CORTIR PHASE 2 – Cost, Risk and Transition Zone Innovative Reinforcement

Project description

Introduction

In this project, initially, the Bladena's Cost and Risk tool (CAR Tool) will continue been developed becoming gradually into a more holistic tool and providing for the first-time feedback to other sections of the project in relation to risk in maintenance strategies. The tool, apart from dealing with transverse cracks as the main structural damage, will also incorporate leading edge erosion, lightning, and especially, shear-web disbonding as a new failure mode to analyze.

The project will relate this failure mode of shear web disbonding to a new retrofit solution, here referred to as the Reinforcement-Transition-Zone Solution (RTZ Solution). This retrofit solution is presented in the section "Theme B: Shear web disbonding and new innovative retrofit solution" and is also supported by the CAR Tool, which will analyze the business cases and the Return-of-Investment (ROI) for the new innovative retrofit RTZ Solution. Other alternatives to approach the shear web disbond failure mode will also be studied, evaluated, and compared to the RTZ Solution.

In the cost and risk studies of maintenance options, different monitoring methods and techniques for early detection of critical failure modes will be considered, including a damage tolerance approach (see description in Theme C below). Furthermore, new innovative inspection strategies will be developed and demonstrated in the field and presented in guidelines which can be used by Wind Turbine Owners (WTOs), Independent Service Providers (ISPs), and Original Equipment Manufacturers (OEMs) working with blade repair in the field.

Therefore, the project is divided into three Themes, which are illustrated in Figure 1:

Theme A: The implementation of the Cost and Risk Tool for business analysis to assist the WTOs in their O&M decision making.

Theme B: Research focused on the shear web disbond failure mode, including field measurements, large-scale sub-structural and smaller-scale sub-component testing, cohesive fracture analysis, as well as the development of the new retrofit RTZ-Solution.

Theme C: Creation of New Innovative Field Inspection Strategy (NIFIS) including the demonstration of new monitoring techniques.

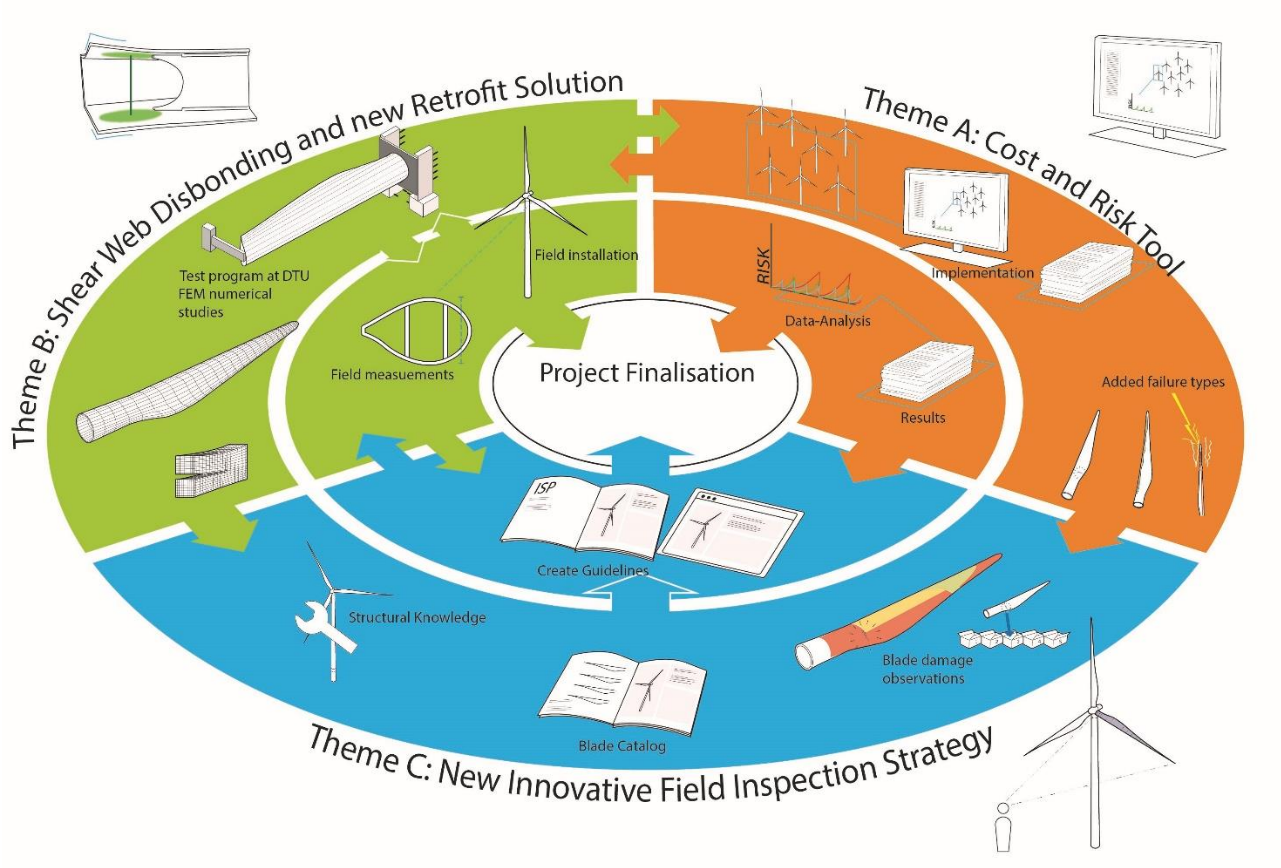

Figure 1: Project overview and interconnection between the three themes. The outer ring is the first part of the project and the inner ring is the second part with project finalization in the middle. With green is Theme A. The CAR Tool will be implemented and used to analyze maintenance strategies from the project start, where also added capabilities, such as more failure modes and advanced loading will be implemented in the tool. In the second part of the project, the CAR Tool will provide valuable data to NIFIS about the cost and risk of applying different maintenance strategies. Theme B has got the color green. This is the development of the RTZ Solution. The test and demonstration activities start in the lab and later moves out in the field. Lastly with blue is Theme C. This is the development of NIFIS, which is supported by the other two themes.

The figure above illustrates the interconnection between the three Themes, representing how the project will evolve. A brief summary is added below:

Starting with Theme B, a set of field measurements in the root-transition zone will be obtained. Together with a validated global Finite Element Model (FEM), the boundary conditions for a set of large-scale sub-structural blade section tests will be obtained. Combined with cohesive fracture mechanics analysis and smaller-scale sub-component and material characterization testing, the expected result from these efforts will be a Crack Propagation Rate (CPR) function for the shear web disbonding failure mode, with corresponding uncertainties. This knowledge and data will be transferred to Theme A, adding shear web disbonding to the CAR Tool.

In parallel with the definition of CPR functions developed in Theme B, a damage tolerance approach will be validated in Theme C. Here, a group of monitoring techniques and inspection methods will be studied and knowledge will be gathered about their functionalities and for which specific damages they prove most useful, especially with regards tor shear web disbonding. Theme C, apart from providing feedback to Theme B, will also provide input to the CAR Tool concerning inspection methods, specifically about Probability of Detection (POD) curves.

Going back to Theme B, the mentioned Finite Element Models will be part of a number of numerical studies which will both provide information about boundaries and loads for the large-scale blade section test setup, as well as assist in the final development of a new retrofit RTZ Solution for the shear web disbonding failure mode. Furthermore, the RTZ Solution will be studied from a risk perspective using the CAR Tool.

Once the CAR Tool has inherited the developed technology from Themes B and C, and leading edge erosion and lightning has been added to the its functionalities, the CAR Tool has been developed into a more holistic tool. The CAR Tool will be used to assess new maintenance strategies in terms of risk and cost, and this will be documented in a set of inspection guidelines, which will be part of NIFIS developed in Theme C.

Theme A: Cost and Risk Tool

Initially, the focus was to make a Minimum Viable Product (MVP) of the CAR Tool to demonstrate that it was possible to create a software tool which could support the WTOs in their maintenance strategy decision making. Despite the limitations in a MVP, the tool managed to achieve, within its limited field of application, the main goal of assessing selected maintenance strategies by providing an estimation of the expected cost of each O&M lifetime strategy. The total expected cost was expressed as risk, and it was presented together with an economical study which analysed the viability of the project by adding Net Present Value (NPV), payback time, Internal Rate of Return (IRR), as well as other statistical parameters which helped the users to better understand the consequences of their strategy.

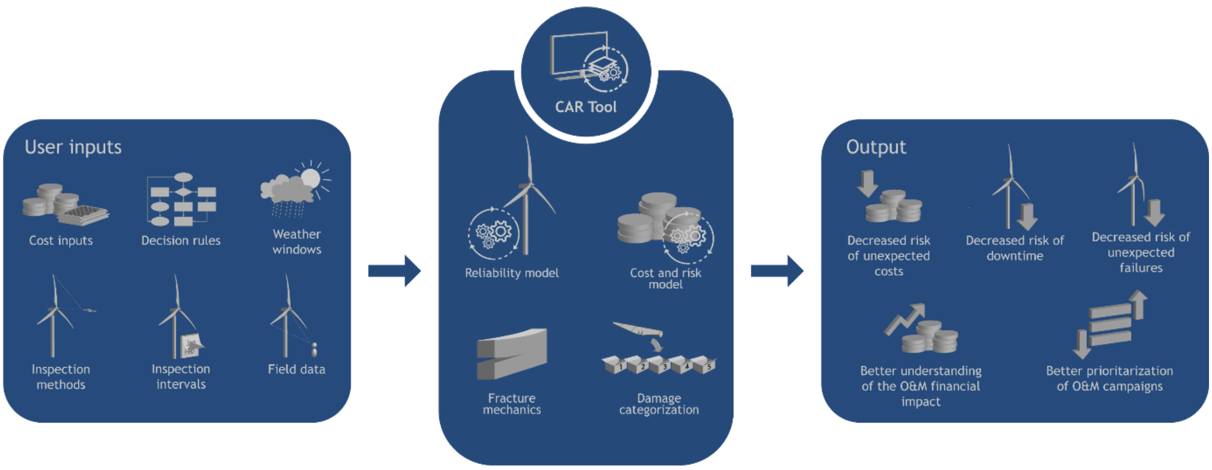

Figure 2. General scheme of the CAR Tool. On the left, the users introduce a set of variables creating a maintenance strategy that is analyzed by the CAR Tool solver (center), which calculates the risk and other economical parameters helping in the decision making for a WTO.

Due to the increased size of wind turbines and the amount of offshore sites, WTOs dedicate more and more time and resources to plan and optimize their maintenance strategies. With an outset in this reality, the CAR Tool will the second phase of the project focus on identifying the main sources of expenses in each strategy, obtaining at the same time an optimized solution. This implies that all the parameters which influence on the WTO decision making, will be analysed in more depth with the objective of identifying the optimal combination of the parameters. Information regarding KPI (Key Performance Indicators) is also part of the analysis that will be performed in the project.

In addition, today, WTOs are often planning their inspection campaign, taking leading edge erosion and lightning into consideration, and the common practice is to use drones or on-ground cameras. For larger blades, structural damages have become more frequent and additional **inspection methods** are being applied. Most of the damages cannot be observed from the outer surface of the blade and internal inspections are required; in some cases also utilizing NDT techniques. Each inspection method has its own particularities, and WTOs has increased awareness on the importance of this topic. Because of this, the CAR Tool will also focus on identifying an optimal strategy which considers the inspection method, taking into account the duration of inspections for the calculation of the total inspection cost, and the probability that an inspection is successful.

This project is intended to do further research into the influence of inspection methods, as well as into the human/organizational aspects regarding these inspections.

These human factors in relation to inspections including NDT refer to the influence on the inspection reliability (POD curve), due to aspects such as organization, environment, access, communication, training and clarity in procedures. Human factors are considered important in other industries (aviation, offshore, …) modelling the reliability of inspections and NDT by POD curves. The aim will be to review knowledge from these other industries and develop a procedure / recommendation for how to account for the human factor in inspections and NDT of wind turbine blades.

With regard to inspections, when the damages are found the categorisation is very often based on the size of the damage, but not the position on the blade. The **position of the damage is** very important to consider. If the position is in a secondary non-load-carrying structure, it is less critical than if the damage is located in the primary load carrying structure.

With structural knowledge test facilities, theory on risk assessment and numerical analysis tools, brought into the project by Bladena, DTU and AAU, a more updated damage categorisation scheme can be realized for all damage types included in the CAR Tool. The cost and risk of maintenance strategies will be analysed by using the CAR Tool, seen in a holistic perspective including now erosion and lightning issues as well. Also, loading considerations will be improved to achieve more realistic results. Turbulence and individual oscillations of flapwise and edgewise loads will also be taken into account in this project.

The inclusion of a larger range of damages represents the next step to further improve the CAR Tool, including the addition of the new failure mode, shear web disbonding, which will be studied in the current project. Shear web disbonding is one of the most critical failure modes the market is identifying in large newer blades . The following sections explain the steps to follow in order to achieve the inclusion of this new failure mode.

Theme B: Shear web disbonding and new innovative retrofit solution

The main failure mode investigated in th current project focusses on shear web disbonding from the load carrying spar caps. The investigations are realized using state-of-the-art and innovative sub-component test techniques on different length-scales and with different levels of loading complexity, utilizing the advanced structural testing facilities in DTU Structural Lab. Furthermore, advanced fracture analysis methods will be demonstrated to determine the accuracy of these methods compared against test results, and to predict the damage tolerance and residual lifetime of shear web bondlines in terms of closed-form CPR functions to be utilized in CAR Tool through reliability and risk analysis.

The work will include conducting fracture mechanics characterization testing of cohesive bondline interfaces, including fatigue testing, in order to determine the fracture mechanical properties for the bondlines under investigation. The fracture mechanics analysis and testing will be demonstrated as a matured analysis and assessment tool. Procedures for applying fracture mechanics will be implemented from earlier obtained knowledge, where the sandwich face/core debond failure mode was investigated.

When sub-component tests are performed today, they are performed using *perfect* lab specimens. However, in this project the difference in testing *perfect* specimens versus more representative (manufactured blade cut-outs) specimens will be investigated, demonstrating the influence of typical manufacturing imperfections in current blade production. The test scheme will aim to demonstrate and validate the Building Block method, see Figure 3, with a focus on disbonding of shear web components in current large blade designs. The output from this work will be CPR functions to be implemented in the CAR Tool. The uncertainties of the CPR functions will also be quantified in order to perform reliability and risk analyses.

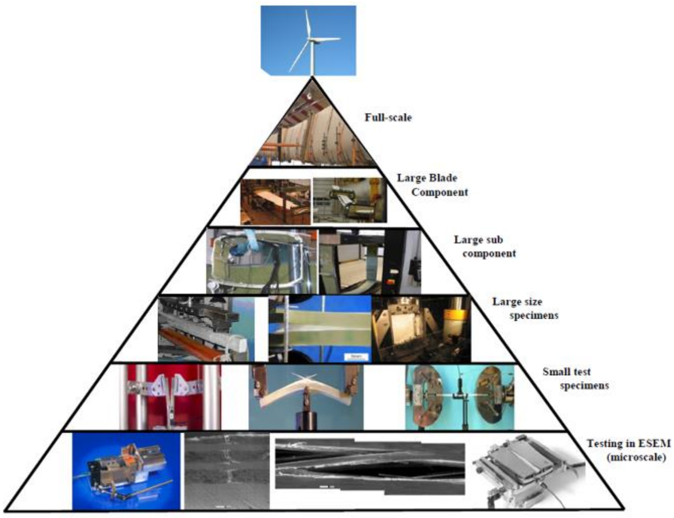

Figure 3. Building Block Method

Figure 4illustrates the structural damage to be mitigated by the use of a technical retrofit solution, based on a Bladena patent, the RTZ-Solution. The RTZ-Solution aims to remove the root cause of the shear web disbonding failure mode. The loads acting on the blade during normal operational conditions generates oscillatory transverse panel deformations or in popular tems named “breathing”, which generates peeling stresses in the cohesive bondline between the inner sandwich panel face sheet and the shear-web. Exposed to continued fatigue loading, the impact of this deformation mechanism is a cohesive damage in the bondline, leading to a disbonding of the adhesive bondlines in the shear web.

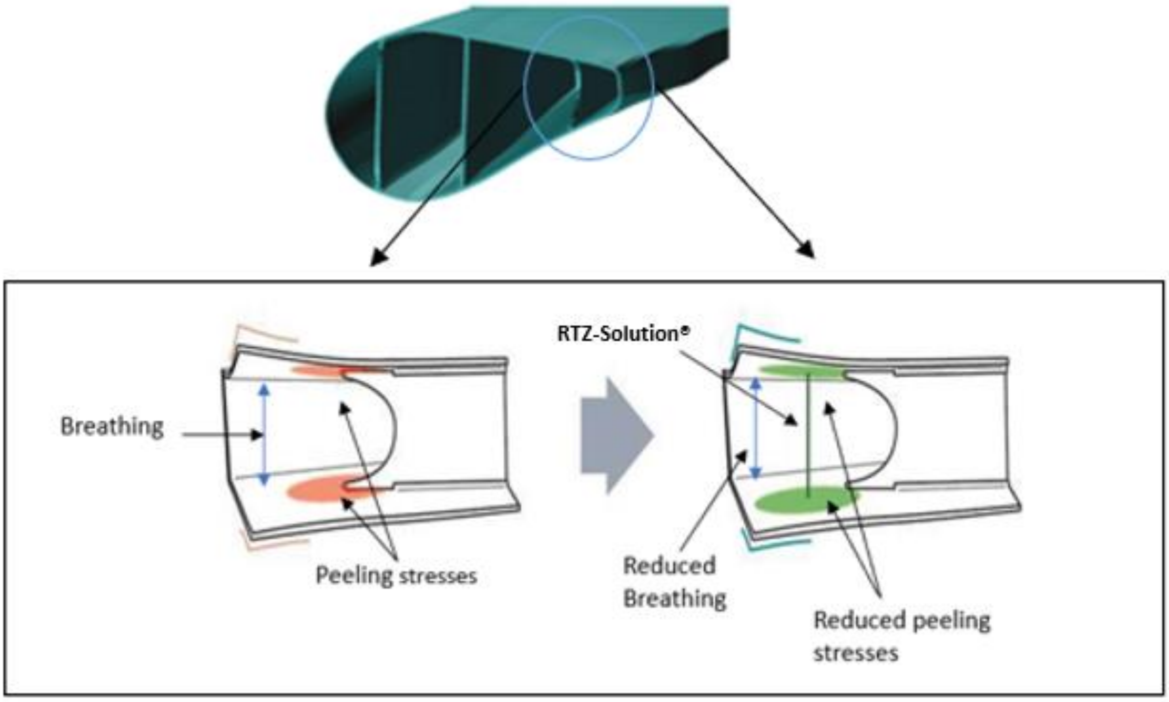

Figure 4. Panel breathing (deformation) in the transition zone generates high peeling stresses at the secondary shear web. The effect and impact of the *RTZ Solution* will be analyzed numerically on different blade concepts.

The validation of the global FEM model against test results and calibrations will be used to conduct a numerical study to identify how global and local deformation phenomenas such as CSSD (Cross-Sectional Shear Distorsion) and panel out-of-plane deformations changes for different blade types e.g. large and small flatbacks and different amount of shear webs in the blade design. The numerically investigated designs will be blade concepts including flatback designs as well as concepts with a change of sandwich core material from balsa to foam in a scaling study.

Boundary conditions for large-scale sub-structural blade section testing will either be obtained from Finite Element Analysis (FEA) or a combination of field measurements and global FEA, depending on the complexity. Field measurements will include deformation measurements captured using a data acquisition system on a blade in operation. The field measurements will then be analyzed statistically by AAU to provide input to DTU's testing campaign, where three scale-levels of testing will be performed: 1) Large-scale sub-structural blade section testing, 2) Smaller-scale sub-component testing (e.g. a single bondline), and 3) Material and fracture mechanical characterization testing.

Together with the test program and numerical studies, the effect of the *RTZ Solution* will be further analysed during a FEM study on different blade concepts. The *RTZ Solution* is illustrated in Figure 4. The analyses of the effectiveness of the new retrofit solution is intended to raise the product's Technical Readiness Levels (TRL).

The retrofit RTZ Solution will be matured, with an additional option to install the solution already during production of larger blades. The RTZ Solution will be qualified for potential installation in the root transition zone, where the cross-sectional shear forces are very high, and where shear web disbonding can potentially lead to a catastrophic blade failure.

The use of the RTZ Solution and its potential benefits in terms of cost reductions will also be studied using the CAR Tool. The retrofit solution will be benchmarked up against alternative repair solutions which are used today.

Theme C: New innovative Field inspection strategies (NIFIS)

The New Innovative Field Inspection Strategy (NIFIS) will be developed in the current project, with the aim to guide the industry in a systemized approach for monitoring and detecting damages inside the blades and making the best possible decisions on maintenance strategies.

With this objective, on one side, the existing standardization framework about OpEx will be considered. WTOs and ISPs shall comply with both national and international standards (e.g. IECRE) and must follow the stated rules regarding inspections and repairs. The CAR Tool will assist the decision making, assessing in the most cost-optimal way to fulfil the requirements here established.

On the other side, this innovative strategy will also be based on what it is identified as a **Damage Tolerance Approach**, because in the current inspections, it can often be difficult to conclude how critical a damage is by only having performed one single inspection. In many cases the observed damage requires monitoring to identify whether the damage continues to develop, or the damage arrests, either due to redistribution of the forces, and/or because the composite materials can absorb the fracture energy. The "absorption", results in damage growth, but as long as damage growth is stable and not critical, it is safe to keep the blade in operation and only the increased repair cost have to be considered.

This approach is known in other industries as a Damage Tolerance Approach, and especially composite materials are often damage tolerant, so that in most cases, a damage does not have to be repaired immediately after it has been observed, but can continuously be monitored and repaired later, if needed. It is therefore crucial that the turbine continues under operation, when a repair campaign is under consideration. Therefore, in the current project, the shear web disbonding will thoroughly be investigated and analysed, with the objective of determining which inspection strategy is the optimal, when this damage type is observed.

Many structural damages observed in wind turbine blades are fatigue-driven failures. The main aim will therefore be to determine, when the blade is safe but economically viable at the same time, and this is why the damage tolerance approach could be used and in effect increase the reliability of wind turbine blades.

Thus, instead of requiring a blade with no damages resulting in overly many repairs, the severity of each crack will be determined by evaluating the crack propagation and the importance of a repair in order for the structural integrity of the blade to be insured, and for the blade to be safe for operation. The residual strength level of the blade will be evaluated, and further repair will be determined if it is needed.

This approach will make use of the results from the fracture mechanics analysis from Theme B as well, in combination with other areas of study like costs and risks through the CAR Tool, field inspections by Non-Destructive-Testing (NDT) and Acoustic Emission (AE), as well as field data considerations.

Being able to identify and to understand the capabilities of the different available monitoring methods and techniques, will allow the application of the damage tolerance approach. In addition, selecting the most suitable inspection method with respect to the blade types, expected critical damages and wind farm conditions and accessibility, is considered as a key element to guarantee the success of any maintenance strategy. Through an appropriate field inspection, WTOs will be able to detect with detail the damages in their blades (damage categories, position, size) and through the damage tolerance approach,they will determine the consequences of those damages and therefore the possible actions that can be taken.

The current project will study a range of different monitoring methods and techniques. Information will be gathered to increase the understanding and application of these methods and **to validate the CPR function of shear web disbonding** from Theme B. The effectiveness of the RTZ Solution will also be documented and the solution validated.

Techniques and methods will include AE sensors and cameras using Artificial Intelligence (AI). AE sensors are considered an appropriate inspection method to monitor the adhesion levels between individual layers, for example, delaminations or shear web disbonding. Benefits and drawbacks of using drones, on-ground cameras, rope access, platform and robots fitted with unique scanning technology will be investigated in the project.

Moreover, various NDT techniques and health monitoring methods will be compared checking their performance to detect and track damages like transverse cracks on the shells and shear web disbonding. A grading system will be created based on the NDT technique's ability to detect specific damages, the time it requires, and the ease of use. These studies will contribute to finding the optimal maintenance and inspection strategy.

Together with the other fields of work in this project, the level of documentation should be enhanced to capture the actual condition of a turbine blade. Historically, the blade inspection and repair reports come in various forms, with different scopes, categorization of damages and reporting templates, making it difficult to obtain an overview of the condition of the entire blade. Therefore, standardization of the documentation is required. In the current project, a standardized damage categorization scheme and a standardized inspection report template will be developed which will not only help the repair process, but also offer a step forward in enhancing and standardizing inspection and repair reports.

The intention is to include guidelines on what and where to inspect, including a check list of the areas of potential damage, a descriptive section defining terms and concepts, and a final detailed list of damages, with their corresponding damage categorization, and the consequent recommended repair/inspect actions.

Moreover, the creation of these **inspection guidelines** will be realized in collaboration with the WTO and ISP partners. WTOs and ISPs have a high level of expertise regarding in-field inspections and repairs. WTOs and ISPs will contribute with input to and evaluation of the new inspection and repair strategies and recommended actions. They can propose alternatives and can in general, analyzed from a field-based experience and the results from the current project, assist in creating a practical guide, which WTOs and ISPs are expected to find useful in the coming years.