content for the documentation
B2 Report on quality control	B2.1 Report on review, building	Plan for quality control: type, level and extent of quality control, building Results of quality control and conformity assessment, building
	B2.2 Report on control, sections	Plan for quality control, type, level and extent of quality control, sections Results of quality control and conformity assessment, sections
B3 Report on supervision	B2.1 Report on supervision, building	Plan for supervision, types and level of supervision, extent of supervision, building Results of supervision and conformity assessment, building
	B2.2 Report on supervision, sections	Plan for supervision, types and level of supervision, extent of supervision, sections Results of supervision and conformity assessment, sections

Four important characteristics of the framework deserve special attention: design basis, division of the building structure into sections, report on design process and finally the request for documenting QA.

3.2 Characteristics of the Framework

3.2.1 Sectioning of Building Structures

In modern construction industry, structures are – as many other building components - delivered not by one single supplier but by a wide array of designers, manufacturers, contractors and service providers. Except for rare occasions of total deliveries by one single system supplier, the usual project calls for a massive coordination effort, to ensure that deliveries from one manufacturer fits with requirements as well as connected structural elements. This coordination must also cover the associated documentation. This ‘division of deliverables’ leads to a ‘division of responsibilities’ and finally a ‘division of documentation’ that was unknown in classic previous construction projects, dominated by a strong design team. In a dominating share of the reported incidents, issues of importance for the structural consistency and safety remain unsolved or solutions are based on wrong prerequisites or inadequate assumptions.

It is suggested to overcome this division of responsibilities by a strict division of documentation corresponding to strict sectioning of the building structures each having one and only one responsible supplier. As a consequence of the proposed sectioning, a person responsible for coordination of the documentation should be appointed and tasks relating to the individual parts of the documentation should be outlined both for the engineer in charge of the main design and for the individual engineering tasks for all elements of the structure including drawings and structural calculations.

3.2.2 Design Basis

A comprehensive design basis is necessary for all involved suppliers to relate to and it should ensure that all contributions to the documentation are in accordance with the same prerequisites. The design basis must comprise references to all relevant regulations and requirements necessary to perform adequate drawings, models and calculations. It is suggested that a design basis is constituted as a separate document - with a formal and standardised structure - and kept updated continuously throughout the entire project period.

3.2.3 Documenting control and review

It is crucial to emphasise planning, execution and documentation of control and review activities related to the documentation of the building structures. The framework contains definitions for control, review and inspection, including types and levels of control, planning and execution of control and finally inspection and alteration under construction in order to finish with an ‘as-built-documentation’.

Finally, the framework in (Aagaard & Feddersen 2009) is supplemented with a set of check lists and advice on document management in practice, including how to administer, document, identify and draw up the individual parts of the documentation including principles for handling the digital parts of the documentation and how these parts are incorporated into the documentation.

Conclusion

Strengthening of the culture for quality assurance in the construction industry is necessary in order to maintain the safety levels of load-bearing building structures in the future. Initiatives must take the increased division of labour and responsibilities into consideration, and in practice this calls – among other things - for standardisation of structure of documentation of load-bearing structures as well as project processes; preferably on an international level.

Emphasis must be on review and control of documentation as integrated tasks in the design and construction phases. Special attention is required on review and control of use of ICT and modelling in structural design.

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