

Developments in damage assessment by Marie Skłodowska-Curie TRUSS ITN project

A González

College Lecturer and TRUSS ITN Project Coordinator, Civil Engineering School,
University College Dublin, Dublin, Ireland

Email: arturo.gonzalez@ucd.ie

Abstract. The growth of cities, the impacts of climate change and the massive cost of providing new infrastructure provide the impetus for TRUSS (Training in Reducing Uncertainty in Structural Safety), a €3.7 million Marie Skłodowska-Curie Action Innovative Training Network project funded by EU's Horizon 2020 programme, which aims to maximize the potential of infrastructure that already exists (<http://trussitn.eu>). For that purpose, TRUSS brings together an international, inter-sectoral and multidisciplinary collaboration between five academic and eleven industry institutions from five European countries. The project covers rail and road infrastructure, buildings and energy and marine infrastructure. This paper reports progress in fields such as advanced sensor-based structural health monitoring solutions – unmanned aerial vehicles, optical backscatter reflectometry, monitoring sensors mounted on vehicles, ... – and innovative algorithms for structural designs and short- and long-term assessments of buildings, bridges, pavements, ships, ship unloaders, nuclear components and wind turbine towers that will support infrastructure operators and owners in managing their assets.

1. Introduction

Buildings, energy and transport infrastructure are key elements for supporting society in their day-to-day activities. The infrastructure network is ageing and deteriorating rapidly under an increasing demand in operational and environmental loads. While an efficient infrastructure network provides economic and social benefits, infrastructure chaos in terms of capacity or reliability can involve economic costs and lower quality of life. For infrastructure to remain effective and structurally safe, a management strategy that guarantees proper maintenance and best use of the resources available is needed. However, this is a complex task due to uncertainties associated to the structural capacity and to the demand on a structure. TRUSS (Training in Reducing Uncertainty in Structural Safety) is a 4-year Marie Skłodowska-Curie Innovative Training Network (ITN) project [1], which started in January 2015, aiming to improve infrastructure management via advanced structural reliability and monitoring methods. Figure 1 illustrates the TRUSS concept. TRUSS consortium (Figure 2) is composed by:

- 5 Universities (University College Dublin –UCD– and Trinity College Dublin –TCD– in Ireland, Universitat Politècnica de Catalunya –UPC– in Spain, University of Nottingham –UNOTT– in UK and Université de Nantes in France).
- 11 Industry participants (Lloyd's Register EMEA, Full Scale Dynamics Ltd, AECOM and Microlise in UK, Equipos Nucleares S.A. –ENSA–, COMSA and COTCA in Spain, Arup and Burgmann Packings in Ireland, Phimeca Engineering in France, and Greenwood Engineering in Denmark).



- 1 Research institute (Transport Research Laboratory –TRL– in UK).

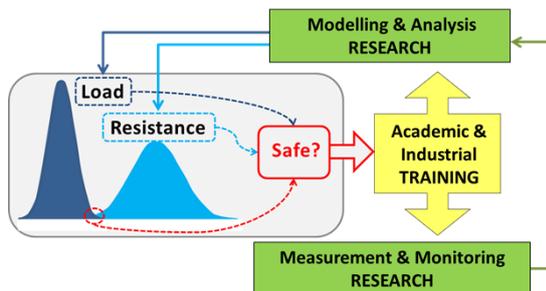


Figure 1. Concept of TRUSS.



Figure 2. TRUSS consortium.

The main objectives of TRUSS are twofold:

- To develop reliable monitoring systems and structural, material and loading models to be achieved through research that will contribute 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.
- To offer a high-quality intersectoral and multidisciplinary training in structural safety to a new generation of Early Stage Researchers (ESRs) through network-wide and local activities. The training programme combines taught modules with original research supported by secondments, which will allow ESRs gaining experience and enhancing their career prospects in both industrial and academic sectors.

In order to meet these objectives, 14 ESRs have been recruited to carry out research in 14 different individual projects. While moving forward the state of the art in the topics of these projects, TRUSS prepares ESRs for dealing with the challenges faced at the assessment and management stages of aging large scale structures. TRUSS is structured into five Work Packages (WPs): WP1 on Management (led by UCD), WP2 on Dissemination and Outreach (led by UPC), WP3 on Structured Training (led by UCD), and two research WPs: WP4 on Buildings, Energy and Marine (led by UCD) and WP5 on Rail and Road infrastructures (led by UNOTT). The following sections report on the progress of the project in the period up to December 2016.

2. Dissemination and outreach

Following a recruitment period, ESRs joined TRUSS ITN between September and December 2015. In their first year, ESRs have published a total of 25 technical papers: 2 in peer reviewed journals and 23 in conferences, that are included in the list of references. 16 of these papers include academic and industrial co-authors, which shows evidence of the narrow collaboration between both sectors. Dissemination by TRUSS (WP2) is keenly aware of the importance of not only producing and presenting research outputs for the scientific community and key stakeholders (i.e., via conferences, workshops, publications and reports), but also engaging the general public in line with the Innovation Union objectives [2]. TRUSS activities contribute to make citizens aware that:

- infrastructure is aging and failing, and funding has been insufficient to repair and replace it,
- the important role of the Marie Skłodowska-Curie Actions [1] in forming 21st century engineers that will have the skills to face the formidable challenge of modernizing the fundamental infrastructure that supports civilization.

The website (<http://trussitn.eu>) has 135 pages of content with the top 8 countries with more visitors to the website being United States, United Kingdom, Ireland, Spain, India, France, Germany and Italy. TRUSS social media profiles include Facebook (<https://www.facebook.com/trussitn.eu>), Google+ (<https://plus.google.com/+TrussITN>), LinkedIn (<https://www.linkedin.com/in/trussitn>), Twitter (<https://twitter.com/TRUSSITN>), YouTube (<https://www.youtube.com/c/TrussITN>), Research Gate (https://www.researchgate.net/profile/Truss_Itn), and Blogger with TRUSS ESRs that have delivered 81 posts so far. The fact that the research topics impact directly on the day-to-day lives of people gives the research a relevance that captures the interest and inspire younger students with an interest in engineering. With this in mind, TRUSS has carried out outreach activities that include activities in Junior and High Schools, research exhibitions and Open Days at Universities. Therefore, TRUSS researchers have been featured in press releases in mainstream Italian and Spanish newspapers, in Italian and Irish magazines and on Irish television.

3. Training

Figure 3 illustrates the TRUSS training programme, which it is structured in two ways:

- Network-wide and local training activities, and
- Supervised research towards a doctoral award.

TRUSS holds network-wide meetings approximately every 6 months. During these meetings, ESRs have an opportunity to practise their communication skills, and to receive academic and industrial training and feedback. The network-wide training programme is extended by a range of advanced research methods, project management, language courses, transferable skills and communication modules available for the ESR at each host. Another significant form of training is on-the-job training, which ESRs have received from the local research group at their host, and at the institution/s where they are seconded.

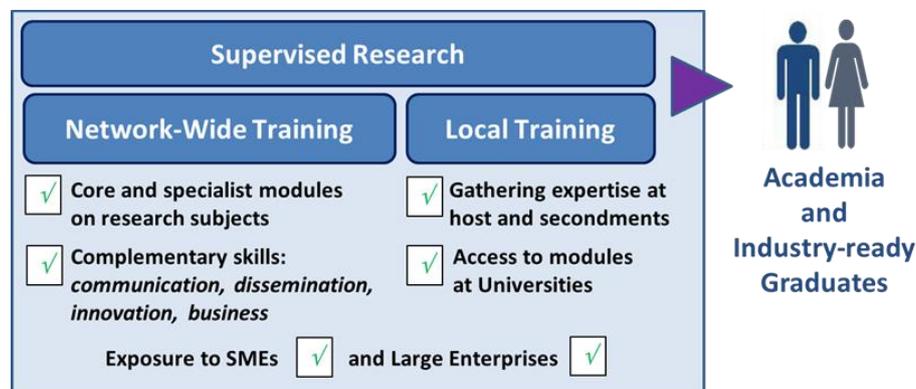


Figure 3. Structured training.

Each ESR is registered to a PhD programme in one of the academic beneficiaries. The primary support to help ESRs to conduct the high-level research necessary to achieve a PhD is their main supervisor and Doctoral Studies Panel (DSP) composed by consortium experts. In addition to the formal supervision structure, each ESR is required to maintain a Personal Career Development Plan (PCDP). Following presentations by the ESRs at the network-wide meetings, the consortium provides feedback and then, each ESR meets with his/her DSP in a focus group that discuss the PCDP and future plans of action. This structure plays a major part in informing the direction of the research and training and empowers ESRs to take ownership of their individual projects.

4. Research on buildings, energy and marine infrastructure

Table 1 lists the TRUSS projects falling within WP4, which is characterized by the very aggressive environments that the infrastructure is subjected to (corrosive, radioactive, non-linear structural responses) or relatively high uncertainties regarding materials and modelling.

Table 1. Individual research projects in WP4.

	Title	Host	Secondment
ESR1	Reliability of Concrete Structures Reinforced with Braided FRP	University College Dublin (Ireland)	Burgmann Packings (Ireland)
ESR2	Reduction of Uncertainty in Assessing Concrete Strength of Existing Structures	Arup (Ireland)	University College Dublin (Ireland)
ESR3	Reduction of Uncertainty in Design of Free Standing Nuclear Spent Fuel Rack	Equipos Nucleares, SA (Spain)	University College Dublin (Ireland)
ESR4	Probabilistic Optimization of the Design of Offshore Wind Turbine Towers	Trinity College Dublin (Ireland)	Lloyd's Register (UK)
ESR5	Integrity Management of Ship Structures	Lloyd's Register EMEA (UK)	University College Dublin (Ireland)
ESR6	Residual Life Assessment and Management of Ship Unloaders	Lloyd's Register EMEA (UK)	University College Dublin (Ireland)

4.1. Materials and buildings

Uncertainty in material strength is addressed via reliability models of concrete structures reinforced with Basalt Fiber Reinforced Polymer (BFRP) (ESR1) and assessment and testing of concrete strength of existing structures (ESR2).

4.1.1. Reliability of concrete structures reinforced with braided FRP. This project by Antonopoulou et al [3-5] aims to assess the reliability of structures manufactured using braided BFRP reinforcement. Basalt fibres and epoxy resin are used as reinforcement and matrix respectively (Figures 4, 5 and 6). Bars are manufactured using braiding and a vacuum assisted resin infusion technique. The work conducted so far can be summarised into the following tasks. The first includes the design and manufacture of braided BFRP preforms while changing key parameters (angle, no of layers). Ten different configurations in various diameters (5, 8, 10 mm) have been produced in Burgmann Packings Ltd. Then, the suitability of manufactured BFRP samples for epoxy resin impregnation in both regular and spiral configurations was explored in SuperTEX Austria, Burgmann Packings Ltd and UCD. Finally, a theoretical numerical approach based on the Classical Laminate Theory has been developed for the prediction of the elastic properties of braided BFRP rebars based on the influence of geometrical factors and processing conditions.



Figure 4. Braided preform.

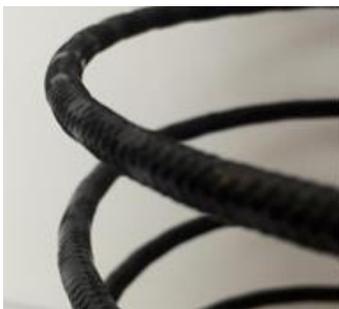


Figure 5. Resin impregnated braided BFRP.



Figure 6. BFRP sample.

4.1.2. Reduction of uncertainty in assessing concrete strength of existing structures. With the goal of reusing and extending the life of structures, assessment of concrete strength in existing structures is a must. Non-destructive tests (NDTs) allows quick collection of data at a limited cost for such assessment. As most NDTs indirectly measure concrete strength, they introduce uncertainty in the overall assessment. Existing NDTs are best suited in assessing the uniformity and quality of concrete in the structures. High variability in results have been observed following some preliminary studies using rebound hammer (Figure 7) and ultrasonic pulse velocity tests. Complete pullout failure during the pullout of post-installed concrete screw has potential to measure compressive strength of concrete as threads of screw installed in the drilled hole cut into concrete and exert bearing force on the surrounding concrete. Research into the application of post-installed screw for concrete strength assessment is being conducted and evaluated for practical application by Sourav et al [6,7].

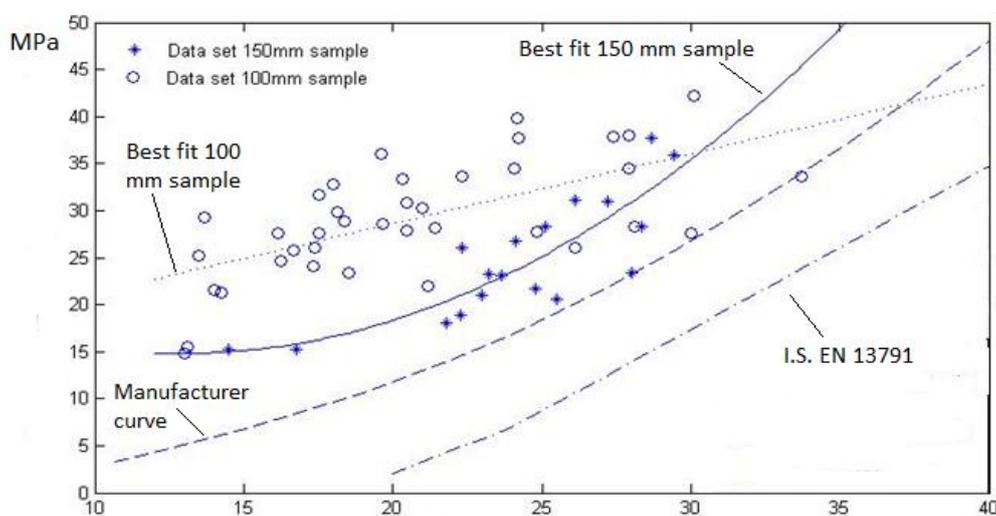


Figure 7. Compressive strength versus rebound number.

4.2. Energy infrastructure

Uncertainty in the design of energy infrastructure is addressed via different response models for a free standing nuclear spent fuel rack (ESR3) and probabilistic optimisation for wind turbine towers (ESR4).

4.2.1. Reduction of uncertainty in design of free standing nuclear spent fuel rack. Spent fuel racks rest in free-standing conditions submerged in water at 12 m depth (Figure 8). Their seismic response exhibits a highly geometrical nonlinear behaviour with dynamic contacts and large displacements influenced by the fluid-structure interaction. An ad-hoc methodology implements the added mass concept to represent the water effect in a cost-effective way. The transient analysis is therefore carried out in a Finite Element (FE) structural model (Figure 9) with direct integration of the equation of motion. However, some

dispersion of results still exists and several sources of uncertainty have been identified. Modelling issues have been introduced and a parametrical analysis of the stochastic input variables has been launched. Moreover, a 2-rack physical model has been designed to study the water coupling forces between units. As a result, a better understanding of the rack seismic behaviour is being gathered and current safety margins will be quantified more accurately. A direct application of the results can lead to increase the storage capacity of the existing fuel storage pools, which would bring an increase in the operation span of nuclear power plants without fuel reprocessing or dry cask storage. The dynamic analysis of other submerged sliding structures can also benefit from the research undertaken here by Gonzalez et al [8-10].

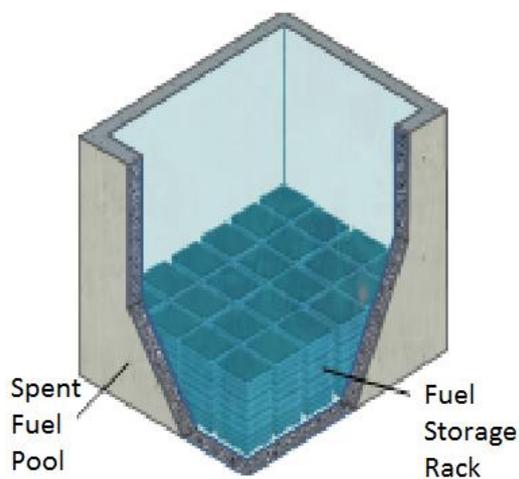


Figure 8. Fuel storage racks resting on the bottom of spent fuel pool

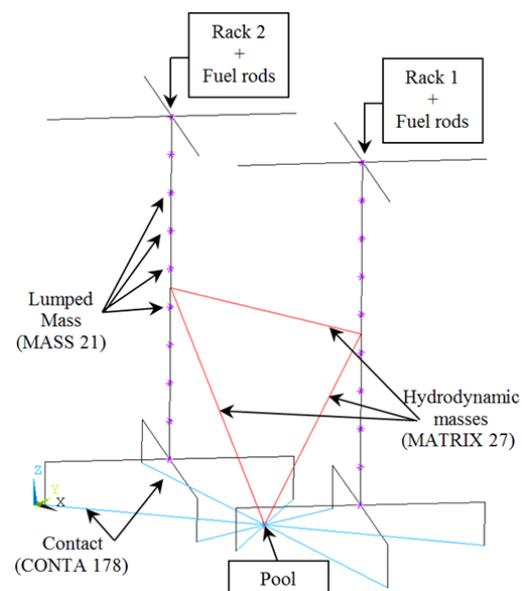


Figure 9. Finite element model of free standing rack.

4.2.2. Probabilistic optimization of the design of offshore wind turbine towers. In the particular case of Offshore Wind Turbines (OWT), despite a relatively new sector, the implemented practices still disregard the need of a fully comprehensive description of the system's behavior. In such a complex system, the space of variables to analyze grows fast, making the approach to create robust designs very resource intensive. Quantifying OWT long-term uncertainty on a practical basis has been therefore a major topic of research in the presented framework. It is of major importance in the field of OWT engineering to establish techniques to extrapolate extreme events and quantify their uncertainty. Substantial work has been developed in this topic and on how to accurately and efficiently quantify the long term uncertainty in both; the external loading variables (e.g., wave characterization) and on the OWT itself. Results show that new reliability approaches can efficiently approximate the long term occurrences based on short-term data, e.g., Figure 10. This project by Teixeira et al [11,12] connects research and its real application via the partnership with Lloyd's. A main line of research connected with improving the efficiency of the probabilistic design of offshore wind turbines using surface models, such as the Kriging models, is being exploited. These, known also as Gaussian process models, are of interest for the topic of reliability analysis due to their interpolation capacity, the flexibility to approximate arbitrary functions with a high level of accuracy and the capability of accounting for a local uncertainty measure. Currently, an integrated model of an offshore wind turbine with monopole foundation is being built and the model response being fitted to a Kriging surface.

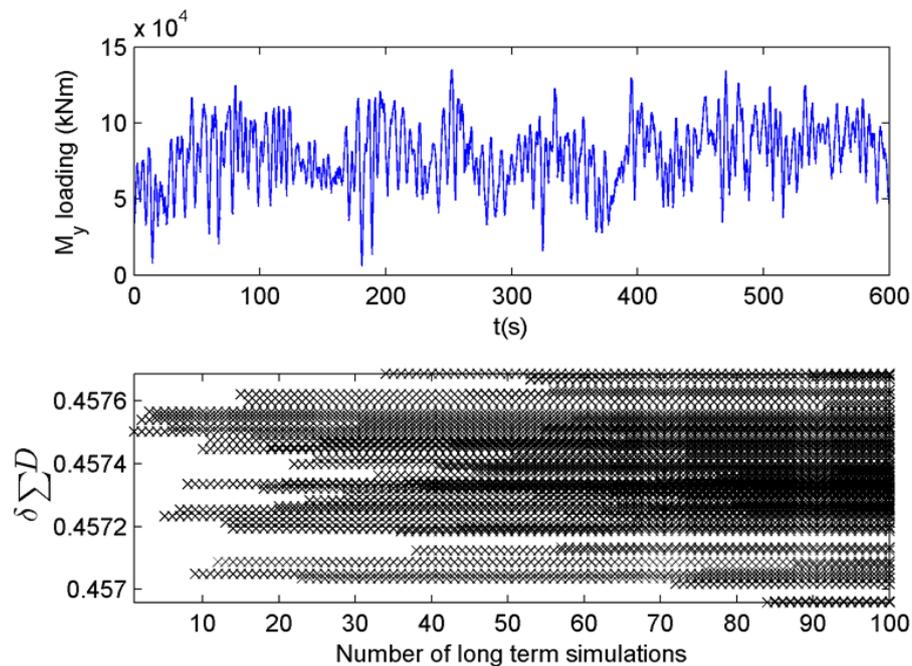


Figure 10. Example of statistical characterization from short-term system description to long term response.

4.3. Infrastructure in a marine environment

Uncertainty in the assessment and residual life of infrastructure in a marine environment is addressed via an integrity management based on long-term monitoring data for ageing marine structures (ESR5) and ship unloaders (ESR6).

4.3.1. Integrity management of ship structures. Numerical investigations have been carried out on: 1) fatigue reliability with S-N model and fracture mechanics (FM) model); 2) Crack initiation and reliability-based inspection planning; 3) Calibration of equivalent initial crack size (EIFS); 4) Calibration of time-to-crack-initiation (TTCI). This project by Guang et al [13,14] proposes to use a fracture mechanics based reliability analysis method that takes the crack initiation stage into account via the concept of TTCI. The optimum inspection plan for a fatigue prone ship structural component (i.e., Figure 11) is derived by the new approach and compared to the commonly-used method that only considers crack propagation life. Two inspection planning approaches are tested to investigate the influence of incorporating crack initiation period: (i) target reliability approach and, (ii) equidistant inspection times approach. With each planning approach, two inspection methods are adopted: close visual and magnetic particle inspection. Recommendations on the inspection method and planning approach to adopt are provided depending on the crack initiation stage (Figure 12) being considered or not. The following step is to develop a normalized calibration procedure of FM model to S-N curves, followed by research on probabilistic crack management and maintenance planning.

Primarily, this project will contribute to life-cycle fatigue management methods for ship and marine structures, and will lead to optimum decisions for the design, inspection and maintenance of structures in an integrated framework. Secondly, the project will facilitate the establishment of a crack database in marine engineering by providing the least data that need to be measured and stored, and showing how historical data can be utilized in decision-making for inspection and maintenance actions. Lastly, the project will bring awareness and facilitate the use of reliability methods to the marine community, by demonstrating their strong capacities in incorporating uncertainties associated with wave loads, material properties, structural geometries, analysis, inspection and maintenance methods.

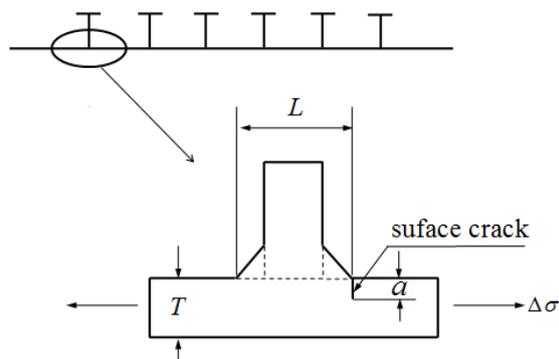


Figure 11. A fillet welded joint in a stiffened plate.

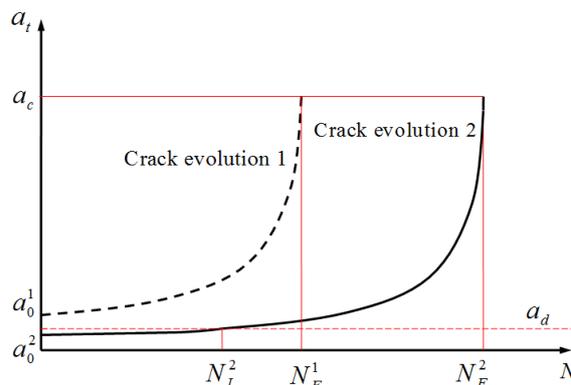


Figure 12. Schematic representations of crack evolution.

4.3.2. *Residual life assessment and management of ship unloaders.* This project by Milana et al [15-17] focuses on residual life assessment of ship unloader. Incidences related to a potential failure on these cranes or their parts can have catastrophic consequences in terms of both fatalities and economic impact. In addition, the deterioration process for ship unloaders is generally higher than for other infrastructures, since they are exposed to both an extremely aggressive environment and continuous alternating loadings. Following an initial phase of the state-of-art review, the standard procedure for fatigue life assessment in Figure 13 has been identified. New concepts and additional analyses, shown in red, represent some ideas formulated in order to reduce uncertainties arising from assumptions involved in the process. Data provided by a monitoring system have been processed and used to calibrate a FE model of the structure. Comparing results from the FE model to the recorded stresses, it has been noticed that the dynamic amplification factor currently used is very conservative for some locations. Therefore, location-specific DAFs has been introduced to improve the assessment of the structure while keeping calculations relatively simple. It is planned to investigate next the impact of end pins not free to rotate on fatigue life. As a result of this research, the residual life of an existing ship unloader will be assessed in a more reliable way with a significant impact on operational capacity and safety of ports.

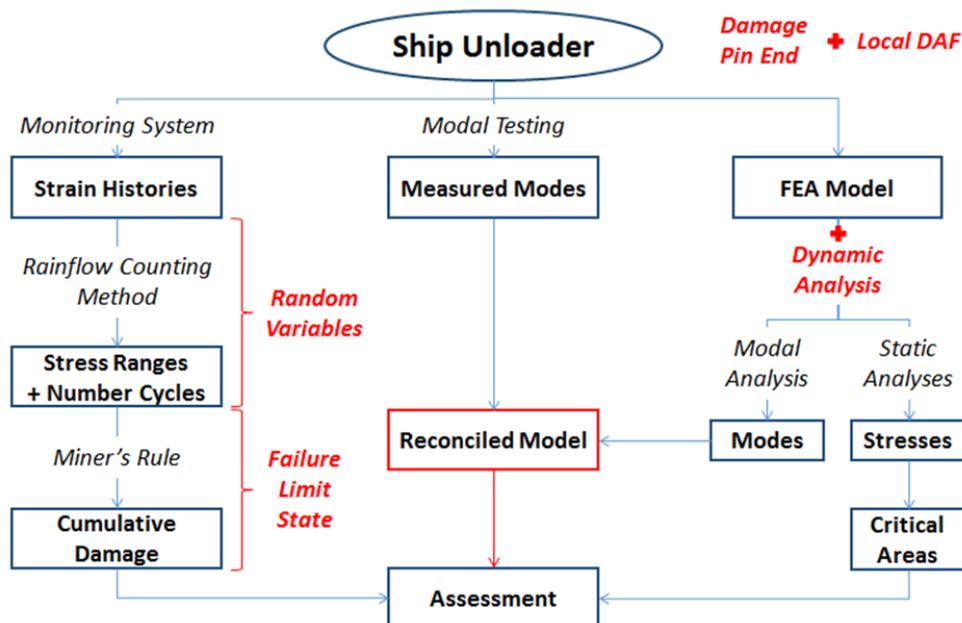


Figure 13. Procedure for fatigue life assessment.

5. Research on rail and road infrastructure

The infrastructures covered in WP5 are characterized by a variable traffic load, and they include individual research projects ESR7 to ESR14.

Table 2. Individual research projects in WP5.

Title	Host	Secondment
ESR7 Railway Bridge Safety and Condition Assessment	Full Scale Dynamics Ltd (UK)	University College Dublin (Ireland)
ESR8 Probabilistic Modelling of Bridge Damage based on Damage Indicators	Phimeca Engineering (France)	University College Dublin (Ireland)
ESR9 Railway Bridge Condition Monitoring and Fault Diagnostics	University of Nottingham (UK)	AECOM (UK)
ESR10 Assessment of Bridge Condition and Safety based on Measured Vibration Level	Universitat Politècnica de Catalunya (Spain)	COMSA (Spain)
ESR11 Development of Optical Fibre Distributed Sensing for SHM of Bridges and Large Scale Structures	Universitat Politècnica de Catalunya (Spain)	COTCA (Spain)
ESR12 Bridge Damage Detection Using an Instrumented Vehicle	University College Dublin (Ireland)	Greenwood Engineering (Denmark)
ESR13 Using Truck Sensors for Road Pavement Performance Investigation	University of Nottingham (UK)	Microlise (UK) TRL (UK)
ESR14 Reduction of Uncertainty through Regularized, Automated Road Inspection	University College Dublin (Ireland)	Arup (Ireland)

5.1. Bridges

Uncertainty in bridge safety is addressed a new damage detection algorithm based on rotations due to a moving load (ESR7), reliability analysis of damage indicators (ESR8), condition monitoring and fault detection methods (ESR9), assessment of the damage sensitivity of various vibration parameters to develop a condition index, with a vibration parameter range that could serve as safety limits (ESR10), testing of different adhesives for the deployment of fiber optic sensing (ESR11) and application of an instrumented vehicle for bridge monitoring purposes (ESR12).

5.1.1. Railway bridge safety and condition assessment. In this research by Huseynov et al [18,19], numerical and experimental analyses are carried out in an effort to develop damage detection methods for bridge structures using rotations as the main parameter. Initially, an algorithm is developed in MATLAB, that employs the Influence Line (IL) and Moment – Area theorems, to simulate a moving vehicle loading across the hypothetical 2-D bridge structure. Formulations involved enable to define different levels of damage severity in terms of change in stiffness. A 3 m long simply supported beam structure is built in the lab to test the proposed damage detection concepts (Figure 14). The beam structure is instrumented with 9 inclinometers (at equal distances) to record rotation while a point load is moved (statically) across the length of the structure several times. Later, the structure is strengthened and the foregoing damage detection concepts are applied to successfully identify the location and severity of change in stiffness across the length of the beam structure (Figure 15).

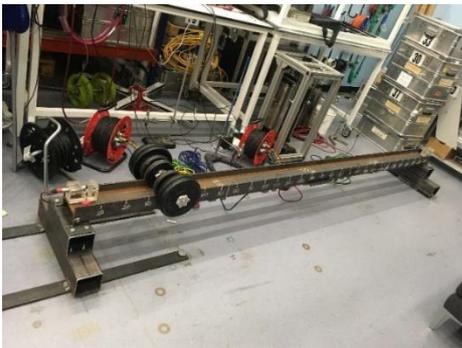


Figure 14. Lab test set-up.

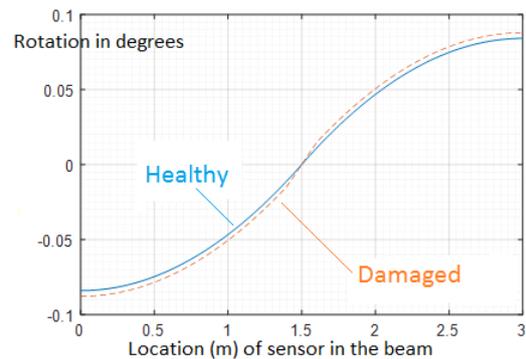


Figure 15. Rotation versus sensor location.

5.1.2. Probabilistic modelling of bridge damage based on damage indicators. This project by Heitner et al [20,21] is developing a bridge safety model in a probabilistic context. It involves Weigh-in-Motion data on the traffic load side, while it relies on results reported in the literature on the dead load and resistance sides. One of the main aims of the project is to improve this initial model using Bayesian updating and incorporating damage indicators (DIs). So far the focus has been on DIs based on deflection and rotation measurement data. It is important to note that most of the available sensors or health monitoring systems, which target to observe the actual performance of the entire structure, are able to provide information related to the stiffness of the bridge and therefore it has also been a crucial issue to find an appropriate way of connecting information of stiffness change to resistance change. Figure 16 reveals both the strong and obvious connection between the DI and the bar area loss; and the great amount of uncertainty related to the DI, which needs to be addressed appropriately.

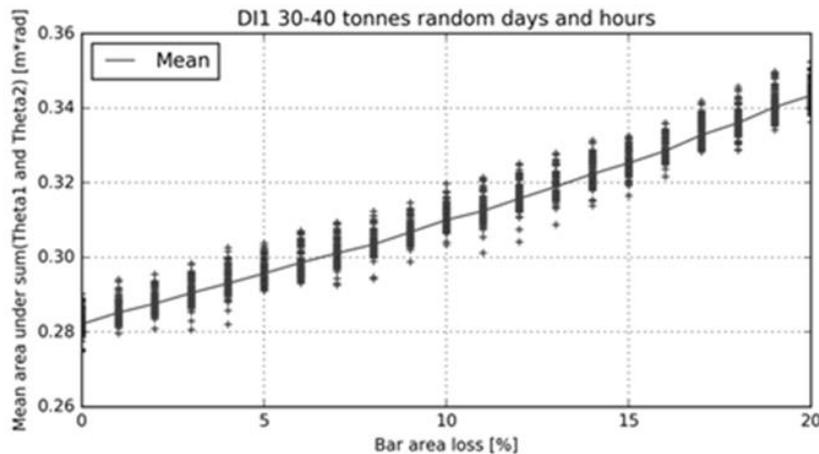


Figure 16. Relationship between reinforcing bar area loss (due to corrosion) and a DI based on rotation measurements for hourly random (30-40 tonnes) truck traffic flow in a 20 metres long simply supported reinforced concrete slab bridge.

5.1.3. Railway Bridge Condition Monitoring and Fault Diagnostics. Railway bridges are key elements for the reliability, availability and safety of the whole railway network, as they are pushed to their physical limits due to continuously changing environmental conditions, such as increasing of traffic and climate change that produces extreme events. In order to maximise the reliability, availability and safety of the railway network, bridge condition-monitoring strategies can help the railway industry by providing rapid and reliable information on the health state of each bridge. With this aim, a Bayesian Belief Network (BBN) method is developed by Vagnoli et al [22] in order to monitor in real-time the health state of a steel truss railway bridge. A FE model is perturbed by simulating the degradation mechanisms of the bridge elements, and the data collected from these simulations is used to as input of the BBN. As soon as a new measurements of the bridge behaviour are available, the BBN is able to assess in real-time the health state of the steel truss bridge and to identify the most degraded element of the bridge (Figure 17). This research will allow bridge managers to know the health condition of the

bridge in real time and, consequently, the maintenance schedule will be optimized leading to efficient usage of the available budget.

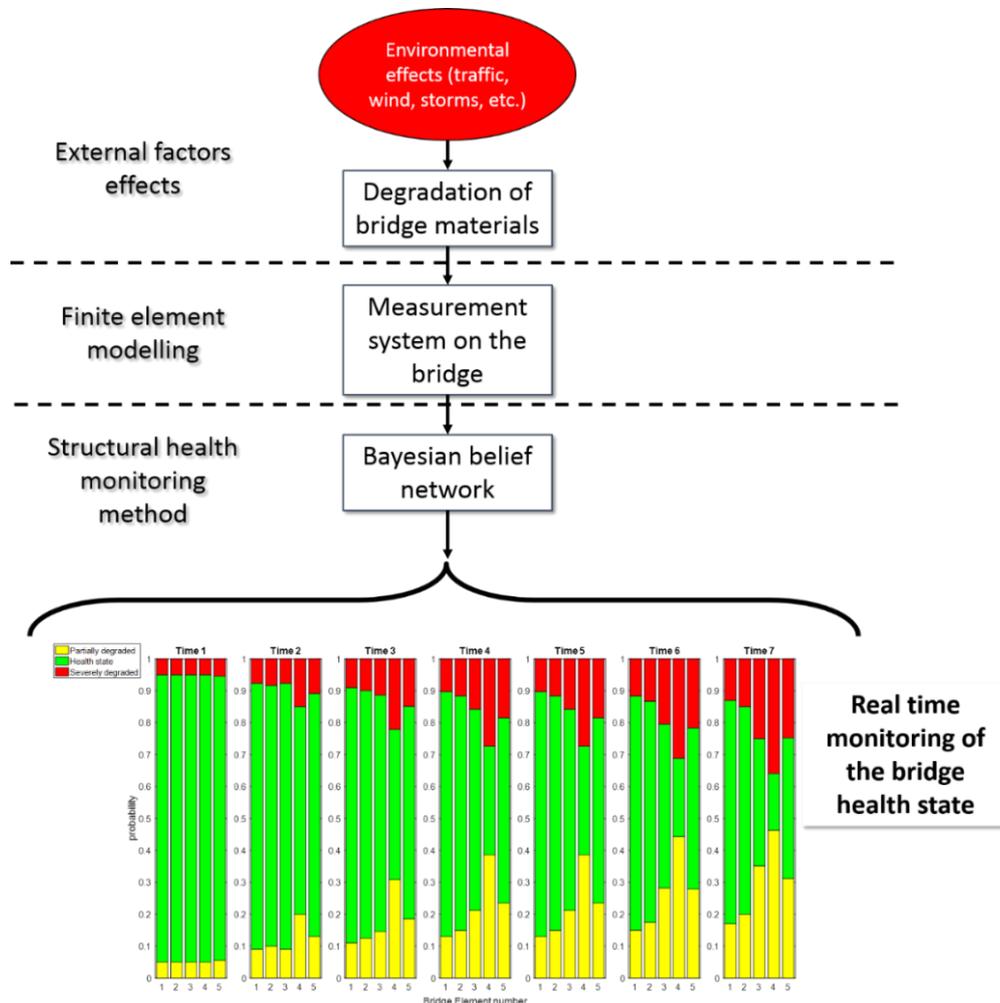


Figure 17. Bayesian Belief Network for structural health monitoring.

5.1.4. Assessment of bridge condition and safety based on measured vibration level. The primary technical achievements of the project by Moughty et al [23-26] thus far centre about the damage sensitivity assessment of numerous vibration parameters. This work was completed on data obtained from two real bridges in Austria and Japan, which were intentionally damaged incrementally and subjected to different loading regimes: ambient vibration and truck passage over the bridge, respectively. Results from this phase shall advance the shared knowledge regarding the performance of some of the more under-utilised damage features in the world of bridge SHM. Figure 18 demonstrates the degree of damage sensitivity and resolution that can be achieved using one such vibration parameter (vibration intensity). Additional technical achievements have been accomplished regarding the mitigation of uncertainty surrounding sources of ambient vibration, while present focus now surrounds the currently trending problem of accurately analysing non-linear, non-stationary vibration signals recorded from damaged bridges. This research has the potential to develop an empirical relationship between vibration level and bridge condition for various bridge types, resulting in a reduction of safety uncertainty. If successful, the standard protocol of bridge inspection may be changed from the compulsory 2 year period to a condition-based inspection philosophy for sufficiently instrumented bridges. This would improve bridge inspection efficiency and accuracy, while also drawing closer attention to bridges that present signs of deterioration. The knock-on socio-economic impact of this would be that bridge owners

could save money through increased efficiencies and fewer bridges would deteriorate unnoticed. This could prevent possible collapses / closures resulting in lost revenues to communities and reduced access to important services.

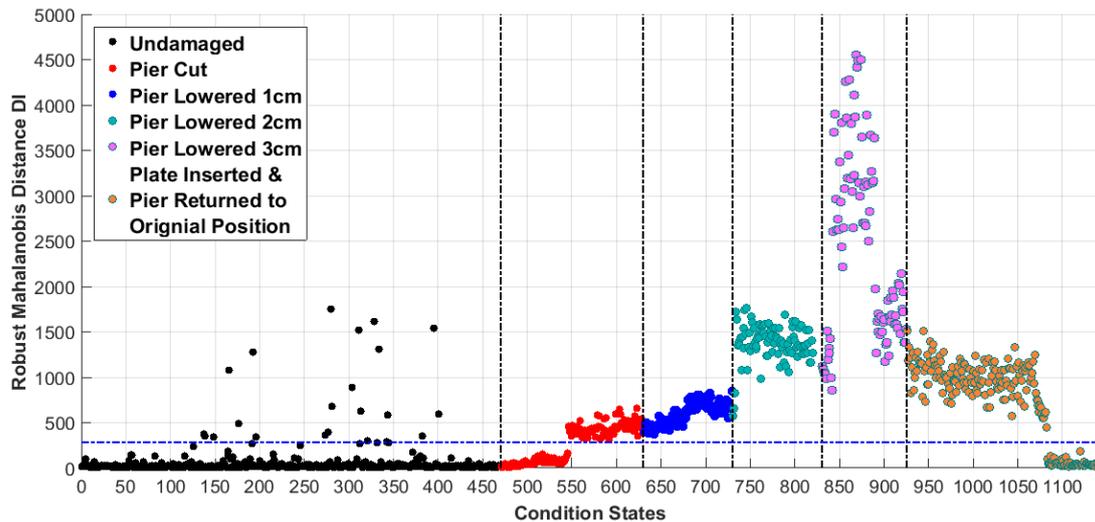


Figure 18. Robust Mahalanobis distance versus condition state.

5.1.5. Development of optical fibre distributed sensing for SHM of bridges and large scale structures.

This project by Barrias et al [27-31] investigates the applicability of distributed optical fiber sensing (DOFS) on the monitoring of concrete structures. The main and predetermined goals of this study are the analysis of the possible spatial resolution, strain accuracy and long-term reliability of the measurements performed with this technology. In this way, a thorough and comprehensive literature review was conducted where the theoretical background of this technology and applications already conducted on civil engineering structures were analysed. As part of the secondment at COTCA S.A., it was possible to participate in experiments conducted at the moment, including an active monitoring procedure of a real-world structure (Sarajevo Bridge at Barcelona) where DOFS are being used (Figure 19). Important takeaways are taken from this experience by witnessing in first-hand the main challenges associated with the use of this technology out of controlled environments. Finally, the first laboratory experiments with innovative implementations of this technology (i.e., regarding bonding adhesives and techniques of attachment) to reinforced concrete elements have been started and their results are currently being assessed (Figure 20). This research will have an important and favourable socio-economic impact since it will bring additional and more accurate information for bridge and large-structures owners and in this way enable better structural health monitoring systems to prevent possible collapses and closures resulting on important savings for the users.



Figure 19. Structural health monitoring using DOFS.

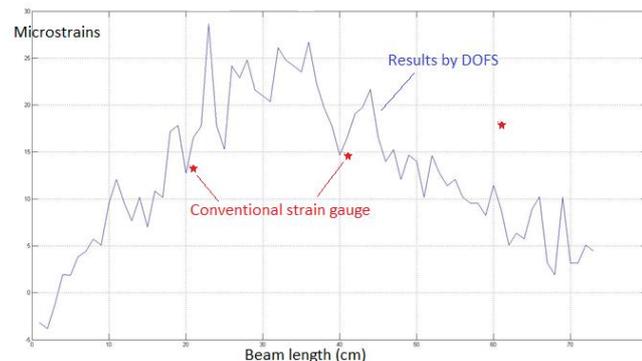


Figure 20. Strain across the beam length using DOFS in a lab test.

5.1.6. Bridge damage detection using an instrumented vehicle. Figure 21 shows the Traffic Speed Deflectometer (TSD). The TSD is a vehicle designed for pavement engineering, where vertical deflection can be calculated through the measured data from the trailer with high levels of resolution. The characteristics of the TSD have the potential to be employed as a damage detection tool for bridges. The curvature of the bridge is traditionally considered to be a highly sensitive damage indicator. Considering that the response of the vehicle-bridge system is time dependent, two types of curvature can be defined using TSD measurements: (1) Instantaneous Curvature (IC) when curvature is calculated at an instant in time using three different positions damage is detected and located from the relationship between curvature and stiffness; (2) Moving Reference Curvature (MRC) is a curvature calculated at different time instants and the information that can be extracted from the damage is limited. Damage can be quantified but not located with MRC. Figure 22 shows variation of IC curvature with the position of the vehicle using simulations for the case of a bridge with two damaged zones. A quick increase in curvature is noticeable at the damaged portions of the bridge. Although MRC is not able to locate and quantify damage to the same extent than IC, it appears to be less sensitive to noisy scenarios. First results using numerical simulations are promising, although the method still needs to be validated on the field. This research by Martinez et al [32-37] has a lot of potential for efficiently monitoring short span bridges which constitute the largest proportion of the bridge stock and where the cost of instrumenting many bridges may result prohibitive.



Figure 21. Traffic Speed Deflectometer.

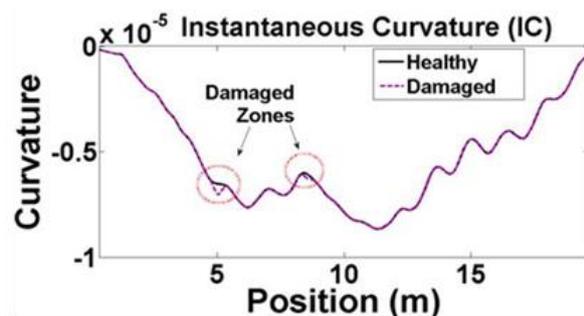


Figure 22. Impact of damaged on curvature.

5.2. Road infrastructure

Uncertainty in pavement safety is addressed via the use of production vehicle sensors (i.e., available engine performances data) for road pavement performance investigation (ESR13) and Unmanned Aerial Vehicles (UAVs) for data collection, using reconstructed 3D data with new algorithms for image-based point cloud damage detection (ESR14).

5.2.1. Using truck sensors for road pavement performance investigation. In a first phase, this project by Perrotta et al [38] focused on the definition of a general methodology for to assess the impact of road surface conditions on truck fleet fuel economy. Using this approach, real time data can be used and any generated model can be progressively updated with time, following improvements in vehicle and road technology. First results show that approximately 3 and 5% of the whole fuel consumption can be, respectively, a result of the evenness and macrotexture of the road. This shows that road maintenance policies can have a very significant impact of fuel costs and greenhouse gas emissions. In a second phase, a validation of the obtained results, extending this approach to a wider range of vehicle and road types, will improve confidence in including the pavement-vehicle interaction component into road pavement Life Cycle Assessment (LCA) studies increasing the applicability of the results. Figure 23 shows predicted fuel consumption versus real measurements referred to articulated trucks with 6 axles in total and Euro 6 engine – 1290cc. The result of these investigations will lead to the definition of more accurate models for the LCA of pavements.

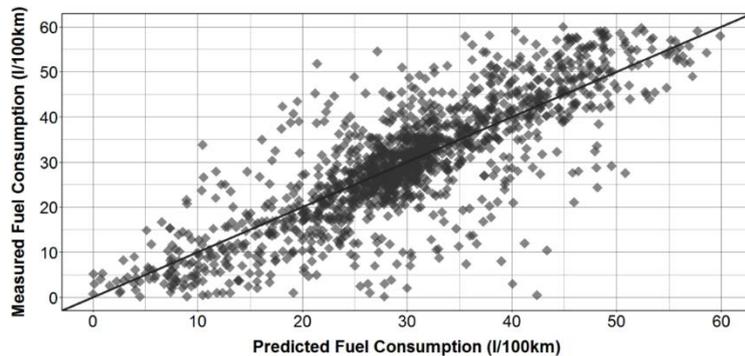


Figure 23. Linear regression: predicted fuel consumption vs real measurements.

5.2.2. Reduction of uncertainty through regularized, automated road inspection. The achievements of this project by Chen et al [39,40] are reflected in several areas. The first represents a state-of-the-art review of the numerous UAVs currently available through commercial and research efforts. Based on this work, a UAV platform customized for inspection data acquisition was developed. This platform is capable of capturing high-quality images and real-time videos for offline and online analysis. Next, the workflow of most popular images-based 3D reconstruction platforms, such as the VisualSFM (open source), PhotoScan (commercial) and Pix4D (commercial), was investigated. These were applied to a wide range of highly varied data sets of buildings, roads and bridges (Figure 24) to test their usefulness, robustness, and scalability. Their respective advantages and disadvantages were compared, from which a data processing strategy was developed. Finally, a framework was developed to determine the accuracy of various 3D reconstruction efforts, which was then used to optimize data efforts. As part of this, a laboratory experiment was devised to explore the interaction of camera angles and shooting distance with respect to the final accuracy level achieved. The current work is now mainly focused on damage detection. This project contributes to develop a safer, cheaper and more efficient way for road infrastructure inspections using UAV technology.



Figure 24. The Boyne bridge reconstruction.

6. Conclusions

This paper has provided a summary of the progress and expected impact of each individual project in TRUSS. The individual projects in TRUSS are quite diverse, focusing on a wide array of application structures. Nonetheless, the need to overcome uncertainty in material, load and structural performance represents a core thread that ties the projects together. This has led to interactions between researchers, and to generate innovations that forms the basis of their PhD research. The objectives of reducing uncertainty and improving infrastructure management are achieved via the development of new material/sensor/monitoring technologies (ESR1, ESR2, ESR11, ESR12, ESR13, ESR14) that allow more efficient data collection, and new algorithms (ESR3, ESR4, ESR5, ESR6, ESR7, ESR8, ESR9, ESR10) that process the data collected from the structure to estimate its safety more accurately than current approaches.

With the help of innovative health monitoring, damage detection, structural simulations and tests, use of new materials and probabilistic assessments altogether, TRUSS will have an impact on: (a) economic activities, by avoiding unnecessary repair works and optimising structures in terms of their entire life-cycle; (b) sustainability, by reducing the waste materials during construction and rehabilitation works and by utilizing innovative and environment-friendly inspection, maintenance and rehabilitation methodologies; and (c) social terms by avoiding unnecessary repairs or replacements, that can affect the public in a variety of forms, i.e., road closures in the case of bridge repairs or failure that will lead to longer travel times and will increase costs in many economic sectors. TRUSS outputs provide tools that will ensure a more durable infrastructure capable of successfully supporting society needs and expectations over the next decades.

7. References

- [1] European Commission 2014 *Horizon 2020 Work Programme 2014-2015 Marie Skłodowska-Curie Actions* European Commission Decision C (2014) 4995 of 22 July 2014
- [2] European Commission 2014 *State of the Innovation Union, Taking stock 2010-2014* Commission Staff Working Document Accompanying the Document “Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions” Research and innovation as sources of renewed growth COM(2014) 339
- [3] Antonopoulou S, McNally C and Byrne G 2016 Developing braided FRP reinforcement for concrete structures *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [4] Antonopoulou S, McNally C and Byrne G 2016 Development of braided basalt FRP rebars for reinforcement of concrete structures *Proc. of 8th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2016)* (Hong Kong, China, December 14-16)
- [5] Antonopoulou S and McNally C 2017 Reliability assessment of braided BFRP reinforcement for concrete structures *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [6] Sourav SNA, Al-Sabah S and McNally C 2016 Strength assessment of in-situ concrete for the evaluation of structural capacity: State of the art *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [7] Sourav SNA, Al-Sabah S and McNally C 2017 Post-installed concrete screws for in-situ assessment of concrete strength *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [8] Gonzalez Merino A, Costas L and Gonzalez A 2016 Uncertainties in seismic design of free-standing HDSFS racks *Proc. of the ninth International Youth Nuclear Congress (IYNC2016)* (Hangzhou, China, July 24-30)
- [9] Gonzalez Merino A, Costas L and Gonzalez A 2016 Dynamic analysis of the nonlinear response of high density fuel storage racks, *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [10] Gonzalez Merino A, Costas L and Gonzalez A 2017 Sensitivity analysis of a finite element model for the seismic analysis of free-standing spent fuel racks *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [11] Teixeira R, O'Connor AJ and Nogal M 2016 Comparative analysis of the probabilistic methods to estimate the probability of failure of offshore wind turbine towers *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [12] Teixeira R, O'Connor AJ, Nogal M, Nichols J and Spring M 2017 Structural probabilistic assessment of Offshore Wind Turbine operation based on Kriging response interpolation, *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [13] Zou G, Banisoleiman K and Gonzalez A 2016 Methodologies for Crack Initiation in Welded

- Joints Applied to Inspection Planning *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering* **10(11)** 1406-1413
- [14] Zou G, Banisoleiman K and Gonzalez A 2017 Reliability-based inspection planning in view of both crack initiation and propagation *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [15] Milana G, Banisoleiman, K and Gonzalez A 2016 Fatigue life assessment methods: the case of ship unloaders *Proc. of the 1st International Conference on Natural Hazards & Infrastructure (ICONHIC2016)* (Chania, Crete Island, Greece, June 28-30)
- [16] Milana G, Banisoleiman K and Gonzalez A 2016 Sources of structural failure in ship unloaders *Proc. of the European Safety and Reliability Conference (ESREL2016)* (Glasgow, UK, September 25-29)
- [17] Milana G, Banisoleiman K and Gonzalez A 2017 Field characterization of location-specific dynamic amplification factors towards fatigue calculations in ship unloaders *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [18] Huseynov F, Brownjohn JMW, O'Brien EJ and Hester D 2016 Analysis of load test on composite I-girder bridge *Proc. of the CSHM-6: Structural health monitoring of new and ageing infrastructure* (Queens University, Belfast, Northern Ireland, United Kingdom, May 26-27)
- [19] Xu Y, Huseynov F, Brownjohn JMW, O'Brien EJ and Hester D 2017 Tracking deflection in the field using optical system: a case study *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [20] Heitner B, OBrien E, Schoefs F, Yalamas T, Decatoire R and Leahy C 2016 Probabilistic modelling of bridge safety based on damage indicators *Procedia Engineering* **156** 140-147
- [21] Heitner B, OBrien E, Schoefs F, Decatoire R, Yalamas T and Leahy C 2016 Evaluation of bridge safety based on Weigh-in-Motion data *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [22] Vagnoli M, Remenyte-Priscott R and Andrews J 2017 A fuzzy-based Bayesian Belief Network approach for railway bridge condition monitoring and fault detection *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [23] Moughty JJ and Casas JR 2016 Vibration based damage detection techniques for small to medium span bridges: A review and case study *Proc. of the 8th European Workshop on Structural Health Monitoring (EWSHM 2016)* (Bilbao, Spain, July 5-8)
- [24] Moughty JJ and Casas JR 2016 Advancements of vibration based damage detection techniques for small to medium span bridges *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [25] Moughty JJ, Casas JR and Rodrigues F 2016 Assessment of vibration intensity as a condition and safety indicator for short-span bridges *Proc. of the Fifth International Symposium on Life-Cycle Civil Engineering (IALCCE 2016)* (Delft, The Netherlands, October 16-19)
- [26] Casas JR and Moughty JJ 2017 Bridge damage detection based on vibration data: past and new developments *Frontiers in the Built Environment* DOI: 10.3389/fbuil.2017.00004
- [27] Rodríguez G, Casas JR Villalba S and Barrias A 2016 Monitoring of shear cracking in partially prestressed concrete beams by distributed optical fiber sensors *Proc. of the 8th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2016)* (Foz do Iguaçu, Brazil, June 26-30)
- [28] Barrias A, Casas JR and Villalba 2016 A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications *Sensors* **16(5)** 748
- [29] Barrias A, Casas JR and Villalba S 2016 Review of civil engineering applications with distributed optical fiber sensors *Proc. of the 8th European Workshop on Structural Health Monitoring (EWSHM 2016)* (Bilbao, Spain, July 5-8)
- [30] Barrias A, Casas JR, Villalba S and Rodriguez G 2016 Health monitoring of real structures by distributed optical fiber *Proc. of the Fifth International Symposium on Life-Cycle Civil Engineering, IALCCE 2016* (Delft, The Netherlands, October 16-19)

- [31] Barrias A, Casas JR, Villalba S and Rodriguez G 2017 UPC - BarcelonaTech experience on the use of Rayleigh based distributed optical fiber sensors for SHM of concrete structures *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [32] Sevillano E, OBrien EJ and Martinez D 2016 Instantaneous curvature in bridge damage detection, *Proc. of the CSHM-6: Structural health monitoring of new and ageing infrastructure* (Queens University, Belfast, Northern Ireland, United Kingdom, May 26-27)
- [33] OBrien EJ, Sevillano E and Martinez D 2016 Monitoring the condition of a bridge using a traffic speed deflectometer vehicle travelling at highway speed *Proc. of the 3rd International Balkans Conference on Challenges of Civil Engineering* (Tirane, Albania, May 19-21)
- [34] Martinez D, OBrien EJ and Sevillano E 2016 Drive-by bridge damage detection using curvatures in uncertain environments *Proc. of Civil Engineering Research in Ireland Conference (CERI 2016)* (Galway, Ireland, August 29-30)
- [35] Martinez D, OBrien EJ and Sevillano E 2016 Damage Detection by Drive-by Monitoring Using the Vertical Displacements of the Bridge *Proc. Structural Engineering, Mechanics and Computation (SEMC 2016)* (Cape Town, South Africa, September 5-7)
- [36] Malekjafarian A, Martinez D and OBrien EJ 2017 Pavement Condition Measurement at High Velocity using a TSD *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [37] OBrien EJ, Martinez D and Malekjafarian A 2017 A New Damage Indicator for Drive-by Monitoring using Instantaneous Curvature *Proc. AustRoads Bridge Conference ABC2017* (Melbourne, Australia, April 3-6)
- [38] Perrotta F, Parry T and Neves L 2017 Using truck sensors for road pavement performance investigation *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)
- [39] Chen S, Laefer DF and Mangina E 2016 State of Technology Review of Civilian UAVs *Recent Patents on Engineering* **10(3)** 160-174
- [40] Chen S, Laefer DF, Byrne J and Natanzi AS 2017 Angle affect on image-based 3D reconstruction for brick structure *Proc. European Safety and Reliability ESREL2017* (Portorož, Slovenia, June 18-22)

Acknowledgments



The TRUSS ITN project (<http://trussitn.eu>) has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 642453.