TRUSS, a European Innovative Training Network Dealing with the Challenges of an Aging Infrastructure Network

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ABSTRACT

Inspections and maintenance of infrastructure are expensive. In some cases, overdue or insufficient maintenance/monitoring can lead to an unacceptable risk of collapse and to a tragic failure as the Morandi bridge in Genoa, Italy, on 14th August 2018. An accurate assessment of the safety of a structure is a difficult task due to uncertainties associated with the aging and response of the structure, with the operational and environmental loads, and with their interaction. During the period from 2015 to 2019, the project TRUSS (Training in Reducing Uncertainty in Structural Safety) ITN (Innovative Training Network), funded by the EU H2020 Marie Curie-Skłodowska Action (MSCA) programme, has worked towards improving the structural assessment of buildings, energy, marine, and transport infrastructure. Fourteen Early Stage Researchers (ESRs) have been recruited to carry out related research on new materials, testing methods, improved and more efficient modelling methods and management strategies, and sensor and algorithm development for Structural Health Monitoring (SHM) purposes. This research has been enhanced by an advanced program of scientific and professional training delivered via a collaboration between 6 Universities, 1 research institute and 11 companies from 5 European countries. The high proportion of companies participating in TRUSS ITN has ensured significant industry expertise and has introduced a diverse range of perspectives to the consortium on the activities necessary to do business in the structural safety sector.

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1. Introduction

1.1 Training

TRUSS ITN delivers structured training consisting of: (i) a 'joint supervision' by industrial and academic experts, with periodic monitoring and updating of a career development plan, (ii) 'network-wide training' where all ESRs have been brought together to be taught transferable skills such as communication, entrepreneurship and management skills in addition to research topics, and (iii) 'local training' allowing the ESR to be exposed to different working and cultural environments. A key aspect of the local training is meaningful placements, with a main host where the ESR has carried out most of the research activity during three years, and secondment periods in other Universities and companies complementing the training at the main host. This mobility, which is a fundamental characteristic of the MSCA ITN scheme, gives ESRs an opportunity to access modules at the Universities, to have exposure to large enterprises and SMEs, to experience the international dimension of the project, and to gather practical knowledge in the application of skills acquired in the taught modules. Under this umbrella, all ESRs have had placements in both research-active industry and academic participants, have conducted work placing them at the forefront of their field, and have been directly exposed to the commercial world getting ready for a subsequent professional career[1].

1.2 Research

For illustrative purposes, Fig. 1 shows the well-known problem faced when assessing structural safety in the simple case of normally distributed demand (*S*) and capacity (*R*) curves. The difference between *R* and *S* defines the *M* curve, also known as failure curve or limit state function, where the level of safety can be characterized by the β-index. The probability of failure, p_f, given by the area under the *M* curve where *S* exceeds *R*, must be below an acceptable probability of failure.

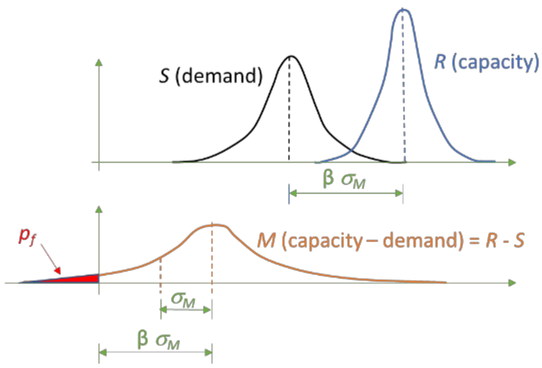


Figure 1. Demand, capacity and failure curves

The *S* curve needs to be defined in probabilistic terms due to its multiple sources of randomness. I.e., the load demand imposed by traffic loading on a bridge can be statistically characterized by collecting Weigh-In-Motion (WIM) data on the bridge site. If site-specific WIM data were not available, then, a code such as the Eurocode will provide a conservative (and deterministic) traffic load model derived from a heavily trafficked route in a European context. The *R* curve is drawn from models based on experience and/or field/lab tests. Similarly, the curve *R* cannot adopt a single value due to uncertainties associated with boundary conditions, distribution of material stiffness and associated stress-strain curves, structure-load interaction, fatigue and aging/deterioration of materials and connections, etc., that can only be removed to some extent. Typically, the values leading to the capacity curve will not be as scattered as the values defining the demand curve, but in any case, the accurate definition of these curves can become a formidable task, both time- and labour-consuming. Therefore, managers of infrastructure networks need to combine complex methods of assessment (i.e., prioritized for key critical infrastructure), with other simpler and faster methods allowing for a preliminary assessment of a major proportion of the infrastructure stock on a frequent basis (i.e., using SHM methods able to detect changes in mechanical parameters as a result of aging and/or aggressivity of loads). A simple assessment will then be cost effective if it demonstrates that the structure is in good condition, and more advanced methods of assessment will be deemed to be necessary in the case of unsatisfactory preliminary results.

Each ESR has been assigned an individual research project that aims to facilitate a quick assessment or to quantify the uncertainty associated with some of the variables involved in a detailed structural assessment. In the case of the increasingly popular but still not so well-known braided Basalt Fiber Reinforced Polymer (BFRP) material, this variable is the stress-strain response, how it reacts to different configurations, load, aging and fatigue, characterized by Sofia Antonopoulou (ESR1) through a comprehensive numerical and lab test campaign (Section 2). Uncertainties can be inherent to a material property, but they can also be related to the measurement of observations, i.e., the deviations in estimation of strength introduced by the indirect measurements of a Non-Destructive Test (NDT). This is the motivation for a new testing method proposed by Shah Nur Sourav (ESR2) that tackles discrepancies found between true strength and in-situ strength measured for concrete (Section 3). These measurements help to reduce or to quantify the uncertainty associated with mechanical parameters of the structure, such as stiffness. An easy-to-implement algorithm able to convert on-site information from traditional sensors measuring the structural response (i.e., displacements, rotations or strains) to operational loads into a realistic assessment of the structural condition is proposed by Barbara Heitner (ESR8) for bridges, although it can easily be extended to other types of infrastructure (Section 4). Traditional SHM technology gathers information only on a few discrete points, typically spaced wide apart to cover a significant portion of the structure. As a result, the response of in-between measurement points is opened to assumptions and to uncertainty that new developments in Distributed Optical Fiber Sensors (DOFS) by Antonio Barrias (ESR11) aim to overcome by providing spatially continuous readings (Section 5). A potential application of DOFS can be the extraction of accurate mode shape curvatures for damage location and quantification, which would remove the need for lots of discrete sensors. Again, cost and limited resources are an issue preventing direct installations and maintenance of sensors beyond a certain number of structures. For this reason, Daniel Martinez (ESR12) propose sensors mounted in land vehicles to gather on-site information from multiple bridges by merely driving over them (Section 6). When getting to a point such that a high level of assessment is required, measured data will eventually need to be brought into mathematical models able to resemble reality by some kind of optimisation technique (i.e., finite element updating). Then, the mathematical models can be used to cover a wider range of scenarios than those contemplated during the testing or monitoring period. There is a degree of uncertainty associated with the mathematical models used in the analysis, even more in the case of highly non-linear scenarios such as those investigated by Alberto González (ESR3), who investigates the variability associated with the response of submerged free-standing nuclear racks subjected to an earthquake (Section 7). Mathematical models can be used to estimate remaining life or reliability, however, this calculation is often far from efficient for complex structures. In order to address the latter, Rui Teixeira (ESR4) proposes Kriging models, as opposed to the more computationally expensive Monte Carlo simulations, to calculate fatigue life in large-scale steel structures (Section 8). Finally, when managing infrastructure, questions arise on when and how to inspect it, that Guang Zou (ESR5) addresses with advanced probabilistic methods taking the probability of detection of damage, the time taken until repair and the cost into account (Section 9).

The following sections report on the aforementioned eight ESR projects. The selection has not been done on the basis of any particular criteria, but the one of showing a variety of research fields within the scope of structural safety. Other TRUSS projects, that have been omitted due to restrictions of space, include: addressing the uncertainty associated with the response of a ship unloader to a moving trolley by Giulia Milana (ESR6), developing damage detection methods for bridges by Farhad Huseynov (ESR7), Matteo Vagnoli (ESR9) and John James Moughty (ESR10), using field data to build a relationship between fuel consumption and road condition for integrating costs within the whole life cycle assessment of pavements by Federico Perrotta (ESR13), and applying Unmanned Aerial Vehicles (UAVs) to full 3D reconstruction of geometry and damage details by Siyuan Chen (ESR14) that can then be used for structural assessment purposes. The readers can deepen into further details and all TRUSS topics by visiting the project website on http://trussitn.eu.

2. Reliability of Concrete Structures Reinforced with Braided FRP

Advanced composite materials, such as BFRP, were recently introduced as a viable replacement to traditional steel rebars in civil engineering applications, mainly due to their non-corrodible nature and high strength-to-weight ratio. These materials have the potential to extend infrastructure's long-term durability and total service life in a cost-effective way. Current approaches use braiding as a manufacturing technique in order to increase ductility and flexibility, as well as enhance the bond between FRP and concrete[2-4]. The aim of this research is to develop an understanding of the textile nature of braided composite rebars and to investigate its influence on their mechanical properties. Micro-computed tomography (μCT) methods can offer a detailed fibre composite material analysis and a precise evaluation of the internal microstructure of braided BFRP reinforcement[5]. More specifically, rebars are designed using basalt fibres and epoxy resin as reinforcement and matrix respectively; composites with a constant cross section of 10 mm diameter are manufactured using braiding and a vacuum assisted resin infusion technique. Samples of 30 mm length are scanned using a Phoenix Nanotom M with DXR flat panel detector nanofocus CT system, at a resolution of 4.2 μm over a 360° rotation, using 2400 projections and 80 kV voltage. The total scan time is 2 hours and a stack of 1000 cross-sectional, gray-scale digital images are produced. Image processing analysis is then performed using ImageJ software and composite's geometrical properties are fully evaluated: geometrical consistency is validated, yarn cross-section deviations from the idealized elliptical shape along the yarn path and nesting effects are observed, fibre volume fractions are calculated, defect development is carefully examined and void content throughout the braid structure is accurately estimated.

Particular attention is given to the detection of composite's void area fraction and spatial distribution of enclosed voids, as these are closely related to the overall quality of BFRP rebars. Voids are imperfections from the manufacturing process, that cause anisotropy in the composite material and can significantly affect its mechanical properties; higher void content usually leads to lower tensile strength and fatigue resistance[6,7]. Fig. 2 illustrates cross-sectional images from four different z-axis locations - 0, 35, 70, 100% of the sample's total length - that were segmented using an intensity threshold. Initial results have shown discrepancies on void area fraction within the sample, from 1.28 to 2.18% with an average void size of 0,041 mm^2. Further investigations using microstructure analysis are necessary to assess both quality and consistency of the braiding manufacturing process towards improved analytical and simulation models.

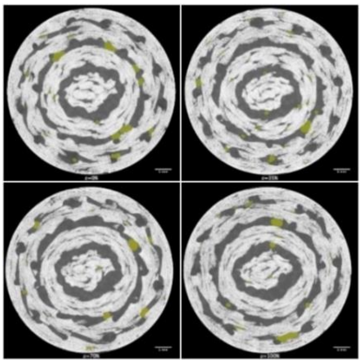
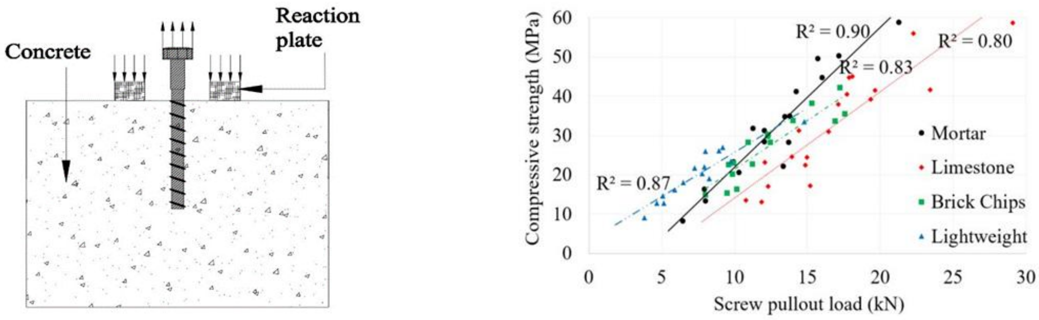


Figure 2. μ-CT cross-sectional images along the xy axis of the braided BFRP composite rebar - Void distribution (yellow shaded area) on 4 different z-axis locations

3. Reducing Uncertainty in Assessing In-situ Concrete Strength

A new NDT, the Post-installed Screw Pull-out (PSP) test, is developed to reliably assess the compressive strength of concrete on site in a cost-effective way[8,9]. During the PSP test, a screw is pulled out of the concrete against a reaction ring to obtain a complete pull-out failure where the concrete under the threads crushes. The peak load at failure provides an indication of the compressive strength of the concrete. Fig. 3(a) shows the arrangement of the PSP test. The laboratory investigation with mortar and three different types of aggregate, i.e. limestone, brick chips and lightweight, showed that the results of the PSP test are influenced by the presence and type of the aggregate in the concrete. The low value of the Coefficient of Variation (CoV) in mortar (CoV = 7%) and concrete with lightweight (CoV = 9%) and brick chips aggregate (CoV = 9%) in comparison to concrete with limestone (CoV = 16%) demonstrate the higher consistency of the PSP test in mortar and concrete with softer aggregate. Fig. 3(b) shows the relationship between the compressive strength of concrete and screw pull-out load of PSP test.



(a) (b)

Figure 3. PSP test: (a) Loading arrangement, (b) Concrete strength versus screw pull-out load

Table 1 shows the statistical significance of the PSP test for each type of concrete. The R-squared values of mortar (0.90) and concrete with lightweight aggregate (0.87) are higher, compared to the values for concrete with brick chips and limestone. Mortar and concrete with brick chip, and lightweight aggregate show low mean residual strength and RMSE compared with the concrete with limestone. Absolute mean residual between actual concrete strength and strength estimated from the best fit line (shown in Fig. 3(b)) as a measure of error is found to be less than 5 MPa in all cases when separate strength relationships were used. The range of error is reasonably small compared with other NDT methods assessing the compressive strength of in-situ concrete. Therefore, the PSP test shows great potential, especially in case of concrete with softer aggregate, yet cost-effective compared to core testing and some other NDTs.

Table 1. Statistical reliability of the PSP test

Aggregates	R-sq	Mean Residual (MPa)	RMSE (MPa)
Mortar (No aggregate)	0.90	3.24	4.47
Limestone	0.80	4.98	6.29
Brick chips	0.83	3.40	3.33
Lightweight	0.87	1.90	2.28
All	0.73	5.26	6.83

4. Probabilistic Modelling of Bridge Damage Based on Damage Indicators

The project by ESR8 is focused on Damage Indicators (DIs) for bridges based on a combination of load and resistance information. In the first part of this work, different damage indicators are defined based on simple properties of signals captured under random traffic. These are firstly tested with simulated data of strain, rotation and deflection measurements using a WIM truck database to generate random traffic. In order to evaluate a range of DIs, different levels of damage (stiffness loss generated by corrosion of reinforcement) are introduced in the structure. Afterwards, the expected degree of corrosion is updated using these simulated DIs. The advantages of applying this methodology are shown and the different health monitoring systems are compared. It is concluded that rotation measurements are preferred over strain or deflection though this clearly depends on the accuracy of the measuring equipment. Similar DIs are tested based on strain field data collected originally for WIM in Slovenia. The instrumented bridge can be seen in Fig. 4.

Figure 4. View of the equipped bridge in Slovenia

In this database, temperature data recorded simultaneously is included in the analysis. Temperature variation introduces changes in the stiffness of the concrete structure, which can be expressed with a linear model[10,11]:

$$E_T = E_{20} \cdot (1 + \beta \cdot \Delta T) \quad (1)$$

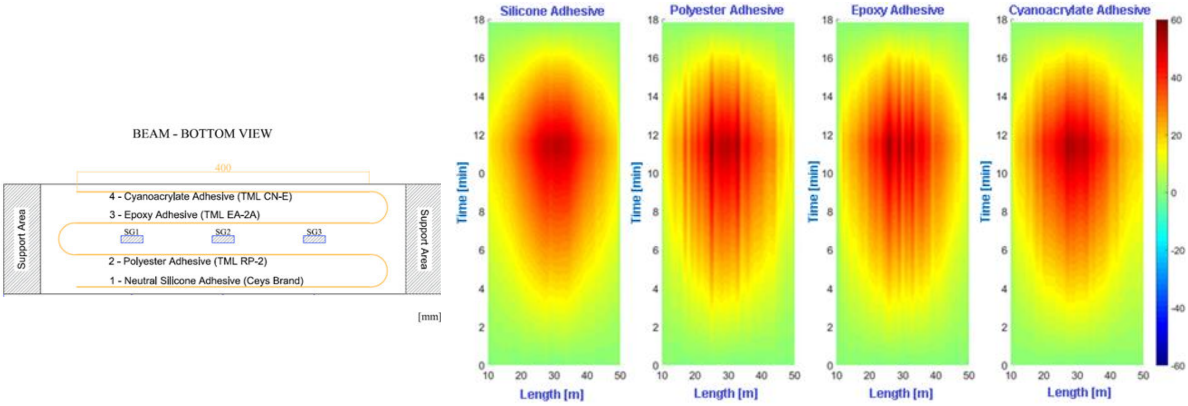
where E_T and E_{20} are Young's moduli of concrete at temperature T and 20°C respectively, β is the thermal hardening coefficient of concrete and ΔT is the difference between T and 20°C. Temperature variation can, therefore, be used as a proxy for real damage to test the sensitivity of DIs. The relationship between the calculated DIs and temperature is established and a polynomial function is fitted. Using the same database, an algorithm to obtain a normalized influence line and the relative axle weights of a truck is tested. This approach combines Moses' algorithm to find weights[12] and an algorithm to obtain the influence line[13] in an iterative approach. The advantage is that no calibration truck is needed and although the absolute values of the influence line cannot be obtained, its relative change can be monitored. This variation can be linked to damage of the bridge. Once again the algorithm is tested based on the stiffness change of the bridge introduced by the variation of temperature.

5. Development of Distributed Optical Fibre Sensing for SHM

The use of Optical Fiber Sensors (OFS) in SHM applications to infrastructure is something that has been widely studied and practiced with promising results. Nonetheless, when dealing with large-scale structures, such as bridges, the necessary number of discrete sensors that are required in order to perform a global and general monitoring action, can increase rapidly and with it the necessary number of connection cables and acquisition systems, which exacerbate the complexity of the entire monitoring system. It is in this context, that ESR 11 investigates the applicability of DOFS to SHM of bridges and other large-scale structures. These sensors take advantage of their distributed and spatial continuity reading capability in order to measure strain and temperature data with relatively high spatial resolution and high accuracy over extensive length stretches of the monitored infrastructure with the use of up to one single sensor. Notwithstanding, due to the novelty of this sensor technology, different challenges and uncertainties were present preventing a more widely and standard use of these type of sensors in civil engineering SHM. Therefore, the objectives of ESR 11 are to analyze the possible spatial resolution and strain accuracy obtained with DOFS, and to quantify the effectiveness of detecting cracks or unusual deflections without failure or debonding of the sensor. Consequently, the most suitable adhesives, as well as the technique of attachment of the fiber to the concrete, are explored. The long-term reliability of the sensor measurements is also investigated. Having these goals in mind, the ESR has made the following contributions to the state of the art:

- A novel implementation technique of the fiber to a reinforced concrete (RC) member is proposed and analysed;
- Different bonding adhesives for the implementation of DOFS to concrete members are performed and assessed (Fig. 5).
- A study of the influence of the inputted spatial resolution on DOFS measurements is conducted.

- The performance of DOFS when instrumented to RC members under a high number of load cycles in order to replicate the long-term reliability of this technology is evaluated when applied in a standard bridge structure.
- Finally, this technology is deployed in two real-world structures in Barcelona where new imperative conditions have to be addressed such as the long-term effect of temperature variation and its compensation.



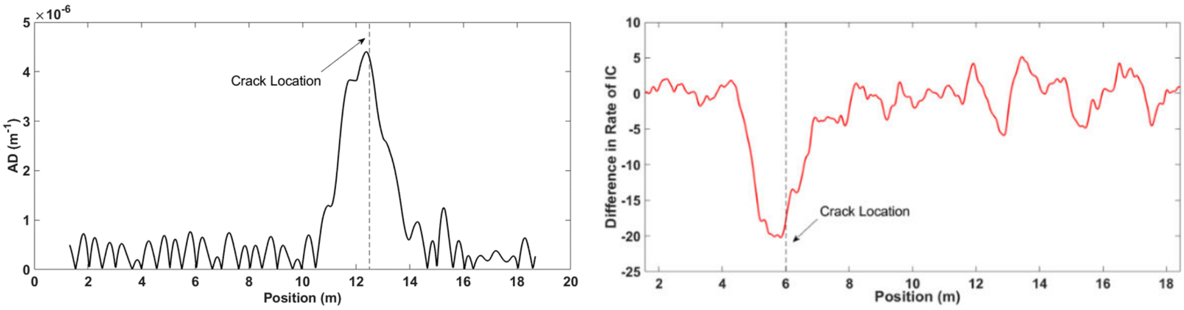
(a) (b)

Figure 5. Bonded sensors: (a) Setup in the bottom surface of RC beam to be tested statically; (b) Measured strain by different bonded segments of DOFS

6. Structural Monitoring Using a Drive-By System

Bridges are often damaged by strikes from over-high vehicles trying to pass underneath. The nature of such damage tends to be local and bridge curvature is proposed here as a means of detecting it. Bridges deflect under moving load which causes curvature, which is defined by the ratio of bending moment to structural stiffness. If stiffness was locally reduced by a bridge strike, it will generate a local peak in curvature [14]. Unfortunately, curvature is difficult to measure. It could possibly be measured using a camera system taking images of the bridge edge but curvature changes significantly as a vehicle crosses a bridge and a very high frame rate would be required to measure the curvature history of the bridge in the one or two seconds taken by the crossing of a vehicle. It is therefore proposed to measure curvature using lasers placed in a specialist vehicle that is periodically driven across the bridge to determine its condition. Laser Doppler Vibrometers can be placed in a rigid beam in the back of a vehicle and pointed downwards at the surface of the road or rail underneath. Hence, they can measure the rate of deflection between the rigid beam and the bridge surface. By integration, they can be converted into a series of deflection measurements. It should be noted that such measurement is relative to the rigid beam in the back of the vehicle. As the vehicle bounces and rocks, deflections will change. A minimum of three simultaneous deflection measurements will be needed to determine Instantaneous Curvature (IC), i.e., the curvature at a point on a bridge at a given instant in time. While vehicle bouncing and rocking have an influence on the deflection, they do not influence curvature. Thus, the relative curvature between the rigid beam and the bridge is exactly equal to the true curvature on the bridge [15]. As the measurements are being taken from a moving vehicle, IC varies in a healthy prismatic bridge with changes in bending moment. Such bending moment does not follow the shape of a conventional bending moment diagram as the loading. and hence the bending moment. is changing with each point being monitored. The key point to keep in mind is that bending moment under a moving vehicle changes smoothly. Curvature also changes smoothly unless a local stiffness loss is reached [16].

Based on the assumption that the specialist vehicle will be of a constant weight and will cross the bridge regularly, a baseline IC curve can be established for the healthy bridge. The Absolute Difference (AD) between IC for the baseline healthy and future cases can then be used as a damage indicator. Using simulations of crossings of a specialist vehicle over healthy and damaged bridges, the AD is calculated and illustrated in Fig. 6(a) for a 20 m long and 10 m wide bridge. The true damage is at 12.5 m from the left support. A clear peak in AD is evident close to the damage location. In practice, integrating the rates (1st derivatives) of deflection measured by Doppler Laser Vibrometers can lead to inaccuracies that have been tested using raw measurements of the rate of deflection. Three such measurements can be used to determine the rate of IC [17], i.e., its first derivative with respect to time. Fig. 6(b) shows the difference in rates of IC between healthy and damaged bridges. A moving average filter has been applied to mitigate the influence of bridge vibration. In this case, the simulated damage was at 6 m and, while the result is not exact, there is a clear peak in close vicinity to the damage.



(a) (b)

Figure 6. Drive-by curvature: (a) AD in IC between a healthy bridge and the same bridge damaged at 12.5 m; (b) Difference in rate of IC between a healthy bridge and the same bridge damaged at 6 m

7. Reducing Uncertainty in Free Standing Nuclear Spent Fuel Racks Design

This project provides an approach for uncertainty quantification in the rack seismic analysis based on probabilistic methodologies. A number of uncertain input variables is assumed to induce probability distributions in the output space. The implementation of this approach includes sampling techniques, surrogate modelling and reliability methods for uncertainty quantification. Fig. 7 shows the global framework used in this uncertainty quantification.

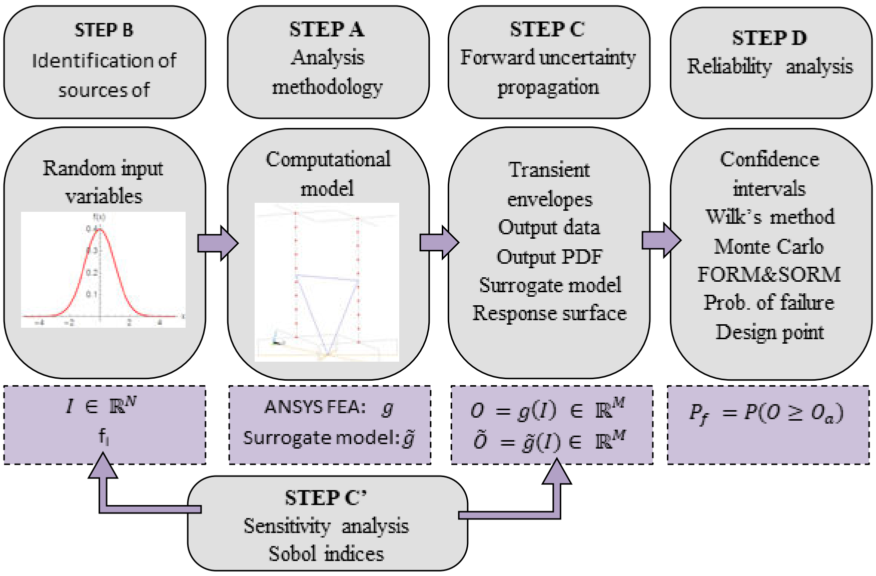


Figure 7. Global framework for uncertainty quantification

In a first step, the current analysis methodology is introduced, the algorithms for implicit integration are reviewed and the application of the hydrodynamic mass concept is investigated. Inherent assumptions of the transient nonlinear analysis are identified and discussed. Numerical simulations are validated through comparison with experimental results collected from a vibration test. In a second step, the sources of uncertainty are identified and the input variables (I) with noticeable influence on the rack seismic response are listed by groups: load data, modelling properties, and solution controls. In a third step, forward uncertainty propagation is carried out. Sample sets are randomly generated via the Latin Hypercube Sampling (LHS). Then, numerical simulations in ANSYS Mechanical return the transient response for the given sets of input variables. The outputs (O) of main interest to the rack design are analysed from a probabilistic point of view. Transient envelopes are computed, probability density functions are inferred, and output statistics are provided. Moreover, surrogated models based upon the Polynomial Chaos Expansions are developed as a cost-effective black box to emulate the numerical simulations. They represent synthetic approximations to the response surface and have fundamental significance in the understanding of the rack design problem. Their analytical equations make possible to carry out multivariate sensitivity analyses with Sobol indices. Such a sensitivity analysis highlights the influence of the inputs variation on the rack response. Finally, reliability methods are applied to compute the probability of failure, locate the Most Probable Point (MPP) of failure and asses the elasticity of the reliability β-index. The coordinates of the MPP in the input L-H space are provided through the second order reliability method (SORM) and represent the values of the input variables leading to failure. The β elasticities provide the influence of each input variable on the probability of failure around the design point. They highlight which variables push in which direction for a given type of failure.

8. Probabilistic Optimization in Design of Offshore Wind Turbine Towers

Fatigue calculations for Offshore Wind Turbines (OWT) involve a significant amount of computational time. OWTs are non-linear dynamic systems that are computationally expensive to evaluate. Moreover, their loading is highly dependent on the environmental variables that load the turbine at a particular time. As the number of environmental variables accounted in the analysis increases, the number of load cases that need to be addressed increases exponentially. As a result, fatigue calculations frequently apply simplified approaches to account for all the environmental loading cases. Current fatigue design practices demand the establishment of several time series at different environmental conditions, counting of loads and cycles, and calculation of the fatigue life using the well-established S-N method (S-N curve + Miner's rule). In order to reduce the computational effort of fatigue assessment, Rui et al [18] propose the usage of Kriging interpolation models as surrogates of the S-N fatigue damage. The idea of using these as surrogates of the S-N analysis procedure is motivated by their potential capability for assessing S-N fatigue damage without the need to perform time-domain counting of loads and cycles at all the operational states.

Fig. 8 illustrates calculations for S-N fatigue design with Kriging models. The Kriging models are implemented to compare the predictions of a full year operational assessment established from recorded data [19]. An innovative infill criterion ψ defines the design of experiments (DoE). This criterion uses a maxima damage and a spatial component to iterate new points to infill the DoE. In the figure, I-IV DoE points, $DoE_{X_{n+1=0}}$ is a randomly selected initial DoE; and X_{n+1} are the iterated points. Fig. 8(a) is the error in the approximation to $\sum D_{SH}^{r}$, and Fig. 8(b) is the value of the ψ search criterion at iteration n+1. The usage of an active learning process confers robustness to the approach, as new points are picked based on a notion of improvement of the current surrogate. This can be identified in the convergence presented in Fig. 8(a) for all the cases. Depending on the initial DoE ($DoE_{X_{n+1=0}}$), the error may decrease to 0 at different rates.

Implementation of the Kriging as a surrogate of S-N fatigue show that the computational effort to analyse the tower component using two input variables could be reduced by a factor of 5 to 7, depending on the slope on the S-N curve, without loss of accuracy. It must be noted that only the variables that significantly loaded the tower are considered [20]. Future works will evaluate the application of the proposed methodology to components that are expected to depend on higher dimensional spaces, such as the foundation.

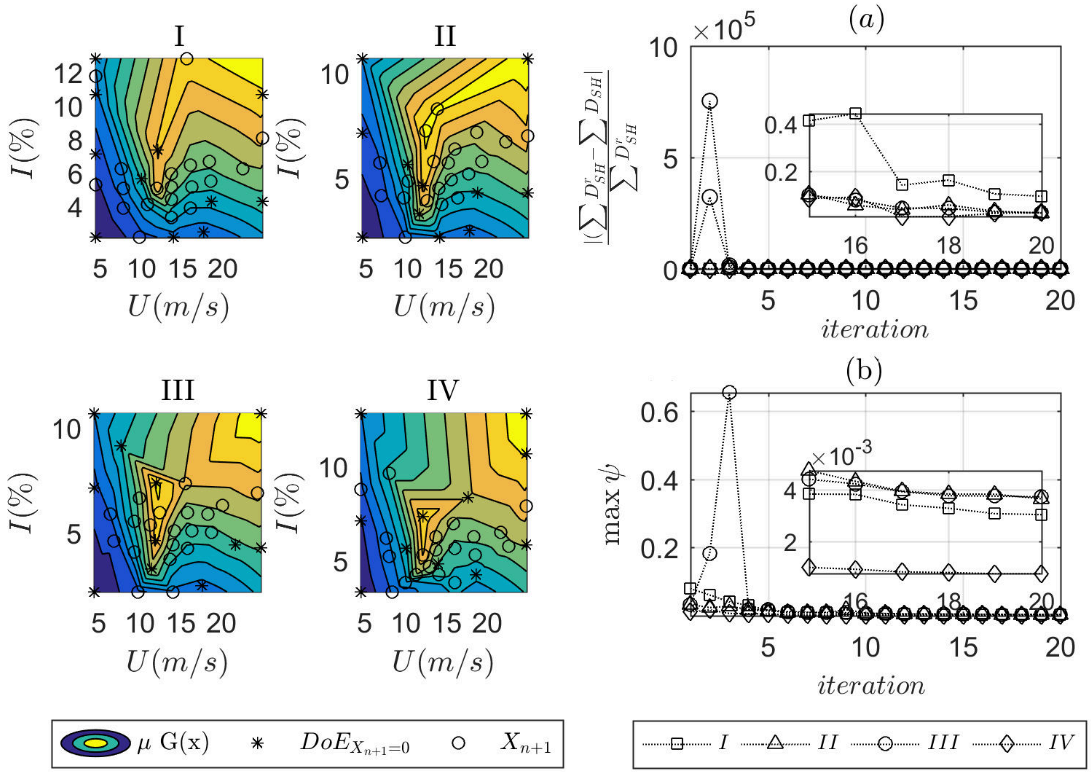


Figure 8. Convergence of the Kriging prediction ($\sum D_{SH}$) to the real S-N damage expected in a full year assessment ($\sum D_{SH}^{r}$)

9. A Risk-Informed Decision Support Approach for Lifecycle Management of Metallic Structural Systems

Metallic structural systems are vulnerable to fatigue cracks. Maintenance costs often account for a significant part of life cycle total costs (LCC), especially for systems with a substantial number of welded details, e.g. ships and offshore platforms. An efficient design and maintenance plan is thus important for risk mitigation, cost reduction and service life extension. The challenges are that fatigue deterioration and maintenance activities are affected by uncertainties in materials, loads, deterioration process, modelling methods, and inspection qualities. Traditionally, conservative Fatigue Design Factors (FDF) and inspection intervals are prescribed, which are not cost-optimal. In addition, fatigue design and maintenance planning are typically disconnected and based on a different theoretical basis, which makes it difficult to learn from past inspection data and to make traceable decisions. ESR5 develops a holistic risk-informed decision support approach for design, inspection and maintenance decision-making under uncertainty for structural systems subjected to fatigue, that has been built considering a probabilistic fracture mechanics (PFM) model, probabilistic inspection modelling, time-variant safety margin, decision tree analysis, Value of Information (VoI) analysis and risk-based optimization.

First, a risk-based maintenance optimization approach is developed for fatigue-critical details. Practical maintenance practices are considered by properly modelling of repair effect and delay, uncertainty in cost estimations, and accidental damages. Quantification method for the VoI provided by inspection or monitoring methods are proposed to derive the optimum inspection strategies, i.e., inspection times and methods. Some original thoughts are provided regarding the choice of optimization metrics, e.g. annual or lifetime reliability/risk, expected service life, annual or lifetime costs, VoI, etc. The influences of optimization metrics and consequence of failure on optimum maintenance strategies are presented. The developed maintenance optimization approach is then extended to incorporate the design process and solved from an initial design perspective. The idea is that the best opportunity for risk mitigation is at the design stage when it's possible to make major changes. Hence, a holistic decision support approach, as illustrated by Fig. 9, is developed for optimizing maintenance strategies together with a design plan, whilst considering the uncertainties affecting life-cycle performance. Calibration methodologies for a PFM model are developed to provide compatible predictions with an S-N approach. FDF and inspection times are optimized based on the calibrated PFM model with the objective to minimize LCC. It is shown that the holistic approach for jointly optimizing fatigue design, inspection and maintenance has the advantage of reducing LCC compared with separate design and maintenance optimization.

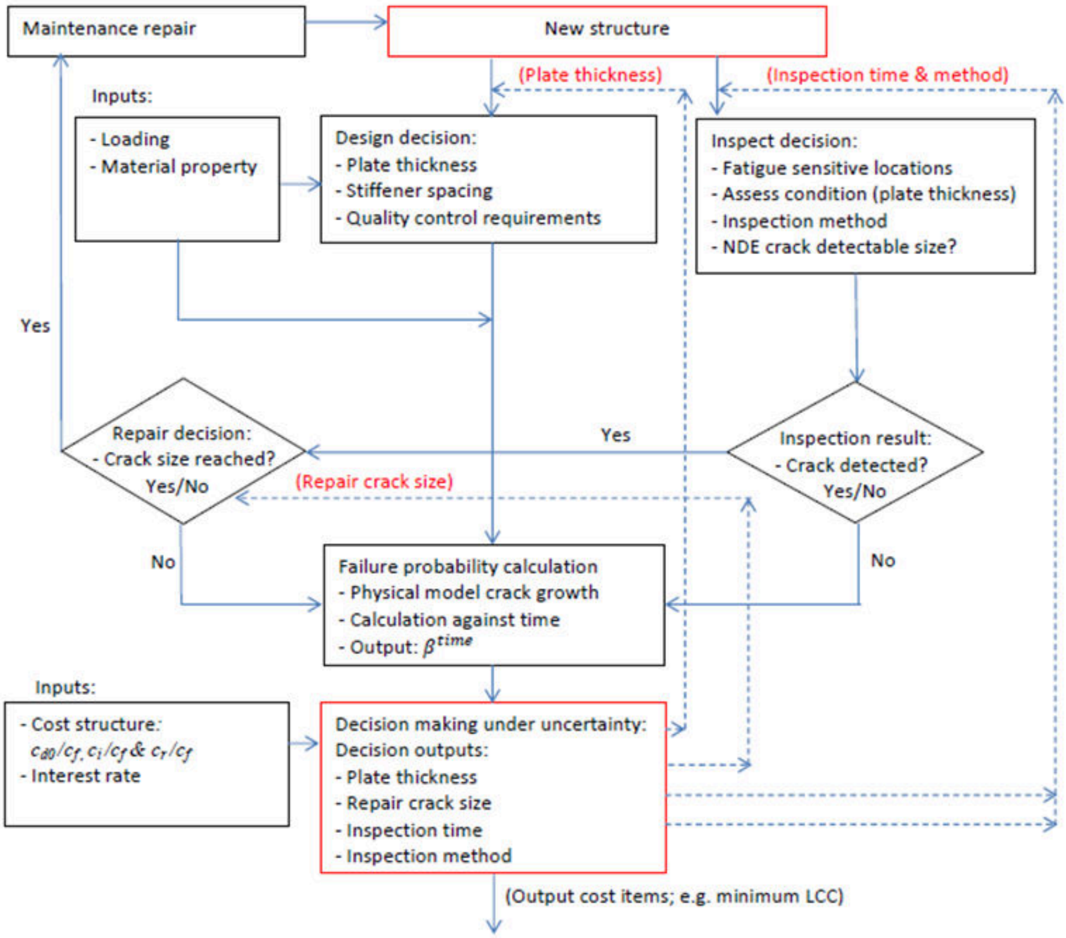


Figure 9. Illustration of risk-informed decision support approach for holistic fatigue management

10. Conclusions

In view of the increasing number of structural failures and its socio-economic impact, it is time to turn more attention and efforts to the maintenance of existing infrastructure. For this purpose, TRUSS has proposed an advanced training and research programme that will qualify 14 ESRs for dealing with the challenges of an aging European infrastructure stock. This paper has reviewed research carried out by some of these ESRs in DOFS, NDT, BFRP, SHM, structural modelling, reliability, and infrastructure management. The knowledge gained in these fields is expected to improve the employability of TRUSS ESRs as well as contribute to a safer and better-preserved infrastructure network.

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