Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2018
June 17-22, 2018, Madrid, Spain

OMAE2018-78218

A GLOBAL-LOCAL DAMAGE ASSESSMENT METHODOLOGY FOR IMPACT DAMAGE ON OFFSHORE WIND TURBINE BLADES DURING LIFTING OPERATIONS

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ABSTRACT

Lifting the latest generation offshore wind turbines using floating crane vessels is extremely challenging. This comes with an elevated risk of blades impacting the tower or surrounding structures due to excessive crane tip motions from wave induced vessel motions. The wind turbine blades are primarily made of composite materials and thus are extremely vulnerable to impact loads causing complex damages and failure modes. One of the most critical damage type for wind turbine blades is delamination because delaminations cannot always be visually detected but can cause significant strength and stiffness reductions. An explicit structural response based approach was proposed in the previous work which is used to derive response based operational limits for single blade lifting operation using floating vessels considering probability of contact/impact and damages in the blade. An assessment of such impact induced damages on the blade was mentioned which includes modelling and predicting damages in the blade for different contact scenarios representing lifting operations in different sea states along with post impact residual strength estimation. This would require an efficient damage assessment methodology which can be utilized in practice with acceptable accuracy along with a reasonable computational cost. In this work, a simplified global-local based damage assessment methodology is presented. The paper focusses on 'shell-to-solid submodelling' based impact damage prediction along with a brief outline of 'shell-solid coupling' based residual strength study. The paper further presents the submodelling technique for impact investigations on DTU 10 MW blade section for a case when a projectile impacts the leading edge. Intraply damage mode based on Hashin failure criteria and Puck's action plane theory was utilized as VUMAT in Abaqus-Explicit along with surface based cohesive behavior to model the interlaminar failure mode. Finally, the damages and failure modes in the blade including impact induced delaminations are reported.

INTRODUCTION

The demand for renewable sources of energy are continuously increasing owing to the increase in the level of carbon dioxide in the environment [1]. Offshore wind energy is one of the most reliable and sustainable forms of renewable energy and has shown a tremendous growth in the last few years, especially in the European market. As per the EWEA report, it is predicted

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that by 2050 offshore wind turbines with a combined capacity of 460 GW will exceed the installed onshore wind turbine capacity [2, 3]. In order to achieve this goal, the installation of offshore wind farms in deeper waters will be necessary. This movement of offshore wind turbines into deeper waters presents great challenges, especially during the assembly and installation phase. The installation phase for an offshore wind turbine is one of the most critical phases and also contributes a major share in the overall CAPEX cost [4]. Currently, jack-up crane vessels are used for installation of offshore wind turbines in the shallow water upto water depths of 55 m and have legs pierced in the sea bed [Fig. 1] while they are performing dynamic lifting operations. This provides a very stable platform while installing blades and nacelle. However, when it comes to installation of turbines in deeper waters, floating crane vessels are required [Fig. 2] [1]. Floating crane vessels are highly influenced by wave induced motion and as a result, the lifted object and the vessel exhibit coupled dynamics and the motion of the lifted object is influenced to a large extent by pitch and roll motions of the vessels [5]. Therefore, the use of floating crane vessels for lifting operations can be very critical and present a very high risk of impact/contact of the lifted object with the surrounding structures due to vessel induced crane tip motions [5]. The consequences of such contact/impact for a wind turbine blade can be significant due to its material characteristics compared to other components of the turbine like monopile and transition piece made up of steel. While a steel structure, with its ductile mechanical behavior, can dissipate kinetic energy from the impact into elastic and plastic deformation, wind turbine blades are much more vulnerable. Wind turbine blades usually consist of adhesively joint subcomponents made of fiber and sandwich composite materials. [6]. Composite materials exhibit excellent in-plane structure performance in fiber direction (on-axis) but are weak in transverse and off-axis directions. Moreover, its anisotropic and brittle material properties make composite materials vulnerable to impact loads. Impact induced kinetic energy cannot be dissipated in composites as easily as for ductile metal structures and often leads to complex and interacting damages below the surface [7]. Again, unlike metallic structures, these damages are not always feasible to be visually inspected as shock-waves arising due to such impacts can cause delamination below the surface [6]. As a consequence, significant strength and stiffness reductions can occur and cause structural blade failure. An analysis of the impacted induced damage levels is important to evaluate if the blades can be installed or have to be replaced [4].

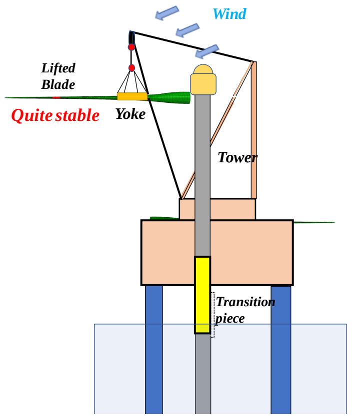

FIGURE 1. Installation of blade using jackup vessel

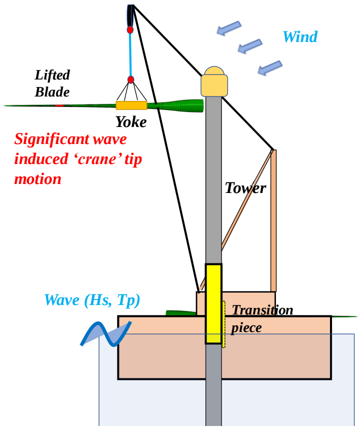

FIGURE 2. Installation of blade using floating vessels

Thus, in order to lift and install the blades safely using floating crane vessels, there are primarily two major interests in the offshore wind community today for efficient planning and controlled execution of such critical operations. The first primary interest from the planning perspective is to establish explicit structural response based operational limits taking into account the risk of impact and thus damages in the blade. These structural limits (in terms of allowable damages) must further be mapped in terms of sea state parameters and would correspond to safe responses in the blade from structural perspective. The other goal is to also develop guidelines as well as to deploy quick onboard decision making simulation tools based on digital twins approach. Such measures would aid the offshore crew in deciding whether the blades are required to be repaired or replaced if such impact/contact event occurs in real time during execution. *Verma et al. 2017* [5] has proposed such an explicit structural response based criteria which can be utilized to determine operational limits for installing blades using floating vessels considering the risk of impact/contact in the blade. It was also mentioned in [5, 8] that such impact/contact risks and thus damages depend upon various parameters like the choice of the pitch angle of the blade lift, sub-phase of the blade lifting as well as the operating environmental sea states. These parameters decide the critical contact scenarios as well as the vulnerable region of the blade to impact. Fig. 3 illustrates the overall approach mentioned in [5]

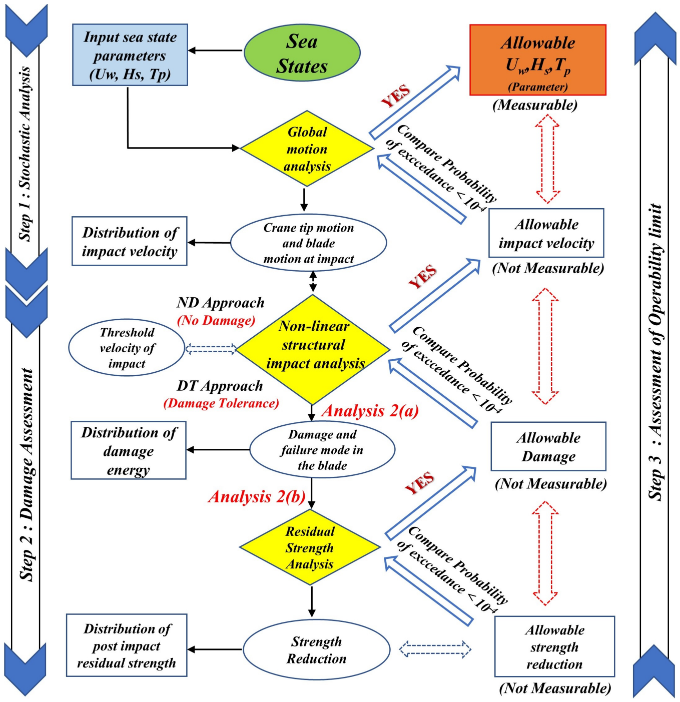

FIGURE 3. Explicit structural response based methodology [5]

which involves three sequential steps. The first step is the global response analysis of the installation system which would estimate the motion of the lifted blade as well as the motion of the crane tip for lifting operations in different sea states. Further, a distribution of impact velocity for various sea states will be established given the stochastic nature of the analysis. Based on such an input distribution of impact velocity, a damage assessment study (Step-2, Fig. 3) is required to determine the damages and failure modes in the blade as well as to predict post impact residual strength. This impact analysis and residual strength estimation post impact (Step-2) mentioned in the context of the approach illustrated by Fig. 3 forms the basis of damage assessment study for which a simplified approach based on a global-local modelling strategy is presented in this paper.

The damage assessment study has been a subject of wide research interest in the aerospace and defense applications for many years. This is mainly motivated by damage tolerance design of the composite structure [7, 9]. The damage tolerance design of the composite structure assumes some inherent imperfections in the composite structures due to manufactering defects or damages incurring due to impact during transportation and installation. Further, the structure is designed to cater to extreme design loads but with some level of allowable damage. The explicit structural response based method mentioned above also takes into consideration this ‘DT approach’ (Damage tolerance approach) [Fig. 3] where operational limits can also be derived based on some level of acceptable impact induced damages in the blade. The approach [Fig. 3] also encompasses evaluation of operational limits based on an ‘ND (No damage) approach’ where only impact velocities lying below the threshold velocity initiating such damages are accepted. It was found in [5] that the ‘ND approach’ can be acceptable for lifting operation using jackup vessel for which the estimated crane tip motion was lesser than the threshold level of impact velocity initiating such damages in the blade. However, for a floating vessel under similar sea states, the motions of the crane tip as well as the impact velocities found were larger than the threshold level. Thus, for practically planning blade installation using floating vessels considering impact/contact risks, the approach must be based on the damage assessment study which includes two sequential steps mentioned: (1) modelling and predicting impact induced damages in the blade (2) estimating post impact residual strength in the blade. This paper presents an efficient approach for both the steps with focus on the accuracy as well as ease of computational demand.

DAMAGE ASSESSMENT METHODOLOGY

The estimation of operational limits for blade installation considering risk of impact/contact using floating vessels is based on a stochastic framework as mentioned in the last section. The most important analysis results for the damage assessment study are the distributions of damage energy and residual strength post impact [Fig. 3] on which the probabilistic assessment is required to be performed to estimate the operability limits [5] (Step-3, Fig. 3). In order to establish these distributions, structural impact analyses are required for various impact velocities (representing different sea states) to establish a deterministic relationship between damage and impact velocity. The most critical issue for establishing these relations is the computational cost required in the first step of damage assessment study which is to model and predict damages in the blade due to impact. The analysis of impact response on a large structure like a wind turbine blade usually involves an explicit algorithm based structural finite element solver given a very large number of degree of freedoms involved [10]. The explicit algorithm is in principle unconditionally stable but requires very small time steps and thus depends significantly upon nature of discretization of the structure into element types, order and size. Moreover, such non-linear impact investigation requires implementation of geometric, material as well as contact non-linearity formulation making the analysis even more complex and computationally demanding.

The area of impact modelling on a composite structure in the literature can be divided into two main categories: impact investigation at a coupon scale and impact investigation on a full scale composite structure [Fig. 4]. There is a significant difference in the modelling approach for both the cases. Most of the literature for numerical impact investigation on a composite at

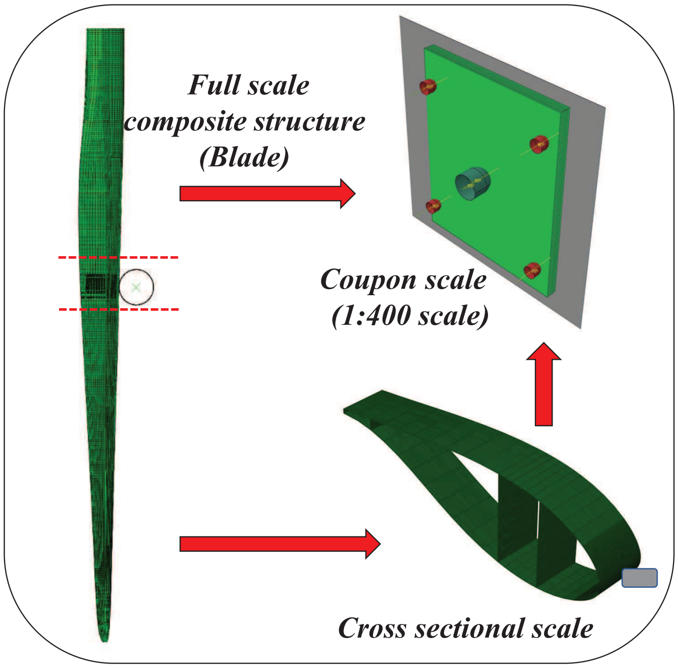

FIGURE 4. Different scale of impact testing on a composite

coupon scale is based on the use of solid elements to discretize the entire composite laminate along with cohesive elements tied at the interfaces to model the inter-laminar failure (delamination) [11, 12]. Solid elements combined with cohesive elements provide 3-dimensional stress state results and discretization of interlaminar failure. However, such an approach comes at a very high computational cost due to the large number of degree of freedoms combined with the small stable time increment for the explicit solution [13, 14]. *Turon et al. 2005* has suggested an alternative approach [15] to model delamination using cohesive elements but with relatively coarser meshes. Again, such an approach is suited to model a very small impact zone and thus the application to model a very large impact zone is quite limited. Alternatively, instead of cohesive elements, cohesive surface based interaction formulation has also shown good results to model the delamination effects in the laminate.

The present paper involves a case where the lifted blade on a crane impacts any structure and the study falls in the second category i.e. impact response on a full scale composite structure. The major difference between the impact response at a coupon scale and at full scale length is the overall flexibility of the composite structure involved in the case of the latter [13]. It has been reported quite extensively, especially in the aerospace sector, that the testing and modelling techniques for impact behavior at a coupon scale could be a poor guide (accuracy as well as computational time) when it comes to mapping it to the performance of a real large scale composite structure [13]. A real composite structure owing to a large flexibility could store more energy elastically due to impact and very less energy would be dissipated as damage energy. Thus, it becomes very important to consider the flexibility of the entire structure to simulate the impact response. Moreover, when it comes to the case involved in this paper where a blade having some initial kinetic energy hits any rigid structure, the consideration of the overall flexibility becomes even more important. It has been found in the past work [4, 8], that the contact area of the blade influenced by such impact events during lifting can be very large when the blade impacts the tower along with only 7-20% of the total internal energy dissipated as damage energy [4,8]. As expected, due to flexibility of the entire blade structure, most of the energy got dissipated in the form of rigid body motions, elastic deformations and vibrations post impact with most of the damage being concentrated at the region of impact [4]. As a result, an important study is to also understand the impact dynamics of the blade post impact. This is required to design more efficient installation equipment like active tugger line systems, guide wires to control blade motions and resist successive impacts with the surrounding structure. Thus, in summary impact modelling on a full scale composite structure would require a modelling technique considering the inclusion of the entire blade model (to take into consideration the flexibility) on one hand at a global scale along with study of damages and failure modes at the local region in the blade.

In order to utilize the flexibility of the composite structure as well as to include full scale elastic response for understanding the impact response, classical shell based impact modelling has been utilized as an efficient option in literature [4, 8]. The advantage of using these elements are that in the constitutive equations, thickness coordinate is eliminated making the solution of ODEs quite cheaper. The thickness formulation is then defined as a section property other than based on nodal coordinates [8, 16]. Moreover, it has been found in the literature that shell elements based impact modelling gives quite closer results when it comes to predict the intra-ply damage state in the composite at a ply scale. However, the major disadvantage of utilizing impact investigation based on these shell elements is that it is not possible to model explicitly the delamination, which is one of the most critical damage modes, especially owing to their potential of propagating further in the presence of dynamic loading. These effects become very important for the blade when it comes to evaluation of residual strength and thus need to be evaluated based on discrete modeling using solid elements to model explicitly the delamination. Again, modelling the entire blade with solid elements is not a feasible option and thus would require a hybrid modelling approach which could take into consideration both shell and solid elements in the same model and is described further.

One of the most important modelling methods which can be utilized to predict the impact response of a large composite structure with many degrees of freedom is based on a global-

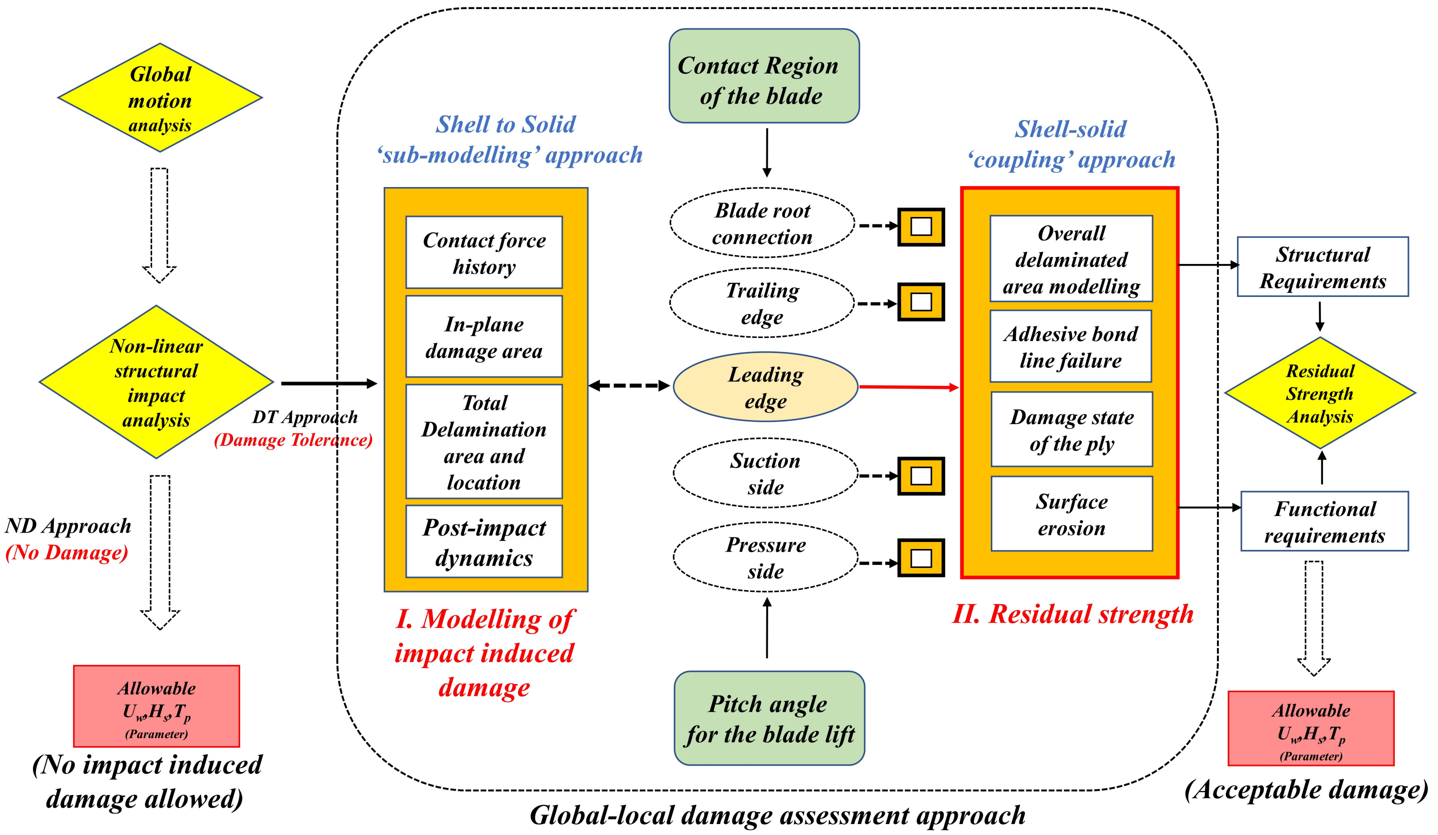

FIGURE 5. Damage assessment methodology

local modelling approach. The present paper presents the overall damage assessment methodology based on such global-local approach [Fig. 5]. This global-local approach is based on a combined multi-scale modelling technique which takes into consideration models with wide disparate detailing requirements as it is required for our case. A coarser meshing technique can be utilized for parts of the structure which mainly contribute to the flexibility along with a very fine meshing technique for the region where detailed solutions for damage states are required. There are two principle global-local approaches utilized for such a purpose: Submodelling approach and Direct connection approach (also known as shell-solid coupling approach) [10] [Fig. 6]. 'The direct connection approach' is based on a principle which uses sharing of nodes between two different meshes, geometries as well as different element types with suitable coupling constraint equations. The major advantage of this approach is that only one set of analysis is required where global and local models along with their results interact together using appropriate kinematic and dynamic interface continuity conditions [Fig. 6] [10, 14]. However, this method is limited in application to model complex structural shapes like a wind turbine blade leading to non-physical response around the coupling interface zone especially developed due to high stress concentrations during impact analysis [Fig. 6]. On the other hand, 'Submodelling approach', a global-local approach primarily based on St. Venant's principle involves a multi-step analysis [10, 16]. St. Venant's principle states that the solution in the local area of interest (submodel) is not changed by the far field effects [10, 16] (global) as long as end loads are statically equivalent for both the cases. Moreover, the added nonlinearity caused by the damage (in the submodel) should not influence much on the global response behavior. Thus, the approach involves a local part of the global model called 'submodel', which is defined with a very refined mesh, geometry and advanced material models and can be analyzed based on transference of the results including displacement fields [Fig. 6] (which correspond to static equivalent end loads) from the global analysis (primary analysis). These results are transferred onto the 'driven nodes' of the boundary of the submodel for the submodel analysis [16][Fig. 6]. One of the main requirements of this analysis is thus to validate displacement field equivalency for both the analyses.The major advantage of this approach is its application to many levels of detailed submodels [10], with complex shapes [Fig. 6] along with computational efficiency. Thus, the present paper proposes the impact modelling approach based on shell to solid submodelling approach as illustrated in Fig. 5. A brief procedure for this submodelling based impact damage approach on the blade is also mentioned in the next section. The paper also presents the approach for a case study on the section of a DTU 10 MW blade where a projectile impacts the leading edge. Once the overall delamination area, location and the damage state of the ply is estimated based on this sub-modelling approach, the next step is the residual strength analysis [Fig. 5]. In the past, *Haselbach et al. 2016* [17] has studied the effect of delamination occuring at the suction side of the blade at the spar cap, where a shell-solid coupling approach was presented with solid and cohesive elements representing the ply and the delaminated regions respectively. The modelling approach provided quite robust results and at an efficient computational cost and is thus considered an efficient option for the damage assessment approach when it comes to establishing residual strength. Hence, the paper proposes shell-solid coupling based residual strength study as illustrated in Fig. 5.

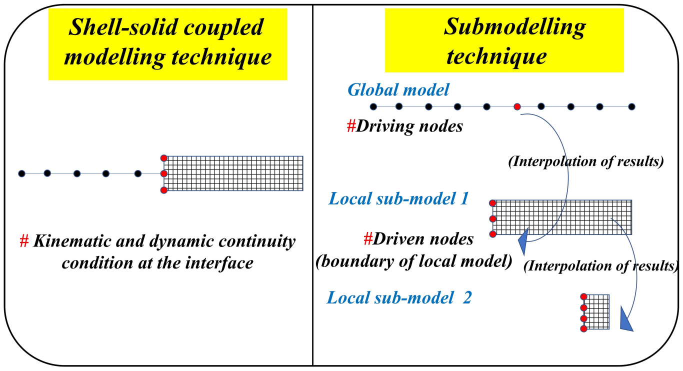

FIGURE 6. Global-local modelling approach

Also, during lifting phase, impact risks vary with different installation methods and thus impact could occur at different regions along the blade [8]. This would present varying effects on the overall residual strength as different regions of the blade are designed to take care of varying structural requirements expected during the operational life. Hence, it would require different residual strength studies to establish acceptable damages which is illustrated by small orange boxes with thick black border in Fig. 5. For example, any impact induced surface indentation on the leading edge could affect the functional requirement of the blade affecting the overall aerodynamics along with the structural requirements. Again, any impact during the mating phase could cause damage to the bolts and would affect the fatigue strength of the blade. Thus, the damage assessment methodology presented also considers this effect of impact at various locations [Fig. 5]. The paper now explains the modelling approach for impact investigation and residual strength study post impact on the blade.

Shell to solid submodelling based investigation of impact response and damage in the blade

The first step for the damage assessment study is shell-to-solid submodelling based impact investigation on the blade. Here, the focus is on the solution of the overall impact dynamics including the effect of the flexibility of the entire structure based on a global shell model of the blade. Further based on such global analysis, results including displacement fields can be derived at suitable boundaries of the global model. These regions in the global model are called ‘driving nodes’ [Fig. 6,7] and are important for transferring the results to the boundaries of a very refined and detailed submodel developed for the second analysis. These regions in the submodels on which such results are transferred are called ‘driven nodes’ [Fig. 6,7]. The green boxes in the flow chart represent the influence of installation methods on the overall impact analysis [Fig. 7]. The lifting sub-phase of the blade installation (Sub-phase 1,2,3) decides the structure with which the blade would suffer impact [Fig. 7]. Again, the impact energy is determined based on the global analysis of the installation systems for different sea states. Thus, these parameters are explicitly illustrated in the procedure for the submodelling based impact investigation [Fig. 7]. The entire global blade model can be descretized with shell elements for the global analysis along with definition of suitable layups to specific regions of the blade model. The details for such composite layup must be available in the uni-directional nomenclature representing stacking sequence in the form of individual plies ([+45/-45/0..]s). In practice, often the layup information available is in the form of smeared multi-directional nomenclature in the form of triaxial-biaxial and uniaxial nomenclature. Such a nomenclature representing multidirectional plies is well suited for global response analysis. However, it is not applicable for impact analysis, as it is not possible to predict the responses of an individual ply based on such a composite layup plan. Thus, the layup in the form of unidirectional nomenclature must be derived [Fig. 7] from the original multi-directional layup. This is followed by a validation check for the derived layup plan confirming no change in the blade characteristics [Fig. 7]. Further, the impact analysis on a global shell model can be performed with the material as well as contact non-linearity formulations implemented. Moreover, results for displacement fields at the driving nodes must be post processed at sufficient output frames to prevent any aliasing error during transfer of the results. These results will be transferred on to the driven nodes on the boundaries of the sub-model for the submodel analysis. Also, the stresses calculated from the global analysis can be used to indicate the boundary/extent of submodel to be developed from the global shell model. The boundary of submodel must be sufficiently far away from the region where the response changes significantly. This is done to satisfy the fundamental assumption based on St. Venant’s principle. Further, similar loading states as utilized for the global analysis need to be defined on the submodel [Fig. 7] along with the displace-

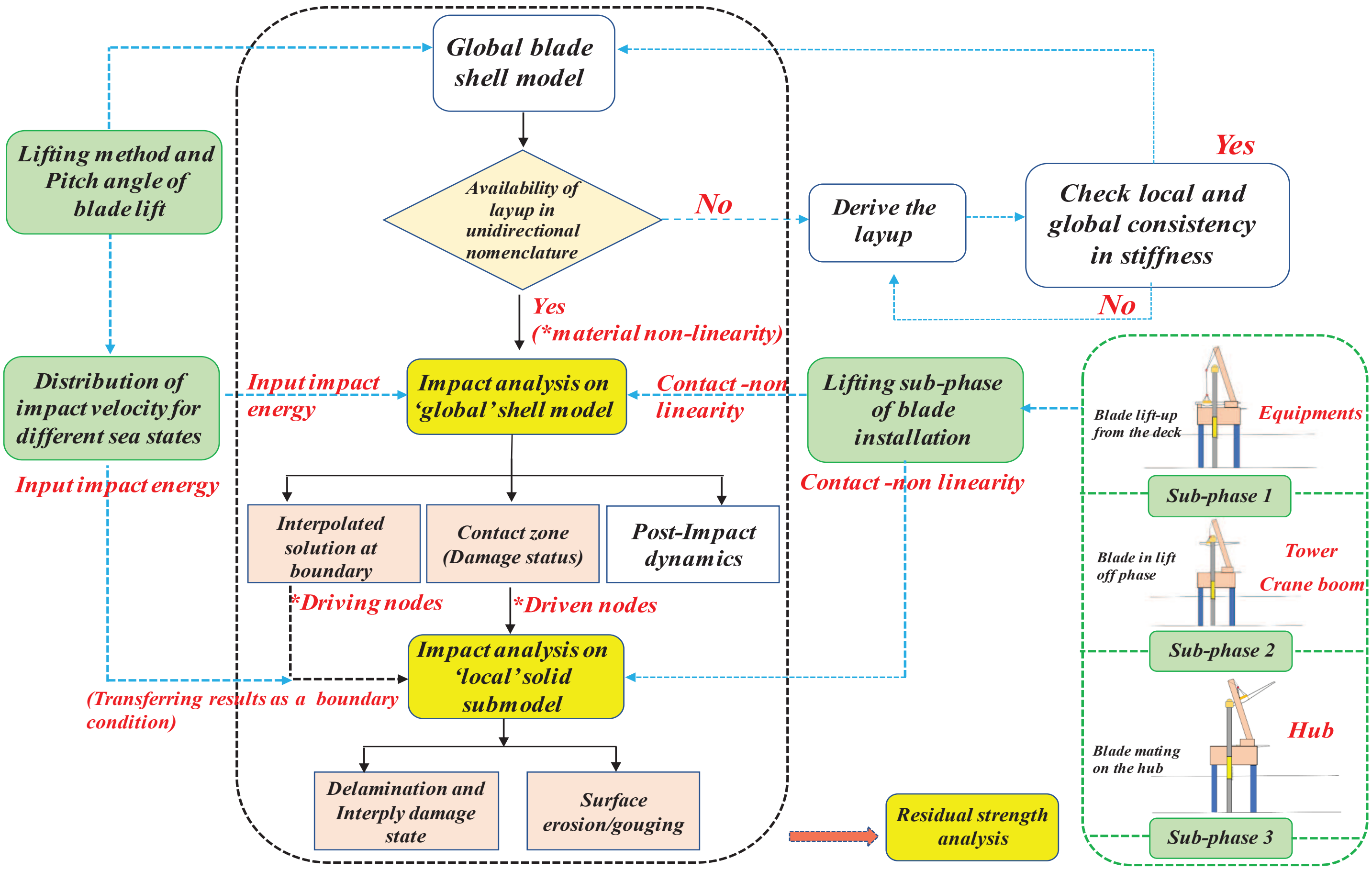

FIGURE 7. Shell to solid submodelling technique for impact investigation on the blade

ment fields (obtained from the global analysis) to be imported as a boundary condition on the driven nodes of the local submodel to finally perform a submodel analysis. This analysis can now be utilized to estimate all critical damages and failure modes in the blade including intra-ply, inter-laminar failure modes and surface erosion effects. Finally, based on these obtained damage modes, a 'shell-solid coupled model' (direct connection approach) for residual strength analysis can be performed.

Shell-solid coupling based approach for residual strength analysis

Based on the damages and failure modes obtained in the blade based on the impact investigation from the previous step, residual strength analysis can be carried out. This step is performed to decide the criticality of such damages and to estimate the extent to which such impact induced damages would influence the strength requirement of the blade. Here, the shell solid coupling approach will be utilized (single step analysis instead of submodelling technique), where the entire blade modelled with coarser shell elements would be connected to a very fine local solid model with a suitable coupling constrain equation. It is also then required to check the validity of this shell-solid coupled model confirming no change in the blade's global characteristics [Fig. 8]. This refined local solid model will further be defined with all the damage modes obtained from the submodel analysis as the initial material and deformation state [Fig. 8]. Again, based on the region of impact, different residual strength analyses need to be performed, such as the effect of impact induced delamination on the buckling strength, effect of surface erosion on the aerodynamic efficiency as well as the effect of impact induced cracks on the fatigue life [Fig. 8]. Again, these structural and functional requirements need to be established and will be considered in future work. Moreover, this shell-solid coupling approach for residual strength estimation is quite well established and thus the paper here only presents the case study for the first part of the proposed methodology which is shell to solid submodelling based impact investigation on a wind turbine blade. The modelling technique for shell solid coupling based residual strength investigation can be found in [17].

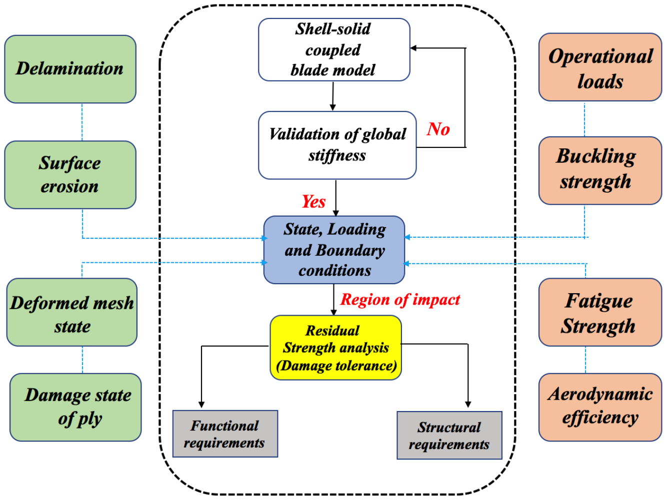

FIGURE 8. Shell-solid coupling based residual strength investigation

SHELL TO SOLID SUBMODELLING BASED IMPACT INVESTIGATION ON A SECTION OF WIND TURBINE BLADE

This section presents the shell to solid submodelling technique for impact investigation on a section of a wind turbine blade. Here, the focus is strictly towards illustrating the efficiency of such an approach and thus the study is restricted to a case of impact on a blade section of reduced length [Fig. 9]. Similar modelling techniques can further be utilized for the case when the lifted blade with some initial kinetic energy impacts any structure. Such studies will be considered in the future after the technique is well established and illustrated at a sectional level. Here, a section of the DTU 10 MW blade [18] is chosen and an impact investigation is performed in ABAQUS Explicit solver for a case when a projectile hits the leading edge. The impact analysis was firstly considered at a global shell model where the focus is to understand the overall impact dynamics considering the flexibility of the structure. This analysis would indicate the region in the global model of the blade influenced by impact induced stresses. This information would be utilized to develop a very refined submodel [Fig. 9]. From the global shell based impact analysis, the displacement field results are obtained for the driving nodes at sufficient rate in order to prevent any potential aliasing error. Further, based on the results obtained at the the driving nodes of the global model, the displacement fields are transferred to the driven boundary nodes of the submodel (as a boundary condition) to perform impact analysis on the local refined submodel. The submodel is descretized with solid elements with cohesive surface interaction defined between each solid layer and can evaluate all possible impact induced damage modes in the blade. Moreover, the impact analysis was studied for three different impact velocities: 2 m/s, 3 m/s and 4 m/s with which projectile hits the leading edge. The section also mentions briefly the various constitutive material models as well as material parameters to model the damage modes in the submodel. Finally, the results for the displacement fields at the boundary of global model and submodel are validated. This is an essential part of the submodelling analysis to verify the fundamental assumption as per St. Venant's principle. The critical damages in the blade developed due to such impact are then presented.

Discussion on the layup utilized for the blade

As discussed, the most important information for the global analysis or local submodel analysis is the information of the stacking sequence of the blade in the form of unidirectional nomenclature. The present paper utilizes the case study on the DTU 10 MW blade. The blade shell model along with the layup was derived from the official DTU 10 MW repository website (*http://dtu-10mw-rwt.vindenergi.dtu.dk*) [18]. The DTU 10 MW blade is 86.4 m long and made up of GFRP plies with balsa as a sandwich core material. The entire blade was divided into 100 sections with each section further divided into 11 separate regions [Web A, Nose, Cap...] for the purpose of layup definitions as presented in Fig. 9. One important point to mention is that the nose region of the blade is considered as the leading edge of the blade in this paper. However, the layup was based on multidirectional nomenclature which represents equivalent properties of individual plies. Fig. 10 presents the layup for the nose region of the section of the blade obtained from the original definition. The reason for implementing such a layup definition is because the main goal for the DTU 10 MW model was to check the global strength of the blade under aerodynamic, aero-servo-elastic and structural loads because of the upscaling effects in terms of its size [18] and thus this layup strategy was utilized for ease and convenience. However, it was explicitly mentioned in the methodology proposed in this paper [Fig. 7] that the layup with unidirectional nomenclature must be considered for the impact analysis. Thus, the unidirectional layup was derived for the impact analysis for this study. Fig. 11 presents the modified layup for the nose region of the section of the blade which will be used for blade in the global and submodel analysis. The check for the consistency of the blade in terms of global and local stiffness was validated. The details for the validation study can be further referred in [8]. The layup for the global shell model was further defined for all the eleven regions of the section of the blade considered in this paper.

Global Analysis

After the layup was defined with a suitable material orientation for the blade section (material principle direction 1 is along the length of the blade which is in the global z direction), the entire blade was discretized with conventional shell S4R elements. These elements are also called thick shell elements and are en-

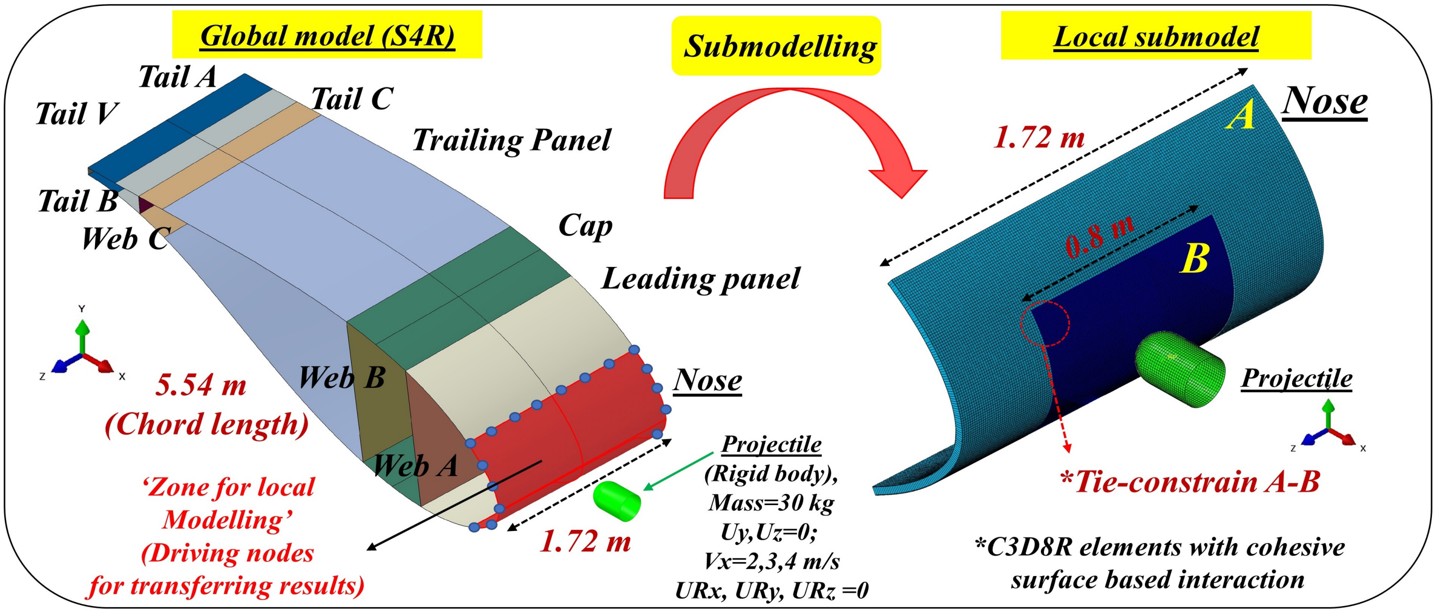

FIGURE 9. Submodelling impact investigation at the cross sectional level

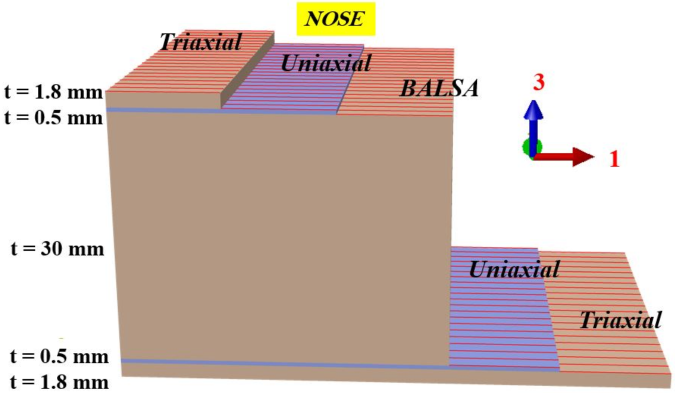

FIGURE 10. Original layup at Nose region of the section

forced by Mindlin shear flexible theory which considers transverse shear stresses in their kinematic assumptions. Thus, these elements were found suitable to model the blade for the global analysis. The entire blade section except the nose and the leading panel were constrained in all the displacement and rotational directions. The projectile impacting the leading edge is modelled as a discrete rigid body (R3D4 elements) [Fig. 9] with inertial mass 30 kg along with a reference point assigned as a rigid body constrain to the whole geometry. Further, this reference point was constrained in all degrees of freedom except displacement in the x direction (U_x) [Fig. 9]. Further the projectile was given an initial velocity in the x-direction as a pre-defined state which corresponds to the energy of impact. The general contact algorithm in ABAQUS was utilized to define the contact between the surface of the projectile and the blade reference surface. The penalty enforcement principle with a friction coefficient of 0.3 along with hard contact interaction property was defined. Again, sufficiently large number of output frames were defined to obtain displacement field at the driving nodes of the global model. These results will be used as a boundary condition on the submodel's boundary (driven nodes) to transfer the solution obtained from this global analysis.

Submodel Analysis

The present paper utilizes node-based submodelling technique available in ABAQUS. After the impact investigation was performed on the global shell model, the entire nose region of the section of the blade was chosen as the region for developing a very refined local submodel. The boundary of this submodel was quite far from the impact induced stresses developed due to impact with the projectile obtained based on the solution from global analysis. The submodel nose region had an overall length of 1.72 m with thickness of 34.6 mm and consisted of 9 layers (8 layers corresponding to GFRP plies and one layer of balsa) [Fig. 9]. Each layer was modelled with C3D8R elements which are standard hexahedral continuum solid element with eight nodes and reduced integrations scheme. The submodel was further divided into two separate regions A and B [Fig. 9], with region A having relatively coarser mesh with element size 0.01 m and region B with extremely fine mesh of size 0.005 m which was chosen based on the mesh sensitivity study. These two regions were further tied constrained. For both the regions A and B, each layer

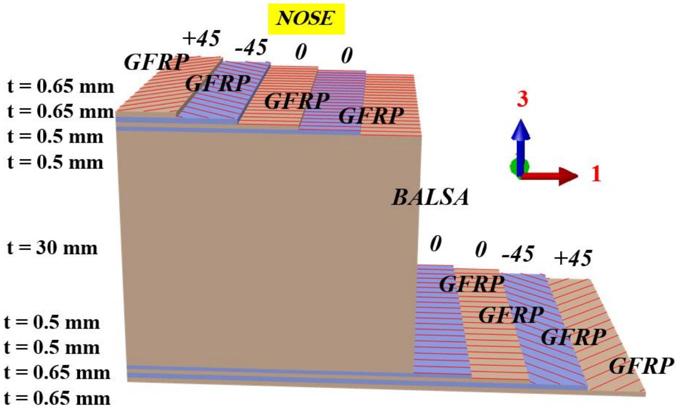

FIGURE 11. Derived layup in unidirectional nomenclature

of the composite ply was modelled with one element through the thickness except the layer of the core which was modelled with 4 elements through the thickness. Moreover, all the layers for both the regions were defined with cohesive surface based interaction along with friction coefficient defined as 0.3 between each ply. The value of contact stiffness and friction parameter was taken from literature [6, 11, 12]. Further, the contact formulation between projectile and submodel was defined only for the finer mesh region (B) where the impact is expected to be concentrated. This definition of region into two layers aids in computational efficiency as contact defined for all the regions of the submodel would be computationally very costly. Again, the contact was defined between the projectile's external surface with all the layers (external as well as internal surfaces) with a friction value of 0.3 along with hard contact over-closure interaction property. The nodal displacement fields obtained from the global analysis were utilized as a boundary condition to transfer the results from the global analysis at the driven nodes of the boundary of the submodel. The projectile's boundary condition was kept similar as in global analysis. The overall size of the entire submodel had around 482K elements. The submodel analysis was performed on an HPC machine with 2 cluster nodes with a total of 32 cores at 2.6 GHz and took about 12 hours to complete the 0.015 s of the total simulation time taken for the study. This computational time was found significantly efficient than impact on a shell-solid coupled model.

Constitutive material damage models implemented

The nose section of the blade considered as submodel is originally a sandwich structure [Fig. 11] for the DTU 10 MW blade. Thus, the impact modelling on the submodel required implementation of damage model suitable for a sandwich structure. A sandwich structure in addition to delamination and intraply failure modes like matrix cracking and fiber failure for GFRP faces, would also require modelling of other additional failure mechanisms like face-core debonding and core crushing. Thus, there were in total three separate constitutive damage models implemented which are discussed briefly below.

The intralaminar damage model for the ply was modelled based on Hashin failure criteria [19] and Puck's action plane failure theory [20] for fiber and matrix failure respectively. This damage model was implemented as a VUMAT subroutine in ABAQUS Explicit with definition of solution depended variables (SDVs). This failure criterion models the onset and progression of damage on the composite ply due to impact. The primary assumption of this criterion is that the elastic stress-strain relation is give by orthotropic damage elasticity [11, 12] where 4 damage variables (two representing failure of fiber in tension and compression and two representing failure of matrix in tension and compression) are introduced. Hashin failure criterion was used for evaluation of fiber failure and corresponding damage variables. Fiber failure occurs when the parameter $f_{\mathrm{ff}} > 1$. f_{ff} is estimated by:

$$f_{\mathrm{ff}} = \begin{cases} (\dfrac{\sigma_1}{X^T})^2 + (\dfrac{{\tau_{12}}^2}{{S_{12}}^2} + \dfrac{{\tau_{13}}^2}{{S_{12}}^2}), \text{ if } \sigma_1 \geqslant 0 \\ (\dfrac{\sigma_1}{X^c})^2, \text{ if } \sigma_1 < 0 \end{cases} \tag{1}$$

The matrix failure of the ply was estimated by Puck's action plane theory described by interfiber failure (IFF) criterion [20]. It is described by the assumption that the failure is created by stresses that act on the fracture plane inclined at fracture angle (θ) to the material plane. The normal and shear stresses which are acting on the fracture plane ($\sigma_{\mathrm{n}}(\theta)$, $\tau_{\mathrm{nt}}(\theta)$ and $\tau_{\mathrm{nl}}(\theta)$) are evaluated by 3D stress tensor transformation from material plane coordinate system. Now, the interfiber failure criterion (f_{iff}) is only dependent on stresses acting on the action (fracture) plane. Matrix failure is reached when $f_{\mathrm{iff}} > 1$. f_{iff} is evaluated by :

$$f_{\mathrm{iff}} = \begin{cases} \sqrt{[(\dfrac{1}{R_\perp} - \dfrac{{P^+}_{\perp\psi}}{R_{\perp\psi}})\sigma_{\mathrm{n}}(\theta)]^2 + (\dfrac{\tau_{\mathrm{nt}}(\theta)}{R_{\perp\perp}})^2 + (\dfrac{\tau_{\mathrm{nl}}(\theta)}{R_{\perp\parallel}})^2} \\ \qquad + \dfrac{{P^+}_{\perp\psi}}{R_{\perp\psi}}\sigma_{\mathrm{n}}(\theta), \text{ if } \sigma_{\mathrm{n}} \geqslant 0 \\ \sqrt{[(\dfrac{\tau_{\mathrm{nt}}(\theta)}{R_{\perp\perp}})^2 + (\dfrac{\tau_{\mathrm{nl}}(\theta)}{R_{\perp\parallel}})^2 + [\dfrac{{P^-}_{\perp\psi}}{R_{\perp\psi}}\sigma_{\mathrm{n}}(\theta)]^2} \\ \qquad + \dfrac{{P^-}_{\perp\psi}}{R_{\perp\psi}}\sigma_{\mathrm{n}}(\theta), \text{ if } \sigma_{\mathrm{n}} < 0 \end{cases} \tag{2}$$

where, $\sigma_{\mathrm{n}}(\theta)$, $\tau_{\mathrm{nt}}(\theta)$ and $\tau_{\mathrm{nl}}(\theta)$ are normal and shear stresses acting on the fracture plane, $R_\perp$, $R_\parallel$, $R_{\perp\perp}$, $R_{\perp\parallel}$ are failure strength perpendicular to the fibers, failure strength parallel to the fibers, transverse shear strength and longitudinal shear strength respectively. The details of the definition and calibrations of all the parameters used for the Puck failure criteria in the study can further be found in [11, 12, 21].

TABLE 1. MATERIAL PROPERTIES IMPLEMENTED

Property	GFRP	Balsa	Units
Density (ρ)	1915.5	110	Kg/m^3
E_1	41.63	0.050	GPa
E_2	14.93	0.050	GPa
E_3	13.42	2.730	GPa
G_{12}	5.047	0.0167	GPa
$G_{23}= G_{13}$	5.0469	0.150	GPa
ν_{12}	0.241	0.5	-
ν_{13}	0.2675	0.013	-
ν_{23}	0.33	0.013	-
X_T	903.6	-	MPa
X_C	660.1	-	MPa
$Y_T= Y_C$	42.1	-	MPa
$S_L= S_T$	58.65	-	MPa
G_{FT}	1200	-	N/m
$G_{FC}=G_{MT}=G_{MC}$	4000	-	N/m

The interlaminar failure model for delamination and face core debonding utilized in this study was based on surface based cohesive interaction with quadratic stress failure initiation criterion (QUADS) along with energy based damage evolution law based on BK (Benzeggagh-Kenane) mixed mode behavior with power $\eta = 1.4$. Thus, this traction separation constitutive model could predict the progressive delamination and debonding at the interface of the plies and ply-core respectively. The linear elastic traction-separation behavior as well as parameters for the damage evolution law to evaluate the degradation of the cohesive stiffness to define the cohesive interaction property between plies and ply-core was assumed same and were derived from [11, 12]. Finally, the crushable foam plasticity model along with isotropic hardening rule was utilized to study the plastic hardening of the core. The plasticity values of stresses and strains for the balsa were derived from [22, 23] and were calibrated. The details for this damage model can be found in many literatures [16, 23] and hence is not discussed further. A brief mention of the material properties utilized in the work is reported in Table. 1.

Results and discussion

The present paper investigates the impact investigation based on shell to solid submodelling approach. Here, the focus of the discussion of the results will be made explicitly on presenting the damage states like matrix cracking, delamination as well as impact induced surface indentation in the local refined submodel. These damages are considered one of the most critical damage modes (in terms of residual effect) when it comes to structural and functional requirements. However, before these damage states are presented, the first important check is the verification of nodal displacement fields (field equivalency) at the boundary of global model and submodel from global and submodel analysis respectively. This is to verify that the results from the global model are correctly transferred at the driven nodes for the submodel which is the most important fundamanetal assumption for submodelling technique defined as per Saint Venant's Principle. Fig. 12 presents the appended layout view of the results for nodal displacement field contour with both models overlapped. The results for displacement of the blade section for the global and submodel analysis display consistent continuity implying that meaningful results satisfying St. Venant's principle have been obtained. Further, the energy conservation requirement is also validated which is a very important check to be considered for an explicit analysis for an impact investigation. Fig. 13 presents the energy evolution history for kinetic energy (ALLKE), internal energy (ALLIE) and total energy (ETOTAL) for the analysis. It can be seen that the total energy remains constant throughout the simulation along with the sum of ALLKE and ALLIE corresponding to ETOTAL. This further confirms the suitability of the submodel for impact investigation on the submodel and now the results for the damage states of the submodel can be presented and discussed.

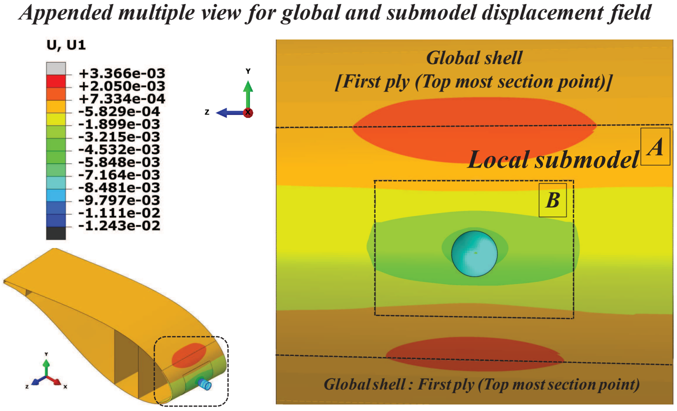

FIGURE 12. Displacement field contour comparison for global model and submodel for V= 4 m/s (*Overlay plot option*)

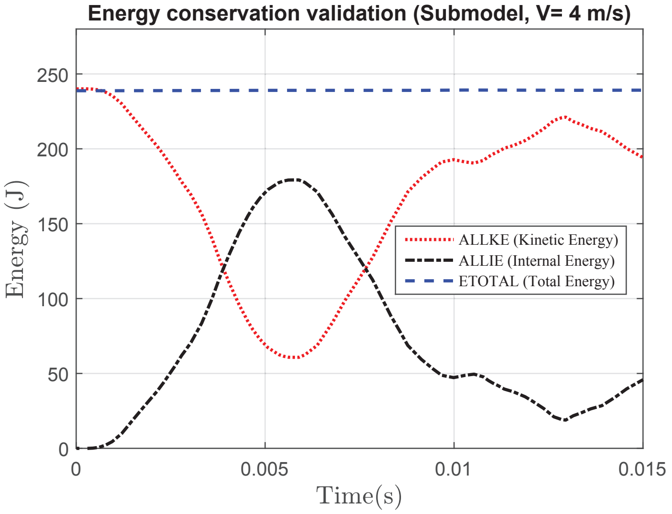

FIGURE 13. Energy conservation history (V = 4 m/s)

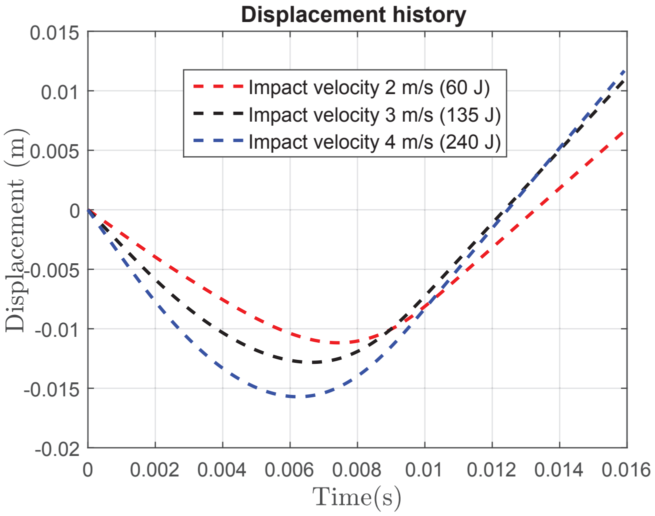

FIGURE 14. Displacement time history for impact velocities

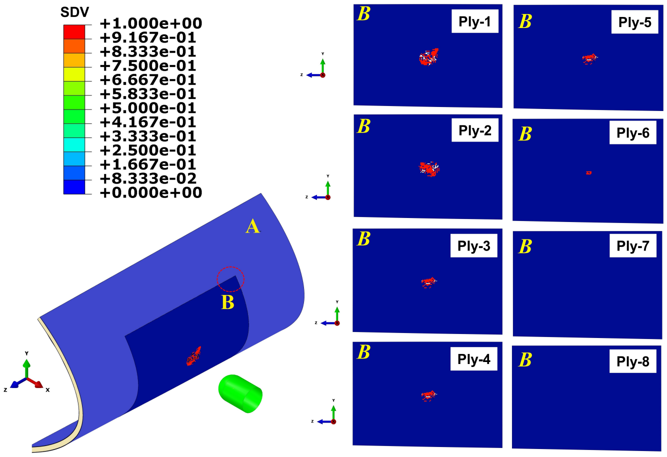

FIGURE 15. Ply by ply matrix cracking for V = 4 m/s at t = 0.015 s

The paper considers a case when a projectile impacts the submodel which corresponds to the blade leading edge for three different impact velocities (V= 2 m/s, 3 m/s and 4 m/s). These three cases represent three different ranges of impact energy (60 J,135 J and 240 J respectively) with the submodel. Fig. 14 presents the displacement time history for the projectile for all the three cases and as expected they present different resistance to the blade section considered for impact. The impact velocity of 4 m/s representing an initial impact energy of 240 J presents comparatively greater displacement [Fig. 14] of the projectile into the submodel and is expected to develop more damages in the blade. Thus the discussion on the damages in the submodel reported due to impact in this work is made with respect to this velocity. Further, the behavior of the trajectory of the projectile during the entire simulation time corresponds with the behavior observed in the literature dealing with low velocity impact analysis of projectiles on composites [Fig. 14]. The results for all the damage states as per the material model were investigated for all the three cases of impact velocities. However, results presented here are for the most critical damage modes like matrix cracking of the ply, delamination, debonding and impact induced surface indentation. Fig. 15 presents the results for the impact induced intraply damage state of the submodel in the form of matrix cracking (at the end of simulation) for a case when the projectile hits the leading edge with a velocity of 4 m/s. It can be seen that most of the matrix cracks developed in the plies were closer to the impact side with some matrix cracking developing even below the core. This qualitatively indicates the occurence of delamination between the plies as it has been widely reported that the matrix cracking in the ply further leads to delamination.

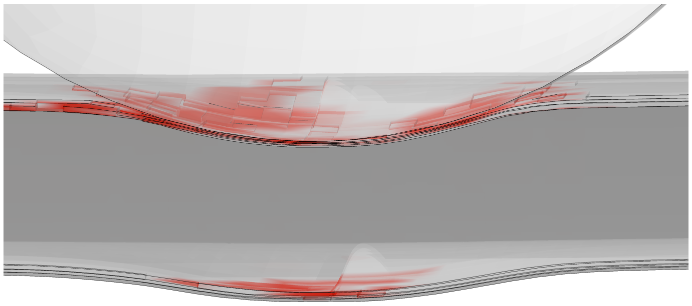

FIGURE 16. Delamination during the impact (*displayed in red, cross-cut view of submodel along the global Y axis*), V= 4 m/s, t = 0.006 s

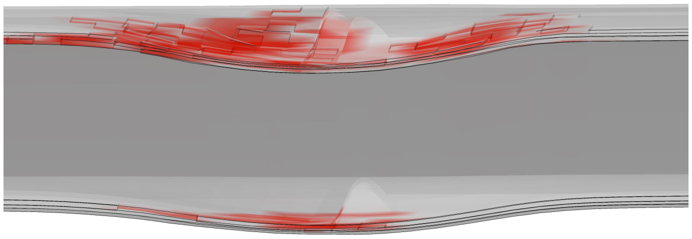

FIGURE 17. Delamination, surface indentation and permanent deformation post impact (V= 4 m/s) at t = 0.015 s

For quantified description of the delamination, the results based on interlaminar failure mode based on quadratic stress criterion is further presented. Fig. 16 and 17 present the cut-sectional view of the submodel which shows the delamination area, permanent deformation as well as surface indentation for the case when the projectile impacts the leading edge (submodel) with a velocity of 4 m/s. Fig. 16 shows the delamination zone through the thickness of the submodel during impact which is illustrated in red. It can be seen from these results that most of the delamination actually occured around the region closer to the impact side, with further significant debonding also occuring along the bottom face and the core. This result is in close proximity with the nature of the evolution of matrix cracks as discussed before. The core being modelled with plasticity model also exhibited significant permanent deformations [Fig. 17] along with the indentation at the top surface which can be quite critical for the leading edge of the blade for the residual functional requirements. Further, the delamination area was calculated for each interface including the debonding between face and core and were added and this variation of delamination area with impact velocity is presented [Fig. 18]. It can be seen that the delamination area increases with the impact velocity (impact energy) which is quite obvious given a large internal energy being developed which increases with the velocity of impact. Thus, from the above results and argument it can be seen that the overall shell to solid submodelling based impact investigation could model all important damages and failure modes including delamination between laminates, debonding between face and core, plastic deformation of the core as well as impact induced surface indentation effects.

CONCLUSION AND FUTURE WORK

The present paper presented a novel damage assessment methodology for impact damages occuring on an offshore wind turbine blade during lifting operations. The main focus of the work aimed towards the estimation of response based operational limits was briefly mentioned. This required a damage assessment methodology which could be accurate as well as computationally efficient. The difference between impact investigation at a coupon level and full scale structural level in terms of flexibility consideration was emphasized. Further, shell to solid based submodelling technique for impact investigation on the blade as well as shell-solid coupling based damage tolerance approach for residual strength estimation was described. Further, the efficiency of shell-solid submodelling based impact investigation was presented for a case when the projectile impacts the leading edge of the blade. The results for the nodal displacement fields for the driving nodes of the global model matched with the driven nodes of the submodel satisfying field equivalency. The critical damage modes like matrix cracking, delamination in the laminate, face core debonding, permanent deformations as well as surface indentation were illustrated. Overall, the submodelling based impact investigation presented a very efficient method for predicting impact response on the blade and can further be utilized to study impact investigation for a case when lifted blade impacts any structure. Also, in the future, these damages will be mapped with the allowable sea states along with a suitable residual strength study based on a shell solid coupled model.

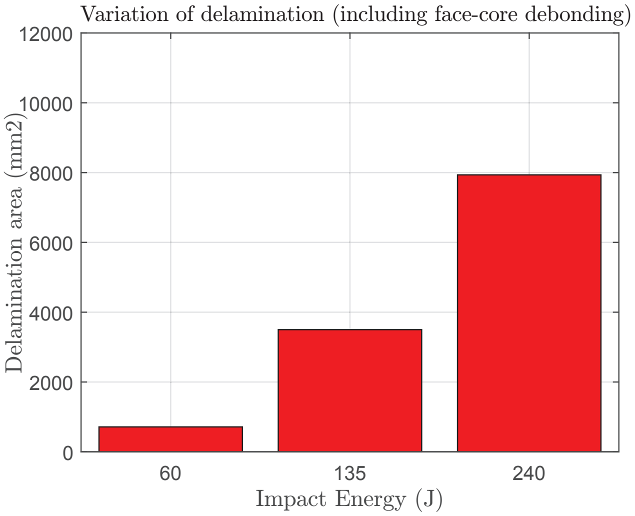

FIGURE 18. Variation of delamination area with impact energy

ACKNOWLEDGMENT

This work was made possible through the SFI MOVE projects supported by the Research Council of Norway, NFR project number 237929. The authors would also like to thank UNINETT Sigma2 for providing computational hours on the cluster.

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