Life-cycle robustness: prospects and challenges

Roman Wendner, Alexios E. Tamparopoulos
Christian Doppler Laboratory LiCRoFast, University of Natural Resources and Life Sciences, Vienna A-1190, Austria roman.wendner@boku.ac.at, alexios.tamparopoulos@boku.ac.at

Abstract. Life-cycle robustness is achieved when a structural member or a whole system is designed to maintain its intended function and required safety level within its desired life-cycle. The different characters of effects that each element will need to undergo (damage, ageing, extreme events, changes in usage) in conjunction with the diversity in the intrinsic material properties, form a demanding problem. Further complexity emerges when one realises that time is not simply a variable, but a factor permeating model choices and uncertainty representation approaches. Different effects on the load side and properties on the resistance side develop differently in time, as does the dependence structure. Spatial randomness of materials, such as concrete, requires careful modelling, especially at a meso-scale. For a log-term analysis, where the influence of uncertainty may dominate over predictability, robust design can prove decisive. On the computational side, challenges often appear since the computational costs of simulations and non-linear analyses may quickly prove infeasible. Suitable numerical techniques for small scale sampling, accounting for arbitrary distribution types and dependence structures, are yet to be developed. The realistic prediction of spatial randomness for now fails due to a lack of understanding regarding the physical basis of main input parameters. Within this contribution the authors present the general concept of life-cycle robustness and the expected prospects that arise from its application to fastening systems. A detailed discussion of the aforementioned challenges and review of the state of the art complement the paper.

Keywords: Life-cycle robustness, Fastenings, Uncertainty, Multi-scale modelling

1. Introduction

Life-cycle robustness aims to expand the concepts of safety, sustainability and cost-efficiency of infrastructure to include highly uncertain and unforeseen events during installation, service life, and demolition. In particular, it can be defined as the ability of a component or a whole system to maintain its intended function and required safety level in spite of damage, ageing, extreme events, or changes in usage throughout its life-cycle. Robustness in the meaning of this concept can have several different aspects, since it needs to include installation, operation, demolition, and recycling phases. Each of these perspectives faces different challenges, as it is subjected to different actions and variations. A careful analysis and synthesis of those robustness aspects reveals more challenges and uncertainties, as the level of detail increases. It also discloses the weaknesses of some currently adopted assumptions in the context of life-cycle evaluation and robust design approaches.

Post installed fastening technology in structural concrete comprises the study of mechanical and chemical anchors. Anchorages are important for integrating precast elements, and for strengthening and retrofitting. They allow the connection of new load bearing structural members with existing elements, as well as the installation of new, not structurally relevant, elements, e.g. sunshades. Often the applications are divided into structural—as part of the main load bearing structure (e.g. in repairs)—and non-structural applications (e.g. handrail installations). Therefore, fastenings are important for any adaptation of existing infrastructure, and for the life-cycle design of new structures. The economic significance of fastenings is indicated by the fact that the potential damage caused by failed fastening elements can be by several orders of magnitude higher than the value of the products themselves. It is also highlighted by the use of fastenings as key-elements of critical infrastructure, such as power plants, hospitals, and utility line systems.

In the present paper, the general concept of life-cycle robustness and the expected prospects that arise from its application to fastening systems are presented. Section 2 contains a discussion on the requirements of an integrated life-cycle robustness design and application framework, focusing on fastening systems. In Section 3, the major challenges of this concept are briefly reviewed. Section 4 outlines the main expected prospects that arise from the application of this concept to fastening systems. The closing section provides a synopsis of the present paper.

2. Requirements of life–cycle robustness

The requirements of life-cycle robustness on fastenings cover a broad range of topics, such as design, development, testing, installation, performance, safety, sustainability, and cost-efficiency. An integrated approach should aim to address each of these aspects, outlined in the next paragraphs.

2.1. Design

Once properly conceptualised, life-cycle robustness needs to be included in the design codes. Current international design codes do not seem to provide a consistent and rigorous framework for performance prediction (reliability levels) and assessment of existing fastening systems. In cases of engineering design pertaining to critical infrastructures, reaching a consensus and formulating design codes requires extensive experimentation and thorough verification.

2.2. Development

The generic requirements for optimised development of new products, and for accelerated development processes, are firmly related to safety and reliability considerations. This cannot be achieved without deep understanding of the long-term behaviour of the materials used in fastening technology. Progress on this front is constantly required, owing to new developments in construction materials (shape memory alloys, materials with negative Poisson's ratio, nano-additives to epoxies). The long-term behaviour of epoxy resins, vinyl esters and unsaturated polyesters, used for adhesive anchors, needs to be investigated, since these materials exhibit strong visco-elastic deformation.

2.3. Testing

Testing methods are required to investigate the effect of geometrical and material properties—as well as ageing—on the load bearing capacity of fastening systems. In particular, it is important to verify numerical computations for the different (1) failure modes (pull-out, breakout, splitting), (2) types of systems (mechanical, chemical, plastic), (3) base materials (concrete, masonry) and, (4) loading conditions (static, dynamic, seismic). Given the large number of these combinations, extensive testing is required. However, the number of tests can be significantly reduced when experiments are combined with virtual testing. In this context, Bayesian updating techniques are frequently used (Zhang and Mahadevan, 2001).

Tests can be performed using destructive and non-destructive methods. The role of suitable data acquisition systems in both approaches is of great importance for calibrating and verifying the assumed failure models. Furthermore, highly accurate measuring instruments are required, due to the very low strain of concrete at failure. Typical examples of non-destructive testing methods are acoustic emission, thermography, electronic speckle pattern interferometry and digital image correlation. Most of these sophisticated methods heavily depend on Information Technology, and can be very costly. Moreover, the type and volume of acquired data stress the need for data analysis methods that go beyond traditional statistical inference.

2.4. Installation

The role of fastenings in critical infrastructure and the increasingly tight budgetary constraints call for faster and automatised construction. Post-installed fastening systems are of particular interest, thanks to their flexibility and ease of installation on reinforced concrete structures. In this context, geometrical tolerances, variations, and possible mistakes in the installation procedure need to be taken into account.

2.5. Performance

Life-cycle robust design aims to ensure adequate prescribed performance levels for fastenings. This process is not straightforward, due to the different character of effects that each element will need to undergo (damage, ageing, extreme events, changes in usage) in conjunction with the diversity in the intrinsic material properties. Performance requirements may vary from serviceability to ultimate capacity. Since performance is mostly studied with probabilistic tools, detailed and careful uncertainty modelling is a prerequisite.

2.6. Safety

High and transparent safety standards in fastening technology need to be imposed. In particular, sufficient safety margins are required in order to ensure robustness throughout the whole service life. The assessment of safety levels has to be extended from installation until the end of the product lifetime. It also needs to include direct load and indirect environmental influences. The role of uncertainty assessment and propagation in this process highlights the need for more careful approaches in the computation of failure probabilities. Moreover, issues related to possible secondary consequences, progressive damage and disproportional failure effects should be investigated when an integrated framework is desired.

2.7. Sustainability

A design approach should include provisions that go beyond the anchor's life time. Sustainability in the disassembling and disposal process can be guaranteed by properly formed (e.g. resettable, non-monolithic) connections between elements. Given that those connection play also a critical role in safety and performance, their design can prove highly complex and demanding.

2.8. Cost-efficiency

Life-cycle robust design is highly important in order to protect long-lasting building investments. On the testing side, there is a need to reduce costs by limiting experimental verification to numerically optimised systems and by virtual investigation of different possible life-cycle scenarios. Finally, aspects such as intervention, optimised maintenance planning, rehabilitation, renovation, repair, replacement, are of great importance with respect to cost, when viewed over the intended lifespan (Frangopol et al., 2004).

3. Challenges of life–cycle robustness

The current state of fastening technology reflects only 25 years of systematic research. So far, practice has been limited to simple solutions, to naïve methods for estimating lifetimes, to the assumption of unreinforced concrete, and to mere addition—as opposed to realistic combination—of safety factors. The load carrying capacity has been mostly studied under static short term but not under dynamic loads. Deeper understanding regarding the load carrying mechanisms faces a number of challenges. More accurate prognostic models will allow for an optimised design of new fastening systems, and for a reliable assessment of existing systems. Therefore, such models will facilitate efficient maintenance management over the full product lifetime.

As discussed in the preceding section, life-cycle robustness has several aspects and related requirements. In each of these perspectives, different challenges may arise. As the level of detail in the investigation increases, more challenges and uncertainties can be disclosed. These challenges are related to temporal effects, system diversity, computation of failure probabilities, involved uncertainties, dependencies among the input variables, multi-scale modelling, cost, and organisation of a multidisciplinary approach. An overview of these challenges is given in the next paragraphs.

3.1. Temporal effects

As mentioned earlier, it is required to realistically assess and predict the life-time performance of anchors, including the material properties. When attempting to formulate models for life-cycle robustness, it quickly becomes evident that time is not simply a variable, but rather a factor permeating fundamental model choices and uncertainty representation approaches. In fact, the life-cycle performance and robustness of fastening systems is influenced by several time-dependent processes, which alter the initially assumed mechanical characteristics. Some of those effects develop monotonically in time—albeit not in a linear fashion—whereas others have a periodical nature. Environmental influences may occur due to concrete carbonation, chloride effects, steel corrosion, UV radiation, and freeze-thaw cycles. Concrete creep may have significant influence on the long term performance of fastening systems; therefore, models that accurately describe this phenomenon are needed (Bažant, 2001). Actions can be imposed by fatigue, fire, earthquakes, explosions, traffic accidents, etc. These loads cannot be foreseen and modelled akin to the typically encountered loading scenarios. Monitoring and updating of prediction models can be challenging, since concrete fracture initiates at a very low scale. Stochastic degradation prognosis approaches need also to include appropriate monitoring concepts for steel corrosion. Finally, possible consequences of ageing need to be investigated, not simply in the narrowed view of the fastenings themselves, but rather with respect to the broader system which they operate in.

3.2. System diversity

The lifetime performance of traditional fastening systems, as well as new future products, is determined by the performance of every single component and their interaction. The different lifetimes of components call for a modular framework for lifetime simulation. A unified approach for estimating lifetimes is hindered by the existence of many different failure modes. Further system diversity emerges from variations in geometry, cracking of concrete, reinforcement type, loading type, different base materials and different intended applications.

3.3. Low failure probabilities

A structure's performance is assessed in the regimes of small probabilities, where the influence of uncertainties can be large. The tails of the input distributions are not known with accuracy; furthermore, sample size, model uncertainty, and possible dependence structure can seriously affect the computation of low probabilities. Small failure probabilities demand large samples for simulation. On the other hand, small sample size is of great importance when very intensive computations are required, e.g. in a nonlinear analysis (Bergmeister et al., 2009). Variance reduction techniques in sampling are still relevant today, since model complexity grows with the rise of computer power.

3.4. Uncertainties

Life-cycle robustness design faces a multitude of aleatory and epistemic uncertainties. The amount of deviation that has to be expected depends both on the scatter in the applied loads as well as on the amount of uncertainty in the mechanical properties of the used materials, due to inherent heterogeneities. In fact, a significant part of uncertainty can be attributed to the heterogeneity of concrete at lower scale, which is linked to a variety of macroscopic effects during failure. However, the mechanical properties of materials and members after many years of operation are largely unknown. Further uncertainties arise from geometrical tolerances and variations in the installation procedure. Tolerance against installation inaccuracies (installation robustness) constitutes a major challenge. Furthermore, resistance against extreme events or environmental influences faces the problems of unpredictability and intangibles in the account of consequences.

If the time dimension is added to the problem (as required for any life time prediction) the uncertainty associated with the predicted mean response increases significantly with the time span of extrapolation, in particular if degradation processes and extreme events are to be considered.

3.5. Dependencies among the input variables

The simulation of stochastic response of fastening systems is a challenging task. The influence parameters of resistance and load are uncertain, to some degree, and typically expressed as probabilistic, possibilistic or fuzzy quantities. Moreover, the identification and determination of deterioration mechanisms is greatly influenced by the interaction between components in time. Not accounting for statistical dependence may lead to overestimations—adding safety factors reflects an assumption of perfect positive correlations, which is greatly conservative. It can also lead to underestimations, when the dependence among the input parameters is not properly modelled.

Generating correlated inputs required for the simulation of resistance, failure probabilities or lifetimes has long been studied. Especially where the model is computationally intensive, small yet representative samples are necessary. The significant effect of dependence, an often overlooked issue, has been recently highlighted, in particular in the area of low target failure probabilities (Dutfoy and Lebrun, 2009). As the number of the variables increases, this observed effect can become dominant.

Two main approaches for tackling the problem of generating correlated variables can be employed, aiming to induce the set of given linear or rank pairwise correlation coefficients. The first, due to Iman and Conover, is based on sample reordering, aiming to match the desired correlation matrix (Iman and Conover, 1982). This method was further refined by implementing stratified sampling (e.g. latin hypercube sampling) and optimization (simulated annealing) techniques (Vořechovský and Novák, 2009). The second approach involves the use of copula functions, a tool that has seen a widespread adoption over the last 20 years (Embrechts et al., 2003). Copulas have been used also in lifetime reliability studies, e.g. (Pellerey, 2008). Copulas are able to represent any type of dependence structure, and remain invariant under monotone transformations of the variables.

3.6. Multi-scale modelling

The macroscopic behaviour of fastening systems is linked to the micro-scale properties of base materials, e.g. concrete. A multi-scale modelling approach aims to connect these two different perspectives of the system of concern. This problem can be numerically tackled by modelling concepts such as coarse graining or homogenization (Vorel et al., 2012).

Several continuum and discrete damage models for concrete have been developed over the last years, using finite element or finite difference formulation. The Lattice Discrete Particle Model (LDPM) is such a discrete meso-scale model ($10^{-2} - 10^{-3}$m), able to capture the macroscopic behaviour of concrete in elastic, fracturing, softening, and hardening regimes (Cusatis et al., 2011). LDPM reproduces with great accuracy the concrete response under uniaxial and multiaxial stress states in compression and tension, and under both quasi-static and dynamic loading conditions. Still, the performance of such models under more complex conditions is yet to be verified.

3.7. Cost

The cost of developing accurate models of fastenings performance in time is far from negligible. There are significant experimental verification costs, since interactions, correlations, and uncertainties are hard to capture. Moreover, different theoretical models need to be investigated. The costs resulting from the sheer volume of required tests and from the equipment for performing non-destructive testing comprise a major challenge. As previously stated, these costs can be reduced when experiments are combined with virtual testing. Stratified sampling techniques can contribute to reducing computational cost.

3.8. Multidisciplinary approach

In view of the main requirements and challenges outlined throughout the present paper, it becomes evident that a multidisciplinary approach is needed in order to develop an efficient life-cycle robustness framework for fastenings. The large volume of multi-dimensional data acquired by sophisticated measurements and meso-scale simulations need to be studied with advanced data analysis techniques. The collection and calibration of available testing databases require long laboratory experience and deep understanding of mechanics. Physics and material science knowledge is important when dealing with base materials. Reliability analysis tools are necessary for effectively studying ageing and time dependence. Since the design model is driven by the type of anchor and the load bearing mechanism, the role of statics and dynamics is critical.

4. Prospects of life-cycle robustness

There are several theoretical prospects of developing an integrated multidisciplinary approach of life-cycle robustness of fastenings. Firstly, incorporating state-of-the-art in research on concrete behaviour (creep, shrinkage, etc.) and on other base materials will allow for developing much more refined prediction models (Wendner et al., 2014) and their uncertainty quantification. In this context, existing research on physics and material science can be utilised.

The quest for performance-based design concepts, transparent safety levels, and durability can lead to processes that realistically simulate the behaviour of fastening systems. Stochastic models for input variables in space and time are constantly being developed (Eliáš and Vořechovský, 2012). Uncertainty importance analyses focusing on the intended applications will indicate the parameters that mostly influence the performance of fastenings in time. Thus, research efforts can be efficiently allocated to base material properties, time effects, loading scenarios, fracture development, testing procedures, and representation of spatial or other variations.

Practical prospects include the study of installation, maintenance, repair, and replacement within a unified framework. Construction planning can take great advantage of realistic evaluations of system performance and cost efficiency. Fast and automated construction techniques can be developed, and future market demands can be captured. The assessment of existing fastening systems can significantly reduce cost and increase the reliability of complex systems. Currently used reliability indices reflect only the failure frequency and not the consequences of failure. On this front, utility-based performance and safety evaluation can facilitate fastening applications.

In the next years, a more effective use of new laboratory technology is expected. Accurate testing procedures can be formulated, following the technological developments in data acquisitions equipment and the related analysis methods.

5. Synopsis

In recent years, steadily increasing budgetary constraints have led to a strengthened awareness regarding the importance of life-cycle performance and cost considerations. The tight dependency of society with the proper functioning of infrastructure, leads to higher exposure and economic significance of structural systems. Life time design of infrastructure and extension of existing structures has become increasingly important (Bergmeister, 2012). Numerically and experimentally based reliability assessment methods with respect to different actions have been developed (Strauss et al., 2013). However, up to now maintenance aspects hardly enter the decision process regarding the construction of new buildings or structures. Moreover, most of the research progress in material science, in sophisticated testing procedures, or in uncertainty analysis remain confined to simple theoretical conceptions. In the present paper, the requirements of a desired framework for life-cycle robustness of fastening systems were outlined. Addressing the emerging challenges in this venture can pave the way to new prospects and theoretical advancements as well as to novel construction approaches.

Acknowledgements

The financial support by the Austrian Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

References

Z. P. Bažant. Prediction of concrete creep and shrinkage: past, present and future. *Nuclear Engineering and Design*, 203(1):27–38, 2001.

K. Bergmeister. Life-cycle design for the world's longest tunnel project. In *Life-Cycle and Sustainability of Civil Infrastructure Systems: Proceedings of the Third International Symposium on Life-Cycle Civil Engineering, Hofburg Palace, Vienna, Austria, October 3–6, 2012*, 51–59, 2012.

K. Bergmeister, D. Novák, R. Pukl, and V. Červenka. Structural assessment and reliability analysis for existing engineering structures, theoretical background. *Structure and Infrastructure Engineering*, 5(4):267–275, 2009.

G. Cusatis, D. Pelessone, and A. Mencarelli. Lattice discrete particle model (LDPM) for failure behavior of concrete. I: Theory. *Cement and Concrete Composites*, 33(9):881–890, 2011.

A. Dutfoy and R. Lebrun. Practical approach to dependence modelling using copulas. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 223(4):347–361, 2009.

P. Embrechts, F. Lindskog, and A. McNeil. Modelling dependence with copulas and applications to risk management. In T.R. Svetlozar (ed.), *Handbook of Heavy Tailed Distributions in Finance, Volume 1: Handbooks in Finance, Book 1*, 329–384. North-Holland, 2003.

J. Eliáš and M. Vořechovský. On the effect of material spatial randomness in lattice simulation of concrete fracture. In M. Vořechovský, V. Sadílek, S. Seitl, V. Veselý, R. L. Muhanna, and R. L. Mullen, (eds.), *5th International Conference on Reliable Engineering Computing (REC 2012)*, 2012.

D. M. Frangopol, M. J. Kallen, and J. M. van Noortwijk. Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials*, 6(4):197–212, 2004.

R. L. Iman and W. J. Conover. A distribution-free approach to inducing rank correlation among input variables. *Communications in Statistics-Simulation and Computation*, 11(3):311–334, 1982.

F. Pellerey. On univariate and bivariate ageing for dependent lifetimes with archimedean survival copulas. *Kybernetika*, 44(6):795–806, 2008.

A. Strauss, R. Wendner, K. Bergmeister, and C. Costa. Numerically and experimentally based reliability assessment of a concrete bridge subjected to chloride-induced deterioration. *Journal of Infrastructure Systems*, 19(2):166–175, 2013.

M. Vořechovský and D. Novák. Correlation control in small-sample Monte Carlo type simulations I: A simulated annealing approach. *Probabilistic Engineering Mechanics*, 24(3):452–462, 2009.

J. Vorel, V. Šmilauer, and Z. Bittnar. Multiscale simulations of concrete mechanical tests. *Journal of Computational and Applied Mathematics*, 236(18):4882–4892, 2012.

R. Wendner, K. Bergmeister, and A. Sandini. Life-cycle robustness in fastening technology: A Christian-Doppler laboratory. In *Proceedings of the 4th International Symposium on Life-Cycle Civil Engineering*, Tokio, Japan, 2014.

R. Zhang and S. Mahadevan. Integration of computation and testing for reliability estimation. *Reliability Engineering & System Safety*, 74(1):13–21, 2001.