# Final report

## 1.1 Project details

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| **Project title** | IMProved Adhesive ConnecTions for wind turbine blades(IMPACT) |
| **Project identification (program abbrev. and file)** | EUDP J. nr. 64016-0065 |
| **Name of the programme which has funded the project** | ENERGITEKNOLOGISK UDVIKLINGS-OG DEMONSTRATIONSPROGRAM |
| **Project managing company/institution (name and address)** | DTU Wind Energy<br><br>Frederiksborgvej 399, 4000 Roskilde, Denmark |
| **Project partners** | LM Wind Power – Blades, DNV-GL Copenhagen, DNV-GL Oslo |
| **CVR** (central business register) | DK 30 06 09 46 |
| **Date for submission** | 30.05.2019 |

## 1.2 Short description of project objective and results

English version:
The objective of *IMPACT* is to decrease O&M costs by decreasing manufacturing costs and increasing the reliability of structural adhesive bondlines in wind turbine blades. Therefore, *IMPACT* develops computationally efficient numerical fatigue life prediction tools with a high level of fidelity. These models are validated against fatigue tests and consequently integrated into LM Wind Power's design workflow. *IMPACT* produced three different fatigue models for predicting laminate failure, bulk adhesive failure and adhesive interface failure. These models are implemented as plugins for the commercial finite element software package *Abaqus*. *IMPACT* produced a novel optimisation based sub-component testing method for the experimental investigation of shear failure modes in tapered adhesive bondlines. The results are disseminated in scientific papers and compiled in an adhesive bondline design review report issued by *DNV-GL* Copenhagen.

Danish version:
Formålet med *IMPACT* projektet er, at sænke Levelized Cost of Energy (LCoE) ved, at reducere produktionsomkostninger og øge pålideligheden af strukturelle limsamlinger til vindmøllevinger. *IMPACT* har udviklet pålidelige og effektive numeriske værktøjer til forudsigelser af udmattelseslevetiden. Disse modeller er validerede igennem udmattelsestest og er derfor integrerede i LMs design workflow. *IMPACT* har udviklet tre forskellige udmattelsesmodeller til forudsigelse af skader i lamineringen, skader i selve limningen og skader i limningsgrænsefladerne. Disse modeller er implementerede som plugins for det kommercielle finite element software *Abaqus*. *IMPACT* har udviklet en ny optimeringsbaseret testmetode for delkomponenter til at lave eksperimentelle studier af forskydningsrelaterede skader i limsamlinger. Resultaterne er formidlede i videnskabelige artikler og samlet i en redegørelse for design af limsamlinger udgivet af *DNV-GL* København.

## 1.3 Executive summary

The aim of *IMPACT* is to demonstrate that advanced numerical fatigue analysis tools improve the adhesive connection technology for large utility wind turbine rotor blades. *DTU Wind*

*Energy* developed three different fatigue analysis tools: for the laminate **MultiFat**, for the bulk adhesive **CritiFat** and for interface failure **InterFat** whose application increase the blade reliability and enable a reduction of manufacturing and O&M costs. The higher fidelity in these models is attributed to the simultaneous consideration of all stress components in the bonded joint and their contribution to multiaxial fatigue damage. That is to say, both the location and instant of failure in time can be predicted. Moreover, the models were purposefully developed for fast computation making them ideal for fatigue damage screening as well as adhesive joint optimisation at an early blade design stage. The development of the numerical tools was supported through the experimental campaign on sub-component level. Specifically for the purpose of experimentally investigating the shear strength of thick adhesive bondlines, optimisation techniques were employed to find the optimal shape of the sub-component. Similar attempts were made previously by other institutions but the sub-component developed by *LM Wind Power Blades* was the first to successfully demonstrate the ability to consistently induce multiaxial shear failure in the designated gauge area of the bondline. This considerable step forward in testing technology enables the calibration and validation of numerical prediction models with data unbiased from boundary failure phenomena. The project results comprise of three multiaxial fatigue models readily implemented into software plugins written in *Python* language to be used with the commercial finite element software package *Abaqus*. All models were subsequently validated against available test data in the literature and data provided by *LM Wind Power*. The models **CritiFat** and **InterFat** were used to conduct a parametric study on a generic adhesive T-joint in order to investigate potential cost savings in comparison with standard design methods. In due course of the research, an additional outcome was an analytical method that can be used to correct the stress fields in vicinity of re-entrant corners in adhesive joints, enabling a more accurate prediction of the bonded joint stress stated when loaded. The project results will be utilised through a step-by-step implementation of the software packages into the design workflow of LM Wind Power. The novel test results are used to benchmark existing test data where both the developed test-rig and test method will be used for future projects e.g. ReliaBlade. The findings of *IMPACT* will be compiled in a report issued by *DNV-GL* Copenhagen in which the potential of the advanced numerical calculation tools will be highlighted. This report is intended to initiate a broader discussion among industry and *DNV-GL* to improve adhesive joint design rules, with the aim of improving wind turbine blade reliability, optimize adhesive consumption in blade designs and ultimately reduce the levelized cost of energy.

## 1.4 Project objectives

The aim of this collaborative effort between *DTU Wind Energy* [1], *LM Wind Power* [2], and *DNV-GL* [3] is to demonstrate the benefits of a new adhesive connection technology for wind turbine blades. The advanced numerical fatigue life prediction capabilities increase blade reliability enabling a reduction of manufacturing and O&M costs. The adhesive connection technology developed in *IMPACT* is defined by the ability to accurately predict and better understand the underlying mechanical phenomena to ultimately improve the existing adhesive connection design. The novel adhesive connection technology developed in *IMPACT* reduces the cost by improving the fatigue life of *LM Wind Power*'s blades and by increasing *LM Wind Power*'s competitive advantage. In the long term, the results are used to improve the design standards at *DNV-GL* which benefits the entire wind energy sector and eventually reduces the cost of wind energy.

The project start was delayed until 1st of February 2017 due to lengthy legal negotiations concerning the collaboration agreement and the acceptance letters. Furthermore, the initial project's main applicant José Blasques resigned and Martin A. Eder (Senior Researcher, *DTU Wind Energy, SAC*) took over as project manager. Meanwhile, a hiring process was initiated where eventually Christian Carstensen was employed by *DTU Wind Energy* to conduct the programming and implementation tasks of *IMPACT*. The project started with an intense discussion of the numerical capabilities *LM Wind Power* needs in order to improve adhesive bondline technology. In parallel a thorough literature review of existing fatigue life calculation methods was undertaken by *DTU Wind Energy*. It became soon clear that *LM Wind Power* wished to pursue a stress-based approach in contrast to fracture based approaches, micro-mechanical models or other hybrid approaches such as cohesive zone models. It was concluded that the necessary advantages in terms of computational speed and ease of applicability to blade models with relatively coarse mesh resolutions outperformed the disadvantages of the stress-based approach. During discussions in bi-weekly meetings between *LM Wind Power* and *DTU Wind Energy* as well as during quarterly steering committee meetings it was agreed that the complex failure modes of adhesive joints need to be decoupled into substrate failure, bulk adhesive failure and adhesive interface failure. The interaction of these failure modes was neglected for the sake of simplicity and computational efficiency. The starting point of WP2 (Implementation of fatigue life prediction tools) was the work by Hahne [4] where his approach was implemented into *BECAS* [5] and the model coined **MultiFat**. The model was fully functional and validated against *Optidat* [6] databases by November 2017 and handed over to *LM Wind Power*.

In December 2017 Christian Carstensen resigned where it is important to emphasise that the reason for his withdrawal was his desire to join industry.
His resignation created two major risks:

- Risk of significant delays of WP2 and consequently WP3 due to the acquisition process for Christian's successor.
- Risk of loss of programming resources inside *IMPACT* jeopardizing the ability to further implement the remaining tools into *BECAS*.

Whilst the research on the theoretical developments of the bulk adhesive model **CritiFat** continued in close collaboration with *LM Wind Power*, two risk mitigation measures were employed: First, a project extension was requested for end of November 2018 and agreed upon with Hanne Asferg Thomassen. Since the budget of *IMPACT* was not sufficient to hire external staff, internal co-funding was raised to cover for increased salary demands for available internal staff whose availability was rather scarce. It took until February 2018 until Leon Mishnaevsky (*DTU Wind Energy, COS*) could be commissioned to implement **CritiFat**. The second measure for risk mitigation was to shift the software developments into Python programming language intended for its use with the commercially available finite element software package *Abaqus* [7]. This switch did not pose any disadvantage in terms of its practical applicability (i.e. the commercial value of the software) and implementation in the design flow since *Abaqus* is well-established software used by *LM Wind Power*.

In the meantime, Thomas Karl Petersen (Chief Engineer, *LM Wind Power Blades*) joined the project as counsellor for numerical analysis and was appointed as additional steering committee member to *IMPACT*. With Maurizio Sala (Test Engineer, *LM Wind Power Blades*) additional resources were allocated for the development of the sub-component tests defined in WP4. Per 26$^{th}$ of October 2017 the former steering committee member Amilcar Quispitupa representing *DNV-GL* Copenhagen withdrew from his position. His appointed successor was Vasileios Karatzas (Senior Engineer Rotor Blades, Mechanical Structures*, DNV-GL Copenhagen*) who took over all responsibilities from Amilcar. These staffing changes did not affect the overall progress of *IMPACT*.

As the implementation evolved it was discovered that computation time became impractically slow predominantly related to inefficient access to the *Abaqus* results file (*Abaqus* type odb). Moreover, despite its low computational performance the model crashed and did not run through. These issues have been reported to *LM Wind Power* at the 18th of April 2018 and remained unresolved in the third steering committee taking place on the 20th of June at DNVGL. Thomas Karl from *LM Wind Power* suggested to use ASCII type output files which can be accessed faster. In order to mitigate the risk of further delays an intense search for the availability of other internal resources commenced with the emphasis on Python programming excellence. From 30$^{th}$ of July 2018 Sergei Semenov (*DTU Wind Energy, SAC*) took over – part time - the coding and implementation tasks from Leon. By the end of August 2018 the bulk adhesive failure model **CritiFat** was readily implemented and fully functional. Computational speed was significantly improved by optimizing the reading process and shifting it into C++ programming language. The model **CritiFat** agreed well with three-point bending fatigue test data and was handed over to Michael Wenani Nielsen (Senior Manager, *LM Wind Power Component Lead Bondlines*) on 16$^{th}$ August 2018. It became clear by mid-August that the technical problems of implementing the models can indeed be handled but that the project needs an extension to successfully adhere to the deliverables. A project extension was therefore proposed for end of May 2019 and agreed upon with Hanne Asferg Thomassen (Senior Executive Officer, *EUDP*). The final deliverable for WP2 - the interface model **InterFat** - was successfully implemented mid-October 2018 and consequently handed over to Michael Wenani Nielsen from *LM Wind Power*.

Scientific and technical discussions about experimental validation (WP4) commenced early in the project with opinions being initially at variance but intensified and converged in July 2017. It became clear that LM's strategic goal was to extend its test database with shear dominated failure of thick adhesive bondlines. It was subsequently concluded that standard tests are hardly capable of reflecting this particular failure type; which simultaneously meant that this kind of test data was probably also not available to competitors and therefore posing a competitive advantage. It was then unanimously decided between *LM Wind Power* and *DTU Wind Energy* to develop a novel sub-component testing method which most realistically represents a real world adhesive bondline situation of a wind turbine rotor blade.
This created two major risks:

- Risk of significant delays due to extensive development efforts of a new testing method
- Risk that the method fails to induce the desired pure shear failure mode

In order to mitigate these risks additional resources namely Thomas and Maurizio (*LM Wind Power*) were assigned to develop the sub-component together with the test rig. Furthermore, a literature study of similar and already tested sub-components was taken as the basis for further development which mitigated the development effort. In order to further mitigate the second risk it was decided to invest more time in the optimization of the sub-component in order to increase the confidence in experimentally achieving the desired failure mode. The time required to rebuild or retro-fit already existing specimens would consume exponentially more time. The effort required to optimize the specimen shape was considerable and involved several design and full 3D finite element modelling iterations exploiting additional resources from LM. It soon became clear that the sub-component requires a non-standard, custom-made test rig which needs to be fitted into an existing servo hydraulic uniaxial testing machine in LM's test centre. First pilot tests commenced on the 8$^{th}$ of March 2018. Whilst the static tests were successful, an unforeseen issue arose in the cyclic load application inasmuch the sensitive hydraulic actuator was affected by a secondary transverse force component acting on the latter, which exceeded the allowable threshold stipulated by the manufacturer. This entailed design modifications of the load application system. Moreover, it affected the controller of the machine leading to unintended emergency shut-downs of the testing machine. The persisting controller issues in conjunction with the machine service intervals started to affect the testing time-window (i.e. machine booking schedule) and risk mitigation measures were discussed: It was contemplated to relocate the test-rig to *DTU Wind Energy Risø* campus where the testing campaign could be completed. Eventually, the controller issues were resolved by *LM Wind Power* internally and testing continued until the end of the machine reservation period in February 2019.

It was realised in due course of the project that the tasks defined in WP3 were to a high degree dependent on two coupled aspects, namely; model validation (WP4) and realistic loading scenarios (WP6). That is to say, the significance of parametric studies depends to a large degree on using validated numerical models as well as the adoption of realistic stress histories as they occur in real wind turbine rotor blades. With increasing complexity of the numerical models it became increasingly difficult to retrieve and access experimental data which proved itself applicable for model validation. In fact, some of the required material properties e.g. the interface shear SN-curve are not available as the test method required does to date not exist. The lesson learned with hindsight of *IMPACT* is that future research projects should address the experimental knowledge gap in order to better utilise the advanced numerical models. The parametric study undertaken in WP3 was based on some assumed stress histories which could still be used for comparison purposes of the different methods. However, the significance of the results could have been increased by the adoption of aeroelastic simulation data in conjunction with full 3D blade models and sub-modelling techniques. Hence, the demonstration of technological benefits (WP6) would have been more accurate.

Discussions between LM, *DTU Wind Energy* and *DNV-GL* crystallised the insight that the development of new design guidelines (WP5) entails a formal and legal procedure of considerable extent, which involves comprehensive test and analysis campaigns all of which exceeding both the monetary and temporal volume of *IMPACT*. In lieu thereof, it was decided that *DNV-GL* compiles the models, modelling results, test method and test results in a technical report which compares the state-of-the-art approaches developed in *IMPACT* with the existing ones. The report focusses on pointing out the potential benefits of the new approaches and serves as a basis for future follow up discussions with industry on improving adhesive joint design guidelines.

Summary of milestones:
The incorporation of the new numerical fatigue lifetime prediction software **M1** is partially fulfilled. All the software packages namely *MultiFat*, *CritiFat* and *InterFat* fully functional and equipped with a user friendly GUI are handed over to *LM Wind Power* (Michael Wenani Nielsen) via the secure *DTU* share point. These models are currently subject to LM's internal scrutiny and validation process. The sensitivity of the fatigue lifetime values **M2** and the sensitivity of the fatigue lifetime models **M3** is established. Range of validity of the fatigue lifetime numerical models **M4** is partially fulfilled through validation with the available test data from WP4. The redesign of the blade to demonstrate cost savings enabled by the new fatigue model **M5** was adjusted along the project path. Cost savings of the entire blade are demonstrated by extrapolation of cost savings achieved in single T-joint. The dissemination of a set of new design guidelines **M6** proved to be overly ambitious exceeding the timely and financial capabilities of *IMPACT*. Instead it was agreed to compile a project review report that serves as a basis for future discussions. The commercial milestone for the release of the *BECAS* Fatigue analysis module **CM1** is not yet reached due to exclusivity of right clause. However, the modules will be made available after the expiry of the agreement. Readiness of commercialisation of new adhesive technology **CM2** is not yet reached due to changes in the internal organisation structure and policies after the merge of *LM Wind Power* with *GE*.

Summary of unforeseen key factors influencing the project:

- Shortage of resources and overbooked staff resulting in low contingency.
- Strong attraction of academic staff to join industry resulting in disruptive fluctuations of the workflow.
- Training and acquaintance of staff replacements accumulating delays.
- Complexity of the development of new testing methods.

## 1.5 Project results and dissemination of results

The main activities of **WP2** were dedicated to the development and the implementation of novel more advanced stress based fatigue damage models for adhesive bondlines. During the validation of the models with experimental data the importance of considering prevalent multiaxial stress states became apparent. It was realised that fatigue damage calculation of the combined stress signal is crucial in contrast to damage calculation of the single signals especially in the case of non-proportional loading. Moreover, it was realised that damage calculations based on single stress components can underestimate the damage caused by simultaneously acting multi-axial stress components. All models are implemented as plugins for the commercial finite element software package *Abaqus* which is also used by *LM* Wind Power. The plugins are straight forward to employ and emphasis was put into robustness and user friendliness such that they can be immediately used by blade design engineers without the requirement for special training or programming skills. Stress history extraction has been optimized in computational speed and the results can be saved as a pickle file. This means that ensuing fatigue damage calculations do not require re-extraction. A graphic user interface allows the selection of different options inside *Abaqus*. Importance to the model development was further attributed to general applicability. As such material- and/or geometric non-linearity does not pose a limitation all of which making the three models versatile tools.

Good agreement was obtained with the laminate fatigue model **MultiFat** with experimental data. The critical plane approach used for the bulk adhesive looks promising since prelimi-

nary results show good agreement with three point bending tests. An effective means to reduce damage computation time was achieved by reducing the stress signal size through load signal based turning point extraction. The method although an approximation was statistically proven to be practically applicable and to significantly reduce the time required for rainflow counting. The bulk adhesive fatigue model **CritiFat** is based on the critical plane approach. The main focus in the development of **CritiFat** was put on computational speed where two approaches are available: The slower albeit more robust approach relies on a search plane sphere where the number of required search planes was reduced by equidistant point distributions. The fast but less robust approach relies on a gradient based optimization method named basin-hopping. This optimizer is especially designed for non-convex problems such as the present one to find the true global minimum i.e. the critical plane. The interface model **InterFat** is a completely novel development and as such not available elsewhere. It considers the simultaneous interaction of multiaxial interface stress states and converts them into a triple of equivalent damage indices.
*IMPACT* produced an additional unexpected theoretical framework to correct the numerically predicted stress fields in vicinity of reentrant bi-material corners by fitting the analytical near vertex field to the numerically predicted far field stress. This feature is similar to the well-known hot-spot method but its formulation more fundamental following linear fracture mechanics. The theoretical approach is implemented into the **InterFat** model for crack fronts following any smooth and monotonic 3D space curve and for any arbitrary notch opening angles.

In **WP3** validation of the three fatigue lifetime prediction models were undertaken. The multiaxial laminate model was extensively validated against different kinds of coupon test data. The results agreed well with the majority of cases found in the publically available database Optidat. Sensitivity studies of different laminates using **MultiFat** showed that the governing damage mode is transverse failure and less frequently caused by shear failure. The critical plane bulk adhesive fatigue model **CritiFat** was validated against proprietary three-point bending test data provided by *LM Wind Power*. Both, the predicted fatigue failure location and the fracture plane agreed well with experimental observations corroborating the underlying assumptions of the bulk adhesive failure model. It was found that the computational speed was very sensitive towards the critical plane search method used. It was found that a fast screening can be done using the optimization based solver followed by a more detailed computation of selected areas in hot-spot regions. The interface model **InterFat** was validated against the new hour-glass sub components developed in WP4. The location was correctly predicted and the failure mode corresponded to the experimental failure mode observed. It was found that failure always initiated at the sharp corner created by the adhesive between the web foot and the cap. The reason was identified as a stress singularity induced by the sharp corner geometry and the material mismatch between the glue and the substrate. Stress singularities represent a drawback for stress based models and means of remedy were investigated. The analytic near vertex correction was studied and different cut-off criteria were investigated. It was concluded that the plastic zone size serves as an indicator. It is recommended that for crack initiation at re-entrant corners a fracture based approach can be developed based on the theoretical framework developed in a future research project. In general it can be stated that adhesive bondlines comprising of thinner bond-lines exhibit an improved fatigue performance.

In **WP4** *LM Wind Power* developed a novel sub-component adhesive joint testing method. This aim of this method was to generate out-of-plane shear failure in the bondline at a specific region – the gauge area – away from the restraints and the load application points. In this way, the measurement results are unbiased from boundary effects. While similar approaches were available in the literature, none of the available methods proved to provide satisfactory results due to spurious failure modes i.e. failure modes that were not intended. Therefore, *LM Wind Power* developed these methods further by initiating an extensive in-house sub-component design optimization campaign. Several design iterations led to an hour glass shaped sub-component test specimen comprising of two caps adhesively connected to a shear web. The caps were made of unidirectional polyester resin & glass fibre whereas the web was made of a sandwich core material with biaxial skin layers. The tapered geometry allows the simulation of very realistic fatigue stress situations in wind turbine rotor blades. In addition to the test specimen a new test rig was designed which could accommodate the sub-component cantilever beam in a servo hydraulic uniaxial testing machine. It needs to be stressed that uniaxial testing machines are not designed for such a rather unconventional test setup. The machine is especially sensitive towards any secondary transverse force induced by the load application and special test rig design measures were required to enable safe operation of the test equipment. *LM Wind Power* has an entire family of adhesive bondline tests spanning different length scales ranging from coupon tests to full-scale wind turbine blade tests. The new test method developed in *IMPACT* bridges the gap between tests on small scale and tests on full scale and taking an intermediate step in the testing pyramid. In fact, the hour-glass shaped sub-component test specimen offers test data situated in-between small-scale double lap shear tests and three-point bending tests. The static and fatigue tests conducted during *IMPACT* shows that the double lap shear tests over predict the fatigue life whereas three-point bending tests have the tendency to under predict the fatigue life due to a high level of simplification of the test component design compared to a real blade structural bondline situation. Furthermore, the results showed the 1 MPa rule is very likely to be overly conservative.

In **WP5** it was agreed by all project partners that a revision of the design rules is a lengthy and elaborate process which requires a comprehensive set of test series and validation cases which are beyond the scope and the budget of *IMPACT*. Discussions during several steering committee meetings identified potential short comings of the, at that time still valid, 1 MPa rule. The shortcomings are the negligence of the dependency of the strength on the different adhesive types, the lack of consideration of the effective width (details of the joint geometry) and the difficulty to determine the underlying safety factor of the 1 MPa rule. Instead of the revision of the DNV GL design guidelines it was agreed to compile a short report containing the findings of the *IMPACT* project. This report serves the purpose to document the findings which could be relevant for future improvements of design recommendations. Therefore, DNV GL conducted a literature review on existing fatigue design calculation methods. Additionally the results of WP2, 3, 4 and 6 were added to the report and compared with the existing approaches. It was remarked that the newly developed fatigue models indicate good agreement with experiment but require more validation in order to add statistical significance. Especially the interface fatigue strength SN-curves are not readily available and requires the development of more dedicated tests in order to increase the fidelity. Note that during the course of the project, new DNV/GL and IEC guidelines have been released where improvements to the 1MPa rule are given.

In **WP6** dedicated to the demonstration of the technological benefits different fatigue design approaches were compared. Comparison between the *LM Wind Power* established *Equivalent Load Approach* and the more advanced approach using *Markov matrices* shows that the partial safety factor can be significantly reduced by the adoption of the latter. Therefore, *LM Wind Power* will direct its developments away from the equivalent load approach towards more sophisticated calculation methods such as the models developed in *IMPACT*. A typical T-joint geometry was created where the readily available sub-modelling technique in *Abaqus* was utilised to couple the detailed T-joint with the full 3D finite element shell model of a *LM Wind Power* blade. Aeroelastic loads were applied to the model and the stress time histories in the T-joint model extracted. The readily implemented fatigue models **CritiFat** and **InterFat** can be used as *Abaqus* plugins to subsequently compute the fatigue damage. By undertaking such a study it was found that the bondline becomes less effective if the width exceeds a certain threshold value. That is, any additional adhesive material does not add additional strength to the T-joint and becomes increasingly ineffective. This effect is not accounted for in any analytical design approach where the shear force is just divided by the bondline width. In other words, any additional adhesive material exceeding the effective bondline width can potentially be saved. Moreover, by restricting the bondline to the effective width additionally the likelihood of manufacturing defects can be decreased which increases the reliability of the joint.

The non-proprietary scientific content of the results will be disseminated by *DTU Wind Energy* through peer reviewed journal papers in agreement with Michael Wenani Nielsen (*LM*

*Wind Power*). Owing to the chronic scarcity of resources the focus in *IMPACT* was put on completion of the vitally important tasks at the expense of publications. However, the results will certainly be published after the finalisation of *IMPACT* in 2019. The interface model **InterFat** and hour-glass sub-component tests have been published in Eder et. al [8]. The near tip stress correction for bi-material Mode-III notches Eder and Sarhadi [9] was submitted to *Engineering Fracture Mechanics*. Other journal papers in preparation [10, 11] are listed in the Annex of this report.

## 1.6 Utilization of project results

The aim of *LM Wind Power* is a step-by-step implementation of the software tools into the design workflow. Since *LM Wind Power* merged with GE the implementation procedures became even stricter. Consequently the timeframe required to implement the tools into the design workflow and to get these internally approved exceeds the timeframe of *IMPACT*. It is common practise that the utilisation of research results takes time as high confidence and multiple validations are needed first.

*LM Wind Power* wants to further build on the project results provided by *IMPACT* partially through continuation with new or existing research projects such as ReliaBlade and Duraledge. One of the project aims was to improve the 1 MPa design rule which does not consider different adhesive materials nor did it comply with the new probabilistic concept of partial safety factors. It was unforeseen at the start of the project that the 1 MPa rule will be superseded in due course of the project by a new set of updated design standards. This can in any case be considered as a positive development. The results produced by *IMPACT* are nevertheless contributing to improve the design guidelines through the prospect of further reducing partial safety factors. Further reduction of partial safety factors can be achieved by increased confidence in the computation method provided by the advanced fatigue tools developed. Any reduction of the partial safety factors entails a reduction of adhesive material consumption and therefore reduces manufacturing costs and consequently LCoE.

The novel adhesive bondline testing method developed in this project enables *LM Wind Power* to utilise the competitive advantage of the new design tools through more accurate benchmarking. Despite its use for numerical validation the new test data provides valuable insight into the effect of stress concentrations in bondlines which other tests hardly can provide. The test data produced by *IMPACT* will be utilised by *LM Wind Power* to update their internal characteristic adhesive bondline design strength values. The latter will be used to further increase the reliability of *LM Wind Power*'s blades.

The fatigue model suite developed by *IMPACT* will be implemented into the *DTU Wind Energy* cross-section analysis tool *BECAS* and subsequently commercialised through license agreements. Commercialisation of the software tools will commence after the expiry of the exclusivity of use agreement between *LM Wind Power* and *DTU Wind Energy*.

## 1.7 Project conclusion and perspective

The following conclusions can be drawn from the project:

i. The fatigue software tools developed in *IMPACT* will be commercialised after the expiry of the exclusivity of use agreement. Therefore, the currently available Python *Abaqus* plugins will be implemented as *BECAS* plugins. These *BECAS* tools will be commercialised through the *DTU Wind Energy* license agreements.
ii. The fatigue models serve as a basis for further developments and research at *DTU Wind Energy*. Currently the bulk fatigue model **CritiFat** already found an application in another project named *Duraledge*. It can be expected that the fatigue models will find further applications in more future research projects.
iii. The main aim of the project was to challenge the 1 MPa rule which was already superseded by new standards. The new approach of the design standards is based on partial safety factors. That is, the safety factors decrease with increasing fidelity level of the fatigue design tools. Therefore, the high-fidelity models developed through

*IMPACT* utilise lower safety factors, which ultimately lead to a reduction of LCOE in the future.

iv. Fatigue calculations that are based on single load components are considered as non-conservative inasmuch the simultaneous contributions of the other stress components are neglected. This issue gains in severity when the loads are non-proportional and non-linear as they typically occur in wind turbine rotor blades. It is therefore important that rainflow counting and damage calculations are performed on combined stress histories.

v. The consideration of the simultaneous interaction of all stress components in stress based fatigue calculations is crucial. The widely adopted approach of considering a single 'governing' stress component only can lead to over-predictions of the fatigue life.

vi. LM Wind Power has developed a novel mechanical fatigue testing method in the *IMPACT* project. The novel method allows the experimental investigation of the shear strength of thick adhesive bondlines, which closely emulate the real world situation, i.e. at sub-component level. Comparison of tests results shows that the new test method bridges the gap between double lap joint tests and three-point bending tests. This additional experimental capability allows *LM Wind Power* to increase the confidence level in its adhesive joint bond strength design. Moreover, the test method allows better validation of the numerical fatigue models.

vii. The novel test method can become a new standard for testing adhesive bondlines in wind turbine rotor blades. It is already designated to be further applied in another research project named *Reliablade*.

viii. DNV GL issues a report in which the future perspective of the improved numerical models and testing method is highlighted. One further development could be a fracture mechanics based crack initiation model which uses the V-notch stress intensity factor as initiation criterion. This report serves as a basis for future discussion of possible improvements of existing design methodologies.

**Annex**


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[10] M.A. Eder, C. Carstensen, *A performance evaluation of an equivalent Puck stress based high cycle fatigue model*, Fatigue & Fracture of Engineering Materials & Structures (*in preparation*)

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