COST Action TU0601 – Robustness of structures : A summary

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1. Background

A significant area of research in structural engineering, particularly in the last decade has been robustness of structures. The need for the concept of robustness lies in the fact that structural design codes are based predominantly on the design of structural members or the consideration of member failure modes. Furthermore design codes and their users may not always include all relevant design situations of relevance for the integrity of the overall structural performance. Robustness is broadly recognized to be a property which is not only associated with the structure itself but needs to be considered as a product of several indicators; risk, redundancy, ductility, consequences of structural component and system failures, variability of loads and resistances, dependency of failure modes, performance of structural joints, occurrence probabilities of extraordinary loads and environmental exposures, strategies for structural monitoring and maintenance, emergency preparedness and evacuation plans and general structural coherence.

On an international scale, the research on structural robustness and development of methodologies to ensure an appropriate level of structural robustness in building structures and societal infrastructure in general has so far been dominated by North America and Europe. The most promising contributions to this research field have roots in the theory of structural reliability and in this respect the contributions from the Joint Committee on Structural Safety (JCSS) are worth mentioning.

In 2005, the JCSS in collaboration with the International Association of Bridge and Structural Engineering (IABSE) organised a workshop on robustness of structures, attended by more than 50 experts representing research institutions, companies and government representatives from around the world. The general consensus of this workshop was that robustness is not only of extreme importance but that the present situation with regard to ensuring sufficient structural robustness through codes and standards is highly unsatisfactorily. With regard to what is understood by structural robustness, again a general agreement could be observed. However, despite agreement on the attributes of structures which contribute to structural robustness, no immediate agreement could be established on how to quantify this. Furthermore, and maybe even more importantly, there seemed to be no suggestions on how to establish criteria on what might be understood as sufficient robustness. What could be agreed upon at the workshop was, however, that a future framework for the quantification of structural robustness and for establishing acceptance criteria for structural robustness should be based on considerations of risk, such that the different decision alternatives with regard to improving structural robustness are assessed in terms of their implied risks and ranked accordingly.

As a follow up activity from the workshop, a proposal for a joint European project on structural robustness was established and turned out to be successful. The project 'COST Action TU0601 : Robustness of Structures' (website : http://www.cost-tu0601.ethz.ch/) commenced in February 2007 under the auspices of the COST (European Cooperation in Science and Technology) programme. The COST Action has brought together a group of European professionals with the mission to set up a sustainable basis for exchanging and promoting research in the area of structural robustness over a sufficient period of time and thereby to provide the basis for improved standards and regulations in design and assessment of structures in Europe. The Action will conclude in October 2011; a summary of the work carried out in the Action is provided in this paper.

2. Objectives

The main objective of the COST Action is to provide the basic framework, methods and strategies necessary to ensure that the level of robustness of structural systems is adequate and sufficient in relation to their function and exposure over their life time and in balance with societal preferences in regard to safety of personnel and safeguarding of environment and economy.

In reaching the main objective of the present COST Action several sub-objectives are strived for. These include;

1. Establishing a mid to long term platform of European professionals working in the area of structural robustness, risk assessment of infrastructures and buildings, engaged in or with stakes in pre codification and codification of structural design, assessment, monitoring and condition control.
2. To reach a consensus in the engineering profession and improving the state of the art on how robustness may be assessed, possibly quantified and improved for new and existing structures.
3. Providing a pre-normative probabilistic model code on how to assess and ensure a sustainable degree of robustness of structures.
4. Developing and distributing a guideline for practicing engineers on how to assess and enhance the robustness of structures from a holistic life-cycle perspective.
5. Disseminate through conferences, workshops, publications and internet new knowledge on robustness of structures to the engineering profession in Europe as well as on an international scale.
6. Conducting training for students, young researchers as well as already practicing engineers on the issues of robustness of structures.
7. Improving the European impact on international codification on robustness of structures.

8. Reducing risks in the built environment in Europe and thereby enhancing a competitive and sustainable development of Europe for the future.

The end users of the results of the COST Action are European pre-codification and codification committees on structural design as well as all actors in the European building and construction industry including design, architectural and consulting companies as well as contractors and owners of structures at both a public and private level.

3. Scientific approach

The principal hypothesis of the Action is that risk informed decision making can strongly enhance the robustness of structures (JCSS 2008). In principle, if a design is risk-based and takes into account all relevant aspects of system effects and design cases, then there would be no need for specific robustness considerations. Traditionally robustness is considered to be an inherent property of a structure defined through the design of the structure. However, the envisaged risk based approach considers robustness from a life cycle perspective to be a product of design together with strategies for operation, maintenance and control as well as appropriate emergency response measures. Assessment of robustness necessitates the consideration of the possible scenarios leading to collapse, their probability of occurrence as well as the corresponding consequences.

This more differentiated and rich perspective of robustness not only allows for its assessment and in some cases its quantification but also for a categorization of structures such that codes and standards for a given type and use of a structure more adequately may;

- Provide guidelines with regard to how to improve robustness efficiently.
- Set minimum requirements to the acceptable robustness.

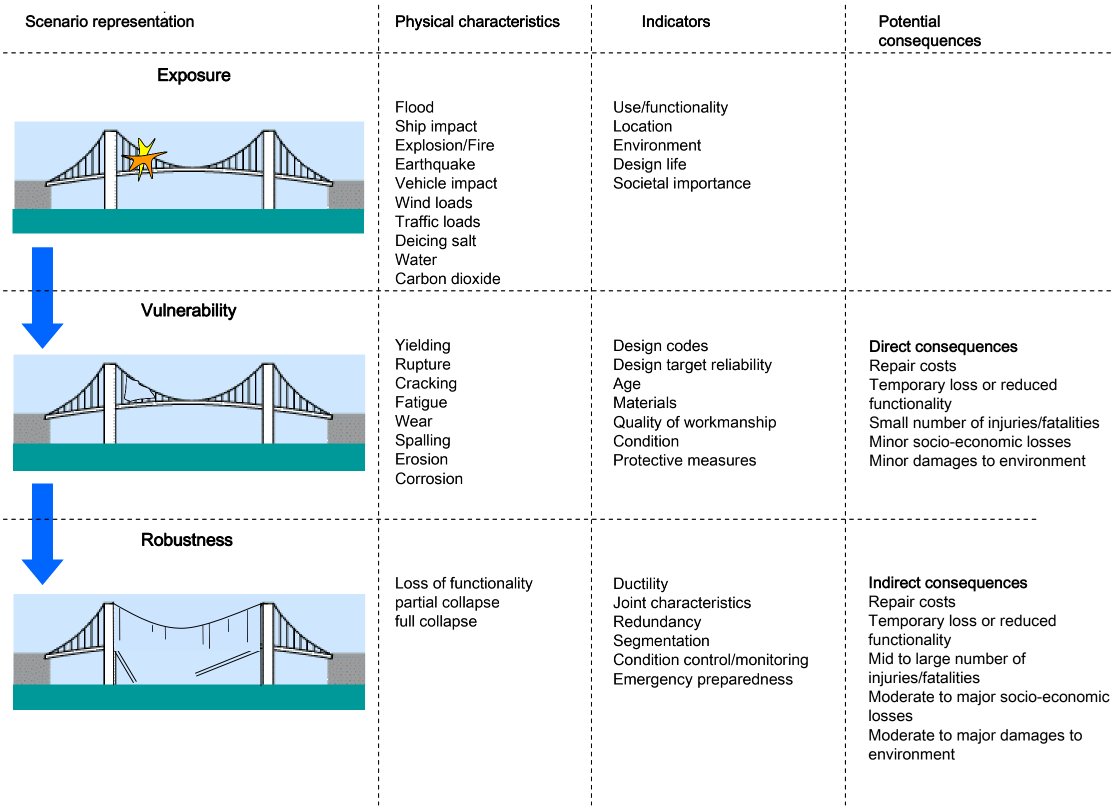

Figure 1 Illustration of system representation in the risk based approach to robustness assessment of structures.

The fundamental idea followed in the COST Action has been based on recent developments in structural risk assessment which take the perspective that the “system” subject to assessment may be represented in terms of the exposures acting on the structure, the damages which may result on the individual components of the structure as an immediate consequence of the exposures and finally the impact (consequences) of the damages on the overall structural systems integrity as well as consequences derived hereof. The principle is illustrated in Figure 1.

As indicated in Figure 1 exposures may be understood as any effect acting on the structure with the potential to imply damage to the constituents of the structure. In this way exposures include fires, explosions and impacts by vessels but also aggressive environments such as de-icing salt, water and carbon dioxide. The vulnerability of a structure is described through the degree the structural constituents (members) are damaged by the effects of the exposures. Structural damages may thus constitute loss of one or several structural members but also just through the reduced performance of individual members or joints. The structural robustness is understood as the ability of the structure to sustain the damages implied by the exposures without partial or fully developing collapse. The envisaged approach, to a high degree, utilizes the different indicators which may in some way be observed or assessed for a given class of structures or for a specific structure and which contain information in regard to exposures, vulnerability and robustness.

Whereas structural design codes at the present time are focusing on ensuring structures with appropriate safety in regard to component failures and thereby are implicitly addressing mainly vulnerability aspects of the structural performance, this COST Action has worked towards establishing a better understanding on the aspects related to the robustness, i.e. focussing on how structures may be designed, operated and maintained such that potential damages are sustained with an appropriately high level of safety.

Following Figure 1 structural robustness can be considered as being conditional on the prevailing exposures as well as the specific characteristics concerning the structural vulnerability. When assessing the robustness of a structure it is thus in principle necessary to consider all relevant exposure and immediate damage scenarios. However, the robustness characteristics of a structure for given types of exposures and damages may also be interesting in the context of codification of structural design and assessment.

As structural robustness here is understood as the degree to which structural damages may be sustained by the structural system or other measures thereby reducing additional consequences in terms of collapse, the COST Action has also studied in detail the assessment of consequences of damages and collapse of structures.

4. Organisation of the Action

Research teams drawn from 24 countries representing both academia and industry formed part of the Action. The work carried out in the COST Action was organized into a number of activities as illustrated in Figure 2; the work flow and the interactions between the different activities are also indicated.

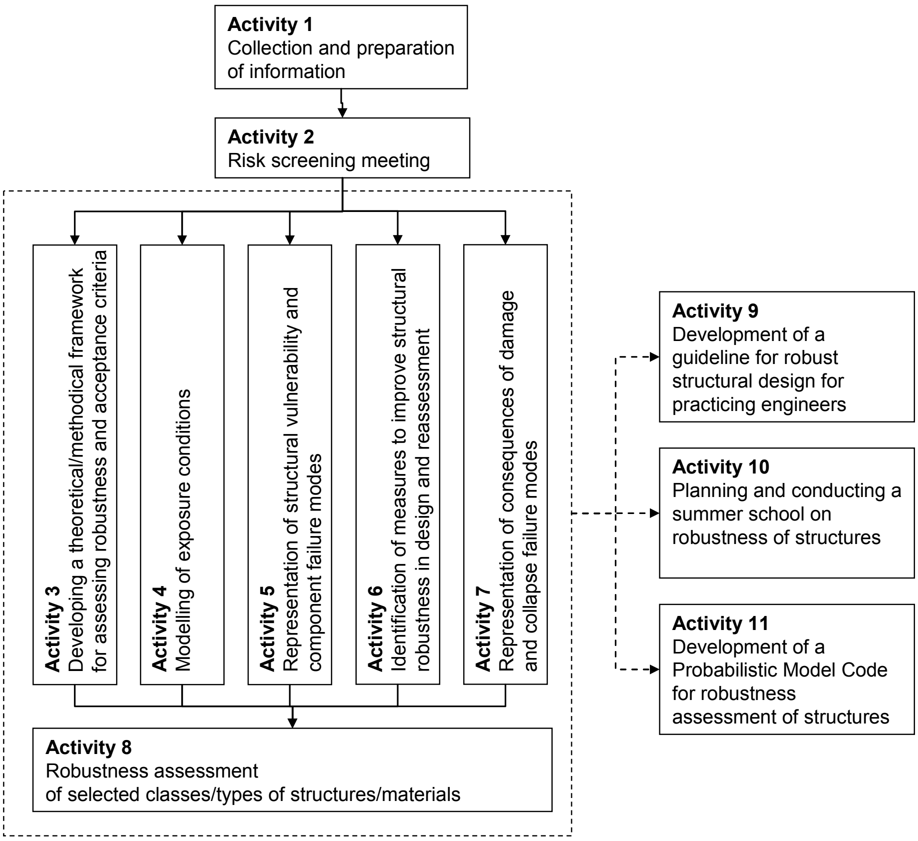

Figure 2 Illustration of interaction between the activities of the COST Action.

To facilitate a coordinated and efficient progress of the work to be performed within the COST Action, the activities of the Action were grouped into 3 Working Groups. Working group 1 was mainly responsible for the development of a sound theoretical and methodological framework for assessing robustness (activity 3) whereas Working Group 2 was responsible for the issues related to engineering modelling of exposure conditions and the representation of vulnerability and failure modes in structures (activities 4 and 5). The work of WG 3 was related to implementation aspects concerning robustness; these include the identification of strategies to improve robustness in design and re-assessment and the representation of consequences of failure modes in structures (activities 6, 7 and 8). A task group constituted by researchers from all working groups and the management committee was responsible for the formulation and dissemination of the results (activities 9, 10 and 11). The remaining activities 1 and 2 were managed by the Management Committee of the COST Action.

5. Results and deliverables

The major deliverables and achievements of the Action are:

- A series of technical factsheets that provide focused reporting on issues concerning robustness of structures. These factsheets are published in the proceedings of the conferences and workshops organised by the Action. The Action has organised two workshops in Zurich (2008) and Ljubljana (2009) and one conference in Prague (2011). Further details about these events and the proceedings can be obtained from http://www.cost-tu0601.ethz.ch/events.html and also in the references.

- A document on the theoretical framework on structural robustness, which can serve as the basis to develop a probabilistic model code on design for robustness of structures.

- A document on structural robustness design aimed at practising engineers.

- Educational material from a training school on robustness of structures for students, researchers and practicing engineers.

The document on the theoretical framework as well as the document on robust structural design aimed at practicing engineers can be found in this report. The educational material from the training school will be made available on http://www.cost-tu0601.ethz.ch/. A summary of the scientific contributions from the proceedings of the Action workshops and conferences is provided in this section.

The first workshop of the Action was held in Zurich, Switzerland on the 4th and 5th of February 2008. The principal aim of the workshop was to focus the efforts of the work and research to be performed in the Action. The contributions from the workshop provided an ideal platform to carry out a risk screening exercise by a thorough consideration of the following issues with regard to robustness:

- Classes of structures
- Exposures acting on structures
- Damages to structural components/members
- Failure/collapse modes for structures/systems
- Consequences
- Methodological framework for robustness
- Strategies for risk reducing measures and achieving robustness

Table 1 provides a listing of contributions that featured in the proceedings of the first workshop of the Action.

Table 1 : Contributions to the first workshop

Title	Contributors
Activity 1 – Collection and Presentation of Information	
Draft proposal for the classification of failure causes of civil engineering structures	*Radu Bancila, Nicole Taranu, Silvia Rominu and Oana Ionita*
Robustness evaluation of failed timber structures	*Eva Frühwald, Sven Thelandersson, Fulop Ludovic and Tomi Toratti*
Models for exposure conditions – a review of available data for snow and flooding in the Czech republic	*Milan Holicky and Miroslav Sykora*
Working Group 1 – Theoretical and Methodological Framework	
Strategies for achieving robustness in buildings and mitigating risk of disproportionate collapse	*Bruce Ellingwood*
Building a robustness index	*Sara Casciati and Lucia Faravelli*
Design optimization methodologies to achieve structural robustness	*Dimos Charmpis*
Vulnerability analysis of structures	*Jitendra Agarwal*
Risk-based assessment of robustness: what can it do and what can't it do?	*Jack Baker*
Factors affecting a risk-based interpretation of robustness	*Marc Maes*
Working Group 2 – Modelling of Exposures and Vulnerability	
Simplified assessment of structural robustness for sudden component failures	*Bassam Izzuddin*
Crumple zone design for buildings	*Mike Byfield*
Redundant and robust frame structures by joint ductility	*Ulrike Kuhlmann and Lars Rölle*
Robustness oriented analysis of concrete structures subjected to blast exposure	*Krzysztof Cichocki*
Robustness oriented analysis of structural joints of steel-concrete composite frames	*Marian Gizejowski, Leslaw Kwasniewski, Wiole Barcewicz and Wael Salah*
Inherent robustness of RC slabs and beams	*Geoffrey Decan and Luc Taerwe*
Working Group 3 – Robustness Assessment and Implementation	
A first draft of guidelines to satisfy the robustness prescriptions of structural codes	*Pietro Baratono and Fabio Casciati*
Robustness of structures - Danish approach	*John Sørensen*
Robustness of lifeline systems	*Selcuk Toprak, A. Cem Koc, Engin Nacaroglu and Orhan Cetin*
Robustness and progressive collapse requirements in view of risk acceptability	*Dimitris Diamantidis*

As part of an inter-domain collaboration programme between this COST Action and COST Action E55 from the Forests, their Products and Services (FPS) domain, a joint workshop of the two Actions was organized in Ljubljana, Slovenia on the 21st and 22nd of September 2009. The contributions from the workshop were organized into the following themes:

- Experience,
- Principles,
- Exposures,
- Vulnerability,
- Assessment and Implementation.

The proceedings of this workshop were published as a compilation of technical factsheets representing the joint state of knowledge of the two Actions and made available on an open access basis on the websites of the two Actions for wider visibility and dissemination of the work carried out in the two Actions. The contents of the proceedings are listed in Table 2.

Table 2 : Contributions to the second workshop

Title	Contributors
Theme : Experience	
Robustness considerations from failures in two large-span timber roof structures	*Jørgen Munch-Andersen and Philipp Dietsch*
Assessment of failure and malfunctions in steel bridges	*Radu Bancila, Edward Petzek, Rominu Silvia and Oana Ionita*
Theme : Principles	
Definition of robustness and related terms	*Gerhard Fink, René Steiger and Jochen Köhler*
Robustness – theoretical framework	*John Sørensen, Enrico Rizzuto and Michael Faber*
Robustness – acceptance criteria	*Enrico Rizzuto, John Sørensen and Inger Kroon*
Theme : Exposures	
Probabilistic modelling of exposure conditions	*Ton Vrouwenvelder*
Modelling of human error	*Ton Vrouwenvelder, Milan Holicky and Miroslav Sykora*
Probabilistic modelling of internal gas explosions	*Ton Vrouwenvelder and Bernt Leira*
Water vapour balance in a building – moisture exposure for timber structures	*Gerhard Fink and Jochen Köhler*
Theme : Vulnerability	
Modelling and analysis	*Leslaw Kwasniewski, Bassam Izzuddin, Miguel Pereira, Carmen Bucur and Marian Gizejowski*
Steel structures	*Ulrike Kuhlmann, Lars Rölle, Bassam Izzuddin and Miguel Pereira*
Concrete beams and slabs	*Geoffrey Decan and Luc Taerwe*
Behaviour and modelling of timber structures with reference to robustness	*Sven Thelandersson and Daniel Honfi*

Title	Contributors
Theme : Assessment and implementation	
Robustness of buildings in structural codes	*Dimitris Diamantidis*
Categorisation and assessment of robustness related provisions in European standards	*Harikrishna Narasimhan and Michael Faber*
System reliability of timber structures – ductility and redundancy	*Poul Kirkegaard, John Sørensen and Dean Čizmar*
Robustness design of timber structures – secondary structures	*Philipp Dietsch*
Improvement of robustness through monitoring and smart materials/devices	*Sara Casciati and Lucia Faravelli*
Earthquakes and robustness for timber structures	*Jorge Branco and Luís Neves*

The final conference of the Action is being held in Prague on the 30th and the 31st of May 2011. This final conference is intended to disseminate the scientific work of the Action carried out during its latter period; the featured contributions are listed in Table 3.

Table 3 : Contributions to the final conference

Title	Contributors
Theme : Experience	
Robustness of existing structures	*Miroslav Sykora, Jana Markova, Milan Holicky and Karel Jung*
Robustness analysis of a timber structure with ductile behaviour in compression	*Dean Čizmar, John Sørensen, Poul Kirkegaard and Vlatka Rajčić*
Robustness of structures: lessons from successes and failures	*Jitendra Agarwal*
Theme : Principles	
Robustness of structures – theoretical framework	*John Sørensen*
Acceptance criteria	*Enrico Rizzuto and Krzysztof Cichocki*
Theme : Exposures and vulnerability	
Modelling of hazards	*Ton Vrouwenvelder and Bernt Leira*
Catenary action in RC elements	*Geoffrey Decan and Luc Taerwe*
Steel structures	*Ulrike Kuhlmann, Lars Rölle, Bassam Izzuddin, Miguel Pereira, Christos Bisbos and Simos Gerasimidis*
Composite structures	*Ulrike Kuhlmann, Lars Rölle, Marian Gizejowski, Leslaw Kwasniewski, Wioleta Barcewicz, Bassam Izzuddin and Miguel Pereira*
Reliability analysis of ductility in steel structures	*Max Gündel, Markus Feldmann and Ton Vrouwenvelder*
Numerical analysis of frame systems in case of progressive collapse	*Marcin Balcerzak, Leslaw Kwasniewski, Luis Costa Neves and Marian Gizejowski*
Amplified Monte Carlo simulation methods for analysis of systems reliability	*Bernt Leira and Arvid Næss*

Title	Contributors
Theme : Assessment and implementation	
Building failure consequences	*Victoria Janssens, Dermot O'Dwyer and Marios Chryssanthopoulos*
Consequences of failure: bridges	*Boulent M. Imam and Marios Chryssanthopoulos*
SHM-based robustness: a super-tall structure case study	*Raed Al-Saleh, Sara Casciati and Lucia Faravelli*
Robustness aspects of CC3 buildings	*Dimitris Diamantidis, Gerard Canisius and Vanessa Diamantidis*
The cost of satisfying structural design requirements on progressive collapse resistance	*Anastasios Kontogiannis and Dimos Charmpis*

6. Self-appraisal

6.1 General comments regarding the scientific success of the Action

As was clear already from the beginning of this Action the topic 'Robustness of Structures' constitutes a topic associated with strong opinions and controversy within the structural engineering community. The topic, however, has always been a highly relevant one; and with the recent events of terrorism and other disastrous events such as the earthquake in Japan robustness is more in the focus of engineering than ever.

From the outset of the Action there was no commonly accepted framework for assessing structural robustness. Here and there in scientific papers and codes and standards suggestions on how to assess and ensure robustness of structures could be found, however, mostly related to rather specific types of structures and/or loading conditions. A philosophical basis was clearly missing.

The present Action thus took basis in research by the proposer and colleagues to investigate whether it would be possible to establish a formalism and a metric for the assessment of robustness based on risk assessments and furthermore whether such developments could help in establishing a stronger consensus within the structural engineering community on how to ensure robust structures in the future.

The present Action – as documented from the documents enclosed to this report and also from the proceedings of the workshops and conference organised by the Action – has indeed succeeded on most if not all objectives as listed in the Memorandum of Understanding (MoU) of the Action and also in section 2 of this paper.

Establishing the Action itself provides a partial fulfillment of sub-objective 1). However, it is beyond doubt that through the interactions within and beyond the members of the Action over the last four years a broader and at the same time also a more focused network of experts in the area of structural robustness has materialized. This network will surely prevail and evolve for years to come.

In regard to sub-objective 2) the Action has if not proven then at least supported the hypothesis that risk informed decision making can strongly enhance robustness of structures. There is general agreement that if risk assessments were always made as basis for the design of structures, then there would be no particular need for addressing robustness. The best design would be identified as those with the smallest expected costs fulfilling the given requirements to life safety.

However, robustness is needed due to the fact that best practices in structural design among others have a certain focus on individual failure modes – and a perspective to reliability management based on a component perspective. In conveying and appreciating this perspective the Action has been rather successful and to serve in this role it has been found that the risk based approach is indeed feasible.

Some open points remain – not surprisingly. One of the more interesting of these at the philosophical level concerns formulating and specifying risk criteria to the robustness of structures – i.e. answering the question – How Robust is Robust Enough? Some proposals have been made in this direction, however, they still need to be developed and assessed further. Other difficult and interesting issues are related to the type of advanced structural analysis required for assessing the risks for structures in the performance regime far beyond linear elasticity. The difficulty associated with the realistic and precise modelling of extreme structural performance is increasingly being recognized by the engineering profession. There is still some way to go before such analysis can be performed accurately and effectively. A third difficulty is associated with the codification issues of structural robustness. It so turns out that traditional structural design codes actually account for robustness in design – mostly implicitly – and in general not consistently. Suggestions on how to enhance design codes to improve and manage structural robustness have been made within the Action – however, the required change of best practice design codes will surely be an obstacle for the implementation.

Concerning sub-objective 3) there has been very good progress and the developed document on theoretical framework for structural robustness can serve as a strong basis but still a bit of work to be done before completion. The remaining work will be undertaken by the Joint Committee on Structural Safety (JCSS).

Regarding sub-objective 4) the development of a guideline for support of practicing engineers on how to design and maintain robust structures this activity has been finalized and the corresponding document can be found enclosed to this report.

With respect to sub-objective 5) dissemination of the results and activities of the Action significant efforts have been invested. Within the Action dissemination has taken place through open conferences and joint conferences with other Actions from other Domains (Action E55). Moreover participants have been very active in organizing special sessions at important conferences such as the ICOSSAR 2009, the upcoming ICASP11 (summer 2011, Zürich) and the IABSE symposium (fall 2011, London). The work of the Action has also been presented at major international conferences in the field of structural safety and reliability (Faber et al., 2011; Vrouwenvelder and Sørensen, 2009). It should also be mentioned that a future special issue of the journal ‘Structural Engineering International’ (published by IABSE) on the topic of Structural Robustness will contain selected publications from the final conference of this Action (Prague, May 2011). Finally, the Action homepage (http://www.cost-tu0601.ethz.ch/) has contributed to spreading the message and attracting attention to the activities and people of the Action. One of the anticipated activities, namely the Action Training/Summer School, could not be carried out due to administrative limitations within the lime limits of the Action. However it has been decided by the members of the

Action to conduct this summer school in 2012 – and the detailed lecture programme for this summer school has been developed.

The STSM activity, sub-objective 6), has been significant within the Action totalling 7. In the beginning things were a bit slow – but later the STSM caught momentum and in the end there was no budget to support further such activities.

Concerning sub-objective 7) it is a pleasure to be able to mention that the concepts and ideas developed and assessed within this Action are already at this very early time being implemented in some North-American codes and standards (e.g. ASCE SEI Committee on Disproportionate Collapse Standards and Guidance).

Finally in regard to sub-objective 8) – any progress in pointing at the relevance and importance of assessing and managing risks in the built environment will have a positive effect. Time will show if it will be possible to assess a positive effect of this Action on risk reduction through improved robustness of structures. The most important thing is to be able to actively impact and improve current knowledge and engineering best practices. This has been accomplished.

6.2 Comments on the working mode of the Action

It should be highlighted that the participants of the Action have contributed very constructively to the success of the Action. Despite the fact that the budgets were being reduced towards the end of the Action the enthusiasm of the participants was outstanding and the attitude was goal striving.

It is always an issue with this sort of collaborative non-funded research projects that progress is made stepwise, just before the meetings. This does impair progress of research in some manners – compare to funded research – however, in the present Action the working discipline has been outstanding. This should not least be attributed to the very committed and competent Working Group leaders of the Action.

7. References

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