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Contributions by Marie Skłodowska-Curie TRUSS-ITN towards Reducing Uncertainty in Structural Safety of Buildings, Roads, Energy and Marine Infrastructure

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Abstract. There is multitude of models available to assess structural safety based on a set of input parameters. As the degree of complexity of the models increases, the uncertainty of their output tends to decrease. However, more complex models typically require more input parameters, which may contain a higher degree of uncertainty. Therefore, it becomes necessary to find the balance that, for a particular scenario, will reduce the overall uncertainty (model + parameters) in structural safety. The latter is the objective of the Marie Skłodowska-Curie Innovative Training Network titled TRUSS (Training in Reducing Uncertainty in Structural Safety) funded by the EU Horizon 2020 research and innovation programme (http://trussitn.eu). This paper describes how TRUSS addresses uncertainty in: (a) structural reliability of materials such as basalt fiber reinforced polymer, (b) testing techniques in the assessment of concrete strength in buildings, (c) numerical methods in computing the non-linear response of submerged nuclear components subjected to an earthquake, (d) estimation of life of wind turbines, (e) the optimal inspection times and management strategies for ships, (f) characterization of the dynamic response of ship unloaders and (g) the relationship between vehicles fuel consumption and pavement condition.

1 INTRODUCTION

TRUSS (Training in Reducing Uncertainty in Structural Safety) is a Marie Skłodowska-Curie Innovative Training Network (ITN) running from January 2015 to December 2018 that aims to address uncertainties present in today's critical infrastructure as listed in Table 1. This introduction gives an overall picture of TRUSS ITN before moving to a discussion of gaps in the literature and specific research undertaken by the project.

Table 1: Research, innovation and impact by TRUSS

Uncertainties in state of the art	TRUSS	Impact
❖ In material strength ❖ In mathematical models ❖ In loads and performance ❖ In damage indicators ❖ In structural safety	➢ Complex modelling and analysis as well as measurements of material strength, structural behavior and loading conditions (i.e., via novel load and structural monitoring systems that will allow calculating long term safety in existing infrastructure). ➢ Innovative probabilistic approaches validated with theoretical simulations and experimental data.	Improved reliability which thus may result in more efficient designs and maintenance strategies or in the cancellation of costly and unnecessary interventions in existing structures

The aim of a Marie Skłodowska-Curie ITN programme is to train a new generation of creative, entrepreneurial and innovative researchers, able to face current and future challenges and to convert knowledge and ideas into products and services for economic and social benefit. In the case of TRUSS, these knowledge and ideas refer to reliable monitoring

systems and structural, material and loading models contributing to: (a) more efficient infrastructure design, assessment, monitoring and management, (b) maintain current infrastructure stock in operation while minimizing risks, and (c) reduce infrastructure costs and demand for non-renewable and carbon intensive resources while maintaining or improving safety levels. However, this is a complex task due to uncertainties associated to the structural resistance and to the load on a structure. Figure 1 illustrates how TRUSS ITN undertakes this task via an advanced training programme containing network-wide and local taught modules combined with original and impactful research. The latter is supported by secondments that give 14 Early Stage Researchers (ESRs) recruited for the project significant insights and exposure to technologies evolving rapidly, and to research and innovation in both academia and industry.

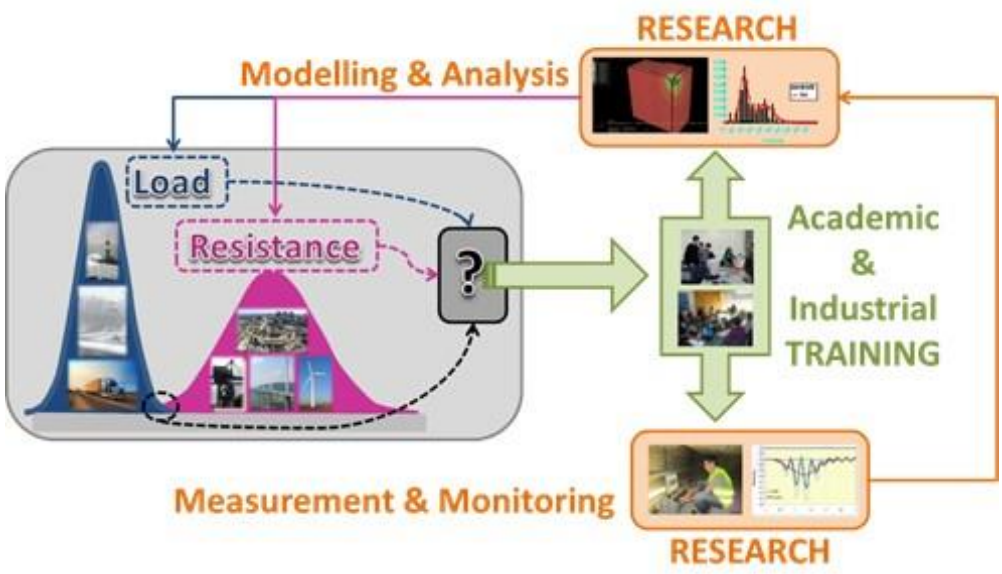


Figure 1: Concept of TRUSS.

González (2017) provides an overview of the training, communication activities and research delivered by TRUSS in the period up to December 2016. These activities are facilitated by an intersectoral and multidisciplinary collaboration between 6 Universities (University College Dublin / coordinator and Trinity College Dublin -Ireland-, University of Nottingham -UK-, Universitat Politecnica Catalunya -Spain-, Université de Nantes -France- and Aalborg University -Denmark-), 11 Industry participants (Lloyd's Register, Full Scale Dynamics Ltd, AECOM and Microlise -UK-, Equipos Nucleares SA, COMSA and COTCA -Spain-, ARUP and Burgmann Packings -Ireland-, Phimeca -France- and Greenwood Engineering -Denmark-) and 1 research institute (TRL -UK-) from 5 European countries (Fig. 2).

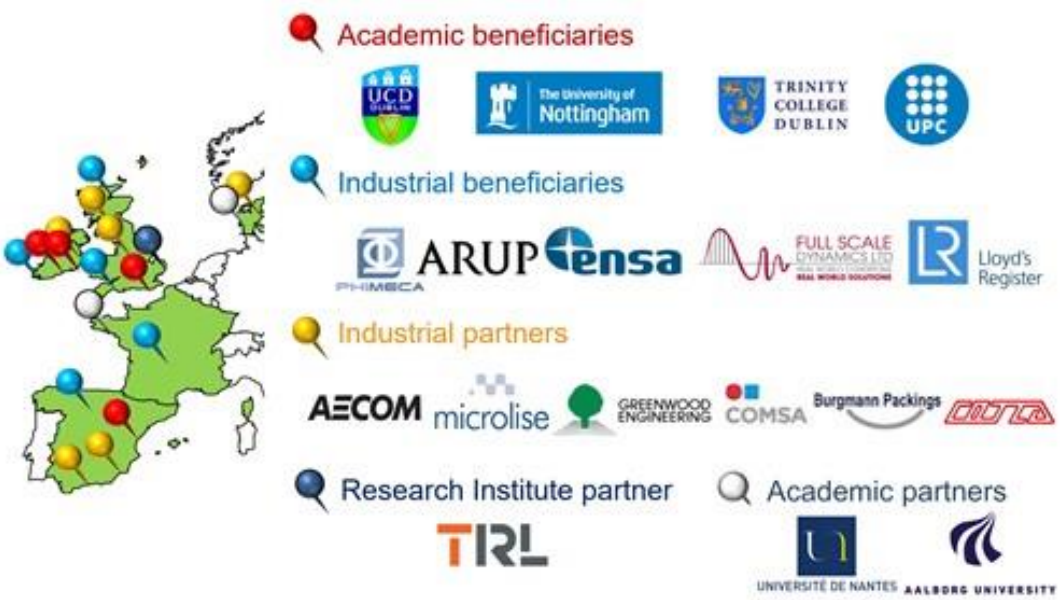


Figure 2: TRUSS ITN consortium.

The diagram in Fig. 3 shows the management structure and organization into Work Packages (WPs). Individual research projects are quite diverse and they cover materials, buildings, nuclear components, off-shore wind turbines, ships, ship unloaders in WP4, and pavements, and rail and road bridges in WP5. Latest TRUSS developments in reducing uncertainty about the condition of rail and road bridges have been reviewed in González et al. (2017, 2018). Therefore, the following sections report on methodologies for reducing uncertainty in infrastructure other than bridges.

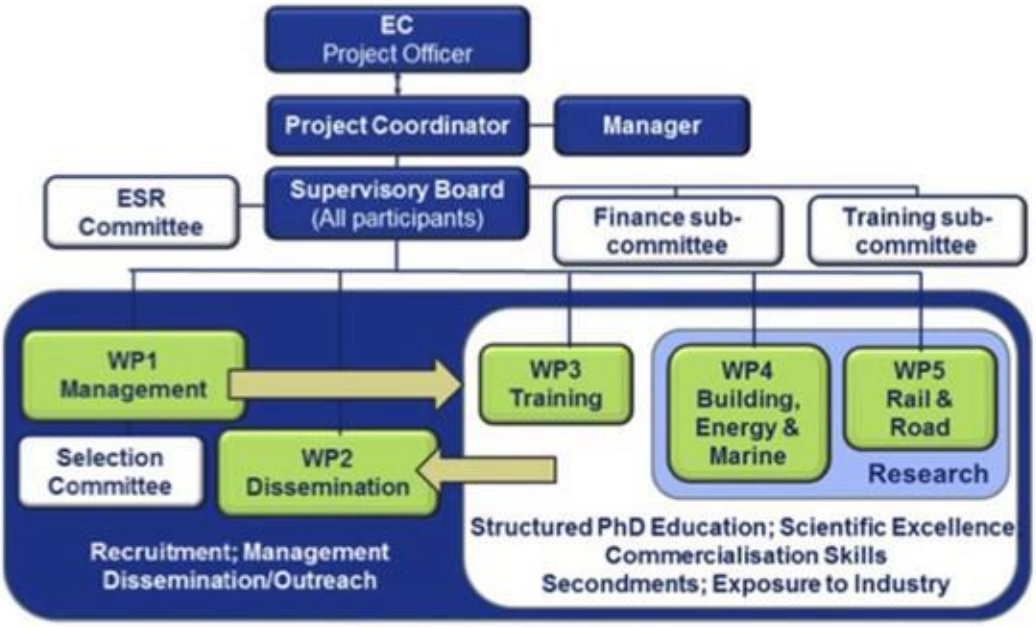


Figure 3: Management structure.

2 RELIABILITY OF CONCRETE STRUCTURES REINFORCED WITH BRAIDED FRP

Degradation of reinforced concrete structures due to corrosion of steel is a crucial factor that affects long term durability, total service life & structural safety of RC elements (Fiore et al., 2005). It is noteworthy that the global cost of corrosion is estimated at about $2.5 trillion (Koch et al., 2016) and current approaches (stainless, epoxy coating etc.) have been found to be unable to successfully address this problem in a cost-effective way (Hollaway 2010). As a result, there is increased interest in alternative reinforcing materials, particularly advanced composite materials, such as Basalt Fibre Reinforced Polymer (BFRP); these have the potential to provide long-term durability while minimizing maintenance costs for infrastructure applications. These materials can offer significant advantages related to both their non-corrodible nature and their enhanced physical and mechanical properties. There are however limitations that prevent their use on a larger scale, and their brittle behaviour is the most significant (Elgabbas, Ahmed and Benmokrane, 2015).

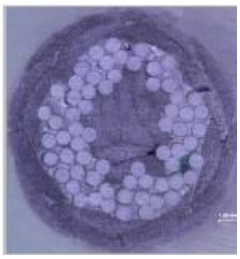
The most common method for manufacturing a FRP rebar is pultrusion; this provides high unidirectional strength but leads to a brittle material. Braiding is proposed as an alternative as it has the potential to provide increased ductility, flexibility and enhanced bond between FRP and concrete. TRUSS explores the potential of braided BFRP composites as internal concrete reinforcement through design optimisation and evaluation of their structural performance. Braided BFRP preforms in three different sizes and configurations (5, 8, 10 mm outer diameter) are designed and manufactured, while changing key braiding parameters (yarn size, no of carriers, angle, no of layers), in order to meet the performance characteristics of existing rebar reinforcement (Fig.4a). Successful epoxy resin impregnation trials in regular and spiral configurations confirm the possibility of manufacturing braided BFRP composites in complex shapes (Figs. 4b and 4c). Bars are manufactured using braiding and a vacuum assisted resin infusion technique. PET fibres are also used to promote resin flow on the samples (Antonopoulou, McNally and Byrne, 2016a, 2016b, 2017). Moreover, a theoretical numerical approach based on classical laminate theory is developed to determine the stiffness properties of braided composites. Tensile tests on BFRP samples are performed using Instron 500 Universal Testing Machine in accordance to B2_ACI 440.3R-04 standard to experimentally validate the numerical results. Initial results show significant discrepancies between theoretical and experimental values, and this uncertainty is being investigated further (Figs. 4d and 4e). Figure 4e shows a typical stress-strain curve corresponding to BFRP along with technical braiding details, numerically determined elastic moduli and fibre content using CLT approach A sensitivity analysis is conducted on the parameters affecting cost as a function of elastic modulus using a Monte Carlo approach, showing that the effect of the braiding process is to reduce the variation arising from the material input properties (Antonopoulou and McNally, 2017).



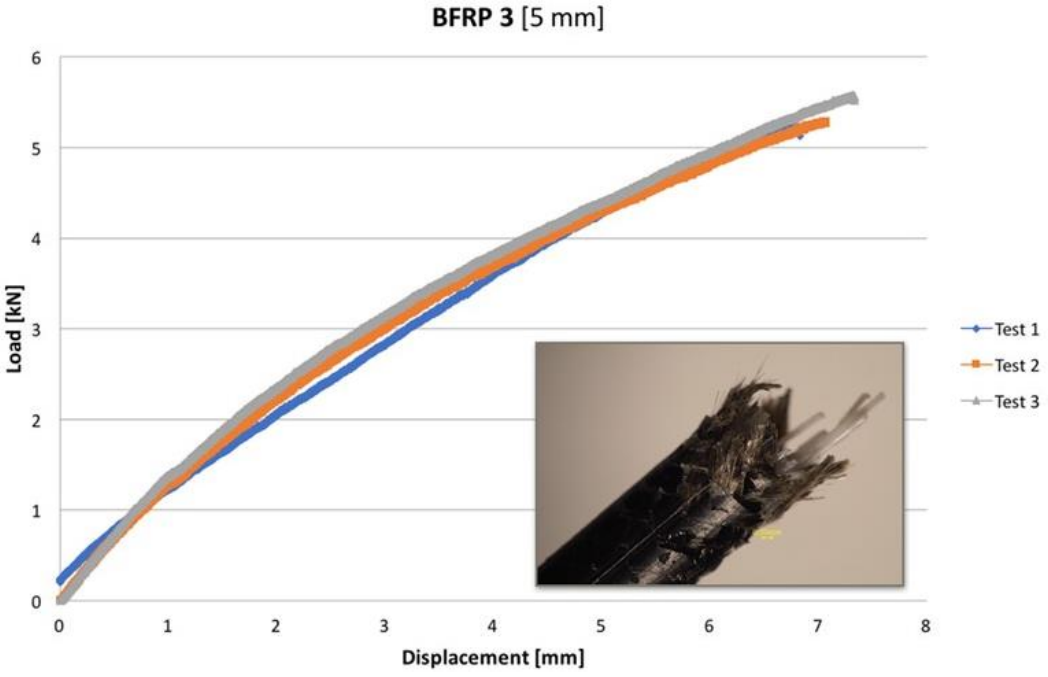
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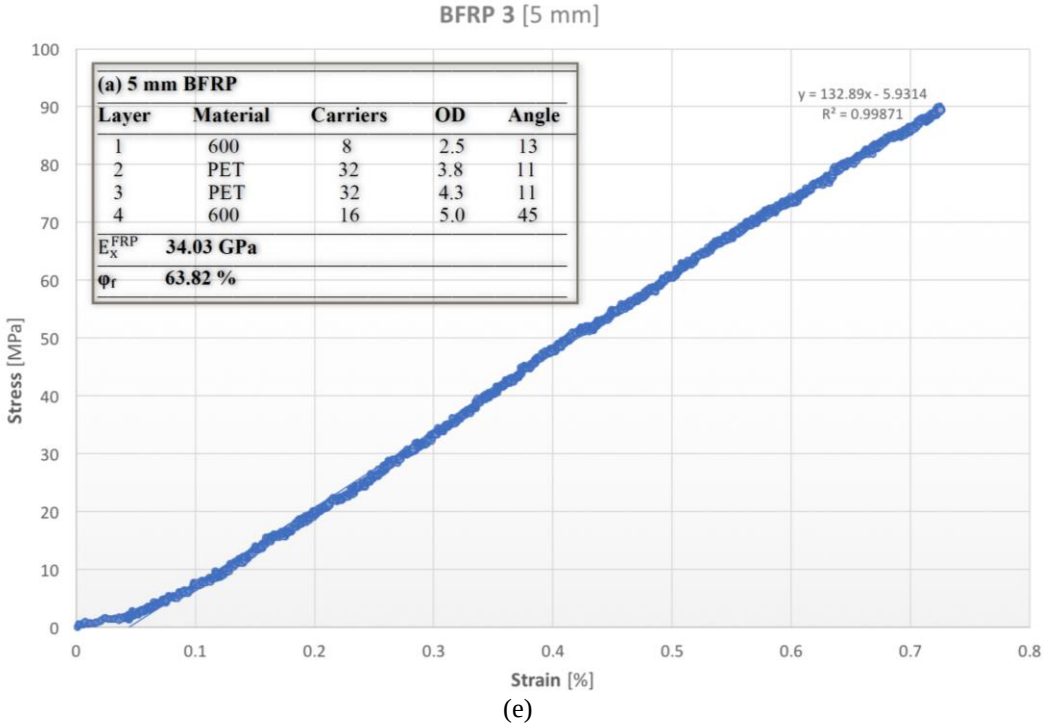
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(c)



(d)

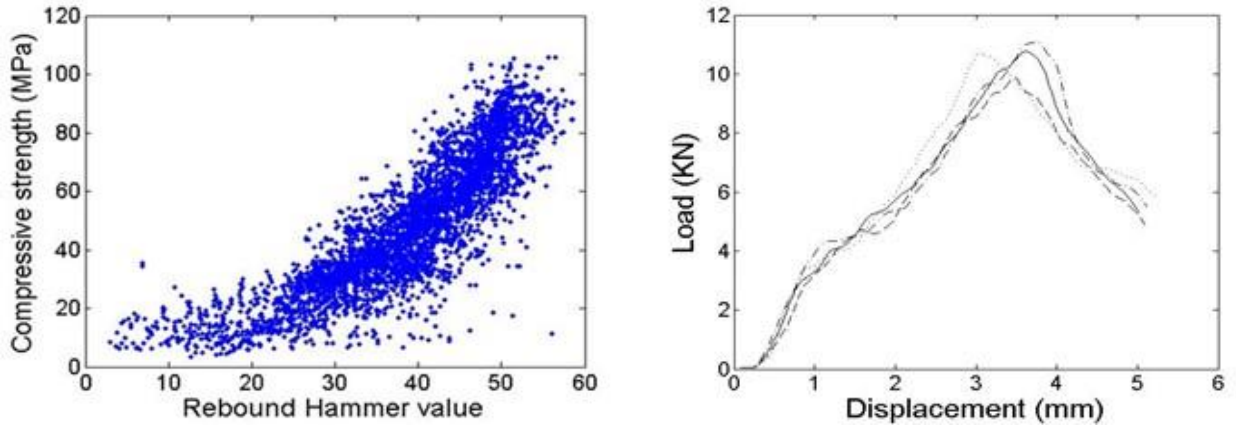


(e)

Figure 4: (a) Braided BFRP rebar preform, (b) Resin impregnated braided BFRP rebars, (c) Digital micrograph of braided BFRP structure, (d) Load-displacement curve for sample ‘BFRP 3’ along with close-up of sample’s fractured surface, (e) Stress-strain curve for sample ‘BFRP 3’.

3 REDUCTION OF UNCERTAINTY IN ASSESSMENT OF CONCRETE STRENGTH IN EXISTING STRUCTURES

With the intention of ensuring the safe operation of existing concrete structures, compressive strength of concrete materials needs to be ascertained as material properties are a key input towards carrying out a structural assessment. A recent study (Sourav, Al-Sabah and McNally, 2016) demonstrates the use and limitation of the currently practiced non-destructive techniques (NDTs) in concrete strength assessment of existing structures. NDTs offer indirect measurement of compressive strength with a considerable degree of uncertainty. NDTs are affected by several uncontrolled factors including measurement error and environmental factors leading to their limited use in the field. There is no general theory to correlate the obtained NDT results with the compressive strength of concrete. Rebound hammer is a popular NDT in assessing concrete strength. However, lab and field data collected from several sources in the literature, shows how rebound hammer results can be misleading when a proper calibration is not obtained (Fig. 5). As an alternative to current NDTs, TRUSS aims at introducing a novel technique named screw push-in test with the purpose of achieving a better level of accuracy, and reducing the uncertainty associated to concrete strength. The new technique is based on creating a mechanical bearing by the use of post-installed screw in already hardened concrete similar to the bearing mechanism of threaded reinforcement bar that is cast in concrete. Literature reveals a strong relationship between the bond strength of reinforcement bar and concrete strength when the failure mode is restricted to the shearing failure along the outer edge of the threads of the bar (Lorrain and Barbosa, 2011; Silva et al., 2014a, 2014b). The screw push-in test and failure mechanism are presented in (Sourav, Al-Sabah and McNally, 2017). Figure 5(b) shows a typical load-displacement curve.



(a) (b)

Figure 5: (a) Compressive strength vs Rebound hammer results, (b) Load-displacement curve in screw push-in test.

Figure 6 compares screw push-in test, rebound hammer test and ultrasonic pulse velocity test for compressive strength assessment of mortar. It can be seen that generally the screw push-in test results predict compressive strength of mortar more accurately than the other two NDTs.

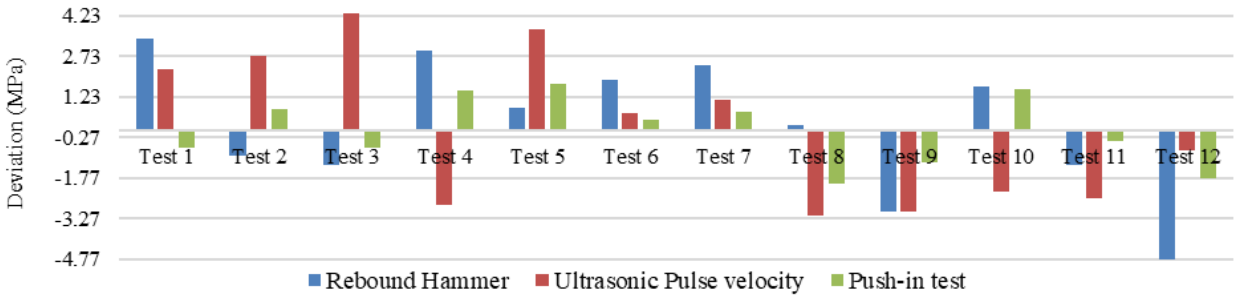


Figure 6: Deviation obtained in compressive strength assessment of mortar.

When the screw push-in test is conducted in concrete, load carrying behavior of the screw is affected by aggregates as aggregate particles cover most of the concrete. Threads of the screw suffer damage during the installation and load application due to the interaction of the screw with the aggregate particles. Currently the research is focused on quantifying those factors affecting the test results.

4 REDUCTION OF UNCERTAINTY IN DESIGN OF FREE STANDING NUCLEAR SPENT FUEL RACK

Racks are around 60 tons and 5 m high steel structures used to store nuclear spent fuel. Figure 7 shows a layout of racks rest free-standing in the depths of the spent fuel pool. The analysis of the racks response to seismic conditions is a fluid-structure interaction problem with a highly nonlinear transient dynamic behaviour. Numerical outputs reveal a dispersion in the results of the methodology that TRUSS project intends to evaluate via simulations and experimental tests.

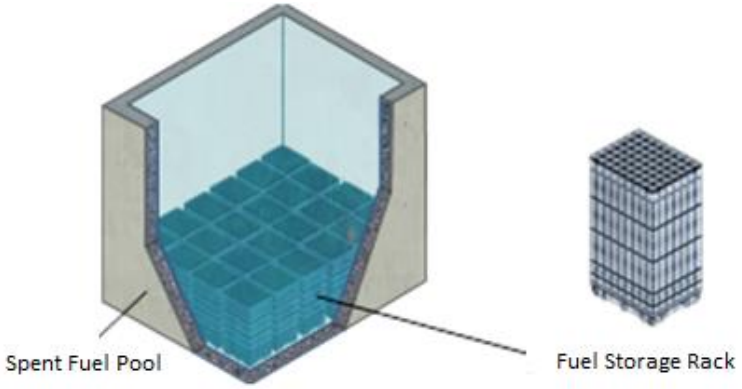


Figure 7: Location of rack units within the spent fuel pool.

González Merino, Costas and González (2016) identify the main sources of uncertainty associated to the methodology. The significance of this uncertainty is approached through the study of input variables expected to have a noticeable influence on the final results. A total of 17 variables related to input data, modelling properties and analysis parameters are investigated. A parametrical analysis one-factor-as-a-time (OFAT) is conducted on a simple two-rack model to see the impact of a slight variation in one variable when the others are set at their nominal value (González Merino, Costas and González, 2017). Furthermore, a sensitivity analysis is carried out using Monte Carlo statistical method with Latin Hypercube Sampling to explore the multidimensional input space by considering any possible set of variables combination. The response surface resulting from a preliminary sample of 500 FE analyses provides a straightforward insight of the robustness of the outputs of most interest used in the rack design. For instance, Fig. 8 shows the distribution of the transient sliding displacements of a rack unit over the pool liner throughout the seismic duration. It plots the maximal and minimal bounds and the mean and standard deviation of the sample at every instant. It is noted how the dispersion of results boosts after the first second of the transient seismic analysis.

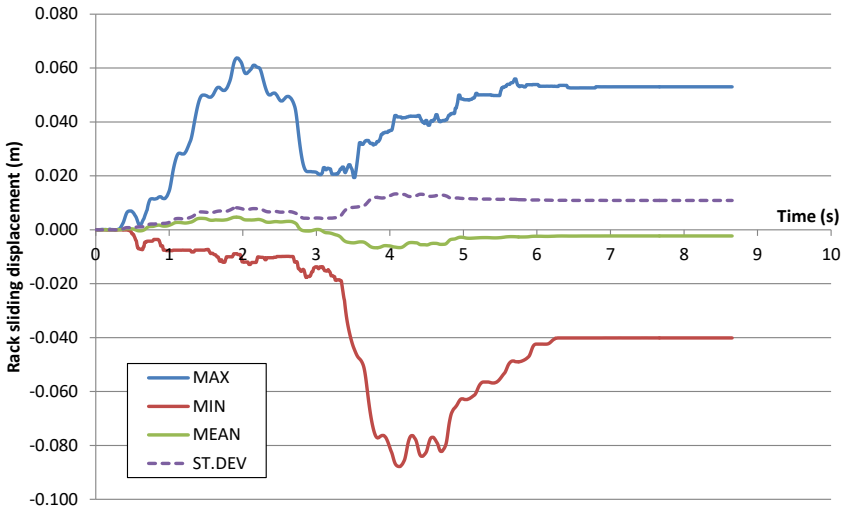


Figure 8: Rack sliding displacements model for the transient seismic analysis.

Additionally, these response surfaces can be approached through mathematical models called surrogate models. Those surrogate models based on Polynomial Chaos Expansions allow the quantification of the weight of each variable in the final result through the Sobol Index Method. Such metamodels represent a cost-effective tool to provide approximated results for additional sets of input variables without launching additional FE analysis. They are especially useful in conducting Monte Carlo simulations for reliability analysis involving multiple input variables and computationally expensive simulations such as the rack seismic analysis.

5 PROBABILISTIC ANALYSIS OF FATIGUE LIFE USING KRIGING SURROGATE MODELS

Current practices applied in the design of Offshore Wind Turbines (OWTs) are restricted in how much uncertainty they can account for. Veldkamp (2008) presents one of the more prominent works in quantifying and qualifying the uncertainty that affects operational fatigue. Still, incorporating uncertainty in the design phase is limited by the design process, which is highly resource consuming. The current design methodology for OWT towers is regulated by the standards such as IEC (2005, 2009) or DNV (2014). The damage in the structure is calculated using an equivalent load approach, counting of range and mean loads and their cycles, and linear damage summation with Palmgren-Miner's equation. Being unfeasible to run the whole lifetime of the OWT in operation, a statistical distribution is defined and the long-term loads are extrapolated with a Peak-Over-Threshold approach. Extrapolation has a very important character in the design but substantial uncertainty may arise from it as seen in Teixeira, Nogal and O'Connor (2017). Nevertheless, fitting a statistical distribution out of the tail is no different. While in the case of composite (high SN slope) components the current practices may be adequate being the main uncertainty related to the process of extrapolating the tail as more or less statistical weight may be given to the tail in the extrapolation depending on the considered quantiles; for the tower, steel component, (lower SN slope) the lower load ranges account for significant damage (Fig. 9) and uncertainty needs to be addressed in the whole distribution.

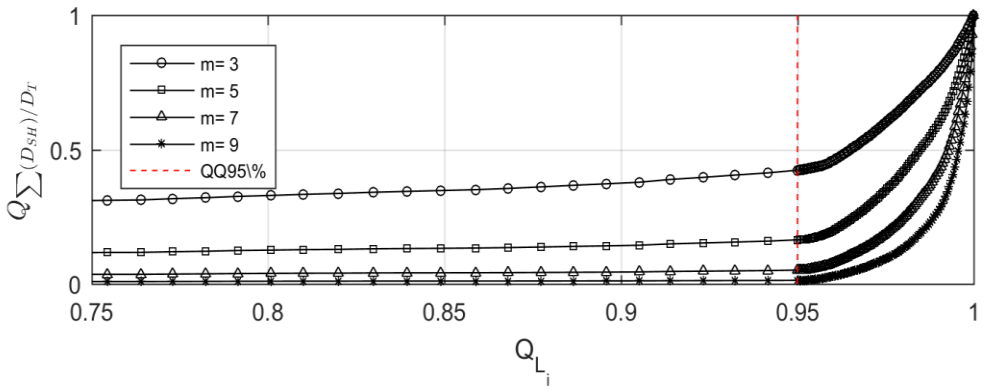


Figure 9: Quantiles of damage contribution for different values of the SN curve slope.

This difficulty of dealing with the uncertainty in extrapolation, the deterministic account of lower load ranges, and the computational effort demanded, fomented the development of a new technique to design and optimize OWT towers to operational fatigue, i.e., the use of damage surfaces with Kriging surrogate models. Surrogate models are particularly suitable to fit the response of complex systems while accounting for some degree of uncertainty. In the case of the tower component, this model may be applied to replicate the short-term damage (D_{SH}) originated in reference time period T. The idea of using a surrogate model to replicate the short-term damage (D_{SH}) in the OWT tower was introduced in Teixeira et al. (2017), where the non-linear damage surface is approached with a Kriging surrogate model and used to generate independent samples of 20 years of damage, replicating the design uncertainty. Figure 10 shows an example of a noisy Kriging surrogate model generated with a single variable in the design of Experiments (DoE) that characterizes statistically the full DoE. Using long term environmental distributions and efficient fitting techniques, it is possible to decrease the computational time needed to achieve a robust design.

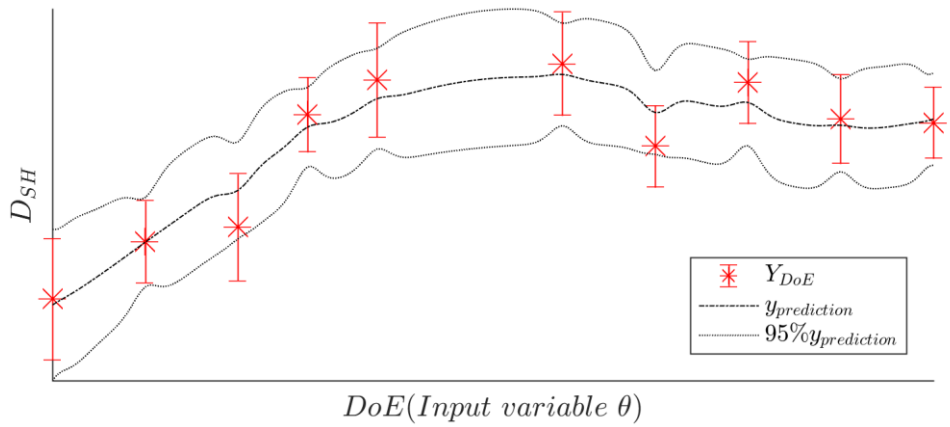


Figure 10: Example of noisy Kriging surrogate model used to replicate D_{SH} with a single θ variable in the DoE.

6 PROBABILISTIC FRAMEWORK FOR FATIGUE CRACK MANAGEMENT – DESIGN, INSPECTION AND MAINTENANCE

In the sea environments, cyclic wave loading and severe corrosion pose high risk to marine structures. Fatigue has gained attention increasingly, given that it can cause sudden failure of the whole structure, and it is difficult to prevent due to high degree of uncertainties associated with both, fatigue loading and capacity. In this regard, probabilistic methods are employed to address those uncertainties and to support fatigue design, manufacture control, inspection and maintenance planning. Probabilistic models are generally developed using fracture mechanics with two assumptions: statistical data on initial flaw size a_0 is known and crack initiation life N_I is negligible compared with crack propagation life N_P. However, those assumptions usually cannot be fully satisfied, especially for some critical structural components which are well-designed and manufactured, so that they can withstand high fatigue loading. For such components, a_0 may be smaller than the smallest detectable crack size a_d by NDT (Lassen and Recho, 2009) and thus, it becomes difficult to obtain data on a_0 even when N_I may account for a large part of fatigue life (Fig. 11). How to develop a probabilistic degradation model as inspection planning basis for such components is a problem that remains to be solved.

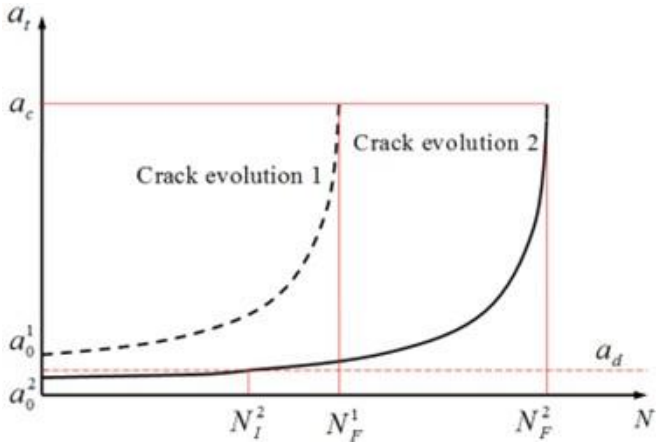


Figure 11: two types of crack evolutions.

Zou, Banisoleiman and González (2016) review the state of the art of treatment methods for N_I and a_0 in crack propagation models. Based on literature studies, four approaches are identified and their strengths and limitations are analysed respectively: (i) N_I is neglected, and distribution of a_0 is assumed to be known, (ii) N_I is modelled approximately with large crack growth theory, (iii) N_I is modelled as a variable, the distribution of which is obtained by specimen tests, and (iv) N_I is modelled accurately with small crack growth theory. Zou, Banisoleiman and González (2017a) investigate an inspection method and planning approach including N_I. Based on the model accounting for N_I and associated uncertainties, inspection plans are formulated with both target reliability approach and equidistant time approach. Results show that taking N_I into account, the number of inspections may be decreased depending on the target reliability (Fig. 12). It is also seen that allowing for N_I, the first inspection interval can be prolonged, but there is not much difference in subsequent inspection intervals.

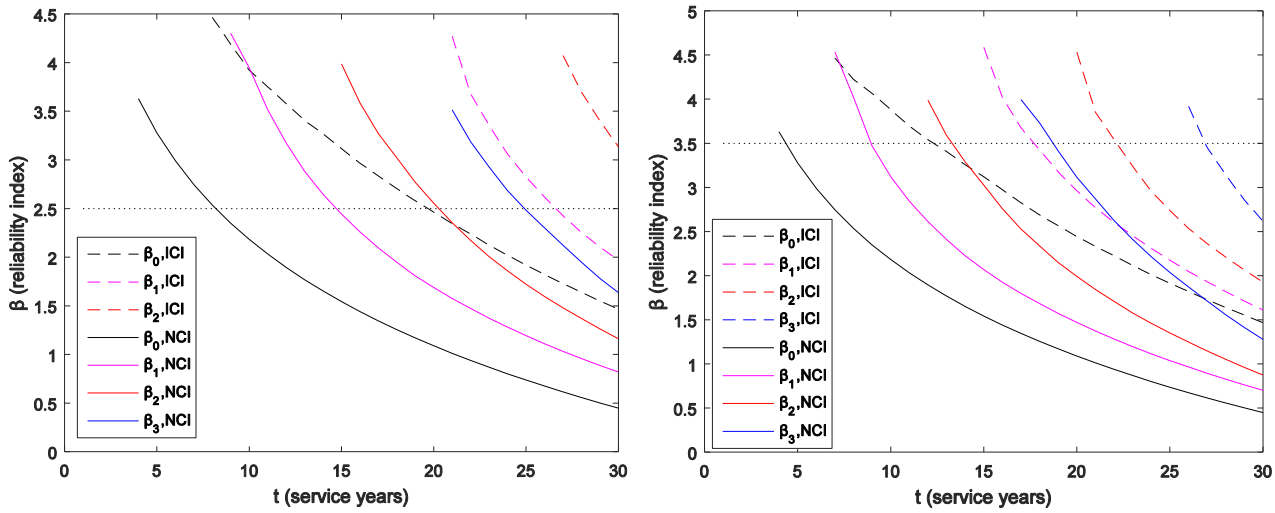


Figure 12: Reliability-based inspection updating (a) $\beta_t = 2.5$ (b) $\beta_t = 3.5$.

Once the impact of N_I is demonstrated, TRUSS proposes development methods for a probabilistic fracture mechanics model including N_I. The basic idea is to determine the unknown initial integrity state of a structural component indirectly using available data on S-N curves or material fatigue and fracture properties or crack evolution test. In Zou, Banisoleiman and González (2017b), the initial integrity state is signified by equivalent initial flaw size (EIFS), and three methods for deriving the EIFS are studied comparatively. It is found that the EIFS derived from S-N curve agrees well with specimen test data, while the EIFS derived from KT diagram is relatively small. In Zou, Banisoleiman and González (2017c), the initial integrity state is characterized via the concept of time to crack initiation (TTCI), and the TTCI is calibrated to S-N curves. Three calibration criteria are tested and it is recommend calibrating with criterion in fatigue reliability and taking into account the uncertainties associated with S-N curves, damage accumulation model, crack initiation and propagation.

7 RESIDUAL LIFE ASSESSMENT AND MANAGEMENT OF SHIP UNLOADERS

The standard procedure currently adopted for evaluating the remaining fatigue life of ship structures is based on first carrying out static analysis, then applying a generalized Dynamic Amplification Factor (DAF) to the obtained stresses to allow for the dynamic behaviour and finally applying Miner's rule to evaluate the remaining number of cycles that the structure is able to carry out (Milana, Banisoleiman and Gonzalez, 2017). Figure 13 shows the DAF provided by FEM 1.001, as function of the kind of crane considered and hoisting speed.

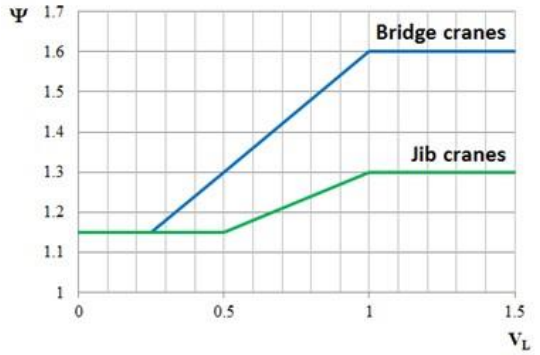


Figure 13: DAF (Ψ) versus hoisting speed (Adapted from FEM 1.001 1987).

The simplicity of this procedure makes it widely used in practice, but it is worth noting that many assumptions within this process have associated uncertainties affecting the reliability of the final assessment. An analysis of the data provided by a monitoring system (strain gauges installed at 16 locations) and comparisons between the dynamic recorded stresses and the estimated static one (obtained applying a cut-off frequency of 0.4 Hz), show that the aforementioned DAF does not resemble the real dynamic behaviour in the majority of the structural elements being monitored. Location-based DAFs are introduced to take into account the dynamic features of each member. DAF is calculated as the ratio between the maximum dynamic and maximum estimated static stresses for each location. Figure 14 shows the value of these coefficients for each structural element for the set of load cycle under investigation. The DAF value by the code is represented by an horizontal black line. Clearly, location-based DAFs allow obtaining a more accurate picture of the remaining number of cycles that each structural element can carry out before failure than a global DAF value.

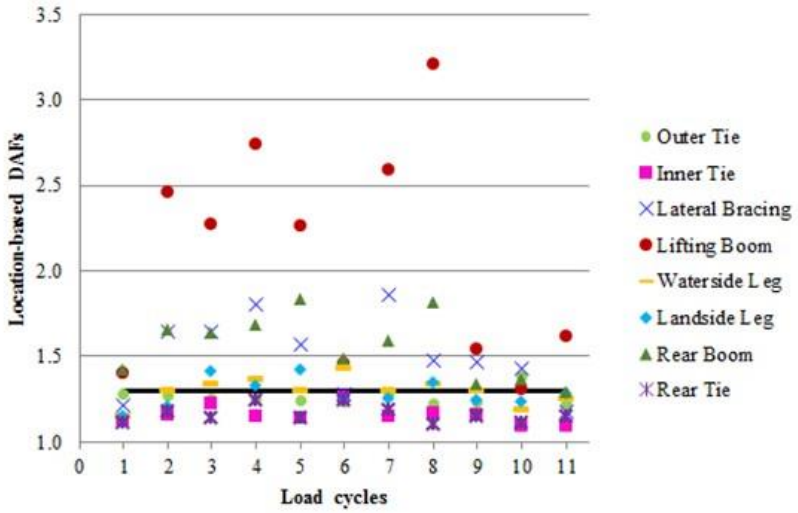


Figure 14: Location-based dynamic amplification factors for axial stress component (Adapted from Milana, Banisoleiman and González, 2017).

8 USING TRUCK SENSORS FOR ROAD PAVEMENT PERFORMANCE INVESTIGATION

Sandberg (1990), Beuving et al. (2004) and Zaabar and Chatti (2010), among others, claim that road surface roughness and macrotexture can impact truck fuel economy by up to 5%. This suggests that improved standards of road maintenance could lead to a significant reduction of greenhouse gas emissions from the road transport industry. However, these studies performed only limited tests, using a few vehicles driven at constant speed, on a limited number of selected road segments. Therefore, the latter may not be representative of what happens at network level under real conditions. For this reason, the conclusions of existing studies cannot be considered exhaustive, and the impact of roughness and macrotexture is not always considered in pavement life cycle assessment studies.

TRUSS seeks to assess the impact of road surface conditions on truck fleet fuel economy based on a 'Big Data' approach. Modern trucks are equipped with many sensors that continuously monitor the performance of the vehicles and help fleet managers to take decisions regarding training of drivers and maintenance of vehicles. Road agencies routinely collect road condition data to inform decisions about maintenance of the road pavement. Using a probabilistic approach based on large quantities of data ('Big Data'), this information can be used to estimate the impact of the road surface conditions on truck fuel economy (Perrotta, Parry and Neves, 2017a, 2017b; Perrotta et al., 2017). As an initial case study, data from 260 articulated trucks driving at constant speed on a motorway in England are considered. The 1420 truck records are for one minute durations and include gross vehicle weight, date and time of travel, speed, acceleration, use of cruise control, applied torque, and engine revolutions. The road condition records include average gradient, radius of curvature, crossfall, roughness (measured as longitudinal profile variance, LPV, at 3, 10 and 30 meters wavelength), and the macrotexture (as sensor measured texture depth, SMTD). From the analysis of the Adjusted-R2, Akaike Information Criterion (AIC), and Lasso regression it is possible to conclude that LPV10 and SMTD are two parameters that significantly influence the fuel consumption of the considered fleet of trucks (Perrotta et al. 2017). These statistics have been used to select the most significant variables to be included in a multiple linear regression model. These are the gross vehicle weight, the road gradient, the vehicle speed, the LPV10 and the SMTD. Results show that the estimated impacts on fuel consumption are up to about 4.5% for roughness and 5% for macro-texture (Perrotta, Parry and Neves, 2017a, 2017b; Perrotta et al., 2017). These results confirm those found in past literature.

In order to generalize these conclusions, more vehicle models, the influence of temperature, wind speed and direction, a wider range of vehicle speeds, and road conditions representative of the entire road network need to be investigated. Application of more advanced statistics, such as machine learning techniques can help in improving the accuracy of the final estimates. In fact, recent applications of support vector machine, random forest (Fig. 15), and artificial neural networks show significant improvement in the overall performance of the generated model and they reduce the uncertainty associated to linear models, which are inadequate to fully describe the fuel consumption.

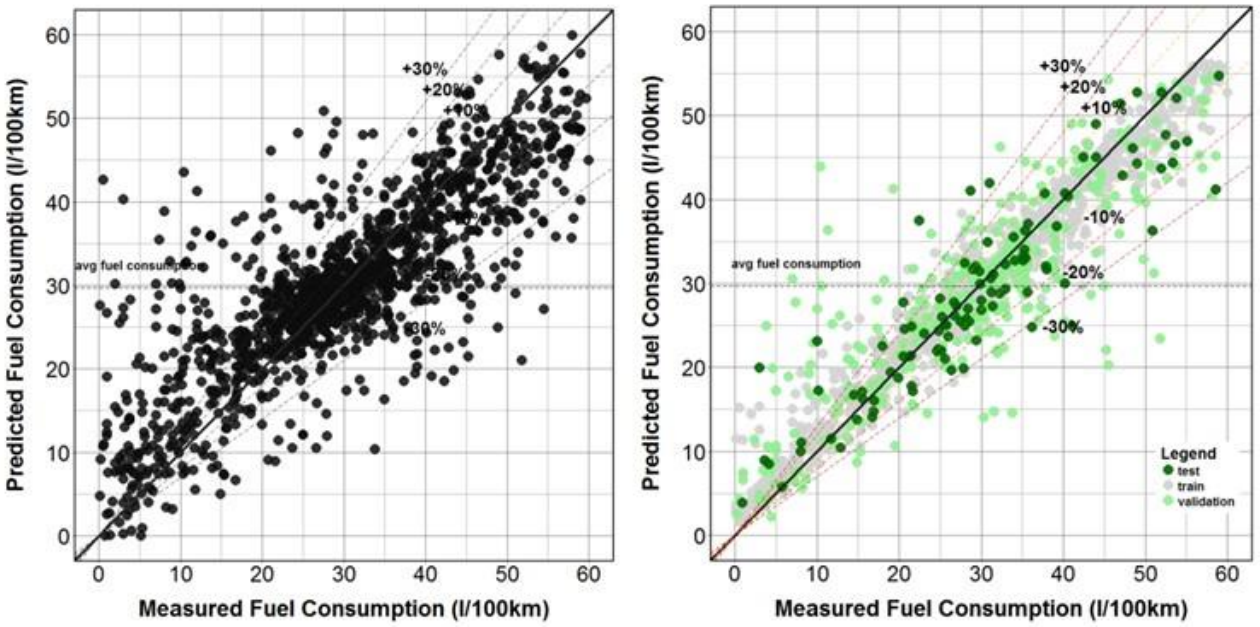


Figure 15: An example of the possible improvement in prediction from a multiple linear regression to a machine learning method (random forest in this case).

9 CONCLUSIONS

Latest efforts by TRUSS ITN in reducing uncertainty by adopting new models for materials, pavements, energy and marine infrastructure presented in this paper can be broadly classified in two groups: (i) projects characterizing the uncertainty associated with a material property, testing technique or structural feature, and (ii) projects aiming to assess the large degree of uncertainty associated with the life of a structure or calculations with lots of variables that are computationally very expensive. Within the first group, braided FRP has being subject to a extensive campaign of tests. A Monte-Carlo approach has been used to quantify the uncertainty associated with the modulus of elasticity as a function of material input properties. The braiding process has appeared to reduce uncertainty in the output. A novel push-in test for measuring concrete strength in-situ has been shown to exhibit less variability than traditional rebound hammer and ultrasonic pulse velocities non-destructive techniques. The response of a ship unloader to a moving trolley has been analyzed via experimental data to identify the variability in dynamic amplification throughout the structure. The latter will be followed by the development of a numerical model resembling the measurements. Within the second group, the uncertainty associated with the non-linear response of a nuclear rack to an earthquake has been investigated using Monte Carlo statistical method with Latin Hypercube sampling. Surrogate models based on polynomial chaos expansions have allowed quantifying the impact of each of 17 variables through the Sobol Index method. Surrogate models, more specifically Kriging, has also been combined with damage surfaces to estimate the fatigue life of offshore wind turbine towers. An inspection strategy depending on the target reliability has been proposed based on a probabilistic fracture mechanics method allowing for crack initiation period. Finally, machine learning techniques have been applied to reduce the uncertainty in the prediction of fuel consumption based on road condition and truck records. While some of TRUSS contributions have focused on improving the assessment of both the capacity and demand of infrastructure to quantify its current state, other contributions have developed forecasting models to quantify its future condition. Although the nature of some individual projects can be very different, they all respond to the same need for maintaining existing infrastructure safe and operational, with the best possible use of the available resources.

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