Collection and Exchange of Basic Information

Name, address, phone/fax and homepage

Prof. Michael Havbro Faber

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Short CV

Michael Havbro Faber has been working at the Institute of Structural Engineering at ETH-Zürich as a professor since April 2000 and in June 2004 he received his tenure. He was born in 1961 and completed his MSc in 1985 as a structural engineer specialized in offshore structural engineering. In 1989 he received his PhD in structural reliability theory from the Institute of Structural Engineering at Aalborg University, Denmark.

Prior to his employment at ETH-Zürich he has been active as an engineering consultant with COWI in Denmark and DNV in Norway but also held positions at the Technical University of Munich, Germany, Aalborg University in Denmark, the Danish Technical University in Lyngby and the University of Newcastle, Australia.

Presently he is responsible for research and teaching activities in the area of risk and safety in civil, environmental and geomatics engineering at ETH-Zürich. Bayesian decision theoretical approaches to risk based decision making and structural reliability analysis play a central role in his research.

Michael H. Faber's main research activities have been centered around time variant reliability analysis, Bayesian decision analysis, reliability based structural design and assessment, probabilistic modeling of fatigue crack growth, probabilistic modeling of corrosion of concrete structures, risk based inspection and maintenance planning, modeling of preferences and consequences in decision making, generic approaches in risk assessment, large scale risk assessment, earthquake risk management, typhoon loss estimation and issues relating to sustainability. He has an extensive practical experience in the development and implementation of theories and methods of statistics and probabilistic structural analysis for the purpose of load analysis, structural design, assessment of existing structures and risk based inspection and maintenance planning. A significant part of his practical experience originates in projects concerning bridges, cable structures, offshore installations, ships and aeronautical structures.

During his career Michael H. Faber has been actively involved in several international committees including the Joint Committee on Structural Safety where he presently is acting as president, the International Forum on Engineering Decision Making (IFED) for which he was the founding president, the European Safety and Reliability Association (ESRA) where he was a member of the general board in the period from 1993-1998 and is currently active in the working group on offshore safety, the ISO committees on Assessment of Existing Structures as well as Risk Assessment of Structures, the international association CERRA: Civil Engineering Reliability and Risk Analysis, where he has been a board member since 1999.

Key literature on robustness

Ellingwood BR. Load and resistance factor criteria for progressive collapse design. In: Multihazard Mitigation Council Workshop on Prevention of Progressive Collapse, Rosemont, Illinois; 2002. 15.

Ellingwood BR, Leyendecker EV. Approaches for design against progressive collapse. Journal of the Structural Division, ASCE 1978; 104:413-23.

Feng YS, Moses F. Optimum design, redundancy and reliability of structural systems. Computers & Structures 1986; 24:239-51.

Lind NC. A measure of vulnerability and damage tolerance. Reliability Engineering & System Safety 1995; 48:1-6.

Lind NC. Vulnerability of damage-accumulating systems. Reliability Engineering & System Safety 1996; 53:217-9.

Ellingwood BR. Strategies for mitigating risk of progressive collapse. In: ASCE Structures Congress, New York, New York; 2005. 6.

Ditlevsen O, Bjerager P. Methods of structural systems reliability. Structural Safety 1986; 3:195-229.

Wen YK, Song S-H. Structural reliability/redundancy under earthquakes. Journal of Structural Engineering 2003; 129:56-67.

Santa Fe Institute. Working definitions of robustness, RS-2001-009. Posted 10-22-01. http://discuss.santafe.edu/robustness/stories/storyReader$9.

Baker, J. W., Schubert, M. and Faber, M. H. (2007). "On the assessment of robustness." Journal of Structural Safety, in press.

Faber, M. H., Maes, M. A., Baker, J. W., Vrouwenvelder, T. and Takada, T. (2007). Principles of Risk Assessment of Engineered Systems. 10th International Conference on Applications of Statistics and Probability in Civil Engineering, The University of Tokyo, Kashiwa Campus, JAPAN.

Faber, M. H., Maes, M. A., Straub, D. and Baker, J. W. (2006). On the Quantification of Robustness of Structures. Proceedings OMAE2006, 25th Offshore Mechanics and Arctic Engineering Conference, Hamburg, Germany.

References on data and assessment of structural failures

Faber, M.H. (2007) Lectures on Risk and Safety, http://www.ibk.ethz.ch/fa/education/ws_safety

Matousek, M. and Schneider, J. "Untersuchungen zur Struktur des Sicherheitsproblem bei Bauwerken", Institut für Statik und Baukonstruktion, der ETH Zürich, Bericht No. 59, ETH Zürich, 1976.

Stewart, M. and Melchers, R. E., "Probabilistic Risk Assessment of Engineering Systems", Chapman & Hall, 1997.

Blind, H. "The Safety of Dams", Water Power and Dam Construction, 35, 17-21, 1983.

Loss, J. and Kennett, E. "Identification of Performance Failures in Large Structures and Buildings", School of Architecture and Engineering Performance Information Centre, University of Maryland, 1987.

Bertrand, A. and Escoffier, L. "IFP databanks on offshore accidents. In V. Colombari (ed.), Reliability Data Collection and Use of Risk and Availability Assessment, Springer-Verlag, Berlin, 1987.

Frühwald, E., Serrano E., Toratti, T., Emilson A., Thelandersson S. "Design of safe timber structures – How can we learn from structural failures in concrete, steel and timber?" Report TVBK-3053, ISSN 0349-4969, ISNR:LUTVDG/TVBK-3053-SE (228), 2007.

Treatment of robustness issues in national codes and regulations

A very general statement can be found in the Swiss Codes SIA 260 “Basis of structural design” in the chapter about ‘Requirements’. It is stated that: “A structure shall (…) be economical, robust and durable.” Robustness is defined in the same document as “the ability of a structure and its components to limit the consequences of damage or failure to a degree which is proportional to the causation.” It is indicated that structural reliability methods might be utilized to assess the robustness.

Treatment of robustness in national education of engineers

Structural robustness is not taught specifically in the Swiss engineering education system. Students are, however, taught about various aspects relating to robustness during their basic structural engineering education.

Students who choose the course on Risk and Safety in Engineering, which is not mandatory, learn about risk based approaches to robustness assessment of structures.

Understanding of robustness

Postulate:

- The performance of a structure cannot be assessed in isolation from its environment, function and use.

Working thesis:

- Robustness is a performance attribute of a *structural concept*, i.e. the structure, its design, execution, function as well as strategies for the operation and condition management over its entire life-cycle.
- A robust structural concept will ensure that consequences arising from any event of deviation (e.g. damage or error) from assumptions related to the structural concept are either zero or reduced to the consequences associated with the event itself (e.g. repair, correction).

Collection and Exchange of Basic Information

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Short CV

Ton Vrouwenvelder, born 28 September 1947, received his civil engineering education at Delft University where he now is a part-time professor in the fields of structural mechanics and reliability analysis. His present main occupation is senior researcher in structural mechanics and risk analysis at TNO Building and Construction Research in The Netherlands. In this function he is involved many national and international research and consultancy projects with applications in the fields of flood protection systems, building structures, bridges en tunnels, offshore structures, and so on.. He has contributed to the development of standards for Basis of Design and Action Codes for buildings and civil engineering structures (National Dutch standards as well as ISO standards and Eurocodes). He is an active member of both research and code committees and the past president of the Joint Committee on Structural Safety.

Committees:

JCSSJoint Committee on Structural Safety

ESRA	Technical committee on Safety in Civil Engineering
ASRANET	Network for Integrating Structural Analysis, Risk and Reliability
ICOSSAR	International Conference on Structural Safety and Reliability
TC 250-SC 1	Eurocode EC1, Actions and Basis of Design
NEN	SC 3510101, Dutch Building Codes, General Part and Loading
ENW	Technical Advisory Committee on Flood Protection, Working Group on Probabilistic Methods

Editorial Boards / review activities:

Structural Safety

Structure and Infrastructure Engineering

Structural Engineering International

Key literature on robustness

Vrouwenvelder, A.C.W.M. and A.M. Gresnigt. Design for accidental actions in buildings. Proceedings ICMS 2006, Polano Brasov, September Balkema Publishers, 2006

Vrouwenvelder, A.C.W.M. Accidental actions on bridges. Implementation of Eurocodes, Handbook 4: Actions for design of bridges, Pisa, October 2005

Vrouwenvelder, A.C.W.M. Accidental actions on buildings. Implementation of Eurocodes, Handbook 3: Action effects for buildings, Prague, October 2005

Vrouwenvelder, Ton. Eurocode 1, Part 1.7, Accidental Actions. International Conference on Structural Safety and engineering, ICOSSAR 2005, Rome, August 2005

Gulvanessian, Haig and Vrouwenvelder, Ton. Robustness and the Eurocodes. JCSS/IABSE Workshop, BRE, Watford, November 2005

Structural Engineering International, SEI, Volume 16, No 2

A. Vrouwenvelder and A.M. Gresnigt. Accidental actions in buildings. Datasheet I-3.4.1, COST C12 – WG 2 2004

A.C.W.M. Vrouwenvelder. Accidental Actions / Collisions and Explosions. Proceedings on “Workshop on Euro Codes - Concrete Bridges and Structures”. New Delhi, March 16-17, 2002

A.C.W.M. Vrouwenvelder. Stochastic Modelling of Extreme Action Events in Structural Engineering. Probabilistic Engineering Mechanics, Volume 15,no1, January 2000

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Matousek, M. and Schneider, J. “Untersuchungen zur Struktur des Sicherheitsproblem bei Bauwerken“, Institut für Statik und Baukonstruktion, der ETH Zürich, Bericht No. 59, ETH Zürich, 1976.

Pugsley, A., "The safety of Bridges", Structural Engineer, July 1968, Vol 46, p 197.

McKaig, Th.H., "Building failures, case studies in construction and Design", McGrawHill Book Company, London, 1962

Ligtenberg F.K., "Veiligheid en catastrofen (Safety and catastrophies) ", TNO-Nieuws, March 1969, No 3.

SBR Studiecommissie B16, "Beveiliging van bouwwerken ter voorkoming van het optreden van calamiteiten (Safety measures to prevent catastrophies in building structures) ", Kluwer, 1978.

Treatment of robustness issues in national codes and regulations

In the present Dutch code a robustness requirement is present. The attention given to it depends however strongly on the local authority.

Treatment of robustness in national education of engineers

In the Delft educational program for structural engineer the notions of robustness are mentioned in several courses; no specific training is present. Since last year there is a 2 day specific post academic course on design for robustness.

Understanding of robustness

Working thesis:

- Robustness is the ability of a structural system to fulfil functions given some degree of damage or deterioration.

Collection and Exchange of Basic Information

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Short CV

Full professor in the field of concrete and timber structures at the Civil Engineering Faculty, University “St Cyril&Methods”, Skopje. Head of the Department on Concrete Structures, Timber Structures and Bridges. Deputy Dean at the Civil Engineering faculty Skopje from 1997 to 2001.Winner of a special award for the best research and scientific work in the field of building materials and structures in the period from 1986 to 1990 from former Yugoslav Society of Materials and Structures. “Certificate of Appreciation” from the USA NSF and US Department of Agriculture for the quality of the obtained results from the US - Macedonian research project “Dynamic Testing of Low-rise Frame Building System” performed from 1988 to 1992 at the Institute on Earthquake Engineering in Skopje.

Member of the National Committee for implementation of European standards (Eurocodes). National representative of European Technical and Scientific Cooperation COST. Member of COST Technical Committee in the Urban and Civil Engineering from 2003 to 2006. Member of the current TUD Domain Committee. Participant and member of the Management Committees and different working groups in the COST Actions C12, C16, E29 and E49. Evaluator of the COST Action E24. Rapporteur of COST Action C26. National coordinator of the ongoing FP6 project (FP6-2002-INCO-MPC-1) titled “Earthquake Protection of Historical Buildings by Innovative Reversible Mixed Technologies” (PROHITECH).

Author and co-author of more than 50 papers. Author and co-author of 5 books in the field of concrete, building and timber structures and bridges. Visiting professor and STSM at Washington State University, Pullman, WA, USA; Oregon State University, Corvalis, OR,USA; MARA Technology Institute – Civil Engineering Faculty, Shah Alam, Malaysia; Civil Engineering Faculty Sofia, Bulgaria; Faculty of Civil Engineering and Geodesy Ljubljana, Slovenia; Technical Faculty Novi Sad, Serbia & Montenegro; IUA Department of Architectural Structures, Venice, Italy; University of Naples Federico II – Department of Structural Engineering, Italy; Instituto Superior Technico of Lisbon, Portugal; Ruhr Universitet Bochum, Germany; etc.

Field activities: definition of mechanical properties of building materials (concrete and wood); design of different types of building structures and bridges; experimental and analytical assessment of the models of historical buildings; experimental and analytical assessment of strength, stiffness, stability and bearing capacity of existing elements, buildings and bridges; protection, maintenance, revitalization and reconstruction of existing buildings and bridges; dynamic testing of large-scale and full-scale buildings under seismic loads and real earthquakes; engineering consulting; evaluation of technical regulations, standards and codes; etc.

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Short CV

Dr Jitendra Agarwal is a Senior Lecturer in Structural Engineering at the University of Bristol. His main areas of research are structural safety, non-linear dynamics, civil engineering systems and computational methods. He has 25 publications in reputed journals and refereed conferences.

Prior to becoming a lecturer in 2002, he designed seismic modifications for nuclear plants while working for WS Atkins. From 1996 to 2001, he was a postdoctoral researcher working with Professor David Blockley and Dr Norman Woodman (both of the University of Bristol). During this time he developed new approaches to assessing the vulnerability of structures. Earlier he has worked as a scientist for four years in Structural Engineering Research Centre and as a structural engineer in a design consultancy in India.

His doctoral research (1991-1994) at the University of Bristol was funded by a Commonwealth Scholarship and he developed an Interacting Objects Process Model (IOPM) for the study of non-linear dynamics and tested it on parallel computing machines. He obtained his first degree in Civil Engineering in 1985 and a Masters degree in Computer Science in 1987 from Indian Institute of Technology Delhi, one of the top institute in India.

Key publications on vulnerability and robustness

England, J.C., Agarwal, J. and Blockley, D.I. (2007) Vulnerability of Structures to Unforeseen Events, *Computers & Structures* (In press)

Agarwal, J., England, J.C. and Blockley, D.I. Vulnerability Analysis of Structures, *Structural Engineering International*, 16 (2006), 124-128.

Agarwal, J., Blockley, D.I. and Woodman,N.J. Vulnerability of Structural Systems, *Jnl of Structural Safety*, 25 (2003), 263-286.

Blockley, D.I., Agarwal, J., Woodman, N.J. and Pinto, J.T.Q. (2002) Structural Vulnerability, Reliability and Risk, *Progress in Structural Engineering and Materials*, 4(2), 203-212.

Agarwal, J., Blockley, D.I. and Woodman,N.J. Vulnerability Analysis of 3D Trusses, *Jnl of Structural Safety*, 23 (2001), 203-220.

Agarwal, J., Blockley, D.I. and Woodman,N.J., Vulnerability of Systems, *Civil Engrg & Env Systems*, Vol 18 (2001), 141-165.

Understanding of robustness

Robustness is an attribute of a system which relates to its ability to fulfill its function in the face of uncertain and adverse conditions such as the loss of a component or abnormal changes in the demands on it.

In the context of structures, it implies the ability of a structure to avoid disproportionate consequences in relation to the initial damage. A structure which is vulnerable in any one way cannot be robust. Generally that vulnerability arises because of an inherent weakness in the structure which could be exploited by one or more potential actions. Hence it is important to analyse the form of a structure.

Structural vulnerability theory, developed at Bristol, is an innovative systems theory of the form of a structure. The purpose of the theory is to help provide robustness and structural integrity by addressing the way in which a structure is connected together. The theory enables the form of a structure to be described so that the quality of its connectivity can be measured. This quality is called the 'well-formedness' of the structure. A measure of well-formedness, based on the stiffness matrices, is used to create a hierarchical model of the structure. This hierarchy is used to search for vulnerable failure scenarios. The most vulnerable failure scenario is the one where the least damage causes the maximum consequences. Consequences are measured in terms of separation from the supports. The minimum demand failure scenario shows how a structure can be damaged with the least amount of effort. The analysis concludes by finding different types of failure scenarios and which include the minimum demand scenario and the most vulnerable scenario. These scenarios can now be examined for their chance of happening and hence controlling risk.

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Short CV

Name	:	Radu BĂNCILĂ
Age	:	born 1945 in Timişoara.
Studies	:	High School "Nikolaus Lenau" (in German) in Timişoara -1962. Faculty for Civil Engineering Timisoara (5 years), graduation 1967.
Doctor's Degree:		1981 – Timişoara (by Prof. Dan Mateescu Member of the Romanian Academy of Sciences); Specialty – Steel Constructions
Function	:	Univ. – Professor / Dean of the Faculty (beginning with 1 April 2004)
Scientific	:	approximately 100 papers, 10 books in the field of Steel Constructions and Steel Bridges
Special Field	:	Maintenance and rehabilitation of (existing) old steel constructions (bridges).
		Official expert of the Romanian Ministry for Transportation.
Special Activities:		Founder of the German – Medium Teaching Program in Civil Engineering at the TU Timişoara (founded 1991); 12 series of graduates.
Various Activities:		Visiting Professor - TU Graz (1994) and ETH Zurich 1995
		Conferences in Munich, Graz, Vienna, Hanover, Konstanz, Liege, Nottingham,
		Diploma for Founder Member of the ESDEP (European Steel Design Education Program) coordinated by The Steel Construction Institute UK.
		Lecturer for the **E**uropean **W**elding **E**ngineer courses
		Honorary Professor of the University from PECS / Hungary
Languages	:	German, English, French

Key literature on robustness

Petzek, E., Kosteas, D., Băncilă, R. Bestimmung der Tragfähigkeit bestehender Stahlbrücken in Rumänien. (2005). Stahlbau 74 Heft 8, pag. 606-613, ed. Ernst & Sohn a Wiley Company, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin, ISSN 0038-9145

Petzek, E., Kosteas, D., Băncilă, R. Bruchmechanische Parameter und Bestimmung der Restnutzungsdauer stählerner Eisenbahnbrücken in Rumänien. (2005). Stahlbau 74 Heft 9, pag. 691-700, ed. Ernst & Sohn a Wiley Company, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin, ISSN 0038-9145

Băncilă, R., Petzek, E., Bolduş, D. General Principles Regarding the Rehabilitation of Steel Bridges. (2005). BID-ISIM, Nr. 3/2005, ISSN 1453-0392, p. 13-30

Petzek, E., Băncilă, R. Criteria for the assessment of existing highway bridges. (2006). Buletinul ştiinţific al U.T. Gh. Asachi Iaşi

Băncilă, R., Petzek, E. General Concepts Regarding the Safety in Operation and Rehabilitation of Steel Bridges. (2004) 5th International Conference on Bridges across the Danube, 2004 / Bridge in Danube Basin, Novi Sad, 2004

Băncilă, R., Petzek, E. Prahoveanu A. Loading Capacity of an Old Representative Cantilever Highway Bridge (Gerber System) over the Mures River in Arad (Danube Basin). (2004) 5th International Conference on Bridges across the Danube, 2004 / Bridge in Danube Basin, Novi Sad, 2004

Băncilă, R., Petzek, E. Rehabilitation of Steel Bridges in Romania. (2005) Japanese German Bridge Symposium, 12 pag., CD, München, august 2005, www.jgbs.de

Băncilă, R., Petzek, E., Bolduş, D. Extended life for old highway bridges from the western part of Romania. (2006) Steel – a New an Traditional Material for Building, ed. Taylor & Francis Group, London, ISBN 0-415-40817-2, p.583-593

Petzek, E., Băncilă, R. Methodology for the assessment of remaining fatigue life for existing welded railway bridges. (2006) Steel – a New an Traditional Material for Building, ed. Taylor & Francis Group, London, ISBN 0-415-40817-2, p.627-633

Petzek, E., Băncilă, R., Kosteas, D. The Determination of Crack Growth Rate for Old Riveted Steel Bridges. (2004). Proceedings of the International Symposium, Computational Civil Eng., Ed. Societăţii Acad. Matei Teiu Botez, ISBN 973-7962-50-8, 2004, Iaşi

Petzek, E., Băncilă, R., Kosteas, D. The Determination of Crack Growth Rate for Old Riveted Steel Bridges. (2004). Proceedings of the International Symposium, Computational Civil Eng., Ed. Societăţii Acad. Matei Teiu Botez, ISBN 973-7962-50-8, 2004, Iaşi

Băncilă, R., Petzek, E., Bolduş, D. New life for an old historical bridge over the Mures river in the Danube basin. (2007) Proceedings of the 6th International Conference on Bridges across the Danube 2007, page 427 – 439, ISBN 978 963 420 935 6, Budapest.

References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulation

In the Romanian codes robustness of structures is not treated directly. Romania will adopt the Eurocodes in short time.

Treatment of robustness in national education of engineers

There is no special course in this direction in Romania.

Understanding of robustness

Robustness - the property of structural survival with limited damage by special events, such explosion, impact, the consequences of human errors.

Robustness – an indicator of the structure considered as a system to sustain general deviations from the assumption subject to which the structure was originally designed.

Robustness can be improved by inspection and maintenance.

Collection and Exchange of Basic Information

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Short CV

Date and Place of birth: March 29, 1960. Castellterçol (Barcelona)

Nationality: Spanish

EDUCATION

Ph. D. in Civil Engineering, Technical University of Catalunya (UPC) 1988.

M.S. in Civil Engineering, Technical University of Catalunya (UPC) 1984.

CAREER/EMPLOYEMENT

Professor of Bridge Engineering, School of Civil Engineering (UPC), 1999-present

Associate Professor of Bridge Engineering, School of Civil Engineering (UPC), 1990-1999

Assistant Professor of Bridges, School of Civil Engineering (UPC), 1988-1990

Research Engineer, School of Civil Engineering (UPC), 1984-1988. Dynamic behaviour of structures. Health monitoring using vibration techniques

SPECIALIZATION

Main field: Bridge Reliability and durability. Structural Safety and maintenance of bridges

Other fields: Bridge design and construction, dynamic testing of bridges, inspection procedures, Probabilistic methods in bridge engineering, data acquisition and processing

Current research interests: Live load modelling applied to reliability and safety analysis of bridges, Bridge Management Systems, advanced non-destructive techniques in bridge evaluation, repair and strengthening of existing bridges with advanced materials, long-term performance of bridges and structures and bridge management systems

ACADEMIC RESPONSABILITIES WITHIN UPC

- Vice-dean of foreign relations, School of Civil Engineering. 1997-2001
- Dean of the School of Civil Engineering. 2001-2004
- Director of the doctoral program “Construction Engineering”. 1992-2001

FELLOWSHIPS AND MEMBERSHIP OF PROFESSIONAL SOCIETIES

Secretary General of IABMAS (International Association for Bridge Maintenance and Safety)

Vice-chairman of Working Comission I on Structural Performance, Safety and Analysis of IABSE

Vice-Dean of the Professional Association of Civil Engineers of Catalonia

Member of Working Comission 5 of FIB (Federation Internationale du Beton)

Member of Association of Professional Engineers of Spain

Member of ACHE (Spanish Association for Structural Concrete)

Member of Working Group 7.5 on Reliability and Optimization of Structural Systems of IFIP (International Federation for Information Processing)

EDITORIAL BOARDS

Managing Editor for Europe of the journal " Structure and Infrastructure Engineering"

Member of the Editorial Advisory Board of the journal "The Open Civil Engineering Journal", edited by Bentham Science Publishers

2000-2004: Associate Technical Editor of the journal "Experimental Mechanics", edited by SEM (Society for Experimental Mechanics)

Key literature on robustness

Wisniewski, D.; Casas, J.R..; Ghosn, M. " Simplified probabilistic non-linear assessment of existing railway bridges". Structure and Infrastructure Engineering. Accepted for publication

Wisniewski, D.; Casas, J.R.; Ghosn, M. "Load-capacity evaluation of existing railway bridges based on robustness quantification". Structural Engineering International, Vol. 16, N. 2, 2006, pp. 161-166

Jara, M.; Casas, J.R. " A direct displacement-based method for the seismic design of bridges on bi-linear isolation devices". Engineering Structures, Vol. 28, 2006, pp. 869-879

Deng, L.; Ghosn, M.; Znidaric, A.; Casas, J.R.: Nonlinear Flexural behavior of prestressed concrete girder bridges. Journal of Bridge Engineering, Vol. 6, N.4, 2001, pp. 276-284

Nowak, A.S.; Park, C.; Casas, J.R.: Reliability analysis of prestressed concrete bridge girders: comparison of Eurocode, Spanish Norma IAP and AASHTO LRFD, Structural Safety, Vol. 23, 2001, pp. 331-344

Casas, J.R.: Safety of prestressed concrete bridges to fatigue: application to serviceability limit state of decompression. ACI Structural Journal, Vol. 97, N. 1, 2000, pp. 68-74

Casas, J.R.: Evaluation of existing concrete bridges in Spain. Concrete International,Vol. 21, N. 8 (1999), pp. 48-53

Casas, J.R.: Safety of partially prestressed highway bridges. Structural Engineering International, Vol. 9, N.3 (1999), pp. 206-211

Crespo-Minguillon, C. and Casas, J.R.: Fatigue Reliability Analysis of Prestressed Concrete Bridges.Journal of Structural Engineering, ASCE, Vol. 124, N. 12, 1998, pp. 1458-1466

Casas, J.R. and Crespo-Minguillón, C.: Probabilistic Response of Prestressed Concrete Bridges to Fatigue. Engineering Structures, Vol. 20, N.11, 1998, pp. 940-947

References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulations

In the Spanish Codes there is not explicit reference to the term “robustness”. Vulnerability is sometimes used, mainly in the regulations concerning seismic assessment of structures.

Treatment of robustness in national education of engineers

Structural robustness is not taught specifically in the Spanish engineering education system.

Understanding of robustness

Postulate:

Working thesis: robustness is the availability of the structure to resist with a limited damage and consequences of failure to loading and action scenarios not identified during the design and analysis. A measure of the degree of robustness is the structural redundancy. To obtain such measures it is necessary to develop computational/experimental techniques for the analysis of structures under the post-peak behaviour.

Collection and Exchange of Basic Information

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Short CV

Dr. Fabio Casciati is Full Professor of Scienza delle Costruzioni at the University of Pavia, Italy, since 1980, and is the Coordinator of the PhD course in Civil Engineering of the University of Pavia since 1994.

He was acting as vice chairman of the COST Action E24 (2000-2005) and is presently serving as member of the Management Committee of the COST Action E55.

Author of more than 200 papers (more than 50 were published in international journals) and of 3 books. He is President of the European Association for the Control of Structures since 1993, and served as President of the International Association, IASC, from 2000 to 2004.

Fabio Casciati is editor of Smart Structures and Systems, member of the Advisory Board of Nonlinear Dynamics and member of the Editorial Board of Struct. Safety, J. of Struct. Control & Health Monitoring, Computers & Structures, J. of Vibration & Control. Text

Key literature on robustness

Casciati F., 2006, Structural Monitoring for the Design and the Retrofitting of the Monumental Heritage, in Structural Health Monitoring and Intelligent Infrastructures, 1, 49-54.

References to be added.

References on data and assessment of structural failures

No owner is happy to share data on failure: this is why only the cases which caused injuries are recorded.

Treatment of robustness issues in national codes and regulations

Italy moved from a Unified Text incorporating structural reliability and rob ustness (DM 23-9-2005) to a flat acceptation of Eurocodes (on the way to be approved).

Treatment of robustness in national education of engineers

In Pavia there are courses devoted to the concept.

Understanding of robustness

Postulate:

Working thesis:

Robustness should be pursued as an extension of the concept of redundancy well known in structural engineering, even if robustness is much wider.

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Short CV

Dimos Charmpis has obtained a Diploma in Civil Engineering (5-year course) from National Technical University of Athens (NTUA) in Greece (1994) and a Master of Business Administration (MBA) from NTUA and Athens University of Economics and Business (1999). He has received a Ph.D. from NTUA (2003) after completing a thesis on the development of efficient finite element methodologies for Computational Structural Mechanics applications.

As a postdoctoral researcher he has worked together with research groups at the Institute of Structural Analysis and Seismic Research of NTUA (2003-2004), at the Technical University of Munich in Germany (2004) and at the Institute of Engineering Mechanics of the University of Innsbruck in Austria (2004-2005).

Since August 2005 he is a Lecturer at the Department of Civil and Environmental Engineering of the University of Cyprus.

Dr. Charmpis has participated in several research projects focused on the development of innovative methodologies for the analysis and design of structures under static or dynamic/seismic loading. His research interests lie in the broad area of Computational Mechanics and aim in the development and exploitation of computational methods for the solution of problems arising in structural engineering applications. More specifically, his research work is related with: finite element methods, reliability analysis of structural systems using probabilistic/stochastic methods, parallel and distributed computing and structural design optimization using evolutionary algorithms and artificial intelligence.

Dr. Charmpis has authored or co-authored several scientific publications and is a reviewer of research articles for international journals. He also has experience from working in the private civil engineering sector in Greece. Aiming at making novel structural analysis and design approaches available to practicing engineers, he has developed specialized software for commercial civil engineering programs. He is currently actively involved in the preparation of the National Annex of Cyprus to Eurocode *EN 1991 Actions on Structures*, concentrating on the topic of *Accidental Actions*.

Key literature on robustness

Maes MA, Fritzsons KE, Glowienka S. Structural Robustness in the light of risk and consequence analysis. Structural Engineering International, Vol. 16, Number 2, May, pp. 101-107, 2006.

Charmpis DC, Schuëller GI. Coping with physical uncertainties in structural mechanics: uncertainties modeling, methods of analysis and applications. In Coping with Uncertainty – Modeling and Policy Issues, Vol. 581 of Lecture Notes in Economics and Mathematical Systems (Springer), K. Marti, Y. Ermoliev, M. Makowski, G. Pflug (eds.), 2006.

Charmpis DC, Lagaros ND, Papadrakakis M. Reliability-based design optimization using evolutionary algorithms and adaptive neural networks. III European Congress on Computational Solid and Structural Mechanics (ECCM-2006), Lisbon, Portugal, 2006.

Liao KW, Wen YK, Foutch DA. Evaluation of 3D Steel Moment Frames under Earthquake Excitations. II: Reliability and Redundancy. Journal of Structural Engineering 2007; 133(3):471-480.

Beer M, Liebscher M. Designing robust structures – A nonlinear simulation based approach. Computers and Structures, in press.

EN 1991-1-7. Eurocode 1: Actions on structures, Part 1-7: General Actions – Accidental actions.

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Engineering Failure Analysis, International Journal (Elsevier), http://www.sciencedirect.com/science/journal/13506307.

Treatment of robustness issues in national codes and regulations

Structural reliability and robustness are actually not treated in current structural analysis and design codes and regulations of Cyprus. Such issues will be considered in Cyprus when the Eurocodes will come to force within the next 1-2 years.

Treatment of robustness in national education of engineers

There is no explicit educational programme or course on structural robustness in Cyprus. As in most engineering education systems in EU countries, students are implicitly taught aspects relating to robustness during their under- and postgraduate studies.

The Department of Civil and Environmental Engineering of the University of Cyprus offers an MSc course on probabilistic methods and reliability analysis in Mechanics. It is intended to enrich the contents of this course by including specific lessons on structural robustness based on outcomes of this COST action.

Understanding of robustness

Postulate:

- Treating structural robustness is a further step beyond controlling structural reliability. A robust structure is not only unlikely to fail, but it is also generally capable, in the event of damage, to sustain consequences in an acceptable/tolerable way.

Working thesis:

- Developing and implementing procedures for the rational quantification and assessment of structural robustness is an essential step towards the consideration of robustness requirements in practical structural applications.

- The fast and effective dissemination of the structural robustness concept within the engineering community can be greatly facilitated by developing software tools incorporating this establishing concept. However, calculating structural robustness (in addition to structural reliability) increases substantially the computing labor of the overall structural analysis. Therefore, customized and efficient computational methods and approaches are required to make such calculations tractable in engineering practice.
- Improved structural robustness can be achieved at little extra cost compared to the overall design and construction expenses by efficient use of material in the structure and suitable configurations for the structural components and the global system (structural design optimization).

Collection and Exchange of Basic Information

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Short CV

Marios Chryssanthopoulos is Professor of Structural Systems at the University of Surrey. His research focuses on reliability of structural systems, with emphasis on infrastructure maintenance and renewal, for which he has been funded by the UK research council, the European Union and industry. He has been a member of JCSS since 1991, acting as the Reporter of the Working Group on the probabilistic model code from 2001 to 2005. He has served on advisory and codification committees, including SCOSS (the UK Standing Committee on Structural Safety sponsored by the Institutions of Civil and Structural Engineers and the Health and Safety Executive) and the Eurocode 3 Drafting Panel on Steel Shell Structures. He is actively involved in ASRANet, a research network on the integration of structural reliability with advanced structural analysis. He is a Fellow of the Institutions of Civil and Structural Engineers.

During the course of his research, he has supervised 14 PhD theses and over 30 MSc dissertations, has collaborated with a number of colleagues both in academia and in industry, and has co-authored over 120 publications in journals and international conference proceedings. He is currently supervising 4 PhD students and 2 research associates on fatigue assessment and repair, risk-based inspection of railway bridges (funded by Network Rail), uncertainty in seismic fragility of steel frames (EU Lessloss), and spatial variability in FRP materials and structures (EPSRC and Ministry of Defence). He teaches first year Structural Design, and contributes to postgraduate courses on Safety and Reliability, Advanced Composites and Bridge Management.

HIGHER EDUCATION

1983-88	Imperial College of Science, Technology and Medicine, UK
	PhD in Structural Engineering - awarded the 1989 Unwin Prize
1979-81	Massachusetts Institute of Technology, USA
	SM in Naval Architecture and Marine Engineering.
	SM in Shipping and Shipbuilding Management.
1976-79	University of Newcastle-upon-Tyne, UK
	BSc(Hons) in Naval Architecture and Shipbuilding.

CAREER SUMMARY

June 2000 -	Professor of Structural Systems, School of Engineering, University of Surrey.
1989-2000	Lecturer/Reader, Dept of Civil & Environmental Engineering, Imperial College.
1988-89	Special Projects Engineer, Flint and Neill Partnership.
1983-87	Research Assistant/Associate, Dept. of Civil Engineering, Imperial College.
1982-83	Engineer, Research Division, Det norske Veritas, Norway

Key literature on robustness

Pugsley A G, *The Safety of Structures,* Edward Arnold, London, 1966.

Blockley DI, *The Nature of Structural Design and Safety,* Ellis Horwood, Chichester, 1980.

Thoft-Christensen P and Murotsu Y, *Application of Structural Systems Reliability Theory,* Springer-Verlag Berlin, Heidelberg, 1986.

Ditlevsen O and Madsen HO, *Structural Reliability Methods,* John Wiley, 1996.

Levy M and Salvadori M, *Why buildings fall down: how structures fail,* WW Norton and Co., New York, 2002.

The Institution of Structural Engineers, *Safety in Tall Buildings and Other Buildings with Large Occupancy,* London, 2002.

Ellingwood BR and Kanda J (editors), *Structural Safety and its Quality Assurance,* ASCE/SEI publication, 2005.

Ellingwood BR, Smilowitz R, Dusenberry DO, Duthinh D, Lew HS and Carino NJ, *Best Practices for Reducing the Potential for Progressive Collapse in Buildings,* NIST Draft Report, August 2006.

Pugsley AG, "The prediction of proneness to structural accidents", *The Structural Engineer*, 51(6), 1973, pp. 195-6.

Ellingwood BR and Leyendecker EV, "Approaches to design against progressive collapse", *ASCE J. Struct. Div.*, 104(3), 1978, pp. 413-23.

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Grierson DE, "Designing buildings against abnormal loading", *Progress in Civil and Structural Engineering Computing*, BHV Topping (editor), 2003, pp. 37-62.

JCSS/IABMAS Workshop on Robustness, Collection of papers, BRE, Watford, November 2005 (selection also published in *Structural Engineering International* 2/2006)

References on data and assessment of structural failures

SCOSS, Standing Committee on Structural Safety, Biennial Reports (from 1976 onwards) and other publications, available from www.scoss.org.uk

CROSS, Confidential Reporting on Structural Safety, a SCOSS initiative aimed at informing practicing engineers through confidential reports to highlight lessons that have been learnt www.scoss.org.uk/cross

Health and Safety Executive, Various reports on accident statistics in different industrial sectors, www.hse.gov.uk

Stewart MG and Melchers RE, Probabilistic Risk Assessment of Engineering Systems, Chapman and Hall, London, 1977.

Further references will be added

Treatment of robustness issues in national codes and regulations

Pertinent UK design codes are: BS8110-Concrete, BS5950-Steel and BS-5628 Masonry. The general philosophy in these codes has been influenced by the 1968 Ronan Point collapse and the ensuing enquiry and recommendations. See, for example the statement in BS 8110 “Structures should be planned and designed so that they are not unreasonably susceptible to the effects of accidents. In particular, situations should be avoided where damage to a small area of the structure or failure of single elements may lead to collapse of major parts of the structure”. All three codes contain, to a varying level of detail, references to horizontal and vertical tie arrangements. The concepts of ‘bridging’ elements, whereby the effect of notional removal of single elements is examined on the adjacent structure, and ‘key’ elements, whereby during the bridging assessment some elements are classed as ‘un-removable’, are also to be found in the codes. The load to which these ‘key’ elements are assessed (34kN/m2) also has its origin in the Ronan point investigation. General statements are made with regard to important aspects related to robustness, such as connection detailing and ductility, though these are generally acknowledged as areas where improved guidance would be desirable. In comparison with the Eurocodes, it is worth noting that British Standards follow a more prescriptive approach, thus attempting to complement general principles with specific guidelines as to how the objectives stated by the former might be achieved in practice.

In addition to the design codes, the other key UK document is the set of Building Regulations, issued by the Secretary of State for the Environment under powers delegated by Parliament through the Building Act 1984. In the context of robustness, Approved Document A (latest version issued in 2004) is the most relevant as it contains an entire section (section A3) devoted to disproportionate collapse. In brief, buildings are divided into four classes, similar to the building classification followed in EN-1991-1-7, with specific robustness requirements that need to be met by the designer. An important addition to the requirements for Class 3 structures (the highest class applicable to buildings with 15+ storeys, grandstands with 5000+ spectators and buildings containing hazardous substances and/or processes) in the latest version of Approved Document A is that “systematic risk assessment of the building should be undertaken taking into account all the normal hazards that may reasonably be foreseen, together with any abnormal hazards”. It is the intention to produce national guidance in support of this requirement, as well in support of requirements for lower classes, particularly in relation to how Approved Document A might be applied to existing structures subject to alterations. It is also perceived that design codes for different materials are not compatible in the treatment of robustness, creating particular problems for buildings of mixed materials.

Treatment of robustness in national education of engineers

In undergraduate teaching robustness is only taught as part of structural design courses, particularly in relation to the execution of design projects that most UK students undertake in their second/third year. It is also the subject of lectures that some universities offer on topics such as ‘Learning from Past Failures’ (Ronan Point, Silver Bridge, some space roofs – in future, Minnesota bridge?), or ‘Forensic Engineering’. However there is no doubt that the treatment is patchy; one of the general concerns noted by a SCOSS sponsored 2006 workshop was the “lack of understanding, by many engineers, of the fundamental principles of robustness”.

The coverage in postgraduate teaching must vary, depending on the objectives of any particular programme of study; there are certainly modules related to advanced structural design (of buildings, bridges etc), structural safety and reliability, as well as specialised courses in structural design against natural or man-made hazards, offered by several UK universities (as a rough estimate: around 10 to 15).

An important role is played by professional bodies (such as the Steel Construction Institute, the Concrete Centre, BRE, etc) which organise (often under the auspices of the institutions of Civil and Structural Engineers) short CPD courses on related topics.

Understanding of robustness

I am perfectly happy to endorse the postulate and working thesis expressed by Michael Faber.

Collection and Exchange of Basic Information

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Short CV

Qualifications:	BE (Civil) 1965, ME (Struct) 1967, PhD (Struct) 1971 University of Burdwan
Awards:	Gold Medal Award in BE. (First Class First)
Professional	CEng: Chartered Engineer of the Engineering Council (UK)
Memberships	FRINA: Fellow of the Royal Institution of Naval Architects (UK)
	FIStructE: Member of the Institution of Structural Engineers (UK)
	FIE: Fellow of the Institution of Engineers (India)

Work Experience:

- August 2001 –
  Professor of Marine Structures, Department of Naval Architecture and Marine Engineering, Universities of Glasgow & Strathclyde
- January 2001
  Professor of Marine Structures, Department of Naval Architecture and Ocean Engineering, University of Glasgow
- October 1999
  Reader, Department of Naval Architecture & Ocean Engineering, University of Glasgow
- October 1995
  Senior Lecturer, Department of Naval Architecture and Ocean Engineering, University of Glasgow
- February 1991 – September 1995
  Lecturer, Department of Naval Architecture and Ocean Engineering, University of Glasgow. Teaching Ship and Ocean Structures, Applied Mechanics, guidance of postgraduate research students (MSc and PhD). Involved in consultancy and contract work.
- July 1984 – February 1991
  Principal Research Officer/Principal Structural Engineer in the Marine Structures and Offshore Division of BMT CORTEC Limited, Wallsend, Tyne and Wear, UK. Worked in the field of static and dynamic structural response of floating and fixed marine structures.
- February 1981 – July 1984
  Research Fellow, University of Glasgow (UK), Department of Naval Architecture and Ocean Engineering. Contributed to projects on reliability-based code development for ring and stringer stiffened cylinders for use in offshore structures and optimisation of stiffened cylinders.

- December 1977 – December 1979
  On secondment to Mazagon Deck Ltd, Bombay, as Deputy Superintendent. Involved in Offshore Structures project in the Design and Construction of Fixed Offshore Platforms for the Bombay High Oil Field.

- April 1973 – August 1974
  On secondment to Department of Civil Engineering (Post Doctoral Fellow), University of Edinburgh (UK). Involved in project on Dynamic Response of Wind Sensitive Latticed Towers.

- June 1965 – January 1981
  Central Mechanical Engineering Research Institute (CMERI) under the Council of Scientific and Industrial Research, India. Scientist-B from 1965 to 1970 and 1970 to January 1981 Scientist-C in charge of the Structures Section. Responsible for various projects involving research, design and consultancy on industrial steel structures, computer-aided structural analysis using finite element technique, damage analysis of structures using analytical and experimental technique, model and prototype testings.

Publications:

More than 200 publications. Author of 1 Book, Chapters contributed to 2 books, Editor of several Conference Proceedings, Author of about 60 International Refereed Journals, several International Refereed Conferences, 5 Invited Papers/Articles, over 100 significant Research, Contract and Internal Reports . Serving as editorial board in many journals..

Supervision:

Supervised many PhD and MSc students; currently 2 Post-Docs RA, 1 RA, 4 PhDs

Research Grants:

A large number of research grants from EPSRC, MOD, HSE, DERA, Classification Societies, Oil Companies, EU (European Union).

University Appointments:

A number of departmental responsibilities such as, adviser of study, deputy Chairman –Research Committee, member of staff promotion committee, Member of teaching and staff-student committee.

External Appointments/Activities:

- Committee member for terms 1991-97 and 2003 - 2006 of the International Ship Structures Congress (ISSC), considered to be one of the most respected international bodies.
- Member of organising Committee of OMAE 'Safety and Reliability' Session Chairman OMAE 97, OMAE-98, OMAE-99,OMAE-00, OMAE-01, PRADS-2001, OMAE-2002, ISC-2002.
- Spent sabbaticals with KCS Ltd (1998), Lloyd's Register of Shipping (1997) and University of California, Berkeley (1996). Instituto Superior Technico, Lisbon (July 2000).
- External examiner of PhD, University of Newcastle Upon Tyne.,University of Aberdeen,University of Surrey,University of Southampton.
- Director of ASRANet Network for Integrating Structural Safety, Risk & Reliability. Established in 1999 with a start-up network grant from the EPSRC, this network is now self-funded.
- Organiser of ASRANet International Colloquium July 2002 (Glasgow) and July 2004 (Barcelona). July 2006 (Glasgow), March,2007 MARSTUCT Conference (Glasgow)
- Member of the Editorial Board of ' The Journal of Engineering for the Maritime Environment' and 'Journal of Ship Mechanics','Journal of Ship & Offshore Structures', @ Journal of Marine Structures.
- Member of EPSRC Peer Review College
- International Technical Committee of 'Thin Walled Structures' 2004.

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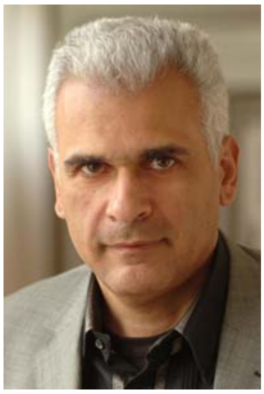

Short CV

Dimitris Diamantidis is since September 1992 professor of structural analysis at the University of Applied Sciences in Regensburg, Germany. He was born 1957 in Greece Athens where he got his school education. He studied civil engineering at the Technical University of Munich Germany (1975-1980). In 1984 he got his doctorate degree at the same University with a thesis examining the reliability of slender reinforced concrete columns.

From 1984 until 1987 he was a senior research engineer at Det Norske Veritas in Oslo Norway. During that period he worked on various projects dealing with code development and reliability analysis of marine structures. From 1987 to 1992 he was a project manager with D'Appolonia managing national and international projects in the field of transportation and structural engineering as well as research projects sponsored by the EC.

He has held research internships at the Lyngby Academy in Denmark and with Elf Aquitaine in Pau, France. Since 1992 he is also a consulting engineer in the field of structural analysis, risk and reliability analysis and also safety verification of existing structures. He has been consultant in various projects and to various companies worldwide.

His main research activities are risk and reliability analysis of structures, safety of existing structures, safety acceptance criteria and also code developments. He has more than 70 publications in recognized scientific journals and international conferences in the aforementioned fields. He has been a member of various scientific committees (C.E.B., I.S.O., A.S.M.E.) and he is currently an active member of the Joint Committee on Structural Safety.

Key literature on robustness

Danish Technical Research Council, 1997, Probabilistic Methods and Models for Reliability-based Reassessment, Report No. 1.

Department of Energy (DOE), 2002, Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities, DOE-STD-1020-2002, U.S. Department of Energy, Washington D.C.

Ellingwood, B.R., 1978and E.V. Leyendecker, Approaches for Design against progressive collapse,, Journal of Structural Division, ASCE, Vol 104.

Hamburger R.O., Douglas, A.F. and C.A. Cornell, 2003, Translating Research to Practice: FEMA/SAC Performance-Based Design Procedures, Earthquake Spectra, Vol. 19, No.2.

Joint Committee on Structural Safety (JCSS), 2007, Probabilistic Model Code, www.jcss.ethz.ch

JCSS and IABSE Workshop on robustness of structures www.jcss.ethz.ch/events

Starossek U. and M. Wolff, 2005, Progressive Collapse: Design Strategies, IABSE Syposium, Lisbon.

Wen, Y.K,, 2000, Reliability and Performance Based Design, 8th ASCE Speciality Conference on Probabilistic Mechanics and Structural Reliability.

References on data and assessment of structural failures

CIB, 2001, Report Risk Assessment and Risk Communication in Civil Engineering, CIB Report 259, TG 32.

Madsen, H.O., Krenk, S. and N.C. Lind, 1986, Methods of Structural Safety, Prentice-Hall Inc., New Jersey, USA.

Matousek, M. and J. Schneider, 1976, “Untersuchungen zur Struktur des Sicherheitsproblems bei Bauwerken“, Institut für Statik und Baukonstruktion, ETH-Zürich, Bericht no. 59.

Treatment of robustness issues in national codes and regulations

There is no direct treatment in the German codes (and Eurocodes). Constructional arrangements in the structures are usually applied to increase robustness and to avoid global failre. A progressive collapse limit state is not specifically verified.

Treatment of education in national education of engineers

Structural robustness is not taught specifically in the German engineering education system. Aspects related to robustness such as impact loads and associated structural damage, etc. are treated during the studies in specific subjects. Constructional aspects (joints, etc) and design strategies (return periods for accidental events, etc) are also sometimes discussed/analyzed during the lessons of advanced structural analysis.

Understanding of robustness

Robustness is a performance characteristic of a structure reflecting its insensitivity to local failure.

Collection and Exchange of Basic Information

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Short CV

Dr. Lucia Faravelli is Full Professor of Structural Safety at the University of Pavia, Italy, since 1991, and Faculty member of the Graduate School in Civil Engineering since 1994.

He is member of the Board of Directors of 1) the European Association for the Control of Structures and 2) ICASP-CERRA. She was serving as Visiting Researcher, Virginia Polytechnic Institute and Technical University, Blacksburg, Virginia (USA), 1985; Visiting Researcher, Stanford, California (USA), 1986, with a NSF Award.

She was Chairperson of the ESF program CONVIB (2001-2005) on vibration control; and Chairperson of the HCM Stochastic Mechanics ERBCHXCT940565.

She is Editor of the Journal of Structural Control and Health Monitoring and member of the Editorial Board of "Smart Structures and Systems" and "International Journal of Reliability and Safety" (IJRS).

Lucia Faravelli is author or co-author of more than 200 scientific papers and served as co-chairperson of three ESF-NSF workshops on Smart Sensor Technology

Key literature on robustness

Casciati F., 2006, Structural Monitoring for the Design and the Retrofitting of the Monumental Heritage, in Structural Health Monitoring and Intelligent Infrastructures, 1, 49-54.

References on data and assessment of structural failures

No owner is happy to share data on failure: this is why only the cases which caused injuries are recorded.

Treatment of robustness issues in national codes and regulations

Italy moved from a Unified Text incorporating structural reliability and rob ustness (DM 23-9-2005) to a flat acceptation of Eurocodes (on the way to be approved).

Treatment of robustness in national education of engineers

In Pavia there are courses devoted to the concept.

Understanding of robustness

Postulate:

Working thesis: Robustness should be pursued as an extension of the concept of redundancy well known in structural engineering, even if robustness is much wider.

Collection and Exchange of Basic Information

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Short CV

Ludovic A. Fulop has been working in VTT, The Technical Research Centre of Finland, from the year 2005. He was born in 1975 and graduated in 1998 from the Civil Engineering school of the “Politehnica” University Timisoara (PUT), Romania. His specialization was in structural engineering and structural dynamics, with focus on steel structures and earthquake design. He received his MSc in 1999 and his PhD in 2003, from PUT in the field of structural engineering, investigating the earthquake performance of light-gauge steel structures.

The major part of his research activity included assessment of earthquake behavior of structures, development of recommendation of reliable detailing and analysis methods. Both experimental and numerical studies were included.

The structural typologies in focus of these studies were multi-storey steel frames with semi-rigid and/or partial strength joints, light-gauge steel buildings for office buildings and domestic structures, and timber houses.

Parts of the research have been carried out in collaboration with researchers from the University Federico II in Naples and The University of Manchester.

He has over five years of experience in the field of structural design, as result of working as engineer at BRITT Ltd. in Timisoara.

Current responsibilities include development of research related to earthquake engineering and design, vibrations mitigation, structural dynamics and structural safety. Consultancy on structural engineering problems related to earthquake behavior and performance.

He is member of the Association of the Structural Design Engineers of Romania (AICPS) and of the Finnish Association of Civil Engineers (RIL).

Key literature on robustness

Alexander S, New approach to disproportionate collapse, The Structural Engineer, 7. Dec. 2004

Canisius TDG, Sorensen JD, Baker JW, Robustness of structural Systems – A new focus for the Joint Comity on Structural Safety (JCSS)

Carlson JM, Doyle J, Complexity and robustness, PNAS vol. 99, suppl. 1, Feb. 19, 2002

Ellingwood BR, Smilowitz R, Dusenbery DO, Duthin D, Lew HS, Carino NJ, Best practices for reducing the potential for progressive collapse in Buildings, NISTIR, Aug. 2006

***, An Engineer's guide to: Concrete Buildings and Progressive Collapse Resistance, Portland Cement Association

References on data and assessment of structural failures

Frühwald, E., Serrano E., Toratti, T., Emilson A., Thelandersson S. "Design of safe timber structures – How can we learn from structural failures in concrete, steel and timber?" Report TVBK-3053, ISSN 0349-4969, ISNR:LUTVDG/TVBK-3053-SE (228), 2007.

Accident Investigation Board of Finland – Onnettomuustutkinta: http://www.onnettomuustutkinta.fi/

Törmänen J.; Leskelä M.: Failures in timber structures (in Finnish: Kantavien puurakenteiden vaurioselvitys, tutkimusraportti RTL 0021). University of Oulu, 1996

Treatment of robustness issues in national codes and regulations

NA

Treatment of robustness in national education of engineers

NA

Understanding of robustness

Postulate:

- Robustness is as intimately dependent on the loading scenario as it is on the structural configuration.

Working thesis:

- Robustness means, in everyday design, only as much as the engineer is able to translate for himself in numbers, checking criteria and detailing conditions.

Collection and Exchange of Basic Information

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Short CV

Marian Antoni Gizejowski has been working at the WUT Institute of Building Structures as a Professor of the Warsaw University of Technology since 2006. He was born in 1951, completed his BSc in 1972 and MSc in 1975 in the specialization of urban and industrial structural engineering. In 1981 he received his PhD in the area of structural steelwork from the Warsaw University of Technology and in 2001 he obtained his DSc degree from the same University.

During his leave and sabbatical periods when employed at WUT he was active in conducting research and teaching in several institutions worldwide. In 1983 he was a Postdoctoral Fellow at the University of Sydney, Australia; he held senior positions at the University of Zimbabwe, Harare in years 1988-94 and at the University of Botswana, Gaborone in years 2001-05. He was a short term Visiting Professor to several universities in Canada and the US. He has gained experience as a structural engineer working at the steelwork design office MOSTOSTAL in Warsaw, Poland and acting as an engineering consultant in countries of his employment, presenting among others a specialized course on the British design code BS 5950 for the division of Ove Arup in Harare, Zimbabwe in 1994 and co-organizing a shot course on masonry structural design in Gaborone, Botswana in 2004 .

Presently he is responsible for research and teaching activities in the area of steelwork design at WUT and at the same time is the Head of the Department of Metal Structures. His current research activities are focused on advanced analysis and computer modeling of the behavior of steel and composite steel-concrete structures, including the effects of joint deformability, strength and deformation capacity and with reference made to practical design concepts adopted in the limit states design according to Eurocodes.

Marian A. Gizejowski's main research activities have been centered around elastic and inelastic stability theory, probabilistic basis for structural design and performance assessment, stability behaviour and design of thin-walled rolled, welded and cold-formed members under compression, bending and under interaction of actions, behavior and design under fire conditions, behavior and modeling of joint behavior in steel, composite steel-concrete and timber nail plate structures, nonlinear analysis of steel and timber frameworks with an integrated effect of joint behavior, failure assessment with regard to the deformation limit resulting from section classes and/or joint restricted plastic behavior. A significant part of his research outputs was published in co-authored books for graduate students and practicing structural engineers.

During his career Marian A. Gizejowski has been actively involved in several committees mostly on the national level, including the National Technical Committee on Structural Steelwork Design and Execution KT 128 of the Polish Bureau of Standards, from its beginning, and the Committee KT 102 for Basis of Design. He has been for many years the member of the Section of Metal Structures of the Civil and Hydraulic Engineering Committee of the Polish Academy of Sciences. He was the member of the Zimbabwe Bureau of Standards in 1992-94 and was an elected chairman of the Botswana Bureau of Standards Committee in 2005. He was the member of teams leading to the establishment of two national codes in Poland, namely PN-90-B-03200 and PN-B-3207: 2002. He was responsible for the translation of EN 1993-1-2 and the development of its national version PN-EN 1993-1-2: 2006 together with the National Annex, as well as he has been acting in the verification exercise of other Eurocodes and their parts being implemented in Poland.

Key literature on robustness

Faber, M.H. Frameworks for risk assessment of structural systems. In: Urban habitat constructions under catastrophic events, Proceedings of COST Action 26 Workshop, Prague; 2007, 359-367.

Practical Analysis for Semi-Rigid Frame Design (Ed. Chen W.F.) World Scientific, Singapore, 2000.

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Schneider, J. Introduction to Safety and Reliability of Structures. Structural Engineering Documents, no. 5, IABSE Series, Zurich, 1997.

Treatment of robustness issues in national codes and regulations

Statements on robustness can not generally be found in Polish National Design Regulations. Only very general statements can be found in the Polish Codes PN 90-B-3000: Building design projects: Static calculations and PN 82-B-2000: Actions on structures: Principles of action evaluations. Robustness is not defined in an explicit way. An ability of a structure and its components to fulfil the requirements of reliability (structural safety, integrity and durability) is verbally stated. The situation is now changing because of a wide implementation of documents elaborated by the International Organization for Standardization (ISO) and European Committee for Standardization (CEN).

Treatment of robustness in national education of engineers

Structural robustness is not taught specifically in the Polish engineering education system. Students are however taught about various aspects of structural performance and factors affecting it as well as about the sensitivity of structures to collapse with regard to change of different design assumptions. It is somehow indirectly related to robustness so that one can say that some aspects of robustness concept exist in basic structural engineering education.

Reliability is the knowledge area that does not constitute the basic minima for undergraduate engineering education curriculum in Poland. Graduate courses are offered at universities on Safety in Engineering which constitute the set of core courses in different engineering disciplines. From these courses one can familiarize herself/himself with an elementary knowledge on risk based approaches to robustness assessment of structures.

Understanding of robustness

Postulate:

- Robustness is an evaluation measure for the condition of sustainable structural performance so that it has to be addressed in performance based design concept. The performance of a structure shall be assessed in relation to aspects of its sustainable built environment, function and use.

Working thesis:

- A robust structural concept will ensure that any event of deviation (e.g. damage or error) from assumptions related to the structural concept are causing consequences that lead to neither structural collapse nor permanent disaster for environment, function and use so that the overall consequences are reduced to only those associated with the event itself (e.g. repair, correction).

Collection and Exchange of Basic Information

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Short CV

Niels Peter Høj is an expert within risk and safety and has been working within this field nearly 25 years. Since 2003 he has worked out of HOJ Consulting which was founded by him and which is working within this field. He was born in 1959 and completed his MSc in Structural Engineering in 1983 from the Institute of Structural Engineering at Aalborg University, Denmark. Thesis: "Estimation of Failure Probability for Frame Structures".

Prior to his foundation of HOJ Consulting Niels Peter Høj worked with risk and safety as well as structural design for COWI and for BHR (now a part of Ramboll)

The special expertise on safety and risk analyses applied as an integrated part of the decision support has been applied in practice to support decision within design and operation of major infrastructure projects and as part of feasibility studies. Mr. Høj has contributed with his experience and developed new methods for safety design by participation in national and international research projects.

Analysis of structures subjected to fire is part of Mr N. P. Høj's expertise. The robustness of structures towards fire and other accidental impact has been part of Mr Høj's activities both in research and in practical engineering.

Mr Høj was the recipient of the 1999 annual IABSE Prize for an out-standing contribution in the field of structural engineering. Niels Peter Høj was awarded the prize in recognition of his "outstanding efforts with introduction and application of modern probabilistic ways of thinking in professional practical engineering activities, in particular related to methods for risk analysis, structural reliability and decision making"

Niels Peter Høj is actively involved in several international committees including JCSS Joint Committee of Structural Safety and particularly its WP2 Risk Analysis, International Tunnelling Association (ITA) Committee on Safety of Underground Facilities (COSUF), Member of steering board, International Tunnelling Association (ITA) Working Group 6, Fire Resistance of Tunnels, International Federation for Structural Concrete (fib) Commission 4, Modelling of Structural Behaviour and Design, fib Task Group 4.3, Fire Design of Concrete Structures, for which he serves as chairman since 1999. In addition he is member of the Editorial Board of "Structural Engineering International" Journal of IABSE

Key literature on robustness

Listing of literature (in addition to the literature mentioned by Michael Faber)

Papers from the JCSS & IABSE WC 1 Workshop, Watford, UK November 2005

Papers in Structural Engineering International Vol. 16, No 2, May 2006 (in total 12 papers with the theme "Robustness of Structures")

Papers in Structural Engineering International Vol. 17, No 2, May 2007 (in total 9 papers with the theme "Forensics in Structural Engineering")

References on data and assessment of structural failures

Listing of literature (in addition to the literature mentioned by Michael Faber)

Papers in Structural Engineering International Vol. 17, No 2, May 2007 (in total 9 papers with the theme "Forensics in Structural Engineering")

Imhof, D. (2004). Risk Assessment of Existing Bridge Structures; PhD Thesis,University of Cambridge; August 2004; 216 pp. + annexes. (Includes data base of 375 bridge collapses worldwide)

Treatment of robustness issues in national codes and regulations

See Basic Information from Michael Faber

Treatment of robustness in national education of engineers

See Basic Information from Michael Faber

Understanding of robustness

Postulate:

There is even among engineers of similar background not always a common understanding of the term robustness. The understanding ranges from a general definition to a specific structural application. The general definition is dealing with systems and their sensitivity of their performance towards deviation of assumptions and interaction with for example the natural environment, accidental events and the intended use of the structures. The systems may be structures, networks or entire countries.

The narrower definition is considering only the structure and defines it as robust "when those parts of the structure essential for safety only has little sensitivity with respect to unintentional loads and defects, or that an extensive failure will not occur if a limited part of the structure fails"

Working thesis:

The engineering community will have to substantiate the term robustness. The starting point can be taken in the following (after Michael Faber):

- Robustness is a performance attribute of a system respectively a *structural concept*, i.e. the structure, its design, execution, function etc..
- A robust structural concept will ensure that consequences arising from any event of deviation (e.g. damage or error) from assumptions related to the structural concept are minimised.

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Short CV

Milan Holický was born in 1943 in Tábor, South Bohemia, Czech Republic in the family of a high school professor of mathematics and physics. In 1965 he graduated at the Faculty of Civil Engineering, Czech Technical University in Prague (CTU). He got his doctor degree, Ph.D. in 1971 at the University of Waterloo, Department of Civil Engineering, Ontario, Canada. In 1972 he defended thesis at the CTU and got the Czech scientific degree Candidate of Science, CSc. At the CTU in 1990 he was awarded the Czech scientific degree "Doctor of science", DrSc. He is now active as a senior scientific worker at the Klokner Institute and head of the Department of Structural Reliability. He is permanently lecturing at the Faculty of Civil Engineering of the CTU in Prague, where he is offering lectures for undergraduate as well as graduate students. In 1992 he was awarded academic degree Associate Professor, Doc., in 2002 he was awarded academic degree Professor, Prof. His teaching activities include applied mathematical statistics, theory of structural design, concrete structures, structural reliability and risk assessment.

Milan Holický is involved in the research of structural reliability and risk assessment of civil engineering systems. In particular he is interested in assessment of existing structures and reliability based calibration of codes of practice. Recently he was involved in reliability assessment of structures under fire design situation and structures after flooding. Presently he is participating in risk assessment and optimization of road tunnel safety based on Life Quality Index. He is an author or co-author of more than 300 scientific publications including text books and four monographs (two in English, published by Elsevier and Thomas Telford Publications). He is participating in international research within JCSS (Joint committee for Structural Safety), Working group 2 “Risk Assessment“, CIB (Conseil International du Batiment), in international standardization within ISO (International Organisation for Standardisation), Technical Committees TC 59 "Building Production" and TC 98 "Bases for Design of Structures" and in the PIARC committee C3.3, working group WG 2 „Risk Assessment“. He was a convener of ISO/TC98/SC2/WG3, responsible for the document "Statistical Methods for Quality Control of Building Materials and Components" (published in 1996 as the International Standard ISO 12491). Since 1991 he is representing the Czech Republic in the European Committee for Standardisation CEN (Comité Européen de Normalisation) in the Technical committee TC 250 "Structural Eurocodes” and subcommittee TC 250/SC1 “Actions on structures”.

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Treatment of robustness issues in national codes and regulations

In the system of Czech Codes robustness is presently implemented through the Eurocode EN 1990 and ISO documents. Traditionally the Czech codes include provisions concerning progressive collapse, overall structural stiffness and operational rules for various ties and empirical formulae for their design.

Treatment of robustness in national education of engineers

In the Czech engineering education structural robustness is treated by a mixture of different aspects partly codified in existing Czech Standards. In particular aspects of progressive collapse, overall structural stiffness and operational design rules concerning various ties, for which empirical design formulae are provided, are explained. In a specific course on structural reliability also an analysis of possible consequences and general methods of risk assessment are illustrated.

Understanding of robustness

Definition:

Robustness is understood as the ability of a structure to withstand all types of unfavourable events (like fire, explosions, impact or the results of human errors), without being damaged to an extent disproportionate to the original cause.

Difficulty:

The term “an extent disproportionate to the original cause” is difficult concept that depends on a given structure and can hardly be identified without discussion amongst all interested parties. Methods of risk assessment may provide an effective tool. However, desired simplification in the form of code provisions and prescriptive rules is hardly conceivable. Achieving “robustness” will perhaps often require more than strict application of codes. But not all designers would appreciate this point.

Collection and Exchange of Basic Information

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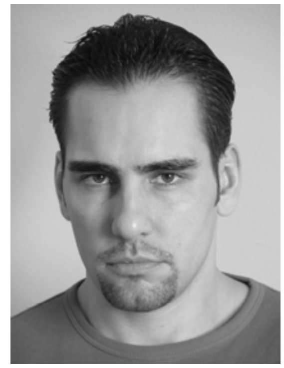

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Short CV

Daniel Honfi has been working at the Department of Structural Mechanics at Ybl Miklós Faculty of of Engineering of Szent Istvan University in Budapest as an assistant Professor since September 2005. He was born in 1977 and completed his MSc as civil engineer at Budapest University of Technology and Economics in 2001. He is preparing his PhD in field of structural optimization also at BUTE.

Prior to his employment to Szent István University he has been working for Vinçotte Hungary coordinating safety and technical inspection services of the company in field of civil engineering.

His research activities have a focus on the optimization and numerical investigation of cold-formed steel members using genetic algorithms, neural networks and finite element simulation.

Working at BUTE he has been involved in analysis of new Danube Bridges (M0 North Danube Bridge, Danube Bridge of Dunaújváros), developing of the Joint Design Module steel connection design software and developing the Lindab light-weight building system.

Key literature on robustness

Agarwal J., Blockley D. and Woodman N. Vulnerability of 3-dimensional trusses. Structural Safety, Volume 23, Number 3, 2001 , pp. 203-220(18).

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Kanno, Y. and Takewaki, I. Robustness analysis of trusses with separable load and structural uncertainties**.** International Journal of Solids and Structures 43 (2006) 2646–2669

Lu Z., Woodman N.J. and Blockley D.I. A theory of structural vulnerability. The Structural Engineer, 1999, 77, 17-24.

Starossek U. and Wolff M. Design of Collapase-resistant Structures. (2005) JCSS and IABSE Workshop on Robustness of Structures

Zalka K. A. and Armer G. S. T. Stability of large structures. Butterworth-Heinemann, Oxford, 1992. p261

References on data and assessment of structural failures

Listing of literature

Treatment of robustness issues in national codes and regulations

Structural robustness is not defined or treated at all in the Hungarian Design Codes.

Treatment of robustness in national education of engineers

Structural robustness is not taught at all in the Hungarian civil engineering education system.

Understanding of robustness

Postulate:

Working thesis:

Collection and Exchange of Basic Information

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Short CV

Bassam A Izzuddin is Professor of Computational Structural Mechanics, and he has worked extensively on numerical modelling and the assessment of various types of structure under extreme loading, such as due to explosion, fire and earthquakes. He pioneered the development of nonlinear adaptive analysis techniques for framed structures, and he has developed numerous novel formulations for modelling the nonlinear large displacement response of frames, plates, shells and integrated structures. These developments have been implemented within the advanced program ADAPTIC, which he has been developing personally and as the supervisor of many PhD and MSc students. He has acted as PI and CI on five EPSRC projects, two of which involved the development of an integrated modelling capability for framed structures under fire and explosion as well as composite floor slabs under extreme loading, work which was first to demonstrate a strong interaction between explosion loading and fire resistance in coupled scenarios, well before the events of September 11th 2001. He has also collaborated with major industrial partners, such as ARUP, BRE, SCI and CORUS, and he has led several projects funded directly by industry, including recent pioneering work on progressive collapse assessment of multi-storey buildings funded by ARUP, failure assessment of floor slabs under extreme loading funded by BRE, and modelling of steel members under blast loading funded by SCI.

During the course of his research, he has supervised 15 PhD theses and 33 MSc dissertations/final year projects, has collaborated with a number of colleagues both in academia and in industry, and has co-authored over 110 publications in journals and international conference proceedings. He is currently supervising 3 PhD students and 2 research assistant on several topics concerned with the structural response under extreme loading conditions. He teaches Computational Engineering Analysis and Nonlinear Structural Mechanics to 3rd and 4th year undergraduates, and gives two courses on Finite Element Analysis and Nonlinear Structural Analysis at MSc level.

HIGHER EDUCATION

1987-91	Imperial College of Science, Technology and Medicine, UK
	PhD in Structural Engineering, *Edmund Davis Scholarship*
1986-87	Imperial College of Science, Technology and Medicine, UK
	MSc in Structural Steel Design, *Distinction*

1982-86	American University of Beirut, Lebanon
	BEng in Civil Engineering, *Distinction*

CAREER SUMMARY

October 2006 -	Professor of Computational Structural Mechanics, Imperial College London
1990-2006	Lecturer/Reader in Computational Structural Mechanics, Imperial College London

Related references

Izzuddin, B.A., Song, L., Elnashai, A.S., and Dowling, P.J., "An Integrated Adaptive Environment for Fire and Explosion Analysis of Steel Frames - Part II", J. Const. Steel Res., 53(1), pp. 87-111, 2000.

Izzuddin, B.A., Vlassis, A.G., Elghazouli, A.Y., and Nethercot, D.A., "Assessment of Progressive Collapse in Multi-Storey Buildings", Proceedings of the Institution of Civil Engineers, Structures and Buildings, Vol. 160, No. 4, August 2007, pp. 197-205.

Izzuddin, B.A., Vlassis, A.G., Elghazouli, A.Y., and Nethercot, D.A., "Progressive Collapse of Multi-Storey Buildings due to Sudden Column Loss – Part I: Simplified Assessment Framework", Engineering Structures, 2007 (doi:10.1016/j.engstruct.2007.07.011).

Omer, E., Izzuddin, B.A., and Elghazouli, A.Y., "Failure Assessment of Simply Supported Floor Slabs under Elevated Temperature", Structural Engineering International, 16(2), pp. 148-155, 2006.

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Understanding of robustness

I subscribe to the general postulate and working thesis expressed by Michael Faber, referring to robustness as a performance attribute of a *structural concept*, including the structure, its design, its execution and so on. In terms of implementation, however, it would be helpful to have the generic definitions referring to a 'system', which allows robustness issues to be considered at various multi-scales. For example, considerable progress can be made on assessing robustness using structural mechanics and knowledge of component performance, before uncertainty and consequence issues need to be considered. I therefore see progress in this area being made at different levels, each of which could be useful in specific contexts.

Since robustness is concerned with unforeseen events, the natural approach is to look at performance under event-independent scenarios. The difficulty lies in defining what constitutes realistic scenarios; in this respect, there will always be a need for engineering judgement if the structures are to be economic as well as robust. Also, given that these events are unforeseen, consideration of the probability of event occurrence should be excluded from consideration; however, relative probabilities of different scenarios could well be considered, and that's where an element of engineering judgement would also be needed.

The work undertaken at Imperial College London in collaboration with ARUP has provided a simplified and coherent framework for assessing the structural robustness of multi-story buildings under two event-independent scenarios: i) sudden column loss, and ii) floor collapse on top of a lower floor. The simplified framework benefits from applicability at different levels of structural idealisation, making it suitable in due course for design-oriented application. The proposed approach can be incorporated within a probabilistic risk assessment framework and could potentially be extended to other types of structure.

Collection and Exchange of Basic Information

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Short CV

Inger B. Kroon has been working in COWI since 1994 and is responsible for risk and reliability assessments in the division for bridges, tunnels and marine structures. She was born in 1966 and completed her MSc in 1991 as a structural engineer. In 1994 she received her PhD from the Institute of Structural Engineering at Aalborg University, Denmark. The PhD specialization was on decision theory applied to structural engineering problems - a subject which she has been working with ever since.

From university and the years with COWI, Inger B. Kroon has wide experience in probabilistic modeling for risk and reliability analysis, code calibration, Bayesian model updating and formulation of operational and strategic decision support tools. The general focus of the modeling is to depict the risks, i.e. the probability of the identified unwanted events, and on this basis to support decisions regarding all types of risk control options in an overall optimal way. Inger B. Kroon has applied the risk, reliability and decision support tools in the fields of bridge, maritime, tunnel, offshore and railway infrastructure engineering as well as for the more general design basis preparation. Recently, she has been focusing on modeling maritime safety and risks associated with decommissioning of off- and onshore structures for decision support regarding risk control options on a strategic level.

Furthermore, Inger B. Kroon has been working with detailed analysis and planning of the Øresund bridge.

During her career Inger B. Kroon has been actively involved in several international committees including the Danish Society for Risk Assessment (RISK), where she is presently acting as vice-president, the Joint Committee on Structural Safety (JCSS) and the International Forum on Engineering Decision Making (IFED).

Key literature on robustness

No particular references to add to Michaels list.

References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulations

As a fundamental demand the Danish Code DS 409:2006 “Basis of structural design” requires that structures are designed to have a satisfactory robustness. In latest code updates much effort has been spend on defining robustness and giving guidance.

Treatment of robustness in practical engineering

Robustness is generally explicitly required without a strict definition of the term and is generally ensured by providing some degree of redundancy to the structural system. Typically a bridge is designed to maintain integrity if a vulnerable element such as a cable stay or a hanger rope is lost. For other structural elements such as the bridge girder, the pylons, the cable etc. full integrity cannot be maintained if the element is lost and the element itself will need to have some robustness.

The vulnerability of the individual elements - i.e. the element in relation to the surroundings - and the related exposure of the elements may be determined by means of risk and reliability assessments.

In later designs the structural elements are divided more explicitly into groups - primary and secondary components - and each group is designed wrt. to group specific limit states. . This is in line with ISO 2394:1998(E) 4.3 d) where measures which should be taken to counter exceptional events in order to limit damages to an extent not disproportionate to the original cause. According to ISO 2394:1998 structural design should be such that secondary structural elements can be removed without causing collapse of more than a limited portion close to the element. Primary - key - elements, for which failure cause collapse of more than a limited portion of the structure close to the element, should - if they cannot be avoided - be designed according to their importance.

Treatment of robustness in national education of engineers

Not aware of how it is taught today.

Understanding of robustness

Understanding of robustness:

- Structural robustness is not an inherent characteristic of a structure but must be assessed in a larger context including the surrounding environment and the use of the structure (…. which also is illustrated from the natural tendency of asking robust towards what?)
- Thus, in order to assess the robustness of some specific structure some measure of the change in conditional system reliability given failure or degradation of the subsystems must be combined with some measure of how vulnerable the various subsystems are to possible exposure. Vulnerability can be seen as a marginal probability of an element or subsystem failure or degradation.

Wish:

- A measure of robustness making it possible to compare solution models in a more direct way.

It is important to remember that robustness is a general requirement and should not only be related to accidental actions.

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Short CV

Ulrike Kuhlmann, née Berz, has been working at the Institute of Structural Design at Universität Stuttgart as a professor and head of the institute since 1995. She was born in 1957 and completed her diploma thesis in 1981. In 1986, she received her PhD in structural engineering from Ruhr-Universität Bochum.

Prior to her appointment to the University of Stuttgart, she worked as a visiting professor at Institut Construction Métallique (Prof. Dr. J.-C. Badoux) at École Polytechnique de Lausanne (EPFL), Switzerland. Later, she worked as an engineering consultant at consulting office Dr. –Ing. U. Weyer and Johannes Dörnen in Dortmund.

Presently, she is responsible for the research and teaching activities in the area of steel, timber and composite constructions.

Starting from her dissertation on the rotation capacity of I-shaped beams and its influence on the flange slenderness limits, Ulrike Kuhlmann supervised 2 dissertations on rotation capacity of ductile steel and composite joints and corresponding research projects.

At present, the selected application of such ductile joints in order to develop robust frame constructions is tested within the framework of a European Research project on robustness. An additional AiF research project deals with the development of ductility criteria for standardized bolted beam-to-post connections in steel construction.

Ulrike Kuhlmann has been actively involved in several international research networks such as C1, C12, C 25 and C26 as well as in several corresponding international and national standardization committees, including her membership in the International Association for Bridge and Structural Engineering (IABSE).

Key literature on robustness

Taylor, D.A.: Progressive Collapse. Canadian Journal of Civil Engineering, No.4, Dec. 1975

Liu, R.; Davison, J.B.; Tyas, A.: A study of progressive collapse in multi-storey steel frames. Proceedings of the 2005 Structures Congress and Forensic Engineering Symposium, New York, April 2005

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Treatment of robustness issues in national codes and regulations

Definition of Robustness in DIN 1055-100 3.1.3.3 and in chapter 4.1 “Requirements” it is stated that a structure has to be designed such a way that accidental local failure leads not to a failure of the whole structural system.

Reference in the German Code DIN 1045-1 “Plain, reinforced and prestressed concrete structures”:

Chapter at the end of the code, “Limitation of damage due to accidental actions” it is stated - --if the provisions of this clause and the other provisions of this standard are met, it may be assumed that the change failure of an individual member or part of the structure or the occurrence of acceptable local damage will not results in the failure of the whole structure.

Treatment of robustness in national education of engineers

Structural robustness is not taught particularly in the German engineering education system (Stuttgart). Students are taught, however, about various aspects relating to robustness during their basic structural engineering education.

Understanding of robustness

Postulate:

- Robustness concerns the sensibility of a structure to disturbances.

Working thesis:

- Structures should be designed to be robust in the sense that small events or disturbances should not cause a catastrophic disaster.

  There are different strategies to achieve this aim:

  - the probabilistic optimisation approach: this more mathematical approach tries to optimise functions that describe the behaviour of a structure in dependence on design characteristic
  - the direct over-strength approach: catastrophic events such as fire, explosion, etc. are simulated directly and crucial structural elements are strengthened in order to withstand such an extreme event
  - the redundancy approach: to cope with unforeseen events structures are created that allow a redistribution of internal forces and joints and members are designed in view of ductility and deformations in order to allow this redistribution

Collection and Exchange of Basic Information

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Short CV

Leslaw Kwasniewski has been working at the WUT Institute of Structural Mechanics since 1988, and as an Assistant Professor since 1998. He was born in 1961, completed his MSc in 1986 in the specialization of structural mechanics. In 1997 he received his PhD in the theory of stability of thin walled structures from the Warsaw University of Technology.

Presently he is responsible for research and teaching activities at WUT in the area of structural analysis, strength of materials and applied finite element analysis. He has been conducting teaching courses of commercial software based on finite element method (FEM) such as MSC. Patran, Abaqus, and Ls-Dyna. His research is focused on application of FEM in the areas within civil and mechanical engineering and advanced analysis using computer simulations. His current research activities are : ultimate loading, failure mechanisms and stability problems, coupled structural-thermal analysis, fluid-structure interaction in moving tanks, stress wave propagation in multilayer repair system (impact-echo method), stress distribution in the pavement under moving wheel loading. Those studies are conducted in cooperation with the several research groups gathering researchers with different multidisciplinary expertise and also strong experimental approach. Part of that research was funded by Polish Scientific Research Committee and Ministry of Science and Higher Education.

In 1999, as a Dekaban Fund Fellow, he was a Visiting Postdoctoral Research Assistant at the University of Michigan, USA. Since 2001 he has been actively cooperating with the FAMU-FSU College of Engineering, in Tallahassee, Florida, USA. He was conducting research and teaching at FAMU-FSU College of Engineering during his leave and sabbatical periods at WUT; 8/2001- 9/2003, 9/2004-2/2005, 7-8/2005, 2-3/2006, 7-8/2006, 2-3/2007, and 7-8/2007. In 2002 he completed the course : "Advanced Training in Impact Analysis" conducted by Livermore Software Technology Corp., Livermore CA, USA. He is participating in the research on crashworthiness and passenger safety, and dynamics of bridges, sponsored by the Florida department of Transportation and U.S. Federal Transit Administration. The research is conducted in the Crashworthiness and Impact Analysis Laboratory and is oriented on the advanced analysis using computer simulations and the experimental validation.

Member of the working group WG1-Fire in the European Technical and Scientific Cooperation COST Action C26, Urban Habitat Constructions under Catastrophic Events. Cooperation with the Expert Group on UN ECE Regulation No. 66 (IG/R.66). Review activities for Journal of Sound and Vibration, Engineering Structures, and Finite Elements in Analysis and Design.

Key literature on robustness

US Departament of Defence. Unified Facilities Criteria (UFC). Design of Buildings to Resist Progressive Collapse. UFC 4-023-03 25 January 2005. www.wbdg.org/ccb/DOD/UFC/ufc_4_023_03.pdf

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Wekezer J., Wuttrich R., Kwaśniewski L. Crashworthiness Assessment of a Bridge Fender Due to Barge Impact, XXI Conf. on Structural Failures, Szczecin-Miedzyzdroje, Poland May 2003, pp. 613-620.

Treatment of robustness issues in national codes and regulations

In the Polish codes the term robustness of structures is not defined in an explicit way. New standards and design regulations, developed by the International Organization for Standardization (ISO) and European Committee for Standardization (CEN), are being implemented now in Poland.

Treatment of robustness in national education of engineers

Structural robustness is not present as a separate subject at Polish technical universities. There are courses in civil engineering departments dealing with related aspects such as failure analysis, reliability and safety of structures.

Understanding of robustness

Postulate:

Working thesis:

A robust structure is supposed to experience minimal deterioration due to limited damage. The robustness can be also analyzed using reverse approach focused on the vulnerability of a structure. The search for the weakest structural elements can be conducted through consideration of possible hazard scenarios and corresponding failure mechanisms.

Collection and Exchange of Basic Information

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Short CV

YEAR OF BIRTH 1954

NATIONALITY Norwegian

POSITION Professor, NTNU, Dept. Marine Technology, Faculty of Engineering Science and Technology

EDUCATION

1987	Dr ing (Ph D) Marine Structures, The Norwegian Institute of Technology at the University of Trondheim, Norway
1978	Sivilingeniør (M Sc) Structural Engineering, The Norwegian Institute of Technology at the University of Trondheim, Norway

EXPERIENCE

1999-Present	Professor , NTNU, Dept. Marine Technology, Faculty of Engineering Science and Technology
1994-1999	Professor II - NTH, Div. Structural Mechanics
1990-1999	Research Manager - Stochastic Modelling and Reliability, SINTEF Civil and Environmental Engineering, Department of Structural Engineering
1989-1990	Research Manager - Bridges and Strait Crossings, SINTEF Structural Engineering
1988-1989	Research Manager - Structural Reliability, SINTEF Structural Engineering
1987	Visiting scholar at Stanford University, USA (10 months)
1979-1986	Research Engineer, SINTEF Division of Structural Engineering

Experience in lecturing:

Has given lectures in following courses:

- Structural Dynamics (M Sc Course)
- Dynamics of Slender Offshore Structures (Dr ing and EEU courses)
- Analysis of Plates and Shells (M Sc Course)
- Finite element methods (M Sc Course)
- Structural Reliability (Dr ing, EEU and NORAD courses)
- Analysis and Design of Marine Bridges (EEU course)
- Offshore Structures (Ph D course at Standford Univ)

- Analysis of Uncertainty (M Sc Course)
- Analysis of Piping Systems (EEU Course)
- Computational Dynamics (Dr ing Course)

MAIN FIELDS OF COMPETENCE

- • Structural Dynamics
- • Stochastic Processes
- • Structural Reliability
- • Earthquake Risk Analyses
- • Design Methods

PROFESSIONAL MEMBERSHIPS

ISO TC67 SC2 WG-3 "Pipeline Design" (Work completed)

API Working Group: "Design of Risers for Floating Production Systems and Tension-Leg Platforms" (Work completed)

NBR Norwegian Committee "Vibration and Shock" (ISO TC 108)

ISO/TC67/SC4/-"Dynamic Production Risers"

ISO/TC67/SC7/WG 5 Panel 6: Risers

ISSC, Committee IV-1: Design Principles and Criteria (Work completed)

CONFERENCE COMMITTEES:

OMAE-Series, ESREL-Series

Key literature on robustness

See lists provided by M. Faber and T. Moan

Plus:

Baker, J. et. al. (2005): ”On the Assessment of Robustness I”, Proc. Of the JCSS & IABSE Workshop on Robustness of Structures”, Watford, UK, November, 28-29.

References on data and assessment of structural failures

See lists provided by M. Faber and T. Moan

Plus:

Matousek, M., “Outcome of a Survey on 800 Construction Failures”, in Proceedings, IABSE Colloqium on Inspection and Quality Control, Institute of Structural Engineering, ETH, Zurich, 1977

Pugsley, A.:”The Safety of Structures”, Edward Arnold, London, 1966.

Smith, D.W.:”Bridge Failures”, Proceedings of the Institution of Civil Engineers, Vol. 60, 1976, pp. 367-382

Treatment of robustness issues in national codes and regulations

See description provided by T. Moan

Treatment of robustness in national education of engineers

See description provided by T. Moan

Understanding of robustness

Postulate:

Robustness of a structure is the ability to withstand a specified set of unlikely events (but not unlikely enough to be neglected) without disproportionate damage, loss of performance and consequences thereof. (By disproportionate is here e.g. implied escalation of a local damage into progressive failure and total collapse. The events can further be associated both with loading and strength parameters/scenarios).

Working thesis:

It should be aimed at defining both a rather precise (although possibly complex) measure of robustness. It should also be aimed at developing a more simplified (engineering-type) of measure which is able to capture the essence of this "precise" measure, but which still is quite simple to compute/evaluate.

Example of hypothetical problem formulation:

Both Robinson Crusoe and Friday (left as you know on a Pacific island) have produced and mounted a separate hammock. After having constructed the hammocks, Robinson has gained a lot of weight.

It can be shown both by structural reliability theory and engineering design analysis that if Robinson uses his own hammock it will fail completely (with probability 1.0), while if he uses the hammock produce by Friday, that one can withstand this partly unforeseen increase of loading. There is an equal chance that Robinson will use the hammock produced by himself and the one produced by Friday.

The consequences/costs associated with failure of any of the hammocks are the same, and are only associated with repair of the hammock. There are no indirect consequences/costs for the society around the structure if a failure should occur (assuming that Robinson is not injured or annoyed if the hammock fails). It is further assumed that the initial cost of construction are the same for both hammocks (measured e.g. in terms of equivalent number of fish, bananas, birds, wild-boar, coconuts or similar). It is further assumed that if the weakest hammock fails, it will be fixed immediately by Friday.

Question:

Is the hammock produced by Friday more robust than the one produced by Robinson, and how should we proceed to measure this robustness ?

Collection and Exchange of Basic Information

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Short CV

Born: in Prague 1995

Education:

Dipl. Ing.(1979), Ph.D. (2000) Czech Technical University in Prague, Faculty of Civil Engineering, branch structures and transport, Assoc. Prof. (2007) Czech Technical University in Prague, Faculty of Civil Engineering, theory of structures

Profession:

1979-1996 designer of buildings and bridges, 1996- till now - researcher in the Klokner Institute CTU in Prague, Department of Structural Reliability

Pedagogical activities:

1998 - till now - pedagogical activities at the Faculty of Civil Engineering and at Faculty of Architecture of CTU, lectures in the framework of whole-life education (for Czech Standardisation Institute, Czech Chamber of Civil Engineers, Czech Concrete Society)

Research activities

Reliability of structures, actions on structures, theory of structural reliability, risk assessment of structures. Co-author of 3 handbooks for students in CTU, of several books of proceedings in the framework of the whole life education, author or co-author of more than 80 research contributions. Involved in several national and international research projects.

Standardisation activities

Translation of Eurocodes to Czech, development of National application documents to prenormative ENV Eurocodes, comparative analysis, probabilistic analysis of reliability, development of National annexes to EN Eurocodes, Czech national technical contact for EN 1991-1-5 Thermal actions, member of international project team for the development of Eurocode EN 1991-1-6 Actions during execution, activities in committees CEN/TC 250 and CEN TC 250/SC1.

Membership in national and international organisations

- member and secretary of Technical committee TNK 38 Reliability of structures (CNI)
- member of Technical committee for construction products at ÚNMZ
- member of national organisation Concrete and masonry
- member of CIB
- member of JCSS (Joint Committee on Structural Safety), WG1 for reliability of structures
- member of ENC Group (Eurocodes National Correspondent Group), Commission Services, representing CR

Treatment of robustness in national codes and regulations

Czech codes include provisions for achievement of safe construction works (empirical rules for dimensioning of structural members, selection of appropriate materials). The new Eurocode EN 1991-1-7 implemented into the system of Czech standards contains some general information concerning structural robustness.

References

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Melchers R.E.: Structural Reliability, Analysis and Prediction, John Wiley and Sons, 1999

Ellingwood B., Best Practice for Reducing the Potential for Progressive Collapse in Buildings, *In: JCSS and IABSE Workshop on Robustness of Structures*, 2005

Menzies J., Use of Robustness Concepts in Practice, *In: JCSS and IABSE Workshop on Robustness of Structures*, 2005

Guidelines for Collapse Control Design, Report, Japanese society of steel construction council on tall buildings and urban habitat, 2005

Holicky et al, Insufficient robustness and structural damage due to flooding, explosion and vehicle impact, *In: JCSS and IABSE Workshop on Robustness of Structures*, 2005

Holicky M., Markova J., Durability Assessment of Prefabricated Balconies, *In: 3rd International Conference on Forensic Engineering*, UK, 2005, pp. 29-34, ISBN 0415 39524 0

Holický M., Marková J., Citiziens safety and structural reliability, *In: Workshop Enhancing the JRC - Czech Republic Collaboration in Security Research*, 12/2005 Prague 6, ČSAV

Collection and Exchange of Basic Information

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Brief CV

Torgeir Moan obtained an M.Sc. in 1968 and a PhD in 1976, both in the Department of Civil Engineering, NTH (NTNU). Since 1977 he has been Professor of Marine Structures. In 2002 he became Director of CeSOS which annually carries out 50 man-years of research. His main research interest is stochastic modelling of structural load effects and reliability and risk analysis, relating to all kinds of marine and civil engineering structures. He has authored more than 350 scientific papers, and delivered more than 20 keynote, plenary lectures in international conferences and award lectures. He has educated 41 and is currently supervising 12 doctoral students and has hosted many foreign postdoctors and visiting professors. He has been a visiting professor at MIT for one year and UC Berkeley (two years).

He has contributed in the development of various structural design standards for offshore structures, ships and floating bridges as well as other civil engineering structures in Norway and internationally, e.g. through the Norwegian Petroleum Directorate (Petroleum Safety Authority); Det Norske Veritas' offshore and Safety at Sea committees, Norwegian Building Standards Assoc. Comm. on Reliability of Structures (Chairman), ISO Standard Reliability of structures IS 2394; and ISO Standards for Offshore Structures. In addition he has been involved in many research programs and projects for regulatory bodies and the industry, partly to establish design bases for novel types of structures not covered by existing codes. This involves the National Norwegian program: Offshore Safety Program, as a board member and especially in Risk assessment of Continental Shelf Activities, conceptual safety assessment of various platform concepts, requalification of jacket platforms at the Ekofisk Field, integrated design and inspection planning and life extension of platforms, design code for TLP and other floating platforms. In particular he has worked on accidental collapse limit states (ALS) including accidental loads and codification of requirements of ALS requirements for offshore structures. Most recently he was responsible for the most modern standard for analysis of loads and load effects for offshore structures (NORSOK N-003) that will serve as basis for ISO standard for floating platforms. He has also been engaged in several accident inquiries; notably the Alexander Kielland, Ocean Ranger, Sleipner platform accidents and the HSLC accident.

He has been involved in international organisations such as ISSC, as committee chairman, Standing Committee member, in 1994-97 as the ISSC chairman; and in organising conferences such as ICOSSAR, Eurodyn, BOSS, FAST and PRADS. He is editor of J. Marine Structures and serves on the editorial board of 7 other journals. Moan is a Fellow of several academies such as the Royal Academy of Engineering in UK, and professional organizations such as ASCE and IABSE.

Additional literature on robustness

Allen, D.E. (1975). “Limit state design - A probabilistic study”, Canadian Journal Civ. Eng.

Allen, D.E., and Schriever. W.R. (1972). “Progressive collapse. Abnormal loads and building codes”. Proc. Am. Soc. Civ. Eng. National Meeting on Struct. Engng., Cleveland, Ohio, 21-47.

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Moan, T. (2006). “Design of Offshore Structures and Ships for Damage Tolerance”, Keynote lecture, Proc. SOBENA Conf., Rio de Janeiro, 27.11-01.12.2006.

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References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulations

Civil engineering codes in Norway follow the Eurocode system. However, the regulatory system for offshore structures and facilities refer to a hierarchy of criteria from very general statements to explicit, quantitative criteria and principles.

For instance the “Facilities Regulations” of the Petroleum Safety Authority specifies:

§57 The main load bearing system shall be designed so that a single component failure or water penetration through the outer wall facing the sea cannot lead to unacceptable consequences.

These Regulations are spelled out in design, fabrication and operational standards by NORSOK (the society of offshore oil and gas operators). For instance, The structural integrity criterion in *NORSOK N-001* for the Norwegian offshore industry is expressed by a two-step procedure based on characteristic actions and resistances:

- the first step is to estimate the initial damage due to accidental actions with an annual exceedance probability of 10^{-4}.
- the second step is to demonstrate that the damaged structure resist relevant functional and environmental actions with an annual exceedance probability of 10^{-2} – without global failure. The characteristic resistance value used for steel is defined as the 95 % quantile. Load and resistance factors for steel structures are taken to be 1.0.

Treatment of robustness in national education of engineers

The background for and implementation of the quantitative Accidental Collapse Limit state for offshore structures is taught for marine structures students. Since the practical implementation of these criteria involves complex structural analyses, relevant methods of structural analysis are also taught.

Students who specialize in Risk and Safety in Engineering, which is not mandatory, learn about risk based approaches to robustness assessment of systems in a wider perspective.

Understanding of robustness

See above “Treatment of robustness issues in national codes and regulations”.

Collection and Exchange of Basic Information

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Short CV

Alan O'Connor is a Chartered Engineer (CEng IEI) with considerable experience in safety assessment of existing structures. His PhD specialisation involved the derivation of site-specific load models for new and existing structures. As part of this work he was responsible for the re-calibration of the Normal Load Model of Eurocode 1, Part 3, Traffic Loads on Bridges at the Laboratoire Central des Ponts et Chaussees (LCPC), in Paris. In recent years his work has involved the incorporation of advanced site-specific traffic loading models and time dependent material deterioration models in safety assessment of existing structures.

Dr. O'Connor was an expert member of COST 345 – Procedures Required for Assessing Highway Structures – workgroup 4, Numerical Methods, and of the subcommittee on Bridge Applications of Weigh-in-Motion of COST 323 – the European Co-ordination Committee on Weigh-in-Motion of Road Vehicles. Dr. O'Connor was an Assistant Contractor in the EU 5th Framework project entitled *Sustainable and Advanced Materials for Road Infrastructures* (SAMARIS). He is currently a task leader on an EU *INTERREG III* funded project for assessment of structures in marine environments. The project has over 10 members from throughout the EU sharing a budget of €2million. The research tasks led by Dr. O'Connor are focused on (a) deterioration modelling and (b) reliability based maintenance optimisation techniques.

In 2001 Dr. O'Connor prepared a guidance document for the Irish National Roads Authority entitled *"High Performance Concrete Bridge Beams – Recommendations on the Use of High Performance Concrete in Prestressed Bridge Beams in Design to BS5400"* pp 45. The purpose of the report was to address the issues facing consulting engineers in the prescription of high performance/strength concrete beams.

Dr. O'Connor was employed in 1998 as a lecturer in Structural and Bridge Engineering at the University of Dublin, Trinity College. During this time he has authored over 60 technical papers and has been responsible for the supervision of both PhD and MSc students in a variety of topics related to structural safety and bridge engineering. He has spoken at numerous international conferences on these topics. He has been the recipient of numerous awards and research contracts.

Whilst employed at Trinity College Dublin, Dr. O'Connor has also been involved in the design of a number of bridge structures as an external consultant to Roughan O'Donovan Consulting Engineers in Dublin. Examples include a pair of 158m push launch post tensioned concrete box girder structures, built near Dublin and the Macken Street Cable Stayed Bridge designed by Santiago Calatrava.

More recently Dr. O'Connor has been performing probability based analysis of bridges with RAMBØLL Consulting Engineers in Copenhagen. Projects have included the 3.2km Storstrøem bridge in Southern Denmark and the 200m Bergeforsen steel railway bridge in Northern Sweden.

Key literature on robustness

1. Agarwal, J., England, J., Blockey, D. (2006). 'Vulnerability analysis of structures', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 124 – 128
2. Ditlevsen O, Bjerager P. (1986). 'Methods of structural systems reliability'. *Structural Safety*; 3:195-229.
3. Gulvanessian, H., Vrouwenvelder, T. (2006). 'Robustness and the Eurocodes', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 167 - 171
4. Maes, M.A., Fitzsons, K.E., Glowienka, S. (2006). 'Structural Robustness in the light of risk and consequence analysis', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 101 – 107
5. Smith, J.W. (2006). 'Structural Robustness Analysis and the fast fracture analogy', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 118 – 123
6. Sorensen, J.D., Christensen, H.H. (2006). 'Danish requirements for robustness of structures: background and implementation', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 172 – 176
7. Starossek, U. (2006). 'Progressive collapse of structures: Nomenclature and Procedures', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 113 - 117
8. Stewart, M. and Melchers, R. E., (1997). 'Probabilistic Risk Assessment of Engineering Systems', Chapman & Hall, 1997.
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10. Wen YK, Song S-H. (2003). 'Structural reliability/redundancy under earthquakes', *Journal of Structural Engineering*; 129:56-67.
11. Wisniewiski, D., Casas, J.R., Ghosn M. (2006). 'Load capacity evaluation of existing railway bridges based on robustness quantification', *Structural Engineering International*, Vol. 16, Number 2, May, pp. 161 - 166

References on data and assessment of structural failures

1. Stewart, M. and Melchers, R. E., "Probabilistic Risk Assessment of Engineering Systems", Chapman & Hall, 1997.

Treatment of robustness issues in national codes and regulations

In Ireland the principal codes used for engineering design are the UK and European Standards. Guidance on robustness is limited as follows:

EC1: Basis of Structural Design

EN 1990:2002 (E)

(7) The provisions of Section 2 should be interpreted on the basis that due skill and care appropriate to the circumstances is exercised in the design, based on such knowledge and good practice as is generally available at the time that the design of the structure is carried out.

2.2 Reliability management

(5) The levels of reliability relating to structural resistance and serviceability can be achieved by suitable combinations of :

e) other measures relating to the following other design matters :
– the basic requirements ;
– the degree of robustness (structural integrity) ;
– durability, including the choice of the design working life ;
– the extent and quality of preliminary investigations of soils and possible environmental influences ;
– the accuracy of the mechanical models used ;
– the detailing ;

BS8110: Structural Use of Concrete – Part 1 Code of Practice for Design & Construction

2.2.2.2 ***Robustness***

Structures should be planned and designed so that they are not unreasonably susceptible to the effects of accidents. In particular, situations should be avoided where damage to small areas of a structure or failure of single elements may lead to collapse of major parts of the structure.

Unreasonable susceptibility to the effects of accidents may generally be prevented if the following precautions are taken.

a) All buildings are capable of safely resisting the notional horizontal design ultimate load as given in **3.1.4.2** applied at each floor or roof level simultaneously.

b) All buildings are provided with effective horizontal ties (see **3.12.3**):

1) around the periphery;

2) internally;

3) to columns and walls.

c) The layout of building is checked to identify any key elements the failure of which would cause the collapse of more than a limited portion close to the element in question. Where such elements are identified and the layout cannot be revised to avoid them, the design should take their importance into account. Recommendations for the design of key elements are given in **2.6** of BS 8110-2:1985.

d) Buildings are detailed so that any vertical load-bearing element other than a key element can be removed without causing the collapse of more than a limited portion close to the element in question. This is generally achieved by the provision of vertical ties in accordance with **3.12.3** in addition to satisfying a), b) and c) above. There may, however, be cases where it is inappropriate or impossible to provide effective vertical ties in all or some of the vertical load-bearing elements. Where this occurs, each such element should be considered to be removed in turn and elements normally supported by the element in question designed to "bridge" the gap in accordance with the provisions of **2.6** of BS 8110-2:1985.

e) A connection is provided between the horizontal ties and the vertical elements.

Treatment of robustness in national education of engineers

Structural robustness is not taught in the Irish engineering system, in its own right. As per other international systems it is taught as a subset of engineering design courses.

Postulate:

Structural robustness in its own right is meaningless unless considered as inherent to the overall suitability of the structure.

Working thesis:

The best way to evaluate structural robustness is within the framework of probability based assessment. Events which initiate partial collapse are in themselves best modeled within the context of probability of occurrence and as such the best treatment of structural response/robustness is within the concept of probability of full/partial failure.

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Short CV

Position:	Senior Lecturer
Qualifications:	BE (NUI), MEngSc (NUI), PhD (TCD), Dip.Con. Tec. (ICT)
Areas of Expertise:	Railway Engineering, Structural Engineering, Bridge Dynamics, Analysis of Historic Masonry Structures, Concrete Technology, Optimization, Heat flow in Buildings.

Robustness of Structures - Relevant Expertise

Railway Bridge Loading:

I have carried out extensive research on the effects of random track irregularities on the dynamic loads applied to railway bridges and on developing algorithms for estimating the cumulative fatigue damage to metal railway bridges.

Masonry Structures:

I have a longstanding research interest in masonry arches and masonry vaults. In addition I am involved in a research project examining the behaviour of cantilevered stone stairs. The work on cantilevered stone stairs is of particular relevance to robustness and would make a very interesting test case.

Membership of Professional Bodies & Awards:

CEng, MIEI, PWI, AREMA

Other activities

Reviewer for the European Commission – railway infrastructure projects including SUSTAINABLE BRIDGES.

Engineers Ireland –Former Chairman of the Structures and Construction Division, Member of the heritage society, former Member of Council.

Collection and Exchange of Basic Information

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Short CV

Work Records:

- November '86 – March '90: CETENA (Italian Ship Research Centre), Hydrodynamic Dept.
- April '90- November 2001: researcher at the Dept. of Naval Architecture and Marine Technology (DINAV) University of Genoa
- Febr. '93 – Febr. '94: guest researcher at the Royal Institute of Technology (KTH) – Stockholm
- From November 2001 associate professor in Ship Structural Design at DINAV

Memberships:

- Since 1997 International Ship and Offshore Structures Congress (ISSC)
  - 1998-2000 (Committee VI.1: Extreme Hull Girder Loading)
  - 2001- 2003 (Specialist Task Committee VI.1: Fatigue Loading).
  - 2004- 2006 (Specialist Task Committee VI.1: Risk Based Design).
  - 2006- 2009 (Committee IV.1 - Design Principles and Criteria)
- Since 2004: advisory council of IFED (International Forum on Engineering Decision Making)
- Since 2006: Joint Committee on Structural Safety (JCSS)

Research Fields:

- Structural reliability and risk based design of marine vehicles
- Loads and responses of marine structures
- Structure-borne noise propagation, acoustical planning on board ships
- Unconventional materials and junctions for marine applications

Key literature on robustness

References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulations

To my knowledge, robustness as such is not covered in the Rules for the classification of ship structures (at national and international level).

Treatment of robustness in national education of engineers

To my knowledge, robustness as such is not covered in undergraduate and graduate national courses in Naval Architecture.

Understanding of robustness

My understanding of robustness for a structural system is as follows:

‘A structural system is robust if the risk due to collapse is suitably distributed among the various independent events that can initiate the collapse itself’

A more quantitative definition (which would be a step forward):

‘A structural system is robust if no more than xx% of the risk due to collapse is allocated to any single independent initiating event’.

The concept of robustness has been somehow considered since long in the design and the verification of ship structures, but in a very implicit way. The challenge is to introduce it explicitly and quantitatively in the normative process.

Collection and Exchange of Basic Information

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Short CV

John Dalsgaard Sørensen is professor at Department of Civil Engineering, Aalborg University, Denmark. He is also affiliated to Risø National Laboratory / DTU, Denmark. He was born in 1956, and completed his MSc in 1980 in structural engineering specialized in Structural Reliability. In 1984 he received his PhD in structural reliability theory from the Department of Building Technology and Structural Engineering, Aalborg University, Denmark.

His research and teaching activities are in the following areas: reliability and probabilistic modeling of civil engineering structures, wind turbines and offshore structures, including risk-based inspection and maintenance planning, reliability assessment of new and existing structures, Bayesian decision analysis, stochastic modeling of environmental and material parameters.

John Dalsgaard Sørensen is active in a number of international and national committees, including the Danish code committee for Loads and Safety for Buildings, CEN TC250/SC1 (Eurocodes), Danish code committee for Loads and Safety for Wind Turbines, JCSS (Joint Committee on Structural Safety) where he presently is acting as reporter for the 'Probabilistic Model Code' and CERRA: Civil Engineering Reliability and Risk Analysis (board member). He has been active in formulating and implementing the robustness rules in the Danish Code for Buildings and in the Danish National Annex to EN1990.

Papers on robustness

Sørensen, J.D. & H.H. Christensen: Danish requirements to robustness of structures – background and implementation. Structural Engineering International, May 2006, pp 172-177.

Sørensen, J.D.: Calibration of partial safety factors in Danish structural codes. JCSS Workshop on Reliability based code calibration. Zurich 2002.

Faber, M.H. & J.D. Sørensen: Reliability Based Code Calibration - The JCSS Approach. Proc. ICASP'09 conf. San Francisco, July 2003, pp. 927-935.

Ersdal, G., O. Kuebler, M.H. Faber, J.D. Sørensen, S. Haver & I. Langen: Economic optimal reserve strength for a jacket structure. Proc. 2nd ASRANet International Colloquium, Barcelona, 2004.

Canisius, TDG, JD Sørensen and JW Baker: Robustness of Structural Systems – A new focus for the Joint Committee on Structural Safety (JCSS). Taylor & Francis, CD-rom proc. for ICASP10 conf., July 2007, Tokyo, Japan., 2007.

Treatment of robustness issues in national codes and regulations

The basis for the robustness rules in the Danish code of practice for buildings and in the National Annex to EN1990 and EN1991-1-7 can summarised as follows.

Much more frequent use of advanced types of structures with limited redundancy and serious consequences in case of failure combined with increased requirements to efficiency in design and execution followed by increased risk of human errors has made the need of requirements to robustness of new structures essential. According to Danish design rules robustness shall be documented for all structures where consequences of failure are serious. The following design procedure shall be followed in order to document sufficient robustness: 1) Review of loads and possible failure modes / scenarios and determination of acceptable collapse extent; 2) Review of the structural systems and identification of key elements; 3) Evaluation of the sensitivity of essential parts of the structure to unintentional loads and defects; 4) Documentation of robustness by 'failure of key element' analysis; 5) Documentation of robustness by increasing the strength of key elements if step 4 is not possible.

Treatment of robustness in national education of engineers

A new 1 ECTS course in 'Robustness of structures' will start this autumn at the Department of Civil Engineering, Aalborg University, Denmark (5. semester). Further robustness is also partly covered in the 2 ECTS course on 'Structural Reliability' (8. semester).

Understanding of robustness

Postulate:

- Structural robustness is a general requirement to the structure and not a requirement related to specific loads, for instance accidental loads. Robustness depends on the function, environment and use of the structure, and is should be verified for all phases in the life-cycle of a structure, incl. execution and operation.

Working thesis:

- A robust structure will not be affected by foreseen or unforeseen hazards resulting in local damages to such an extent that major parts of the structure collapse. A major problem is assessing robustness of structures is related to possible human errors during execution and operation.

Collection and Exchange of Basic Information

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Short CV

Miroslav Sykora was born in 1977 in Ceske Budejovice (Czech Republic). He got an engineering degree (Transportation Engineering, Concrete Bridges) in 2001 at the Faculty of Civil Engineering, CTU in Prague. In 2005 he received a Ph.D. degree (Theory of Structures, topic of the thesis: Probabilistic Analysis of Time-Variant Structural Reliability, supervisor Prof. Dr. Milan Holický) at the Klokner Institute CTU in Prague.

In 1999 and 2000 he was active as a structural designer in PONTEX Ltd. (bridge design and diagnostics). In 2003 he was at the Faculty of Civil Engineering and Geosciences, TU Delft for a study stay (supervisor Prof. A.C.W.M. Vrouwenvelder).

Since 2005 he has been working as a researcher at the Klokner Institute, CTU in Prague. His research interests include structural reliability methods, models for load effects, data evaluation and assessment of existing structures. Presently he is also responsible for teaching activities in the field of structural reliability and structural design. In 2007 he became a member of the Editorial Board of the Building Research Journal.

Literature

HOLICKÝ, M. – SÝKORA, M. Probabilistic Evaluation and Prediction of Discharges on the Vltava River in Prague. In: *Proceedings of the 3rd Czech/Slovak Symposium Theoretical and Experimental Research in Structural Engineering*. CTU in Prague, 2004.

SÝKORA, M. Load combination model based on intermittent rectangular wave renewal processes. In *Proceedings of ICOSSAR 2005*, Rome. Rotterdam: Millpress Science Publishers, 2005.

SÝKORA, M. – HOLICKÝ, M. Probabilistic verification of load combinations using rectangular wave renewal processes with intermittencies. In *Proceedings of ESREL 2006,* Estoril, Portugal, 2006. Leiden: Taylor & Francis/Balkema, 2006.

SÝKORA, M. On accuracy of different approaches to time-variant structural reliability. In *Proceedings of ESREL 2007,* Stavanger, Norway. London: Taylor & Francis/Balkema, 2007.

For additional information about key literature, treatment and understanding robustness please see the basic information provided by Prof. Dr. M. Holicky (Czech Republic).

Collection and Exchange of Basic Information

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Short CV

Professor Nicolae Taranu is currently the Dean and Professor of Civil and Structural Engineering at the Faculty of Civil Engineering, the Technical University of Iasi, Romania. He is also the Director of the Doctoral School of Civil Engineering at the Technical University of Iasi. Between 1996 and 2003 Professor Taranu was the Head of the Department of Civil and Industrial Engineering at the same University. He was born in 1944 and received his MEng in 1967 specialized in Civil and Industrial Construction. In 1978 he received his PhD in Civil Engineering from the Polytechnic Institute of Iasi (currently the Technical University of Iasi). During the academic year 1971-1972 he was a Junior Fulbright Scholar at the University of Virginia, USA.

Professor Nicolae Taranu held a position as an EU Marie Curie Senior Research Fellow at the University of Sheffield, UK (2002-2003) and as a Visiting Senior Research Fulbright Scholar at the University of Virginia, USA (1995-1996).

Presently he is a Senior Researcher and Research Group Co-ordinator at Polytech (Centre for Research and Technology Transfer, at the Technical University of Iasi). In this capacity he is responsible for teaching and research activities in the fields of composite structures, and structural rehabilitation solutions of structures made of traditional building materials using advanced fibre reinforced polymeric composites. His teaching activity also comprises structural steel design, industrial buildings and light-weight layered structures.

Professor Taranu's main research activity has been focussed on composite structures made of fibre reinforced polymer composites with four principal directions: all composite structures, structural sandwich construction made of composites and associate materials, structural members made of traditional materials reinforced with FRP composite elements and structural rehabilitation of structures made of traditional materials (concrete, masonry, timber and steel).

Nicolae Taranu has coordinated 148 research grants, awards and industrial contracts and has published a total of 360 papers and technical reports. He has authored or co-authored 21 books on Structures made of composite materials, Steel structures, Rehabilitation of buildings and Structural sandwich construction.

Professor Nicolae Taranu is a Corresponding Member of the Romanian Academy of Technical Science, Member of the Romanian Association of Structural Engineers, UNESCO Centre for Engineering Education, International Association for Bridge and Structural Engineering (IABSE), American Society for Testing and Materials (ASTM), International Council for Building Research and Documentation, CIB-W89, Building research and Education, President of the Academic Society “Anton Sesan”, Romania.

Key literature on robustness (not very specific)

Virdi, K.,S., Garas, F.K., Clarke, J.L., Armer, G.S.T., eds.” Structural Assessment. The role of large and full-scale testing”. E&FN SPON, 1997.

Melchers, R.E., “Structural Reliability Analysis and Prediction”, John Wiley &Sons, 1999.

*** Redundancy & Robustness in the Design of Tall Building Structures: A Panel Discussion. Structures Congress, New York Hilton & Towers, New York, April 22, 2005

Villaverde, R., “Methods to Asses the Seismic Collapse Capacity of Building Structures: State of the Art. Journal of Structural Engineering, ASCE, January 2007, 57-66

Treatment of robustness issues in national codes and regulations

No special definition and utilization is given to robustness in the Romanian Standard (General Principles for the Verification of the Safety of Structures)

Treatment of robustness issues in national education of engineers

No special treatment is given in general to the structural robustness in our civil and structural engineering education system.

In the elective course “Safety of Civil Engineering Structures” the term is mentioned in connection with the ability of a structure to limit the effects of structural damages caused by different actions.

Collection and Exchange of Basic Information

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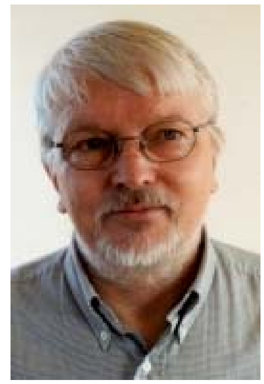

Short CV

Graduate studies and research work in the period 1968 - 1976 within the area of structural fire safety. This work included modelling of building fire processes to describe fire action on structures, resistance of concrete structures exposed to fire as well as reliability and risk analysis in relation to building fire safety.

In the period 1976 - 1984 main research activities involved constitutive modelling and finite element method, with the emphasis on creep, shrinkage and thermal action in concrete structures with applications such as the analysis of nuclear reactor containment structures. During this period I was mainly active in teaching and course development in Structural Mechanics as well as in management of the Civil Engineering program at Lund University.

As head of a timber research program from 1984 to 1989, major areas of work have been moisture actions in wood structures and components, mechanical and adhesive joints, fracture mechanics in wood and various applied investigations on timber structures and timber joints.

As professor and head of the division of Structural Engineering at Lund University from 1989, I am responsible for research and education in Structural Engineering including concrete, steel, timber and masonry structures. Major research areas are structural reliability and timber engineering (reliability of timber structures, optimisation of timber building systems, serviceability of timber structures). From 1994 to 1999 I was leader of interdisciplinary research programs focused on timber frame building systems with a wide spectrum of disciplines involved and close co-operation with industry on the Nordic and European level.

Since the late nineties our research has been more and more focused on reliability and safety issues, in particular for assessment of existing structures where rational methods are especially valuable, since the cost of increasing the safety in an existing facility is very high. Ongoing PhD projects related to safety and reliability under my supervision deals with the following applications

- traffic load capacity on existing road bridges
- safety of pre-stressed concrete containments for nuclear reactors
- safety of hydropower concrete dams

- reliability based analyses of crack control in concrete structures
- thermal actions on concrete bridge structures related to climate data
- probabilistic modelling of moisture effects in wood structural components
- reliability of timber structures

My experience as consultant for the practice (part time) is concentrated on structural engineering in general, in particular concrete and timber structures, tall buildings, investigations of damaged structures, investigations of fire damage, building fire safety, safety barriers for roads and railways.

Key literature on robustness

In addition to the references listed by Michael Faber:

Blockley D.I., Agarwal J. Pinto, J.T: Woodman N.J. Structural vulnerability, reliability and risk. Prog. of Struct. Eng. and Mat. , 2002; **4**: 203-212

Beeby AW. Safety of structures and a new approach to robustness. The Structural Engineer 1999; **77**(4):16-21.

References on data and assessment of structural failures

Matousek, M., Schneider J. Untersuchungen zur Struktur des Sicherheitsproblemes bei Bauwerken. Inst. für Baustatik und Konstruktion, ETH, Zurich, 1976.

Kaminetzsky D. Design and Construction Failures – lessons from forensic investigations. McGraw-Hill, New York, 1991.

Oehme P., Vogt W. Schäden an Tragwerken aus Stahl. Schadenfreies Bauen, Band 30. Fraunhofer IRB Verlag, Stuttgart 2003.

Ellingwood, B. Design and construction error effects on structural reliability. ASCE, J. of Structural Engineering, 13, no. 2, 1987, pp. 409-422.

Walker A.C. Study and analysis of the first 120 failure cases. Structural failure in buildings. The Institution of Structural Engineers, 1981.

Feld J., Carper K.L. Construction Failure. John Wiley & Sons, New York, 1996.

Fraczek, J. ACI survey of concrete structure errors. Concrete International, Vol. 2, No. 12, Dec. 1979, pp. 14-20.

Allen, D.E. Errors in concrete structures, Canadian Journal of Civil Engineering, Vol. 6, No. 3, Sept. 1979, pp. 465-467.

Treatment of robustness issues in national codes and regulations

The Swedish structural code BKR 2003 for buildings specifies in general that the “risk for disproportionate collapse should be limited in design of structures”. This can be achieved by designing the structure so that it can resist accidental loads (fire, vehicle collision, explosions and impact are described as accidental loads in an official design manual) or by designing the structural system so that the extent of the damage is not spread beyond a primary damaged area.

For buildings, the implementation of this in practice is almost without exception made by ensuring that the elements of the structural system are tied together according to special schematic rules. For buildings with heavy concrete structures it is recommended that the capacity for shear and tension forces in boundaries between structural elements should be at least 20 kN/m. For more light-weight structures (such as wood frame) this figure may be reduced in proportion to the lower level of frequent loads on floors.

In the current Swedish bridge code BRO 2004 there are no general statements or principles about robustness on a system level. Specific design values for accidental loads such as vehicle and boat collisions are given for design on the element level. It is also required that failure of stays, hangers, piles or tendons shall be considered according to special rules.

Treatment of robustness in national education of engineers

There are no specific courses in this subject, but the issue is partly covered in general courses in Structural Engineering. However, the education about structural reliability and safety issues for structures is generally quite limited in the engineering educations in Sweden.

At Lund University there are education programs in Fire Safety Engineering as well as Risk Management where the students are given a good training in risk analysis and assessment in general, but these programs are not dealing with structures specifically.

Understanding of robustness

Postulate:

- The performance of a structural system can not be guaranteed only by studying the behaviour of each of its parts. The system has usually some intrinsic characteristics depending on the nature of interaction between its parts and between the system and the environment.

Working thesis:

- Robustness can be seen as the ability of the system itself to limit the consequences of deviations from the behaviour and circumstances postulated when the structure was designed
- A systematic investigation of possible deviations from standard design and the associated consequences should be the starting point for quantification of robustness of a given structural system

Collection and Exchange of Basic Information

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Short CV

Goran Turk was born in 1963, he obtained his B.Sc. in 1987, M.Sc. in 1990 and Ph.D. in 1994. He is employed at the University of Ljubljana, Faculty of Civil and Geodetic Engineering since 1987. Since 1997 he is employed at the University of Ljubljana as a teacher. During his graduate studies in Baltimore, he was teaching assistant for the following subjects: Statics, Theory of structures, and Probability and statistics. During the years from 1994 to 1998 he was assistant for the following subjects: Statics, Strength of materials and Kinematics and dynamics. During these years he (together with the late prof. Marjan Stanek) published three university textbooks: Statics I (313 pp), Statics II (202 pp), and Basics of mechanics of solids (254 pp). In 2005 the improved edition of Statics I (329 pp) was published. Since 1998/1999 he teaches Statistics with the elements of informatics and Probability and statistics. In the last year he started to teach Operational research. He teaches Structural reliability for graduate students.

The university textbook for Statistics is currently in preparation. Its current version is available on web-site: http://www.km.fgg.uni-lj.si/predmeti/sei/vrs1.pdf He was mentor with 20 B.Sc. diplomas and co-mentor with two. Also he was mentor with one Ph.D. Thesis and co-mentor with two.

With his colleagues at the Chair of mechanics he organized thirteen national competitions in mechanics for students of secondary technical school in Slovenia.

During the years after his bachelor graduation he studied the modeling and behavior of fresh concrete: heat of hydration, water vapor diffusion, deformation of mass concrete due to shrinkage, creep, temperature and mechanical loading. During the period of graduate study in USA he was predominately involved in probabilistic methods in civil engineering. After the return from USA he got actively involved in the research program lead by Prof. Miran Saje which dealt with nonlinear structural analysis. He was actively involved in the research of geodetic department. There he contributed to the development of software for geodetic network leveling. Lately, the artificial neural networks were applied in determination of geoid height. ANN were applied also to the prediction of subsidence due to the underground excavation, and to advanced material modeling of soil (oedometer tests) and steel at elevated temperatures. He is active in several research groups who study the effect of fire on reinforced concrete, wood and steel structures.

He was active in action COST E24, Probability of timber structures, which lead to the preparation of Probablistic model code for design in timber structures. During this COST action some other research

activities started. During his three months visit at VTT in Espoo (Finland) he dealt with timber strength grading and reliability analysis of timber structures during fire.
He was involved in the research project DEBRIS (European program Leonardo da Vinci) and is currently collaborating in the project FRANE (European Commission DG Environment). He was twice the leader of the research project group for the project financed by the Slovenian ministry of science: Glulam beams in natural environmental surrounding and Methods of timber strength grading.

The results of his research were published in 106 papers, of which 26 were published in international magazines, 1 part of the monograph, 14 in national magazines, 34 on international conferences and 33 on national conferences.

Key literature on robustness

References on data and assessment of structural failures

Treatment of robustness issues in national codes and regulations

Eurocodes are implemented in Slovenia.

Treatment of robustness in national education of engineers

Robustness is not officially taught in Slovenian engineering educations system. However, the students learn about the sound design of the structures during the courses of Steel Stuctures, Concrete Structures, Earthquake Engineering, etc.

Understanding of robustness

Postulate:

Working thesis:

Collection and Exchange of Basic Information

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Short CV

Dimitri Val was born in 1963 and received his MEng in Civil Engineering in 1985 with specialization in "Theory of Structures". He was awarded a PhD degree in Structural Engineering by the Technion - Israel Institute of Technology in 1995 for research on reliability of reinforced concrete structures against progressive collapse. After completing his PhD he worked at universities in Australia (the University of Newcastle and James Cook University) and Israel (Technion – Israel Institute of Technology) initially as a research associate and then as a faculty member. In September 2007 he joined Heriot-Watt University (Edinburgh, Scotland) as a Reader (Associate Professor) at the School of the Built Environment. He is responsible for research and teaching in the areas of structural engineering and risk and safety in civil engineering.

Dimitri V. Val's research interests are mainly in the area of quantitative/probabilistic risk assessment (QRA/PRA) and its application to civil engineering systems exposed to a variety of man-made and natural hazards. In recent years Val's research has become more focused on such issues as durability and corrosion-induced deterioration of reinforced concrete structures, the use of high-performance concretes, and decision-making based on life-cycle costs (or expected utilities). Other areas of Val's research include risk-based approaches to robustness of structures, the use of FRP composites for strengthening/retrofit of reinforced concrete structures, and performance-based seismic design (in particular, an energy-based approach).

Dimitri V. Val is an active member of the following international technical committees: the Joint Committee on Structural Safety, the IABSE Working Commission 1 on Structural Performance, Safety and Analysis, the ISO committee on Risk Assessment of Structures, and the RILEM Technical Committee TC MAI: "Model assisted service life prediction of steel reinforced concrete structures with respect to corrosion induced damage".

Key literature on robustness

Allen, D. E., Schriever, W. R. (1972). *Progressive Collapse, Abnormal Loads and Building Codes*. Proceedings of the National Meeting on Structural Engineering, ASCE, Cleveland, OH, 21-47.

Burnett, E. F. P. (1975). The Avoidance of Progressive Collapse: Regulatory Approaches to the Problem. National Bureau of Standards, Washington, D.C.

Department of Defense (2005). Unified Facilities Criteria (UFC): *Design of Buildings to Resist Progressive Collapse*. DoD, Washington, D.C.

Ellingwood, B. R.; Dusenberry, D. O. (2005). Building Design for Abnormal Loads and Progressive Collapse. *Computer-Aided Civil and Infrastructure Engineering*, 20, 194-205.

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, NIST, Technology Administration, U.S. Department of Commerce.

Griffiths, H., Pugsley, A., Saunders, O. (1968). *Report of the Inquiry into the Collapse of Flats at Ronan Point, Canning Town*. Her Majesty's Stationery Office, London.

Her Majesty's Stationery Office. (1970). *The Building (Fifth Amendment) Regulations 1970*. Her Majesty's Stationery Office (HMSO), London, UK.

Leyendecker, E. R., Ellingwood, B. R. (1977). *Design Methods for Reducing the Risk of Progressive Collapse in Buildings*. Building Science Series 98. National Bureau of Standards, Washington, D.C.

Smith, J.W. (2006). Structural Robustness Analysis and the Fast Fracture Analogy. *Structural Engineering International*, 16(2), 118-123.

Somes, N. F. (1972). *Abnormal Loading on Buildings and Progressive Collapse*. Proceedings of the Workshop on Building Practice and Disaster Mitigation, National Bureau of Standards, Washington, D.C., 427-470.

References on data and assessment of structural failures

Feld, J., and Carper, K. (1997). *Construction Failure*. 2nd Ed., John Wiley & Sons, New York, N. Y.

Kaminetzky, D. (1991). Design and Construction Failures: Lessons from Forensic Investigations. McGraw-Hill, New York, N. Y.

Mainstone, R. J., Nicholson, H. G.; Alexander, S. R. (1978). *Structural Damage in Buildings Caused by Gaseous Explosions and Other Accidental Loadings 1971-77*. Building Research Establishment, Garston, Watford, UK.

Taylor, N., Alexander, S. J. (1974). *Structural Damage in Buildings Caused by Gaseous Explosions and Other Accidental Loadings*. Current Paper 45/74. Building Research Establishment, Garston, Watford, UK.

Wardhana, K. and Hadipriono, F.C. (2003). Analysis of Recent Bridge Failures in the United States. *Journal of Performance of Constructed Facilities*, ASCE, 17(3), 144-150.

Treatment of robustness issues in national codes and regulations

The term “robustness” does not appear in Israeli building codes. However, three Israeli standards contain provisions concerning progressive collapse. IS 1225-1 "Steel Structural Code: General" in Chapter 5. "Basics of Design" contains only a brief statement that "Local loss of strength or stability should not result in spread of damage beyond a local region (i.e., progressive collapse)".

Much more can be found in IS 466-1 "Concrete Code: General Principles" and IS 466-4 "Concrete Code: Precast Concrete Elements and Structures". IS 466-1 has Section 2.4 "Mitigation of progressive collapse" in Chapter 2 "Basics of Design", which includes a definition of progressive collapse, its causes, and also brief description of the main approaches which can be employed to improve resistance of a structure against progressive collapse; details are given in Annex A, which is normative. IS 466-4 contains Chapter 45 "Prevention of Progressive Collapse". A new revision of IS 466-1 was published in 2003, and its coverage of progressive collapse was mainly based on provisions of IS 466-4 (which has almost not been changed since 1991) with some additions (and corrections) from Eurocode 2: Design of concrete structures.

In IS 466-1(4) progressive collapse is defined as a phenomenon in which “failure of a single structural element, or the limited number of structural elements, leads to collapse of the whole structure, or a major part of it”.

“The collapse can be a result of an accidental event such as explosion of a gas tank or a boiler, vehicular collision, or exceptional natural load. Other possible causes include gross error in design or construction, differential settlement of foundation, excavation near the structure, maintenance defects and their consequences.”

The standards allow spread of damage: vertically – the level of initial local failure, plus two adjacent levels (one above and one below); horizontally – the structural bay associated with initial damage, plus one adjacent bay in each horizontal direction.

The standards contain a general statement that progressive collapse can be mitigated by providing structural integrity and ductility in a building and avoiding sudden weaknesses in structural elements. The standards specify the three main approaches to deal with the problem:

- Design a tying system, which include horizontal peripheral ties, internal ties, ties between floor slabs and column and walls, and vertical ties. The ties should be capable to resist a design value of tensile force 20 kN/m but not higher than 70 kN for one tie (IS 466-1) or 37.5 kN/m (IS 466-4). For a peripheral tie a design value of tensile force is 70 kN (IS 466-1) or 60 kN (IS 466-4). In addition, vertical ties should be capable to transfer tensile force equal to at least 3% of the design vertical load acting on the column or wall at that level. There are a number of other provisions concerning the tie system, which are not mentioned in this brief description. This approach is preferred “from a practical point of view”.
- Provide an alternative load path over a notionally removed structural element, which can be either a column, or a wall (wall panel) of room size, or a floor slab between two adjacent supports (in precast buildings). The load combination used for checking is $G_n+Q_n+W_n/3$, where G_n, Q_n, and W_n are the characteristic values of permanent, variable, and wind load respectively (IS 466-1). Reduced partial safety factors should be also used for concrete and steel. This approach is preferred “from a principle point of view”.
- Design of key structural elements for accidental load, which is defined as 34 kN/m^2. This approach should be used only if the first two approached cannot be implemented.

The standards do not mention any threshold for buildings to be considered, i.e., the provisions should be applied to all buildings.

Treatment of robustness in national education of engineers

Structural robustness is not taught specifically in the Israel engineering education system. However, some aspects of the problem are discussed in structural design courses.

Understanding of robustness

Postulate:

There should be a clear distinction between

- Structural robustness (or the robustness of a structure), which is equivalent to resistance of a structure to progressive collapse and represents a property of the structure alone (or, its load-bearing system although non-load bearing elements may be included in analysis of damage propagation and collapse). Its assessment should only consider what happens with the structure itself and disregard all other factors and consequences; and
- The robustness of a system involving a structure (or structures). Its assessment should include consideration of the structure environment, function, use, and all consequences of its failure.

Working thesis:

- The robustness of a structure is a structural property which depends on its design, execution, and maintenance. It can be affected, e.g., by structural deterioration, repair and strengthening, but should not depend, e.g., on a change of its use (of course, a structure can be assessed as not sufficiently robust for an intended change of use). Non-structural protective measures such as erecting protective barriers against vehicular impact, or forbidding the use of gas in buildings, etc., should not affect it as well. It can be characterise, for example, by conditional probability of collapse given a specified level of initial damage. Material oriented design standards (e.g., for concrete, steel, timber, masonry structures) should only deal with this type of robustness.

- The robustness of a system involving a structure depends on the structure environment and use, including non-structural protective measures. In order to characterise it all consequences of the structure collapse (direct and indirect) should be taken into account. Its measure should be related to risk, i.e., probability of the structure collapse times consequences. Based on its consideration acceptable levels of the robustness of a structure should be assigned. This type of robustness should be addressed in general building codes (e.g., Basis of Design) or/and in standards dealing either with risk assessment for structural systems in general, or with this specific problem, in particular.