# IABSE WORKSHOP

# HELSINKI 2013

*Safety, Failures and Robustness of Large Structures*

**REPORT**

Organized by
Finnish Group of IABSE,
Finnish Association of Civil Engineers RIL

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Safety, Failures and Robustness of Large Structures

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# Preface

Safety, failures and robustness of structures are at the same time very old and very new topics in engineering. Engineers have a tradition for designing structures to resists little extra, to take into account uncertainties in various aspects. Basic concepts like loads and resistance are in recent decades modelled through elementary statistical mathematics to give flavour of intelligence and determinism. This has in some cases concealed the old concept of just increasing the loads, strengthening the structure or tightening the construction quality control whenever notable failures occur. In hands of the experts, sophisticated multi-physics software allows numerical simulation of complex structural models for true time-dependent responses. Results have been in specific cases directly proven with structural monitoring systems or laboratory testing.

Unfortunately, the efforts done for building safe structures are not enough, and structural failures occur time to time. While it appears that old lessons learned from the past are forgotten in time and human errors may always occur, it also appears that totally new modes of failures appear regularly. Whether the hazards are man-made; or due to chemical reactions, substances hazardous to health, climate change or natural disasters; they might ruin our model of a safe structure. Taking this into account, one may start designing structures for robustness: whatever is the reason behind the structure should resist some predefined adverse onset, like a loss of a column in a building structure.

The above kind of fundamental thinking is time-to-time useful for structural engineers. It is an acute topic in Finland, fortunately not for the failures or catastrophes, but because Finland is one of the few countries in the world which was building a new nuclear power plant when the Fukushima disaster 2011 reminded of the power of nature and the limitations of safety design. Nuclear waste disposal system is currently built in Finland, deep inside the bedrock, with more than 250’000 years review period in risks assessments.

As the topic of the workshop is mixture of old experiences and new findings, so is the method of organising it. Today, regardless the affiliation, professionals have less and less time to put on other activities than those that are directly related to the project they are currently working at. The internet has become as an option for quick answer seeking and professional networking. IABSE organisation has started a strategy work to serve its members better for changing demands. The national groups of IABSE have a role in this by arranging various types of events in agile manner. The goal of this workshop is to invite some of the best experts, as multidisciplinary bases, into the same place to interact with each other and the participants. To give answers and highlight drawbacks; to make the event professionally as useful as possible – thus deserving its position on one’s agenda.

Although the workshop is organised in less than one year from initiative to completion, it includes a review process, a proceedings book and a presentation program similar to the bigger IABSE events like conferences. The main thanks from this belong to Ms Helena Soimakallio, Ms Anu Karvonen and Mr Ville Raasakka from Finnish Association of Civil Engineers RIL. Personally, I have been privileged to work with them since the IABSE Conference 2008 in Helsinki. They have developed their skills on structural-engineering event-handling on the top level, while owning sense of humour and good mood in their work.

Helsinki, February 2013

Dr Risto Kiviluoma
Chair of the Scientific Committee

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# Bridge Damage Caused by the 2011 Great East Japan Earthquake

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## Summary

This paper presents damage of bridges during the 2011 Great East Japan earthquake. Effectiveness of recent development of seismic design and implementation of seismic retrofit is evaluated based on comparison of the damage during the 2011 Great East Japan earthquake and the 1978 Miyagi-ken-oki earthquake. Tsunami-induced damage is also presented for bridges along the Pacific Coast. Typical feature of tsunami-induced damage is presented based on a field investigation.

**Keywords**: Great East Japan (Tohoku) earthquake, seismic damage, bridges, ground motions, tsunami, seismic design codes.

## 1. Introduction

The Great East Japan earthquake ($M_w$9.0) occurred at 14:46 (local time) on March 11, 2011 along the Japan Trough in the Pacific Ocean. This was the largest earthquake which ever historically occurred around Japan. The fault zone extended 450km and 200km in the north-south and west-east directions, respectively, as shown in Fig. 1. Extensive damage occurred in a wide region in the east Japan.

A number of strong motion accelerations were recorded in the damaged areas by the National Institute of Earth Science and Disaster Prevention (NIED) and Japan Meteorological Agency (JMA). Most accelerations were recorded at stiff sites as it was the purpose of NIED and JMA to record base-rock accelerations. Fig. 2 shows typical acceleration records along the Pacific Coast. Ground accelerations continued over 200s, and they had at least two wave groups reflecting the fault rupture process. The highest peak ground acceleration of 27.0 m/s$^2$ was recorded at Tsukidate City. However the high acceleration was resulted from a single pulse with 0.2 second period, therefore response acceleration at 1.0s was only 5.1m/s$^2$ as shown in Fig. 3. Consequently damage of bridges and buildings was very minor in Tsukidate City. This clearly shows that only PGA cannot be a reliable index for seismic design.

At soft soil sites in the north Miyagi-ken and south Iwate-ken (refer to Fig. 1), ground accelerations included longer period components leading to higher response accelerations at 0.5-1.5s. For example, response acceleration was over 16 m/s$^2$ at 0.8 s in Osaki as shown in Fig. 4.

Seismic design code of bridges was extensively enhanced since 1990 (JRA 1990, 1995, 1996, 2002, 2012) [1,2,3]. Only a combination of a static elastic analysis assuming 0.2-0.3 seismic coefficient and an allowable stress design approach (seismic coefficient method) was used until 1990 (JRA 1964, 1971, 1980). The static elastic method is still in use today but a combination of an inelastic static analysis and Type I and II design ground motions as shown in Fig. 5 has been the main stream approach in the post-1990 codes. Thus the seismic demand was much enhanced in the post-1990 design codes.

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# Robustness of Structures

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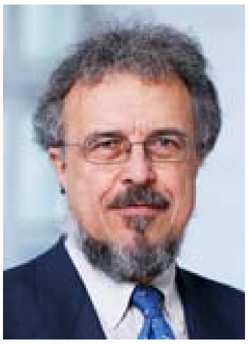

Thomas Vogel received his diploma from ETH Zurich in 1980. He worked for 11 years in consulting and since 1992 as professor of Structural Engineering at ETH. His fields of interest cover the evaluation of existing structures, non-destructive testing methods, ductile design with brittle materials as well as structures designed for and protecting from natural hazards.

## Summary

Robustness has become an important general requirement for both, design of new and evaluation of existing structures, to reduce the global risk caused by structures. Methods to achieve robustness are presented in a systematic order and illustrated by examples. Some important issues to get robust structures are addressed like strength, stiffness, ductility, strain hardening, and continuity. Different definitions of robustness are presented, showing that they slowly converge. Some proposed metrics are discussed, although they are not yet practically applicable. With a example of a bolted steel splice, it can be shown that even in a simple detail robustness as a design criterion may be ambiguous. Finally, the implicit and explicit treatment of robustness in former and actual codes is covered and developments for the future are sketched.

**Keywords**: Alternative load path, continuity, ductility, event control, progressive collapse, redundancy, segmentation, specific load resistance, strain hardening, vulnerability.

## 1. Introduction

Robustness can be defined as the ability of a structure and its members to keep the amount of deterioration or failure within reasonable limits in relation to the cause [1]. In the past, the issue was raised periodically, triggered by events like the progressive collapse of one corner of a 23 storey block at Ronan Point in east London in 1968 due to a gas explosion in the 18th floor, or the car bomb attack to the Alfred P. Murrah Federal Building, Oklahoma City, USA in 1995, which led to the almost complete collapse of its northern façade. Robustness has again become a major theme of structural engineering by the incidents of September 11, 2001. Research has been intensified to look for suitable concepts for all different types of structures and building materials and to quantify robustness. This would be a precondition to cover robustness more precisely by structural codes in the long term. A comprehensive overview on the state of the art is given by the final report of COST action TU0601, consisting of three parts [2], [3], [4].

## 2. Estimating risks

### 2.1 Risk analysis in a perfect world

Risk analysis provides tools to assess the global risk of a structure, for instance by applying the general equation given in EN 1991-1-7 [5]:

$$R = \sum_{i=1}^{N_H} P(H_i) \sum_{j=1}^{N_D} \sum_{k=1}^{N_S} P(D_j \mid H_i) P(S_k \mid D_j) C(S_k) \tag{1}$$

where:
- $N_H$ number of hazards $H_i$
- $N_D$ number of direct (local) damages $D_j$
- $N_S$ number of types of follow-up behaviour $S_k$
- $P(H_i)$ probability of occurrence of hazard $H_i$

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# Failures in large-span roof structures in Switzerland

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## Summary

The present paper describes collapses and failures of three large-span roof structures in Switzerland:

In February 2009 the steel roof of a three years old gym in eastern Switzerland collapsed. Based on visual findings and on a detailed investigation it could be found that the cause of the collapse was a deficient detailing in each of the seven 26 m long, simply supported main steel plate girders. The collapse was triggered by increasing snow load although at the day of collapse the load was 25% lower than the characteristic value according to the Swiss design code.

In November 2003 the roof of a timber multi-purpose hall partly collapsed after a period of rain. The investigations showed that the most relevant reason for the collapse was the incorrect execution of welds at the joints of supporting shoes in conjunction with the marginal design of that detail. From other factors that contributed to the collapse an insufficient drainage system of the roof could be identified as having played an important role.

In 2011 a 180 x 1120 mm$^2$ glued-laminated timber beam with a span of 18 m being part of the secondary structural system supporting the flat roof of a DIY superstore near Zurich failed in bending. The failure had been triggered to a considerable extent due to overloading of parts of the roof by a gravel layer compared to other parts of the roof being of higher depth and specific weight.

From all three incidents it could be concluded that a closer orientation of the design to available design codes and a strict quality control during design, execution and use of the building would have reduced the probability of collapse / failure of the roof structures considerably.

**Keywords**: welded steel plate girder, web buckling, glued-laminated timber, flat roof, quality of welds, box girder, stiffener, compression perpendicular to the wood grain, roof drainage

## 1. Introduction

This paper describes investigations performed by the Swiss Federal Laboratory for Materials Science and Technology, Empa, on recent collapses or failures of large-span roof structures in Switzerland, namely a 1300 m$^2$ gym the steel roof structure of which totally collapsed, a multi-purpose hall suffering from partial collapse of the roof supported by wooden box girders and a superstore that had to be closed immediately due to a failure of a glued-laminated timber beam.

On site and laboratory investigation methods for identifying the causes of the collapses are presented and conclusions with respect to mistakes in design or construction and to future avoidance of similar collapses or failures are drawn.

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# Robustness in Tall Buildings: Earth, Wind & Fire

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## Summary

The aim of this paper is to introduce some of the key concepts in enhancing the robustness of tall buildings. The overarching objective of such a process should be the development of sensible hazard scenarios and realistic acceptance criteria to ensure cost-effective and sustainable design. Due to the complex structural behaviour exhibited, both in loading and response, under common identified hazards some degree of simplification is inevitable so it is important that any hazards considered are treated within a common performance based design framework.

An overview is presented of a design framework in which the performance of buildings under accidental and extreme events can be assessed. A range of analysis techniques is available to the engineer;which technique is chosen depends on the complexity and nature of the building, the specific hazards that the building will be subjected to and the degree of conservatism that can be tolerated in ensuring the robustness of that particular building. Some of the detailed assessment procedures available for such buildings under certain specific hazards within the framework are discussed.

**Keywords**: Robustness; Design Framework; Analysis Techniques; Fire; Blast, Alternate Load Path; Connection Performance.

## 1. Introduction

The financial and economic challenges of development on inner city sites are continuing to push building designs taller and taller. This gives the structural engineer numerous challenges in deriving designs which meet the competing functional requirements of tall buildings in a cost effective and sustainable manner.

A key functional requirement which is becoming increasingly important is the design of the structure to perform satisfactorily during accidental and extreme events. The need for this has been brought into focus by recent terrorist attacks which have led engineers to consider methods of assessing the vulnerability of tall buildings and to consider the measures that can be taken to make buildings more robust in such events.

Since 2004 in the UK and more recently with the introduction of the Eurocodes there is a need to design tall buildings considering the risks of progressive collapse under accidental events. Tall buildings (defined as over 15 storeys tall) fall in the highest risk category for which a systematic assessment of the risks posed by a variety of accidental events needs to be considered. Such accidental events include design against earthquake, blast, fire, vehicle impact, etc.

The attacks on the World Trade Center and subsequent terrorist attacks on other critical infrastructure have brought calls for tall buildings to withstand even more extreme events. However such events can place structural demands on buildings which if met by normal design processes would lead to buildings which are functionally, economically and, moreover, sustainably unviable. Therefore, if such events are to be taken account of in the design, it is important to establish the key performance goals of the structure under the events and establish the necessary

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# Quantifying Redundancy and Robustness of Structures

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## Summary

The paper presents the different definitions proposed for structural robustness and redundancy, as well as the different measures to quantify them, according to the proposed definition. From this review, it is emphasized that almost all proposed definitions are related to sudden damages (impacts, explosions, ...) and unforeseen events. For this reason, in the present paper a new approach to robustness is defined in terms of the ability of the structure to respond to continuous deteriorating processess as corrosion. The paper also shows how most of the proposed measures of robustness are relative, in the sense that they may help identify which structure is more or less robust than another. However, a target or threshold value that defines the border between what is robust or not, normally does not exist. Finally, an example of application of the new proposed measure of robustness to an existing reinforced concrete bridge, in advanced state of deterioration due to corrosion attack, is presented.

**Keywords**: robustness, redundancy, bridges, corrosion, deterioration, reliability, risk.

## 1. Introduction

The occurrence of catastrophic consequences due to extreme events in buildings and bridges has increased the interest of the engineering community in structural robustness. Robustness first received attention about 40 years ago, just after the partial collapse of the Ronan Point building in London in 1968. After this, many other events, such as the collapses of the Alfred P. Murrah Federal Building in Oklahoma City (1995), the World Trade Center in New York (2001), the Windsor Tower in Madrid (2005) and the I-35W Mississippi River bridge in Minneapolis (2007) among others, have awaken the interest of engineers to this concept. Although the referred collapses had different causes, such as the occurrence of a fire, a terrorist attack, or component failure, among others, the fact is that in all the cases the consequences resulting from collapse were considered disproportionate in relation to the initial damage. This concept became particularly clear specially after the 9/11, as the consequences due to structural failure largely supersede the mere rebuilding costs.

On the other hand, the need for a robustness framework has also derived from the fact that structural design codes are mainly based on the design of structural members individually, neglecting, in most cases, the overall structural performance. Robustness is commonly related, and sometimes misunderstood, with some structural properties such as redundancy, ductility, flexibility

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# Extending fatigue life of structures beyond 100 years using monitored data

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## Summary

A methodology inherent to existing structures is presented for the fatigue safety of bridges. The suggested approach allows for the determination of updated action effects explicit considering data from long term monitoring. Monitored data allow for accurate determination of fatigue relevant stresses in fatigue prone bridge structures. Also, uncertainties in the determination of updated action effects are reduced. By means of the presented approach, the fatigue safety of a riveted railway bridge of high cultural heritage value was verified also after 115 years of service duration. Monitored data were exploited by Rainflow analysis and served as the basis for the fatigue safety verification. As the locations of measurements are generally not identical with the cross sections of verification, measured strains were translated to the relevant verification cross section by means of factors that were determined by structural analysis. Sufficient fatigue safety could finally be verified for the entire riveted structure and additional service duration of at least 50 years for this riveted structure could be validated.

**Keywords:** Fatigue safety, service life, riveted steel bridge, structural health monitoring, examination.

## 1. Introduction

In many countries, civil structures have been in service already for several generations. As part of the transportation infrastructure, bridges add value to the public economy. Therefore, there is high interest in economic performance while providing unrestricted utilisation (e.g. without limits on traffic loads) and responding to increasing traffic demands. Obviously, there is a need to extend the service life of civil structures even further, i.e., significantly beyond 100 years which often is the arbitrarily presumed service life of structures.

In this context, structural engineers have to devise novel ways to examine the structural safety of existing structures, in particular when high cultural values are involved. The contemporary approach is based on an inherent methodology that essentially includes collecting detailed in situ information about the structure, for example, by long term monitoring of structural behaviour. Parameters controlling structural safety are determined more precisely and, for example, the structural safety of an existing bridge can be proved using so-called updated values for actions (loads) and resistance. In this way, it can often be shown that an existing structure may be subjected to higher load effects while meeting the safety requirements, thereby avoiding intervention.

Regarding existing bridges, a greater source of uncertainty lies on the traffic loading or, more specifically, the action effects arriving in the structural elements. In recent years, increasingly sophisticated approaches have emerged for load effect estimation using traffic simulations incorporating Weigh-in-Motion (WIM) data which form the basis of load models in design and “assessment” codes. While vital for design, these codes are based on generic heavy vehicle data from a range of locations and therefore may not always represent the site conditions at the existing bridge under investigation. In addition, codes include provisions for illegally overloaded vehicles

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**Safety, Failures and Robustness of Large Structures**

# *Robustness*

# Robustness for Large Steel-Concrete Composite Structures

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## Summary

The paper reports briefly on investigations for large steel-concrete composite structures such as multi-story buildings where the danger of a progressive collapse is prevented by alternate load path methods. Structural redundancy is considered depending on the floor system and on frame action. Focus is given to the influence of joints and the importance of their ductile behaviour for the structural robustness. Report is given also on a new European project developing an advanced design concept for steel-concrete composite structures under defined impact scenarios.

**Keywords**: robustness, alternate load paths, redundancy, joint ductility, over-strength effects

## 1. Introduction

In view of recent disasters and their immense economical and human consequences more and more focus is given not only on the safety of structures - to reduce the risk for the life of people by collapse even under exceptional loading – but on minimizing the disastrous results and to enable a quick rebuilding and reuse. One crucial mean to achieve this aim is the design of robust structures. For large steel-concrete composite structures such as multi-story buildings the danger of an unforeseen event like a small fire next to a column, an explosion or impact or any incident causing local damage may initiate either a successive failure of the complete structure or be confined to that localized area of origin. The way a structure reacts to such situations may be characterized by its degree of robustness. In this context the robustness of a structure is defined as the capability of a structure to mitigate disproportional progressive collapse e.g. due to a column loss.

## 2. Design strategies

### 2.1 General

The approach to robustness adopted by EN 1991-1-7 [1] is based on the design criteria provided by EN 1990 [2] which states that "a structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact and consequences of human errors to an extent disproportionate to the original causes". To design the structure following this criterion means to limit the failure to an acceptable extent by means of structural measures which still should be economically justifiable.

The choice of the strategy of prevention is among others influenced by the characteristics of the accidental actions. By considering the unforeseen occurrence of the events and the practical impossibility to define "a priori" all the possible scenarios, EN 1991-1-7 distinguishes the accidental actions in identified and unidentified actions, see *Fig. 1* [3] [1]. The probability of

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# Assuring Robustness of Non-Prescriptive Building Structures in China

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## Summary

China arguably has one of the best regulatory processes in the world today for validating the designs of tall and complex non-prescriptive building structure designs, thereby assuring their robustness. This paper presents the basic and special requirements of this code / regulation mandated process. While the process often necessitates strenuous analytical and design efforts, it also opens the doors to exciting and robust first principle structural designs.

Future trends in approaches to robust structural design are briefly discussed.

**Keywords:** Robustness, Resilience, Seismic Design, Key Elements, Performance Based Design, EPR

## 1. Introduction

The past few decades have seen a rapid multiplication of the total stock of tall buildings in the major cities of China. This growth has now spread to the so called “second-tier” cities. What is very striking, when looking at these buildings, is the sheer scale and complexity of many of their structures. The building codes of most nations, and China is no exception, set limits on the applicability of their prescriptive design regulations. If these limits are exceeded in a manner or to an extent defined in the codes that renders the prescriptive procedures inapplicable, the structure is deemed non-prescriptive, and special design measures are needed to assure at least the same level of robustness as intended for prescriptive buildings by the codes. Over the years, through several cycles of code and regulation development, China has evolved a very rigorous method for assuring this robustness.

It is appropriate to begin by defining robustness in the context of building structures as the definition changes from field to field. With building structures, robustness can be defined as the ability of the system to mantain its function within defined limits over a preset range of imposed conditions and, when the conditions are exceeded, to ensure that functionality persists and is only lost gradually and not catastrophically to eventual failure. This type of robustness implies assured overstrength of function critical or key components and resilience (ductility, for example,) of typical system components. The requirement for this type of overstrength and resilience is intrinsically embedded in code design requirements to achieve robust structures. But there is a trend towards an evolved definition of resilience as a component of robustness, particularly in areas of high seismicity: where resilience has come to be seen as a measure of a system’s ability to return as closely as possible to its original functionality after experiencing conditions that severely exceed the

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# Nonlinear modelling for Offshore Robustness. A sensitivity study.

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## Summary

The assessment of existing offshore steel jacket structures for use beyond their initial life requires a proper design of an inspection plan aimed to constantly check-up the structural elements (both members and joints). There is consequently a need to define a set of indicators that, possibly combined with a continuous dynamic monitoring system, provides a reasonable measure of structural robustness and damage tolerance. To investigate these aspects the paper proposes to develop non-linear static pushover analyses to assess the system reserve strength: damages, or deteriorations, of primary and secondary structural components are assumed to evaluate their effects on the robustness of the structure and to evaluate the possibility to employ a structural monitoring system as a check-up of the integrity of the structural elements.

**Keywords**: Offshore steel jacket platform; Non-linear structural analysis, Static pushover analysis; Structural robustness; Inspection planning.

## 1. Introduction

Offshore steel jacket structures have been commonly used for oil (or gas) extraction in shallow and moderate water depth for decades, and a plethora of steel jacket platforms are still operational even if they reach the limits of their design service lives. Even if rather large reconstructions, repairs and inspections have to be executed, the use of existing installations beyond their design lives (due to, for instance, the extended oil reservoir estimates) is in various cases economically preferable. The assessment of such structures for use beyond their initial life requires a proper design of an inspection plan aimed to constantly check-up the structural elements (both members and joints). In principle, proper safety evaluation of an existing structure can be ensured by requiring compliance with the actual recommendations, even if how to perform such safety compliance with regards to life extension of existing structures is an open issue. Moreover, assessing additional fatigue life for a structure that has reached its original fatigue design life is not possible only using design regulations, even if no cracks have been detected. It is therefore of importance to develop a scheme which presents a minimum of work to be done in order to ensure proper future safety of a structure beyond its original design life. In this context the inspections, and the subsequent (if necessary) possible repairs, are so viewed as a safety barrier to prevent corrosion failure, fatigue failure, etc. in members and joints (and, of course, to repair them if they have occurred). The amount of inspections, their frequency and their typology (i.e. the proper selection of the elements and/or joints to check-up) is a critical issue (since, for instance, it may not be feasible to inspect all critical components), and inspection planning was for the last decade, and still is, based mainly on probabilistic analysis (Risk Based Inspection, RBI) [1] [2].

The paper aims to deepening these aspects analyzing the robustness of such structures in order to identify a set of indicators that provides a reasonable measure of structural robustness and damage tolerance. Consequently the paper aim to identify methods for evaluating the safety of a structure beyond its design life, taking into account that for a robust and damage tolerant structure the proper structural safety is not restricted by the occurrence of single (members and/or joints) component failures. In this context, robust and damage tolerant means that the structure has an acceptable probability of failure due to extreme loading in intact condition or with a single member or joint failure. The tasks that the paper approaches are then: a) Evaluate indicators for robustness and damage tolerance able to control if a wave overloading is acceptable in intact condition and with one member failed. The damage tolerance and robustness of the jacket structure is evaluated by means of pushover analyses, and indicators are evaluated; b) Evaluate the possibility to employ a

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# Robustness of structures: role of graph complexity

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## Summary

Graphs are widely employed in many fields of Science and Humanities studies, e.g. network analysis, communications, or literature. This abstract representation serves to analyse large systems, in which each element plays a role in the overall behaviour. In this paper, this concept is applied to structural engineering. A scheme with beams (or columns) and joints can be represented, mathematically, as a set of nodes and edges. The information content of a graph, i.e. of the corresponding structure, is used as a measure of complexity by means of the so called Shannon's entropy. The deformation work plays a fundamental role in the description of the behaviour of the loaded scheme. Further, an optimization of the complexity lets to stress the capabilities of the novel metrics in the design of robust structures.

**Keywords**: graph theory; information theory, complexity, robustness.

## 1. Introduction

A graph is defined as a set of nodes and edges connecting the nodes. For their graphical representation and their topological properties, graphs are used in many fields of knowledge, even in those cases in which Mathematics seems not to be involved: a conceptual maps is a common tool for organizing and representing knowledge [1], the dictionary of synonyms and antonyms can be imagined as a set of connected lexical elements [2]. The human language shows some sort of organization and scale-free graph properties, reason for which communication between people speaking different languages is possible [3]. In Biology, metabolic networks show topological properties and exhibit a robust response towards internal defects and environmental fluctuations [4].

In applied sciences, graph representation serves for describing and studying complex systems. Communication networks and power supply can naturally be sketched as a set of nodes and connectors and robustness properties of such objects can be highlighted. Systems like the World-Wide Web can be seen as scale-free networks, i.e. systems in which the probability $P(k)$ that a node in the network is linked with $k$ other nodes decreases with a power-law $P(k) \sim k^{-\gamma}$. They exhibit robustness towards random failures but no survivability in case of a targeted attack [5]. On the contrary, public transport systems present some of the characteristics of small-world networks [6]. To improve their robustness, i.e. not create delays in case of maintenance works, Lu and Shi [7] recommended to identify the most important hubs and links by considering (i) the degree of nodes and (ii) the edges weights.

In structural engineering, Henderson and Bickley [8] used graph theoretical approaches for the evaluation of the topological conditions that govern the degree of statical indeterminacy of a structure. Kron [9] made an analogy between electrical networks and elastic structures. Langefors [10] proposed a complete topological approach to structural mechanics. Various studies were being conduced on the topic throughout the second half of the Twentieth century. Recently, a large contribution has been given by Kaveh, which improved the computation techniques in matrix structural analysis ([11,12] and the references reported herein). From the available bibliography, it seems that very few works have dealt with topological properties of graphs applied to the behaviour

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# Progressive Collapse Analysis of Composite Framed Buildings with Encased in Concrete Steel Beams

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## Summary

Encased in concrete steel beams of trapezoidal shape (Deltabeams) are associated with high values of stiffness, strength and ductility. They can be considered as an appropriate solution for class 2b and 3 buildings according to EN 1991-1-7 with demanding robustness requirements. In this paper the dynamic response of a 30-storey steel-concrete composite building with Deltabeams after a sudden column loss is investigated through the implementation of non linear dynamic analysis (alternate path method). It is found that the catenary actions are highly depended from the type of connections and govern the design. They are also considerably higher than the required tying resistance provided by EN 199-1-7. Finally, unexpected failure modes which may endanger the stability of high-risk buildings are discussed and suggestions on the improvement of EN 1991-1-7 are proposed. This paper offers information from a research project on progressive collapse which is conducted by the R&D department of Peikko Group Corporation.

**Keywords**: Progressive collapse, Deltabeams, alternate path method, non-linear analysis, catenary actions, debris impact, EN 1993-1-1-7

## 1. Introduction

Progressive Collapse of a structure is defined as the failure sequence which is initiated from a local incident, such as the loss of a structural member that leads to a failure of excessive magnitude; large scale collapse. There are many reasons that may cause progressive collapse of a structure for example a gas explosion, a terrorist attack, collision forces or even a serious construction defect. In 1968 the gas explosion in the kitchen of the 18th floor of a 22-story precast building in UK caused the collapse of a large part of the building and the death of three persons. Till that date it was believed that 'hidden over-strengths' which are not taken into account during design are adequate enough to protect the buildings from disastrous domino effects. After 1968 progressive collapse became an issue and many design codes integrated simplified guidelines for avoiding such terrible incidents. The terrorist attack against the twin towers in 2001 was lethal enough to attract the attention of the engineering society and to make clear that a more sophisticated design especially for the case of high-risk buildings is necessary.

From the previous it can be easily understood that modern buildings should be robust against extreme and unforeseeable loadings. Robustness is associated with many structural characteristics the main of which are redundancy, ductility, stiffness and strength. Redundancy is needed so that internal forces can be redistributed to adjacent structural elements through an alternative load-path. Redistribution of forces requires ductile elements and above all ductile connections. But ductility is activated through large deflections that may lead to additional internal forces and P-$\Delta$ effects; thus additional stiffness is needed. Finally, normal forces, shear forces and bending moments during a collapse situation act simultaneously on cross-sections and connections causing an unexpected strength degradation; adequate strength is also necessary.

The design of a robust structure against the threat of progressive collapse is not an easy task. The simplified tying method given in EN 1991-1-7 is for high-rise buildings inappropriate and leads to unsafe results. Elastic analysis is supported by the majority of the commercial softwares but is not realistic since progressive collapse propagates in a non-linear dynamic way. Unavoidably a non-linear dynamic analysis should be employed; alternate path method. Such an analysis is conducted

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# Robustness of steel building structures following a column loss

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## Summary

The present paper gives a global overview on recent developments performed at Liège University in the field of robustness of building structures for the specific scenario “loss of a column”. In particular, the static non-linear response of a steel building structure following a column loss will be first presented and then, a global overview of some recent achievements and ongoing researches will be given with the global strategy aiming at deriving design requirements for practitioners.

**Keywords**: robustness, loss of a column, non-linear response, design requirements

## 1. Introduction

Recent events such as natural catastrophes or terrorism attacks have highlighted the necessity to ensure the structural integrity of buildings under an exceptional event. According to Eurocodes and some other national design codes, the structural integrity of civil engineering structures should be ensured through appropriate measures but, in most cases, no precise practical guidelines on how to achieve this goal are provided. At Liège University, the exceptional event “loss of a column” in a building structure is under investigation, using experimental, numerical and analytical approaches with the final objective to propose design requirements to ensure an appropriate robustness under the considered scenario.

Through first developments, an analytical procedure has been developed to check the robustness of steel or composite plane frames. For sake of simplicity, these first studies have been conducted on the assumption that the dynamic effects linked to the column loss were limited and could therefore be neglected.

More recently, complementary works ([1] and [2]) have been carried out with the objective to address the dynamic effects and a method has been developed that can predict the dynamic behaviour of the frame. The input data of this method are:

- the static response of the frame

- the ratio between the time of failure of the column $t_r$ and the fundamental period of the frame $T$

These dynamic developments are not addressed in the present paper, but more information can be found in [2]. The present paper will mainly focus on the static behaviour of a frame losing a column. Firstly, the global strategy aiming at deriving design requirements will be presented and then a global overview of some recent achievements and ongoing researches in the field of robustness will be given.

## 2. Static behaviour of 2D frames following a column loss

### 2.1 Introduction and general concepts

The present section describes the global strategy adopted at Liège University. The presented study is dedicated to frames only composed of columns and beams; the possible beneficial effect of the slab is presently neglected in the developments. The investigations performed at Liège University in the field of “robustness of structures” are mainly dedicated to the exceptional scenario “loss of a column” in a steel or steel-concrete composite building structure. Under many exceptional actions (explosions, impacts ...), dynamic effects may play an important role. However, it is first assumed that the column loss does not induce such dynamic effects. The main objective of the conducted

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**Safety, Failures and Robustness of Large Structures**

# *Collapses*

# Collapse of the River Verde Viaduct scaffolding system

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## Summary

Explicit risk analysis, a powerful structural safety decision-making tool, was applied to investigate the collapse of a movable scaffolding system (MSS) during construction of the River Verde Viaduct at Almuñécar, Spain in 2005, in which six workers lost their lives. Systematic qualitative risk analysis was conducted to identify the MSS structural safety hazards that may have theoretically caused the collapse. Based on exhaustive experimental and theoretical studies, these hazards were classified by their relevance to the accident. Logical combinations of the hazards were subsequently established to ascertain possible failure scenarios. This was followed by quantitative risk analysis, in which probabilistic methods were deployed to corroborate the likelihood of occurrence of the scenarios envisaged. Without such methods, no credible conclusions could have been drawn.

**Keywords**: bridge construction, automated solution, movable scaffolding system, collapse, forensic engineering, risk analysis, failure scenario, probabilistic analysis

## 1. Introduction

Cost efficiency of the movable scaffolding systems (MSS) used in bridge construction is generally based as fully as possible on automating operating procedures to minimise construction labour costs. Theoretically, automated procedures should also contribute to enhancing on-site safety. The use of sophisticated ancillary equipment generally entails considerable risk, however, as denoted by a number of accidents taking place over a fairly short period of time in recent Spanish history [1]. One such accident involved the collapse of the underslung movable scaffolding used to build the viaduct over River Verde at Almuñécar, Spain, in which six workers plummeted to their death. The severity of the accident and especially its timing contributed to undermining public confidence in the professionals who design and build large-scale civil works and prompted considerable concern in the professional community itself.

The examining magistrate assigned to the case asked an interdisciplinary team of experts from the Eduardo Torroja Institute for Construction Science (IETcc-CSIC), the University of Granada (UGR) and the Polytechnic University of Madrid (UPM) to draw up a forensic report with a dual purpose: on the one hand, to establish the causes of the failure and the mechanism involved, and on the other, to determine whether in spite of the collapse the structure met minimum reliability standards.

The present paper addresses the studies conducted in connection with the first of the aforementioned purposes. The investigation was based on explicit risk analysis, divided into two clearly distinct stages: qualitative and quantitative assessment. The former entailed identifying possible failure scenarios, and the latter calculating the likelihood of those scenarios by means of probabilistic analysis.

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# Testing of full scale pre-stressed concrete beams

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## Summary

This paper deals with testing of pre-stressed I-beams, the behaviour of the beams under loading, strengthening methods and their function.

In the near history in Finland large commercial buildings have been built using pre-stressed prefabricated beams. The cost efficiency has led to designing very slender beams with higher pre-stress forces. This has caused problems in pre-stressed beams around Finland. Damages has been so severe that immediate repair of the beams has been necessary in some cases. Tampere University of Technology helped develop and tested these strengthening methods.

The results of the tests led to development of a formula that estimates the beam’s extra capacity after post-tensioned strengthening method.

**Keywords:** *Testing; Pre-stressing; Concrete beam; Repairing; Strengthening, Post-tensioned bars*

## 1. Introduction

There has been a growth in the construction of massive long span hypermarkets in Finland during the last 20 years. This has led to the use of precast and pre-stressed concrete I-ridge beams. In many cases large holes are made through the web so pipes could go through the beam instead of going underneath the beam. Very often these holes are situated on the ridge area. Normally the biggest bending moment occurs on the central area of the span. This, combined with a poor reinforcement method of the ridge area, has created some problems in Finland. During years 2005-2007 significant cracking has occurred around the holes and on the ridge area. In some cases the damages were so severe that immediate repairing and strengthening of the structure was necessary. [1]

In some cases the damaged ridge area was repaired and strengthened with a steel structure that applied both horizontal and vertical compression around the beam on the ridge area. The large holes in the web were reinforced and cast. However, the function and the capacity of the repaired beams were unclear. This led to testing of full scale pre-stressed I-profile ridge beams in laboratory conditions. The tests were done in Tampere University of Technology. [1]

## 2. Full scale pre-stressed concrete I-beam tests

The tests made in laboratory conditions included five pre-stressed concrete I-beams. Because of the test arrangement the tested beams had to be made five meters shorter than the original damaged beams. Four of the test specimens were similar. They had a big hole in the middle of the beam beginning right underneath the upper flange. The reinforcement and the pre-stressed tendons were similar to the damaged beams taking into account the scale modification. One specimen was made similar to what corresponds today’s way of reinforce pre-stressed beams. This specimen had no holes. All the specimens had 20 tendons and the initial pre-stress was 1050 MPa [2].

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# Failures of dams – Challenges to the present and the future

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## Summary

Under the aspect of recent flood events in Europe and many other countries in the world the safety of water retaining structures and the threat of dam failures, connected with economical and human damages are facts of our daily life. If we consider that such events are global realities and strike all countries, the world-wide communities are confronted in average with one dam failure per week and with the failure of a large dam every two months. Catastrophic failures of levees and dikes which strike in some times also historical constructions which stand in operation under flood conditions during very short periods within a year have changed the opinion that low dams are constructions without risks. Every time failures of tailings dams connected with the loss of the constructions and the outbursts of storages are connected with pollutions of environments. After the destruction of any kind of storage facilities investigations are executed to assess the circumstances and investigate the causes and impacts of such events, knowledge which must be stored for the future.

**Keywords**: Dam; levee; dike; tailings dam; dam failure; data base; concrete dam; masonry dam; embankment ; failure causes.

## 1. Introduction

Dams are significant constructions in civil engineering used for different purposes in our infrastructure facilities. Conventional dams storing water for power production, for irrigation, retention and water supply, canal dams, levees and dikes but also tailings dams exist today in our environment. According to their purposes failures of such constructions have different impacts to our daily life and the causes of breaches are often homemade or influenced by climate changes and the modern way of life. The construction, inauguration and ownership of dams in countries is always connected with the intensification of national pride why failures are tragic events which sometimes kept secret and facts, causes and impacts are classified as non public data.

## 2. Failures of conventional dams

Approximately 1700 cases of dam failures are reported in the Western World and Europe. Including failures in China and Russia more than 5300 cases can be counted. But only a few are registered in databases, more than 3700 cases from China were never reported up to now. According to their construction materials it is distinguished between embankment dams (earth and/or rock) and concrete and/or masonry dams. Approximately 90% of all reported failure cases affected embankment dams. Most of these dam failures were not the result of extreme loading conditions. Rather, embankment dams typically failed due to unforeseen or unrecognized conditions that result in piping or seepage failures (46% of all reported cases), overtopping at less than the design inflow (48% of all reported cases), foundation failures, errors in operation, or other “non standard” failure modes – as examples.

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# Ring Rail Line – Protection structures against aggressive fluids

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## Summary

During the excavations of railway tunnel of Ring Rail Line ground water leakages containing adverse compounds were found under the airport area. The investigations showed that ground water at a minimum pH under 5 is acidic and contains antifreeze agents as ethylene and propylene glycols which have been used decades in aviation. In aerobic conditions the glycol based fluid forms alcohols and organic acids, most relevant of them acetic acid and propionic acid. The fluid is a nutrient for microbes and enables their growth in a tunnel. The microbe growth forms also distinctive odour, which is undesirable at underground railway used by passengers.

To isolate harmful aggressive leakages protection structures were designed for all tunnel sections and station areas where adverse substances were detected. Leakage has been found to be corrosive to steel structures and erode to cement-containing structures so polyethane membranes were designed to install around the railway tunnel structures and all materials which can be in contact with glycol based fluids were chosen for aggressive environments.

**Keywords**: protection structure, isolation, glycol, acids, membrane, microbe growth, concrete element, anchors.

## 1. Introduction

The Ring Rail Line is an important circular route of the Helsinki Metropolitan Area. It is an urban two-track passenger line for local traffic in Vantaa between Vantaankoski and Tikkurila and a rail link from Helsinki to Helsinki-Vantaa airport. The total length of the new line is 18 km, of which 8 km run in twin rail tunnels mainly under the Helsinki-Vantaa airport area.

Construction of the Ring Rail Line began in spring 2009. During excavation works under Helsinki-Vantaa airport area liquid fluid with distinctive odour was noticed leaking into the rail tunnel. The first observations of contaminants were made in summer 2010 and in autumn a comprehensive study of liquid and its origin begun.

Many water samples were taken to define liquid's contents and its impacts to indoor air and reinforcement structures of tunnel. The investigations showed that ground water is acidic and the fluid is nutrient for microbes and enables their growth in tunnel walls and bottom. In aerobic conditions it forms alcohols and organic acids, most relevant of them acetic acid and propionic acid. The microbe growth forms distinctive odour and showed to have a capability to block drainage

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# Vehicle Collision into Steel Pedestrian Bridges

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## Summary

During 2010 a few steel footbridges collapsed in Finland as a result of over-height vehicles colliding into the superstructure. This caused an investigation into horizontal impact loads on superstructures of pedestrian bridges and the magnitude of the collision force. To analyze the collision numerically, many parameters must be taken into account and a dynamic structural analysis must be performed. The magnitude of impact is strongly affected by the mass distributions and rigidities of the colliding vehicle and the bridge during the collision, as well as vehicle velocity, damping, changes in the geometry of both objects, the nature of the contact surface and resulting energy losses etc. The duration of collision time is short, usually only fraction of seconds, causing difficulties in the numerical analysis. In this paper a vehicle collision on bridge deck is reported. Collision forces of design codes are compared to the values obtained by simple spring mass system and results obtained by using dynamic nonlinear finite element analysis.

**Keywords**: Pedestrian bridge, steel bridge, impact, vehicle collision, collision forces, collapse, dynamic analysis, finite element method.

## 1. Introduction

In November 2010 a pedestrian bridge collapsed due to collision of over height vehicle on bridge's superstructure in Laajasalo, Helsinki. The driver did not notice that the loading crane of the truck was in upright position while driving. The crane hit on the superstructure and as a consequence the bridge collapsed.

### 1.1. Structure of the collapsed bridge

The bridge was statically determinate, one span pedestrian steel beam bridge with a wooden deck. The length of the superstructure was 20.2 m, the span 19.5 m and the effective width 3.5 m, respectively. The free height for under-pass was more than 4.6 m (Fig. 1).

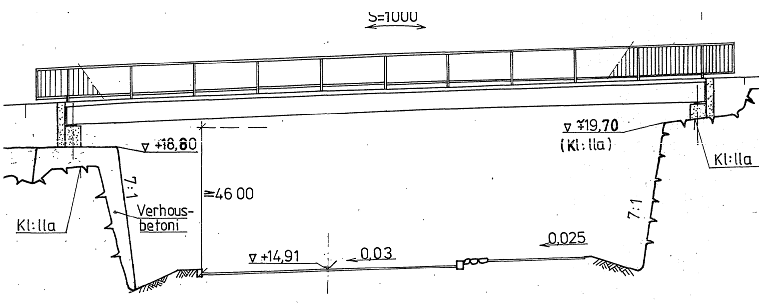


*Fig. 1: Elevation of the collapsed pedestrian bridge.*

The steel frame of the superstructure was a grillage consisting of two main girders (HE 600 B) and six transverse beams (HE 160).

The beams were connected by 5 mm fillet welds to the mid-height of the webs of the longitudinal girders as shown in Fig. 2.

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**Safety, Failures and Robustness of Large Structures**

# *Safety*

# Fire Safe Steel Structures - case studies

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## Summary

This paper presents practical applications of fire protection methods of steel framed buildings and enlightens the research in the background. The challenges to be met are partly due to the fact that especially the commercial buildings are getting bigger all the time and then also the area to be protected is larger. This leads very often to performance based design. In performance based design the realistic circumstances of the building, fire loads, dimensions, use and the fire risks are evaluated so that a sufficient safety level is achieved. In this kind of design normally part of the structural protection is done by traditional methods. This means that it's no use of doing protection with too complicated ways, if some part of the structures is possible to protect cost-effectively and easily.

**Keywords**: Fire safety engineering, steel structures, natural fire design, fire protection,

## 1. Introduction

Fire safety issues have always been a very important part of designing structures. The means of doing it have been developed widely for a long time. The development has naturally followed the requirement history. Also the sizes and shapes of buildings have changed dramatically from the past to modern times. This has an extremely strong influence on fulfilling adequate fire safety level.

Safety in case of fire consists of several different parts, which still are connected tightly to each other. The main aim is naturally to avoid injuries and fatalities of the users and also rescue personnel. Also the spread of fire and damages to the building and to the property have to be avoided. To achieve this, the building's smoke ventilation, integrity and structural fire resistance have to be designed and built so that this is possible within certain probability.

This paper presents practical applications of fire protection methods of steel framed buildingsbased on research and development and enlightens the research in the background. The challenges to be met are partly due to the fact that especially the commercial buildings are getting bigger all the time and then also the area to be protected is larger. This leads very often to performance based design.

In performance based design the realistic circumstances of the building, fire loads, dimensions, use and the fire risks are evaluated so that a sufficient safety level is achieved. In this kind of design normally part of the structural protection is done by traditional methods. This means that it's no use of doing protection with too complicated ways, if some part of the structures is possible to protect cost-effectively and easily.

The performance-based structural design system together with other fire protection methods will be presented, among fire protection with water sprinklers and other more traditional methods. The presentation consists of research and development, the actual methods and real cases built during the last couple of years. This is to show the chain how this kind of research really is worth carrying out to achieve better safety and more optimized solutions.

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# Robustness of a typical beam-column concrete structure exposed to fire

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## Summary

Concrete structures behave mostly well during a fire, however, in some cases collapse is found before the calculated fire resistance is obtained. This premature collapse during fire can be explained when studying the global structural response, as stresses are induced by restraint actions of the thermal deformations. This paper studies the behaviour of a structure consisting of beam-column connections exposed to the ISO 834 fire by means of the finite element package Diana. It is found that the effects of thermal restraint can be modeled. Internal thermal restraint may cause vertical cracks in the concrete element which do not extend towards the bottom surface of the heated beam. External thermal restraint is found as the gradual development of plastic hinges and the increase of shear forces which first appear well before the fire resistance according to the simplified methods of EN 1992-1-2 is attained. Due to the thermal deformations, cracks may also occur in building elements not directly exposed to the fire.

**Keywords**: fire; concrete; cracks; collapse; EN1992-1-2; finite element analysis.

## 1. Introduction

In most cases, concrete structures behave very well during a fire and although they suffer from damage to a certain extent, they mostly show to have a remaining load bearing capacity after fire. Nonetheless, in some cases, concrete structures fail partly or completely due to the event of a fire. The question can then be raised why those structures collapse, as they fail before the fire resistance as found from simplified calculations (e.g. tables, 500°C-isotherm and Zone method) according to EN1992-1-2 is reached.

Recent examples of such premature collapses are found in the underground car park in Gretzenbach (Switzerland) in 2004 [1] due to punching failure and the partial collapse of a hollow core slab in the apartment building Harbour Edge (the Netherlands) in 2007 [2, 3]. Other examples are the total collapse of a warehouse in the port of Ghent (Belgium) in 1974 [4] and the Library in Linköping (Sweden) in 1996 [4], both due to shear failure at the top of the columns.

The mechanism behind these premature collapses is explained at the structural level, namely the influence of restrained thermal deformations at the supports and the interaction with other parts of the structure. The authors have illustrated this concept in [5, 6] with respect to punching shear of underground car parks. From this point of view, the simplified calculation methods of EN1992-1-2 are limited in their capability to assess the fire resistance, as they basically consider the fire resistance of a single element and do neglect indirect thermal actions due to restraints of deformations. On the other hand, the framework and material laws to execute a global structural analysis are stated in the Eurocodes. Nevertheless, due to lack of time and specific knowledge of

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# FDS2FEM – a tool for coupling fire and structural analyses

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## Summary

Computational modelling of fire-structural response requires interoperability of various models describing different physical phenomena. Typically, the most advanced sub-models are found within independent simulation software incapable of interoperability. To address this issue, we have developed a tool for coupling two of such programs: Fire Dynamics Simulator and ABAQUS. We present the main features and theory behind the coupling approach and use an example case to demonstrate how a coupled fire-structural analysis is set up. We also discuss potential applications and present limitations of our approach.

**Keywords**: fire-structural analysis; Fire Dynamics Simulator; Abaqus; fds2fem

## 1. Introduction

Fire-induced damage along with thermal and mechanical strains can have a significant influence on the integrity, insulation and load bearing capacity of a structural element and the overall performance of a larger structure. Theoretical estimates for the fire-performance of structures have traditionally relied on analytical expressions for the temperature of the fire environment. This means a uniform and well-behaved heat exposure — something that might be far from reality. This is especially true in the case of fires in large open spaces. The traditional approach might be overly conservative in some cases, and even unconservative in others.

Present-day computational fire models enable the prediction of realistic, temporally and spatially varying, heat exposures. These can be used as a basis for advanced fire-structural analyses that take into account the dynamic and non-uniform nature of fire-induced thermal stresses. However, the presently available fire simulation tools do not include sub-models for the prediction of structural response. This kind of functionality is available in other software tools developed for continuum-level mechanics modelling. These tools are in turn incapable of predicting the fire environment.

Computational modelling of the fire-structural response can be divided into four steps: modelling of (i) the fire environment, (ii) thermal response of materials, (iii) fire-induced damage and weakening of materials, and (iv) the mechanical response of the structure. Advanced fire-structural modelling requires either integration of these models into a single piece of software or coupling of software developed for the specific tasks. To the best of our knowledge, the former approach has not been realised to date. The latter approach has been utilized in various studies (e.g. [1-4]), including ones related to the investigation of the World Trade Center disaster [1,4]. In this approach, two major problems have to be solved. Firstly, the simulation tools from different developers are seldom able to communicate with each other. An interface that enables data exchange has to be set up. Secondly, there will be differences in the spatial and temporal discretizations. Due to this, also the model geometries are prone to differ. The data that is transferred from one program to another has also to

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# Development of database for the in-service inspection of the concrete structures of the Finnish Nuclear Power Plants

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## Summary

The in-service inspections are an essential part of aging management and condition monitoring of the nuclear power plants. The purpose of the in-service inspections is to prevent the damage of concrete structure from being increased to such a degree that they could risk the normal operation or safety of nuclear power plant structures. The in-service inspections are generally divided into three categories: visual inspections, special inspections, and monitoring and measurements.

The paper is about the development of a database for the in-service inspections data of the nuclear power plants concrete structures. The objectives of the database are to (i) collect the essential and up-to-date data of the condition and the performance of the NPP concrete structures, (ii) store and update these data effectively, (iii) allow sophisticated search strategies, (iv) produce detailed reports automatically for the condition and the performance of the NPP concrete structures and (v) enable data transfer to other software for further analysis.

The design process of the database includes the system analysis, the logical and physical design, and then the final system implementation ant testing. The structure of the database includes the information about the concrete structural and the surrounding climate, electronic documents and digital photos, visual investigation and diagnosis reports and non-destructive and destructive test results. The structure of the database is established to reflect the time dependent structural and functional performance of the concrete structures. The implementation phase involves in-service inspection raw data collection, validation, and harmonization for general use in the NPP. The raw data will be provided by each plant from their files and records and testing laboratories.

Organization of the in-service inspection results in the database will be useful to define in-service inspection and monitoring programs and establish maintenance strategies. In addition, this database will allow access to the data needed for development of ageing trends which in turn will indicate when critical stage is expected or emphasize when remedial actions are needed. It will also enhance the decision-making process for preventing or mitigating ageing effects by providing information for continued service evaluations and remaining service life estimates.

**Keywords**: Nuclear Power Plants; database; in-service inspection; concrete structures; deterioration.

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# Medium scale testing and simulation of aircraft crash

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## Summary

The topic of an aircraft crash against a nuclear power plant building has received increasing attention during the last decade. VTT has carried out series of jointly funded and designed impact tests and also developed numerical methods and models with which this event can be analysed. In addition, simplified computation methods that are especially useful in parametric studies have been developed at Tampere University of technology (TUT). During the crash, fuel in the fuel tanks is likely to burst out of the ruptured fuel tanks. Fuel burning in pools close to the building might cause significant heating of the structures. Also, the flames and smoke may be transported into the air intakes of the building. These two phenomena are mainly studied via numerical fire simulations with experimentally determined boundary conditions describing the fuel spray behaviour. This paper describes the work carried out in these sub-topics of an aircraft crash.

**Keywords**: nuclear power plant, large aircraft crash, impact testing, structural analysis, fire simulation

## 1. Introduction

Crash of a large commercial aircraft against a building made out of reinforced concrete give rise to several threats for the structures of the building and persons and equipment inside it. Loading is comprised of multiple factors resulting different types of response of the structure. Based on the loading type and harm they induce, parts of an aircraft can be roughly divided as follows:

- fuselage of the aircraft,
- motors and other semi-hard parts,
- fuel bursting out of the desintegrated tanks, and
- wings.

The fuselage of an aircraft is considered to be much more deformable, or softer, than the concrete structure that it impacts against. It causes loading which is considered to be mainly mass flow. Response of the structure to this type of loading is mainly bending, leading in extreme cases to large displacements and rupture of reinforcement longitudinal reinforcement and consequently loss of load bearing capacity of the structure.

The hard parts in turn are considered to be much less deformable than the concrete structure that it impacts against. These parts try to perforate the wall causing also scabbing off concrete at the surface of the wall opposite to the impact surface.

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# Impact loads in steel connections

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## Summary

After attacks on World Trade Center (2001), Madrid (2004), London (2005) and Mumbai (2008), special attention was given to the study of robust structures subjected at different accidental loads, allowing localized failure without being damaged to an extent disproportionate to the original cause. The collapse of the World Trade Center (WTC) showed problems in the design of structural elements: columns collapse, beams buckling and brittle failure of connections. Concerning this last topic, it was realised that the joint structural details plays very significant role behaviour in structures subjected to accidentals loads. The accidental loads may result from an object impact, blast, explosions, earthquake and fire.

The work presented in this paper corresponds to the first work package of the research project Impactfire, currently in development at the University of Coimbra; the behaviour of steel beam-column connections against accidental impact loading is the main objective of the project. The current paper is focused in: i) characterization of the impact scenarios in steel structures, ii) influence of strain rate sensitivity steel material model, and iii) previous research studies on the behaviour of steel beam-column connections against impact loading. At the end, the experimental programme of the research project Impactfire is presented.

**Keywords**: connections, design standards, high strain rate, impact scenarios, robustness, steel structures.

## 1. Introduction

The loads associated to an accidental event are normally with severe intensity and resulting in extraordinary consequences. Examples of accidental loads are: fire, blasts, impact, earthquake, avalanches, landslides, and so on; moreover, the combination of these scenarios must also be considered such as fire after impact or fire after earthquake. These topics are addressed in the strategic research agenda of the European Steel Technology Platforms [1], which cites the need for safety in the design, manufacture and performance of steel structures, especially against natural hazards and accidental loading. Thus, it is important to know the type and magnitude of the loads applied in the structure, when an extreme event occurs, in order to evaluate the corresponding response and the role played by each structural component to prevent progressive collapse of the structure.

The Eurocode standards present some specific parts for the design of structures in case of accidental actions such is fire (parts 1.2 of the Eurocodes) and earthquake (Eurocode 8). Additionally, part 1-7 of Eurocode 1[2] gives some guidelines and application rules for the assessment of accidental actions on buildings and bridges with the identified and unidentified accidental actions. The unidentified actions are related to robustness requirements. For the identified actions, impact and explosions are under the scope of this standard. This type of loads can be defined as impulsive, characterized

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**Safety, Failures and Robustness of Large Structures**

# *Structural Design*

# Background of target reliability levels for existing structures

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## Summary

The structural safety of existing bridges can be confirmed by a bearing capacity assessment. The conventional method of evaluating a bridge is the partial safety factor method. A more sophisticated way to assess bearing capacity is the reliability analysis. It allows calculating the reliability index of the structure. The calculated reliability index should be compared to the target reliability index to determine if the structure and related risks are acceptable. Values for target reliability indices are proposed in codes. Structure and load type specific target reliability indices can also be determined. For existing structures, it is possible to calculate more accurate target reliability indices related to the consequences of failure. Increased probability of failure due to lower reliability indices can be tolerated if the consequences of failure are limited and an economic benefit is gained.

**Keywords**: Target reliability, reliability index, structural monitoring, safety level, reliability analysis

## 1. Introduction

In Finland and Europe, the focus of construction industry is increasingly shifting -from new building of bridges to the maintenance of the existing bridge stock due to worsening performance of the ageing stock due to deteriorating. On the other hand the requirements for existing bridges are becoming more demanding due to increased axle loads of both highway and railway traffic and increased speed of railway traffic. Heavy special transports have also become more common in both modes of transportation. These trends lead to an increase in the number of suspicious bridges. That, again, requires more bearing capacity assessments.

There is increasing need to develop and adopt assessment methods for determining the bearing capacity of bridges. In particular, there is a need for assessment methods that allow better detection of their present condition and development in a bearing capacity assessment. With the developed methods it is possible to evaluate the bearing capacity of a bridge more precisely. In addition to the calculation of structural reliability, an important part of assessment is to select a target reliability index.

The importance of the target reliability level of bridge structures is particularly pronounced with existing bridge structures. Too low target reliability of leads to failures, while too high value leads to uneconomical reinforcement solutions. Because of these two reasons, target safety level and target reliability index should be determined accurately. In the case of a newly built bridge, the economic effect of high target reliability is less significant.

It is possible to determine target reliability levels considering the consequences of failure. If it is possible to limit the consequences of failure the higher risk of failure can be tolerated. If there is a dependence between load intensity and consequences of failure under load, it is possible to determine different target reliability indices for different load types.

This paper presents some principles and background for determining an adequate target reliability

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# Load combination

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## Summary

A universal theory on combining loads in structural design is missing. The current codes include three methods: dependent, semi-dependent and independent. These methods are mutually contradicting and inconsistently applied: The paper presents arguments that the structural loads must always be combined dependently. The current load combination is unsafe in comparison with the target reliability. In the Eurocodes for instance the safety factors are up to 20 % too low. Before the load combination, the load distributions must be set up to the appropriate design state. In the Eurocodes, the permanent load distribution is set up correctly. However, the variable load is set up wrongly for one-year loads but should be set up for 50-year loads. Therefore the safety factor for the variable load is too low. 50-year failure probability of the Eurocodes should be 1/15000 but it is 1/1000 assuming that the uncertainty is 10 % and the variable load factor is increased ca 10 %.


**Keywords**: Load combination, code, reliability.

## 1. Introduction

The load combination is the key issue in the safety factor $\gamma_G$, $\gamma_Q$, $\gamma_M$ and the combination factor $\psi_0$ calculation. The dominant hypothesis is that the loads are combined independently if the loads are independent, dependently if the loads are dependent and other loads are combined semi-dependently. However, the permanent loads are independent but combined always dependently. The permanent load and the variable load are combined sometimes independently and sometimes dependently in the failure state but combined always dependently in the serviceability state. Variable loads are combined usually semi-dependently but sometimes dependently.

An explanation is missing why different combination methods are used. A uniform theory on the load combination is missing.

### 1.1 Current theory

The basic load combination theory is revealed by MADSEN [1], MADSEN ET AL [2] and TURKSTRA [3]. Much theoretical research is paid to find out how variable loads are combined and how the load configuration impacts on the load combination. The current variable load combination is based on Turkstra's method TURKSTRA [3]. The combination load is the higher load which is obtained when one load is constant and the other load has a random value. In this load combination, the load configuration has no effect.

The theoretical references [1, 2, 3] and references [4, 5, 6, 7, 8] explaining the actual load combination in the code, describe that the loads are stochastic and combined independently. However, this concept is not consistently applied.

No reference explains why permanent loads are combined dependently although these loads are independent?

If there are many loads, e.g. imposed loads of a multi storey house or many permanent loads, the independent load combination results in an unrealistic outcome, as the reliability vanishes. The unrealistic outcome of the independent load combination is recognized in an Eurocode background document: *Imposed loads on floors and roofs* (1990) "The storey-dependent reduction formulas of the code-draft are not scientifically derived…". The current load combination theory does not address this contradiction either.

The references [1, 2, 3, 4, 5, 6, 7, 8] do not address several other significant issues of the load combination:

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# System Identification of Multi-story Buildings with a Pair of Seismic Recordings

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## Summary

This study presents system identification of ten-story Millikan Library in Pasadena, California with a pair of the Yorba Linda earthquake of September 3, 2002. The fundamental of the proposed approach is based on wave features of generalized impulse and frequency response function (GIRF or GFRF), i.e., wave response at one structural response location to an impulsive motion at another reference location in time and frequency domains respectively. With a pair of seismic recordings at the two locations, GIRF/GFRF is obtainable. With a continuous-discrete model for the structure, a closed-form solution of GFRF, and subsequent GIRF with Fourier transformation of GFRF, can also be found in terms of structural physical properties above the impulse location. Matching the two sets of GIRF/GFRF from recordings and the model helps identify system parameters such as wave velocity or shear modulus.

**Keywords:** Continuous-discrete modeling; Seismic structural responses; System identification.

## 1. Introduction

For seismic design, vibration control, and damage diagnosis of multi-story buildings, such as ten-story Millikan Library building located in Pasadena California, response characterization and system identification are fundamental and typically carried out with a discrete, multi-degree-of-freedom (MDOF) model. As far as one-dimensional (1D) horizontal motion is concerned, the Millikan Library building as shown in Fig. 1a can be modeled as a 10-DOF system with each floor mass and inter-story stiffness (i.e., physical parameters) calculable based on design configuration and materials. These physical parameters can also be calibrated in terms of identified vibratory features (i.e., modal frequencies, damping, and shapes—a function of physical parameters), through Fourier spectral analysis of 11-set acceleration recordings of the Yorba Linda earthquake of September 3, 2002.

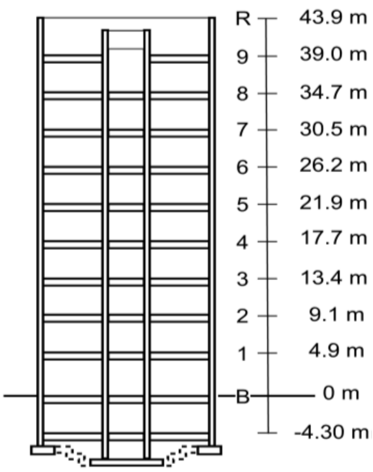


*Fig. 1a: Vertical cross-section of 10-story Millikan Library, Pasadena, California*

While the aforementioned discrete modeling is overwhelmingly used in structural engineering (e.g. [1,2]), it has limitation in characterizing comprehensive seismic motion in structures with a finite number DOF modeling in general, and distorting time-space or wave features of seismic motion in buildings in particular. Misrepresenting the seismic responses in structures would falsely predict, likely underestimate, the maximum inter-story drift, a key index of seismic demand for structural design. This is due to the fact that time-delay peak waves at two neighboring floors would have the drift calculated as difference between one peak amplitude and one non-peak value, which is typically larger than the difference between two peak values without time-delay effect. This time-delay

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# Catenary behaviour in concrete slabs: Experimental and numerical investigation of the structural behaviour

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## Summary

A very important property of concrete structures with regard to robustness is the rigid connectivity with neighbouring elements. When a hyperstatic concrete slab is excessively loaded or when a certain support is lost due to an accidental situation, membrane forces can be activated in order to establish a load transfer to the remaining supports. This favourable effect can considerably enhance the slab's load-carrying capacity compared to predictions obtained from small deformation theories. Thus, membrane actions can prevent or delay a progressive collapse and increase the robustness of concrete structures.

A novel real-scale test set-up has been developed in order to assess the structural behaviour under catenary action in real-scale concrete slabs and the influence of reinforcement curtailment, since in current design practice the main flexural reinforcement is calculated for the slab's critical sections and consequently the reinforcement is curtailed based on the envelope of the acting internal actions. The investigations include the testing of a reinforced concrete slab strip with continuous flexural reinforcement over the entire length and a second test differing only from the reinforcement arrangement, considering current design codes for reinforcement curtailment. The slab specimens were exposed to an artificial failure of the central support and subsequent vertical loading until collapse.

Furthermore, finite element methods allow to simulate the behaviour of concrete slabs under these large deformations. Numerical FEM analysis of the executed real-scale tests will be explained and compared with the experimental results. Finally, the influence of reinforcement curtailment on the overall performance under catenary action will be discussed.

**Keywords**: concrete, robustness, FEM analysis, membrane action, mechanical testing.

## 1. Introduction

Calamities such as the collapse of the apartment building at Ronan Point (UK) in 1968 or more recent catastrophes such as the failure of the Alfred P. Murrah Federal Building in Oklahoma City in 1995 or the collapse of the World Trade Centre in New York in 2001 indicated the need to carefully design reinforced concrete structures in order to avoid progressive collapses.

It has long been recognized that the development of membrane action can considerably increase the load-displacement behaviour of concrete structures [1, 2]. Fig. 1 illustrates the response curve of a fully restrained slab under membrane action.

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# Improving the quality of structural concrete design

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## Summary

Common practise in concrete design engineering is the sectional design approach. The model should be the most simple choice in this approach and will be often a 1D design model. The design process delivers the generalised moments, forces and displacements. The checks to the actual checking code is on a sectional base, where the section evaluation will be made nonlinear. In a more advantage design process the design model will be updated to a 2D design model. The 2D model results are distributed moments and forces, which give an overview of the results over the width of a 2D model. The distributed moments, forces can be integrated to the generalised moments and forces, so a check to the 1D model can be given too. Both models, the 1D and 2D models have a linear distribution over the height of the structure.
The full 3D design model isn't a common model in practices engineering, but by integrating stresses or strains over the height of the 3D model, the similar results coming from 1D and 2D can be generated.
Today checking codes like Eurocode2 and ModelCode2010 allow the designer to use nonlinear analysis as additional tool to the linear approach. For existing structures these nonlinear analysis can help by looking to the remaining capacity and the remaining lifetime of a concrete structure. In this way it is possible to keep 'old' structures in operation on the actual infrastructural network. For new structures it is obvious that at this moment nonlinear design steps of a concrete structure aren't acceptable. It is a too new process in the actual civil engineering practise, where there are no direct failures to the common accepted linear design process. But this nonlinear accepted design process could be moved to a closed concrete design process, where the nonlinear analysis gets the status of controlling the linear design process. A control function could avoid failures in designing the reinforcement or prestressed reinforcement. The designer will be warned already in the concrete design stage for failures or mistakes.
However implementing a full nonlinear analysis isn't an option, but the so-called sequential linear analysis, a quasi nonlinear analysis, is very robust and powerful to minimize the elapse time of this kind of control analysis. While the design process is setup in full 3D, BIM, inspection regime and maintenance are coming more together in an overall process in the near future.

**Keywords:** concrete design, infrastructure, finite elements analysis, design and reexamination, 3D solid model, stiffness adaptation

## 1. Introduction

Most of the bridges in the Netherlands have been built before 1970 and have not been designed for today's amount of heavy traffic and also not the traffic loads of today. Therefor the Civil Engineering Department of the Ministry of Infrastructure and the Environment in the Netherlands wants to know the remaining capacity of these bridges and more in general of all structures in the

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# To the question of risk management for failures of cable-stayed and prestressed bridges in Russia

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## Summary

The characteristic cases of cable-stayed and prestressed bridge structures failures and collapses in Russia are considered. Some results of risk analysis methodology applied to bridge structures are given. The process of identification of potential hazards and possible failure modes, definition the critical risk of failure with respect to the bridge structures are described. In order to improve a technical condition of bridge structures and to reduce the risks of their failures and collapses, some risk management actions were suggested with respect to the cable-stayed bridge on the Russian island in Vladivostok. Some of them are given in the report. For example, an inspection monitoring system, founded on new non-destructive equipment, is developed.

**Keywords:** cable-stayed, prestressed structures, failures, collapses, risk management, life cycle.

Before the beginning of the XXI century, there was the only cable-stayed bridge in Russia over the river Sheksna in Cherepovets with a maximum span of 194.5 m, built in 1979. In 2000, the cable-stayed bridge was built in the Siberian city Surgut, with the largest span of 408 m. Since then, every year in Russia one or more cable-stayed highway, pedestrian and pipeline bridges are built. Now there are about 20 such bridges in Russia. Span length was gradually increased and reached 1104 m for the bridge over the Eastern Bosphorus Strait to the island “Russian” in Vladivostok, which is currently the world record. Height of the pylons of this bridge is 312m and the maximum length of cables is 580.5 m which also is a record.

Aspects of safe, reliable and efficient operation of the bridge on the Russian island were of particular relevance in the design. That's why the general design institute "Mostovik" have requested design bureau "Transmost" to develop individual system of operation, monitoring and maintenance for this bridge. It was required to consider not only unique structures, but also the surrounding environment, characterized by force and violence influences: temperature conditions, corrosion, seismic, wind and wave loads.

This article considers only some aspects related to risk management for failures of cable-stayed and prestressed bridges. The bridge on the Russian island contains both types of such load-bearing structures with a high degree of responsibility. Some data on failures and collapses of such structures were collected and analyzed during operation.

It should be noted that the failures of Russian cable-stayed bridges were hitherto insignificant. Basically, they are diagnosed as wire breaks in some rope sections, excessive dynamic vibrations and local damage from traffic. For example, on the bridge over the Ob River in Surgut several wires in areas close to the anchors on the pylon were broken. The monitoring system also identified adverse frequency spectra induced oscillations of cables. To minimize the negative dynamic effects, the bridge was equipped with additional dampers, and damaged areas were fixed by elongation of anchorage zone.

The small number of failures of cable-stayed structures in Russia is due, first, to their relatively short period of operation, initially increased attention to these structures, as well as their availability for inspection and maintenance. At this point there is another risk group which is no less disturbing - prestressed bridge superstructures. Having the same type of main load-bearing elements, as cable-

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