**Robustness of Structures**
Proceedings of the Final Conference of COST Action TU0601

# Robustness of existing structures

Miroslav Sykora, Jana Markova, Milan Holicky and Karel Jung
*Klokner Institute, Czech Technical University in Prague, Czech Republic*

## Abstract

Uncertainties in modelling of existing structures and assessment of their robustness may be significantly different from those considered in design of new structures. In general, modelling of existing structures should be based on results of in-situ inspections, measurements and tests. Principles for the modelling are outlined focusing on description of basic variables, structural modelling and testing. Since structural modelling is closely related to robustness measures under consideration, provisions concerning robustness of existing structures and commonly applied measures are overviewed. Case studies provide information on experience from selected structural failures.

It appears that actual conditions of existing structures should be taken into account in modelling and robustness analysis of existing structures. Advanced theoretical modelling can be often justified by considerable repair cost savings. A cost-benefit analysis provides a valuable tool for rational decision-making concerning robustness measures such as reduction of exposures, local strengthening and improvements of the redundancy. In many cases such analysis will lead to the application of relatively simple measures, acceptance of the present conditions, and/or orderly measures till major rehabilitation for other reasons.

## Keywords

Existing structures, modelling, robustness measures.

## 1. Background / Introduction

Uncertainties in modelling of existing structures and assessment of their robustness may be significantly different from those considered in design of new structures. Some of them may be less significant than for new structures (modelling uncertainties, deviations from specified dimensions and strengths), some of them may be more significant (data on inaccessible members and connections), Ellingwood (1996). In general, modelling of existing structures should be based on results of in-situ inspections, measurements and tests. Principles are outlined focusing on description of basic variables, structural modelling and testing. Since structural modelling is closely related to robustness measures under consideration, provisions concerning robustness of existing structures and commonly applied measures are overviewed.

## 2. Modelling of existing structures

### *2.1 General principles*

In accordance with Bucher et al. (2005) the actual structural system, conditions and actions have to be compared with the assumptions in the original design. The information can be obtained from original design and construction data, history data (monitoring, special events) and visual inspections and measurements.

Principles of modelling and assessment of existing structures can be found in several standards including ISO 2394 (1998), ISO 13822 (2003) and publications of scientific organisations, see Bucher et al. (2005), Diamantidis (2001), IStructE (1996) and Finnish Ministry of the Environment, Housing and Building Department (2000). Background information for modelling and assessment of existing bridges is provided in the report by von Scholten et al. (2004) and background documents of COST 345 (2004).

### *2.2 Actions and environmental effects*

In analysis of existing structures the load effects should be considered with values corresponding to the actual situation of a structure and foreseen use. For existing structures with significant permanent actions, the actual geometry should be verified by measurements (see the following section) and characteristic values of weight densities of materials should be obtained from statistical evaluation of test results. When overloading was observed in the past, it should be considered in the structural modelling. Verification of the load history may be important in particular for industrial buildings and bridges. Models for climatic actions provided in valid codes should be applied.

In many cases it is necessary to include unfavourable environmental effects causing deterioration. Deterioration reduces resistance and performance of structural members and joints and ultimately reduces reliability of a structural system. Deterioration models are used to predict changes in structural parameters due to foreseen structural loading, environmental conditions, maintenance practices, and also past exposures. Examples of unfavourable environmental effects and defects of structures due to degradation, accepted with modifications from COST 345 (2004), are listed in Table 1.

| Unfavourable environmental effects | Defects of structures due to degradation | | | |
|---|---|---|---|---|
| | Concrete | Structural steel, aluminium, iron | Masonry | Timber |
| Erosion | Cracking | Fatigue cracking | Scaling, spalling and delamination | Splitting |
| Abrasion | Reinforcement corrosion | Fracture cracking | Falling-out of units | Decay |
| Scour | Honeycombing | Corrosion | Cracking | Deterioration of impregnants |
| Weathering | Scaling | | Friability | Elongated bolt holes |
| Wetting | Spalling | | Disintegration of mortar | Corrosion of metallic connectors |
| Leaks | Delamination | | Detachment | |
| Efflorescence | Disintegration | | Corrosion of metallic connectors | |
| Vegetation | Alkali-silica reaction | | Peeling of mortar coating | |
| Freeze-thaw | Breaking-away | | Deformation | |
| | Deterioration of protective coatings | | Deflections | |
| | Damage to mortar coatings | | | |
| | Stratification | | | |
| | Deformation | | | |
| | Deflections | | | |

Table 1: Examples of unfavourable environmental effects and defects of structures due to degradation

General provisions for accidental design situations are covered by codes of practice. The values of accidental actions to be taken into account in the analysis should be based on valid codes or risk assessment.

### *2.3 Geometry*

Actual geometry has influence to the load-bearing capacity, deformations and self-weight of structural members. When original design documentation is available and no deviations are evident, the nominal dimensions in accordance with the original design documentation can be used. These dimensions including position of reinforcement shall be adequately verified by inspection. Occurrence of irreversible deformations should be verified particularly in the case of evidence of past overloading.

### *2.4 Material properties*

Material properties shall be considered according to the actual state of the structure. When original design documentation is available and no serious deterioration, design or construction errors are evident, the values in accordance with the original design may be used. However, it may be useful to determine as-built mechanical properties since actual material strengths are usually greater than the nominal design values. In case of any doubts, the properties of materials shall be determined from material testing including destructive or non-destructive procedures (acoustic emission, liquid penetration inspection, radar methods, ultrasonic inspection).

In many cases it may be appropriate to combine new information from inspection and tests with prior information available from previous experience (material properties known from long-term production, performance of similar structures with similar exposure levels). Theoretical basis for this updating provides Bayesian techniques described by Diamantidis (2001), JCSS (2006) and ISO 12491 (1997).

Mrazik (1987) evaluated extensive measurements of material characteristic of existing steel structures built from 1975 to 1996 which may be used as a prior information, see Table 2. Material properties of existing concrete, steel, timber, masonry and composite structures are given e.g. the Czech National Annex to ISO 13822 (2003).

| Class of steel | Strength | Coefficient of variation |
|---|---|---|
| 11373 | Yield | 0,084 |
|  | Ultimate | 0,070 |
| 11483 | Yield | 0,055 |
|  | Ultimate | 0,050 |
| 11523 | Yield | 0,070 |
|  | Ultimate | 0,058 |

Table 2: Coefficients of strength variation for
steel classes (11373, 11483 and 11523)

### *2.5 Connections*

Modelling of connections is very important in analysis of robustness as they may significantly contribute to structural ductility, influence the ultimate strength of structural members and assure the load redistribution after local damage. Representation of connection details may be needed to prove actual rotational and tensile capacity of as-built connections, Ellingwood et al. (2007).

Joints and detailing of an existing structure may be different from present design practice. The deterioration of connections should be considered. It may be necessary to identify differences between design assumptions and as-built conditions and to estimate influence of deterioration. Advanced analytical models may then be developed.

## *2.6 Structural modelling*

Limited knowledge on performance of existing structures exposed to extreme events causes difficulties to specify structural properties. The effects of foreseen robustness measures are usually indicated by analyses, illustrating structural performance before and after rehabilitation. A common approach is to start from a very simple level with crude assumptions, and increase the level of detail step-by-step. The additional complexity may lead to large computational expenses that can be often justified for existing structures where repair cost savings may be considerably higher than the cost of structural analysis.

Existing structures may be assessed by the alternate path method that allows accounting for the inherent and often substantial collapse resistance due to the natural redundancy and available load paths, commonly found in load-bearing wall structures, DCSG Committee (2010).

Model uncertainties shall be considered in the same way as during design, unless previous structural behaviour (especially structural damage) indicates otherwise.

## *2.7 Structural testing*

Analytical or predictive approaches used to determine structural resistance may be overly conservative due to neglected system effects, load redistribution etc. In these cases proof, diagnostic or dynamic load tests may help update information on structural properties, Bucher et al. (2005). Value of obtained information may be, however, limited with respect to modelling and assessment of robustness.

Proof load tests may be used to estimate the actual load carrying capacity of a structure. A proof load test involves the process of loading and observation of the related behaviour of an existing structure or a part of it. Note that a load test of a full-scale structural member or a complete structure is a costly and time-consuming procedure.

A diagnostic test (test when service loads are applied) may be used to verify or refine analytical or predictive structural models. Diagnostic testing attempts to explain why the structure performs differently than assumed. The disadvantage of this method, as compared with the proof load testing, is that the results determined for service loads need to be extrapolated to ultimate load levels and beyond them.

When the structural damage is small or hidden in the interior of the system, its visual detection may not be possible. A useful tool is then dynamic testing (e.g. horizontal or vertical vibration testing of structural members or a whole structure) that is based on the evidence that the damage or loss of integrity in a structural system leads to changes in the dynamic properties of the structure such as natural frequencies, mode shapes and damping. Dynamic measurements can give information on the position and severity of the damage that has occurred. Generally, the eigenfrequencies decrease while the damping increases.

## 3. Requirements on robustness in standards

### *3.1 Previous standards*

The actual robustness of an existing structure usually links to requirements of standards valid at the time of the design and execution of the structure. These standards were country-specific and it is difficult to provide general overview of previous requirements on robustness. Existing Czech standards and other prescriptive documents provide various provisions:

- Building codes (1886) and (1889): provisions concerning wall dimensions (see Figure 1a), anchoring floors, and ties at each floor,
- Building law No. 211 (1919), No. 65 (1936), and the Building Code (1941): requirements on anchoring of floor slabs,
- Standards ČSN 1050 (1929) and ČSN 731433 (1953): empirical statements, wall thickness, dimensions, restricted number of floors, wall ties, anchors, ring beams at each floor (2$\phi$12),
- Directives for panel houses (1971): requirements on verification of overall spatial stiffness, design of reinforcement of horizontal and vertical joints for 15 kN/m of width or length of a panel house, reinforcement of each joint of vertical and horizontal member by additional or latent ties as indicated in Figure 1b.
- Standard ČSN 73 1101 (1980) Design of masonry structures: reinforcing bars at each floor level required for multi-storey buildings, construction rules recommended,
- Regulation 137 (1998) of the Ministry for regional development of the Czech Republic: A building shall be designed in such a way that explosion, impact or other overloading will not cause inadequate damage.

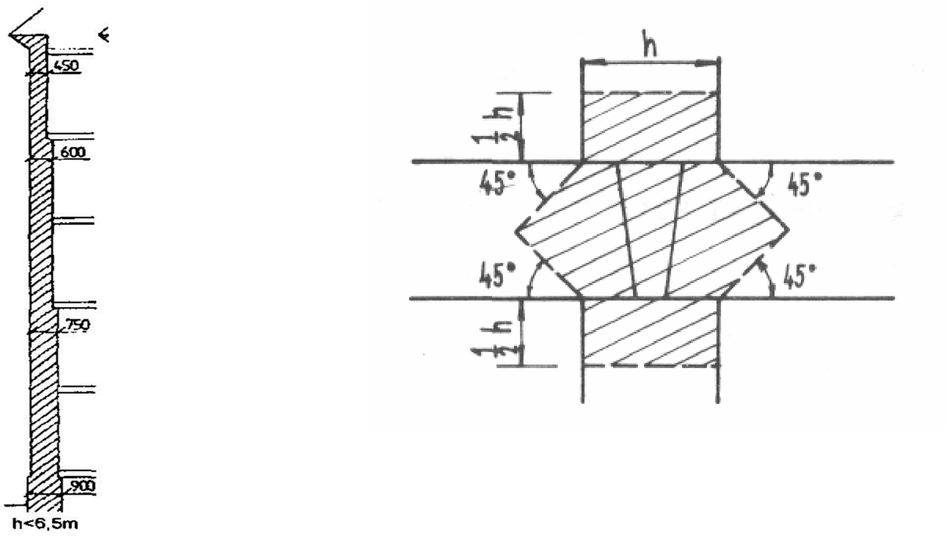

Figure 1a) Gradually strengthened masonry wall, 1b) joint reinforced by ties.

It follows that past standards mostly provided empirical construction rules with a specific emphasis on tying at each floor and roof level.

### *3.2 Present standards*

The summary of requirements and recommendations concerning the robustness of existing structures in present prescriptive documents is provided by Ellingwood et al. (2007). The most important provisions include:

- Reports contracted by the U.S. government: rehabilitation to improve structural robustness should wait for other major rehabilitation (such as seismic upgrade), or the decision should be based on the risk analysis,
- Document of US DoD (2003): all additions to existing buildings should be designed as structurally independent (structural isolation).

Requirements of valid standards may also improve reliability (and consequently robustness) of existing structures under rehabilitation. For instance Eurocodes mostly increase design values of climatic actions to be considered in the assessment of existing structures and design of construction repairs.

## 4. Robustness measures

Strategies for mitigating progressive collapse in an existing building are constrained by as-built conditions (existing geometry, space limitations, construction materials) as well as by demands and activities of the users (economic aspects, aesthetics).

Compared to the design of new structures, this increases costs of robustness measures and additional economic losses due to malfunctioning of a structure. Decision-making concerning construction interventions should be based on a cost-benefit analysis taking into account all failure consequences.

The report by Ellingwood et al. (2007) indicates that the robustness measures may include reduction of exposures, local strengthening to prevent initial failure or improvements of the redundancy of an existing structural system to limit the spread of a local failure.

### *4.1 Reduction of exposures*

It is often difficult to alter existing structural systems and may be convenient to reduce potential exposures by additional measures such as:

- Energy deflecting barriers to reduce the effect of an explosion on the structure when impossible to create a large stand-off distance as a defence against a bomb attack,
- Barriers to prevent vehicles from impacting the structure
- Energy-absorbing and impulse-reflecting shields.
- Improvements of fire resistance by insulation, installation of sprinklers, smoke detection, or better arrangements of fire compartments.

These measures are not constrained by existing detailing and can be often installed with relatively little disruption to building functioning. In many cases they can be more cost-effective than implementation of structural upgrades.

### *4.2 Local strengthening*

Local strengthening is an exposure-specific approach, typically used for explosions, impacts and fire as indicated by Ellingwood et al. (2007). Individual members are locally strengthened to withstand the specified exposure or to develop the full resistance of key structural members without failing the connections or supporting members framing into it. Local strengthening strategies may be distinguished as follows:

- Moment connections of simply-supported beams to columns may be accomplished to enhance the strength of specific beams and improve overall performance (improved tensile capacity of structural connections may increase the level of structural redundancy allowing catenary actions of the beams spanning over a damaged area).

- Robustness of precast concrete structures often needs increased tensile capacity in the connections. Connections having the tensile capability resulting only from friction can be additionally tied, improving significantly the overall robustness.

The feasibility of local strengthening is influenced by correct identification of the potential exposure, the effectiveness of the existing detailing and the flexibility of the existing structure to rehabilitation. Nevertheless, the first step should be focused on prevention of a failure, rather than on mitigation of a progressing collapse. Techniques of local strengthening can be similar to those used for seismic upgrades, Corley et al. (1996). EN 1998-3 (2005) provides guidance for assessment and structural interventions. However, it may be important to consider the following differences between seismic and robustness assessments:

- The seismic event involves the entire structure whereas for progressive collapse, the initial event may be localized.
- Seismic loads are mostly horizontal and temporary; for progressive collapse, the loads are vertical and mostly permanent.
- For earthquake design, damage distributed throughout the structure may be acceptable; for progressive collapse, the goal is to prevent initial damage from progressing.

### *4.3 Redundancy*

Redundancy of the structure is typically accomplished by providing additional rotational and tensile capacity in joints or connections or by creating new alternate load paths. Redundancy of existing structures can be provided by:

- Secondary trusses: when the potential initiating event is the removal of columns at low levels of a structure, it may be feasible to add diagonal members at upper levels, to turn two or multiple-story column and beam systems into trusses,
- Vierendeel action: buildings designed to resist lateral loads with moment frames may have the essential members and connections in place. Proximity of existing moment frames and locations of exposure initiations should be considered. If beams and columns and their connections can be reinforced to support the applied loads, this method can be relatively unobtrusive.
- Catenary action: additional cables may be installed to make the structural members adjacent to a damaged part capable to resist the high horizontal loads.

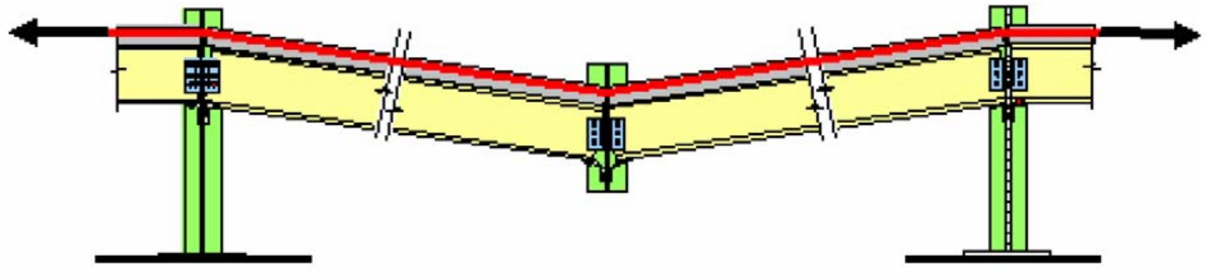

Figure 2: Catenary cables transferring load from a removed column to vicinity members, Astaneh (2003)

Figure 2 shows an example of the installation of cables at the perimeter of the building to increase the integrity of the building that has proven to be a cost-efficient and easy-to-install robustness measure. When a column collapses and the floor parts start to deflect, the catenary action of the cables transfers the load to the adjacent columns and prevents the collapse.

Note that risk-based robustness may be also increased by reduction of consequences of exposures (safety measures like installation of external staircases for safe evacuation of occupants).

## 5. Case studies - robustness measures for concrete and masonry structures

Concrete and masonry members can be often upgraded by encapsulating the existing member by additional reinforced concrete, or strengthened by steel, carbon-fibre or glass-fibre reinforced polymers (FRP). Reinforced concrete beam-column connections can be also upgraded using FRP. The ductility of precast concrete structures can be increased using external cables to provide continuity. Such rehabilitations improve strength and ductility of the structure, Priestley & Seible (1995). Figure 3 illustrates selected methods for upgrading of reinforced concrete and masonry members.

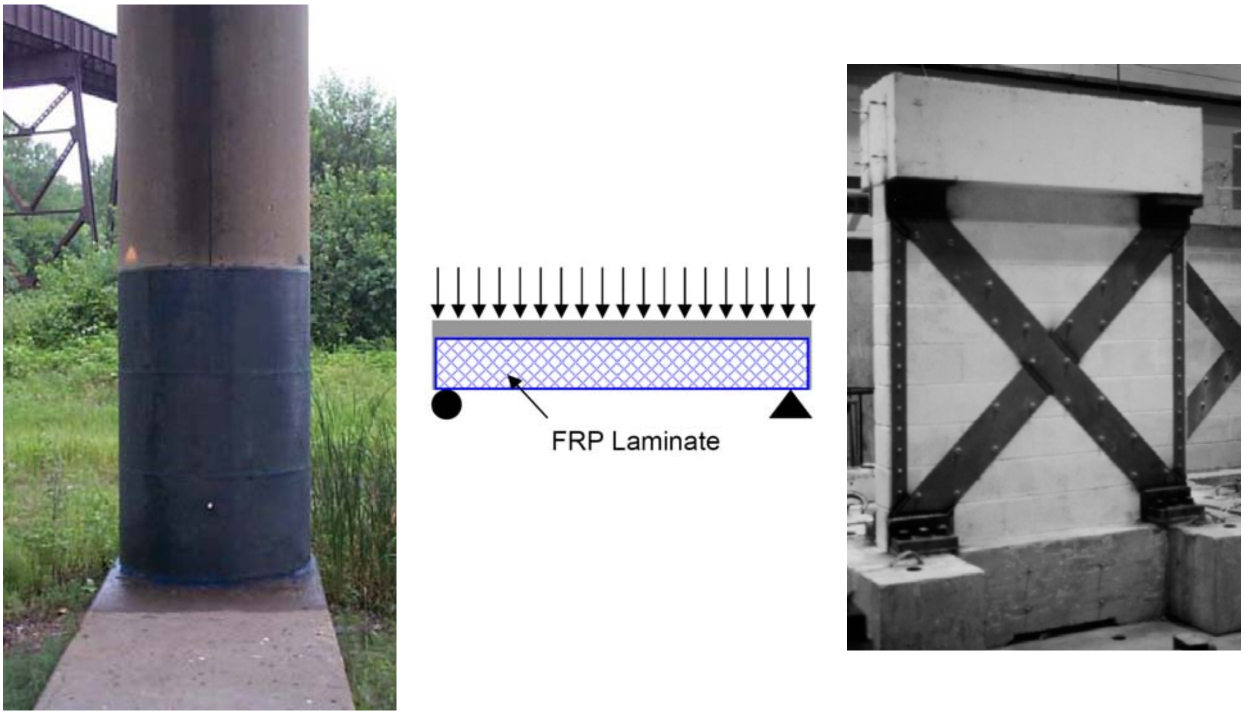

Figure 3 a) Reinforced concrete column wrapped with carbon composite; b) sketch of a reinforced concrete beam strengthened with FRP laminates, Ellingwood et al. (2007); c) masonry panel reinforced with steel strips, Taghdi et al. (2000)

## 6. Case studies - selected structural failures in the Czech Republic

### *6.1 Floods*

Hundreds of structures in the Czech Republic were affected by the floods in 1997 and 2002. The most damage was observed to residential houses, but the floods affected also office buildings, schools, hotels, churches, bridges, subway etc. Masonry was a typical material of the flooded structures. Failure causes included geotechnical causes (insufficient foundation, underground transport of sediments and man-made ground and propagation of caverns, increased earth pressure due to elevated underground water) and structural causes (insufficient robustness, use of inadequate construction materials, material property changes caused by moisture) as concluded by Holicky & Sykora (2009) and Holicky & Sykora (2010). Figure 4 illustrates failures of structures with low robustness.

a) undermined foundations b) missing ring beams

Figure 4: Failures of structures with low robustness

### *6.2 Snowfalls*

In total 249 failures or collapses of structures were reported in the winter 2005/2006 in the Czech Republic. The affected types of structures comprised agricultural structures, residential buildings, industrial structures and public buildings. Failure causes included extraordinary snow load (snow was not removed although required, combination of snow and ice, underestimated design snow loads), errors in design, construction and use (design errors, inadequate quality control, lack of communication, insufficient maintenance, false details). Considerably damaged structures had mostly insufficient robustness (no tying, low resistance of key members or vulnerable structural detailing). Lack of robustness became important particularly in the cases of multiple causes of failures or failures of joints.

A major collapse was that of the light-weight steel-framed ice-hockey stadium in Humpolec, Drdacky (2009). Figure 5 shows the stadium under construction in 2004 and its collapse. The main cause of failure were missing lateral buckling struts of the thin-walled I main girders that were particularly sensitive to lateral buckling. Some missing struts are indicated in Figure 5 accepted from Drdacky (2009). This human error affected nearly the whole structure that was almost uniformly loaded by snow. In such a case the robustness strategy may be rather to make segmentation than to tie a structure.

a) under construction b) collapse

c) missing lateral buckling struts

Figure 5: Stadium in Humpolec

### *6.3 Gas explosions*

Gas explosions represent relatively frequent accidental actions in residential buildings. Figure 6 shows failures of structures with different levels of robustness due to gas explosions.

Figure 6: Failures of structures due to gas explosions

## 7. Conclusions

In modelling and robustness analysis of existing structures, the following aspects should be taken into account:

- The actual structural system, conditions and actions including deterioration effects.
- Past overloading and occurrence of irreversible deformations.
- Realistic models of connections as they may significantly contribute to structural ductility, influence the ultimate strength and assure the load redistribution. Survey of connections may be necessary to evaluate as-built properties and assess influence of deterioration.
- Advanced theoretical modelling of existing structures that can be often justified by considerable repair cost savings.
- Proof, diagnostic or dynamic load tests that may help to update information on structural properties.
- A cost-benefit analysis as a basis of decision-making concerning robustness measures such as reduction of exposures, local strengthening and improvements of the redundancy. In many cases of existing structures such analysis will lead to

the application of relatively simple measures, acceptance of the present conditions, and/or orderly measures till major rehabilitation for other reasons.

It is emphasised that it may be important to assure robustness also in all phases of rehabilitations. If the decision is to replace a structure or a part thereof, the demolition should be carried out in such a way that human safety will be assured, fire flashover will be prevented and propagation of collapse of the structure or a part thereof will be controlled.

## 8. Acknowledgements

This study has been conducted at the Klokner Institute, CTU in Prague, within framework of the research project OC08059 Assessment of structural robustness.

## 9. References

Astaneh, A. 2003. Progressive Collapse Prevention in New and Existing Buildings. *Proceedings of The 9th Arab Structural Engineering Conference, Abu Dhabi, UAE, 29 November - 1 December, 2003.*

Bucher, C., Brehm, M. & Sørensen, J.D. 2005. *Assessment of Existing Structures and Life Extension,* Working documents of SAFERELNET.

Corley, W.G., Sozen, M.A., Thornton, C.H. & Mlakar, P.F. 1996. *The Oklahoma City Bombing: Improving Building Performance Through Multi-Hazard Mitigation,* FEMA-277. Washington DC: U.S. Government Printing Office.

COST 345 2004. *Procedures Required for the Assessment of Highway Structures,* Final Report, Reports of Working Groups 1-6. COST 345.

DCSG Committee 2010. *Design Procedures (draft 27 April 2010),* SEI Disproportionate Collapse Standards and Guidance Committee.

Diamantidis, D. 2001. *Probabilistic Assessment of Existing Structures.* Joint Committee on Structural Safety, RILEM Publications S.A.R.L.

Drdacky, M. 2009. Lessons from the failure of a steel-structure ice-hockey hall under a snow load. In B. Neale (ed.), *Forensic Engineering: From failure to understanding, Proceedings of the Fourth International Conference on Forensic Engineering, London, December, 2-4, 2008.* London: Thomas Telford.

Ellingwood, B.R., Smilowitz, R., Dusenberry, D.O., Duthinh, D., Lew, H.S. & Carino, N.J. 2007. *Best Practices for Reducing the Potential for Progressive Collapse in Buildings,* NISTIR 7396. USA: National Institute of Standards and Technology.

Ellingwood, B.R. 1996. Reliability-based condition assessment and LRFD for existing structures. *Structural Safety* 18(2-3): 67-80.

EN 1998-3: 2005. *Eurocode 8: Design of structures for earthquake resistance, Part 3: Assessment and retrofitting of buildings.* Brussels: CEN.

Finnish Ministry of the Environment, Housing and Building Department 2000. *Probabilistic Calibration of Partial Safety Factors (Eurocode and Finish proposal).*

Holicky, M. & Sykora, M. 2009. Forensic investigation of fluvial flood damage in the Czech Republic. *Proceedings of ICE Civil Engineering* 162(May 2009): 33-37.

Holicky, M. & Sykora, M. 2010. Assessment of Flooding Risk to Cultural Heritage in Historic Sites. *Journal of Performance of Constructed Facilities* 24(5): 432-438.

ISO 12491: 1997. *Statistical methods for quality control of building materials and components.* Geneve, Switzerland: ISO.

ISO 13822: 2003. *Bases for design of structures - Assessment of existing structures.* Geneve, Switzerland: ISO TC98/SC2.

ISO 2394: 1998. *General principles on reliability for structures.* Geneve, Switzerland: ISO.

IStructE 1996. *Appraisal of existing structures.* Institution of Structural Engineers.

JCSS 2006. *JCSS Probabilistic Model Code.* Zurich: Joint Committee on Structural Safety. <http://www.jcss.ethz.ch/>.

Mrazik, A. 1987. *Teoria spolahlivosti ocelovych konstrukcii (in Slovak - Reliability theory of steel structures).* Bratislava: VEDA.

Priestley, M.J.N. & Seible, F. 1995. Design of seismic retrofit measures for concrete and masonry structures. *Construction and Building Materials* 9(6): 365-377.

Taghdi, M., Bruneau, M. & Saatcioglu, M. 2000. Seismic Retrofitting of Low-Rise Masonry and Concrete Walls Using Steel Strips. *Journal of Structural Engineering (ASCE)* 126(9): 1017-1025.

US DoD 2003. *Minimum Antiterrorism Standards for Buildings, Unified Facilities Criteria (UFC) 4-010-01.* US Department of Defense.

von Scholten et al. 2004. *Reliability-Based Classification of the Load Carrying Capacity of Existing Bridges, Report 291.* Road Directorate, Ministry of Transport, Denmark. <htpp://www.vejdirektoratet.dk>.