Explicit Structural Response-Based Methodology for Assessment of Operational Limits for Single Blade Installation for Offshore Wind Turbines

Amrit Shankar Verma, Yuna Zhao, Zhen Gao and Nils Petter Vedvik

Abstract The growing requirements of large-sized offshore wind turbines require heavier components to be lifted to large heights using installation vessels. This imposes a substantial risk of impact to the lifted components especially when floating crane vessels are used. Floating crane vessels are in general sensitive to wave-induced motion, causing substantial crane tip responses and can lead to significant damage to the lifted blades. Currently, the planning for such weather sensitive operation does not include explicitly the risk of contact/impact or damage in the components to determine the operational limits. This is important for wind turbine blades owing to the fact that they are made of composite materials and are vulnerable to damage from contact/impact loads. The present paper proposes a novel methodology to determine response based operational limit for the blade installation by considering impact loads. Structural damage criteria for the lifted blade under accidental loads are linked with global response analysis of the installation system under stochastic wind and wave loads. A case study is also presented where a wind turbine blade lifted horizontally using jack-up crane vessel impacts the pre-assembled turbine tower with its tip region while being installed under mean wind speed of 10 m/s. It is found that under such conditions, it is safe to install blade from structural damage perspective as the characteristic responses obtained were low to develop any damage in the blade. The findings of the study can be used to derive limiting sea states for blade installation using floating vessels, however a damage tolerance approach requiring residual strength analysis post impact is compulsory.

Keywords Offshore wind turbine blade · Operational limits · Contact/impact behaviour · Marine operation · Jack-up vessel · Floating crane vessel

A. S. Verma (✉) · Y. Zhao · Z. Gao
Department of Marine Technology, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway
e-mail: amrit.s.verma@ntnu.no

N. P. Vedvik
Department of Mechanical and Industrial Engineering, NTNU Richard Birkelandsvei 2B, 7491 Trondheim, Norway

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1 Introduction

The average-rated capacity of offshore wind turbines has raised by over 62% in the last decade [1], with the industry further aiming to install bigger turbines away from the shore and into more deeper waters. The latest commercial 8 MW capacity offshore wind turbine is successfully grid connected for the Dong Energy's Burbo bank extension project at the coast of Liverpool in UK [2]. The hub height for this turbine is 105 m with length of the blade around 80 m. This requirement for bigger turbines along with large rotor diameters presents great challenges during the installation phase of the blade. This is because the blades are structurally sensitive and demands very high precision [3, 4]. One of the challenges is the risk of impact/contact to the blade especially when being lifted to tower top heights using floating vessels where it is expected to get large wind speed and the vessel exhibits high dynamic motion under the action of waves. This demands improved and optimized methodology to estimate operational limits for planning and execution of such operations especially from a structural safety perspective.

Wind turbine blades are made of composite materials and are vulnerable to impact loads and are therefore critical when compared with the components like transition piece and monopile made of steel materials. Steel structure displays ductile behaviour where as composite material on the other hand exhibits brittle behaviour and most of the energy absorbed during impact is dissipated either in elastic deformation or damage mechanism, with not always feasible to visually inspect such damages [5, 6]. Moreover, they exhibit quite complex and coincidental interacting failure modes which could affect the residual strength of the blade in a variety of ways [7–9].

Currently, the blades can be installed using jack-up crane vessels upto mean wind speed of 10 m/s which gives less than 2 months of weather window in the North Sea. Some of the new and advanced installation equipment claim to be able to install the blade till 15 m/s [3, 4]. These improvised installation concepts do not consider the structural damage criteria into account for establishing these operational limits, and are explicitly based on safe dynamic responses (for, e.g., vessel roll motions) in the system. In principle, these methodology should also guarantee the safety of the components from structural perspective along with the stability of the installation systems. The present paper proposes a novel methodology which establishes response based operational limits for blade installation in terms of allowable sea states. This would correspond to safe responses in the system also from a structural safety perspective under accidental contact/impact loads for the lifted blade.

In the past, Acero et al. [10, 11] has proposed a generic methodology to derive quite systematically a practical response based operational limits for any particular installation phase by measuring the responses in the system due to normal environmental loads. Li et al. [12] has successfully utilized this approach to study the operability limits for initial hammering process of the monopile using heavy lift floating vessel. Acero et al. [11] has also utilized this methodology to derive the operational limits for mating phase of the transition piece with monopile. The methodology proposed by Acero et al. [10] also includes some guidelines and procedures which can be utilized to study operability limits based on structural damage criteria for impact/contact risks. However, the criteria recommended in the approach is suited for the steel components, like monopiles and transition pieces, where complex damage modes are not expected to occur. Moreover, it was further studied by Li et al. [13] that the damages to the monopile and transition piece due to impact while installation were not significant at acceptable levels of allowable sea states. This is not the case for the blade as Verma et al. [5] found that the blade could suffer significant damages and exhibit quite complex failure mode under impact with the tower even at a low velocity of impact. Thus, for estimating operational limits for blade installation, it is important to link damages developed in the blade with global response analysis of the installation system. Further, the effects of impact induced damages on the blade's structural integrity needs to be considered. The proposed methodology in this paper takes into consideration all these factors and is explained in Sect. 2 of this paper. The methodology is explained with a case study on the DTU 10 MW blade model which is discussed in Sects. 3 and 4. Finally conclusions are presented in Sect. 5 of this paper.

2 Explicit Structural Response-Based Methodology

The choice of installation method for offshore wind turbines is the compromise between number of lifts, weight and number of components, water depth of the site and many times availability of the vessels [10]. Split type installation method is one of the most common methods of installing offshore turbines where all the components are individually installed [14]. Figure 1 presents a very general installation sequence for the components of a typical offshore wind turbine at the offshore site. The installation phase for the offshore wind blade onsets (Operation 5) after the monopile, transition piece, tower, nacelle and hub are successfully installed (Operation 1, 2, 3, 4). In principle, an offshore wind blade is lifted with a crane vessel from the deck and is finally mounted on the hub. Generally, it is horizontally lifted

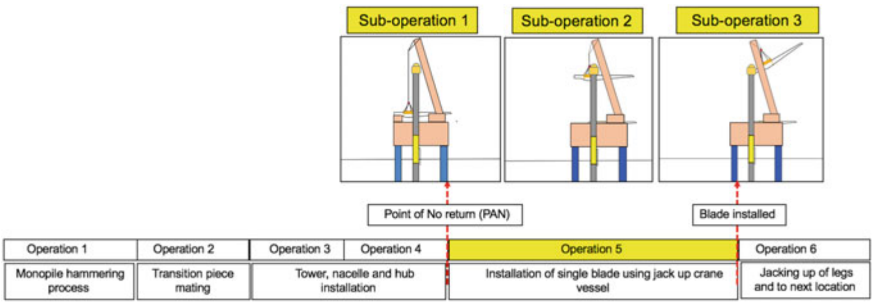

Fig. 1 Different stages of offshore wind turbine installation

Fig. 2 Horizontal lifting of blade [15]

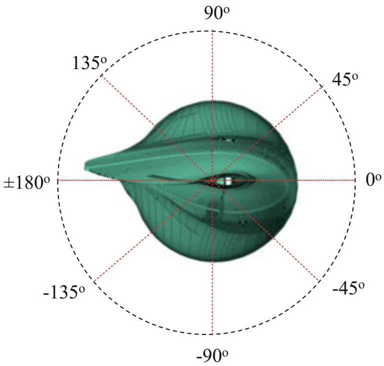

Fig. 3 Pitch angle variation for lifting [4]

(Fig. 2), tilt lifted or vertically lifted [3, 4]. The most common type of lifting method is the horizontal single blade mounting method [3, 4]. It comes with an advantage that the blade do not require a rotation because the blade are horizontally stored on the deck of the vessel. However, this method of lift presents different choices of pitch angle for the lift (varying from 0° to 180°) (Fig. 3) which again decides variation in lift and drag forces on the lifted blade. This would give varying dynamic responses in the blade as different aerodynamic shaped sections of the blade would be exposed in the wind. It is to be also noted that the behaviour and the nature of loads on the blade during lifting compared to the operational phase are different in nature and would also vary with change in the lift height towards hub [3, 4].

For simplicity, the entire lifting phase of the blade can be divided into three different sub-operations/phases (Fig. 4). When the blade is getting lifted-up from the deck and is in close vicinity with other structure and equipment (Sub-operation 1), when the blade is in full lift-off phase moving towards the nacelle (Sub-operation 2)

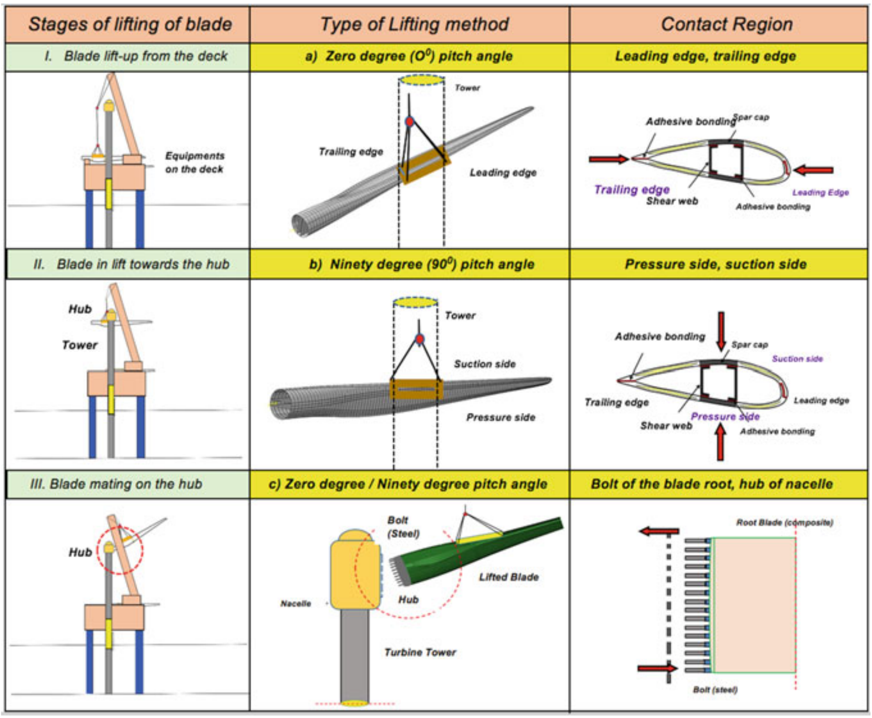

Fig. 4 Different impact scenarios and possible contact regions during lifting

and when the blade root part is going towards the hub for the mating phase (Sub-operation 3). These different sub-operations along with various choices of pitch angle for the lift presents different impact scenarios and contact regions along the blade. For sub-operations 1 and 2, the horizontal lifting with 0° (180°) pitch angle can cause the leading edge or the trailing edge vulnerable to impact whereas lifting with 90° pitch angle can cause pressure or suction side vulnerable (Fig. 4) [5]. These scenarios exposes the composite laminate section of the blade (as well as the adhesive joints and the sandwich sections) to impact. However, for sub-operation 3 (Fig. 4), the bolts of the blade root section, which is made up of steel and embedded in the composite, is vulnerable to impact. Also, for sub-operation 1 and sub-operation 2, the impact can occur at any section of the blade and thus different damage behaviour is expected as different sections of the blade has different layups with varying thickness implying varying strength and stiffness. Again, from structural safety perspective, impact induced damages for different exposed region will have varying influence on the strength of the blade. The delamination in the composite laminate during impact in sub-operation 1 (or 2) can cause sub-laminate buckling and thus effects the buckling strength [7]. Any damage to the bolts of the blade root region during sub-operation 3 can affect the fatigue life of the blade.

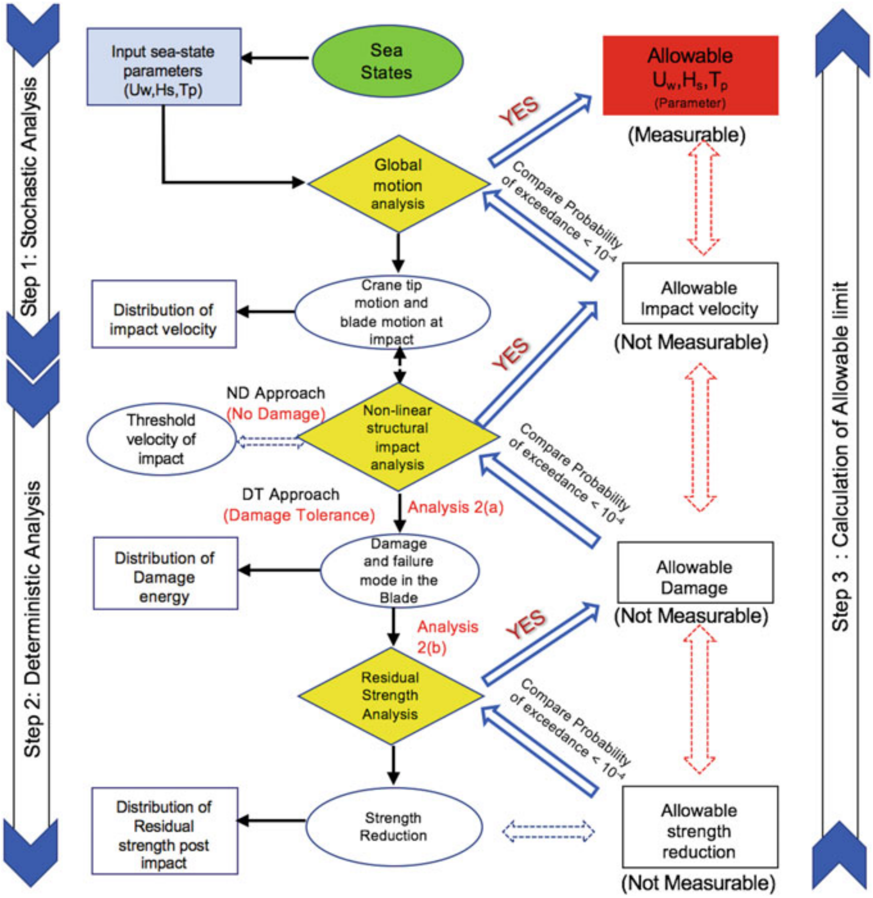

Fig. 5 Explicit structural response-based methodology

The current paper presents explicit structural response-based methodology (Fig. 5) for estimating allowable sea state for the blade installation by considering impact loads. Stochastic global response analysis of the installation system (Step-1) are linked with the structural impact analysis of the blade at different impact locations (Step-2) by estimating the distribution for impact velocity. The deterministic structural analysis considers damage assessment study on the blade (Analysis 2a) along with the residual strength analysis (Analysis 2b) on the damaged blade (Fig. 5). The details of the proposed methodology are described below.

Assumptions and restrictions: The methodology is applied to such cases where the installation philosophy of the offshore wind turbine is assumed to be a split type. It is further assumed that the other components of the turbine like monopile, transition piece, nacelle and hub are successfully installed (Fig. 1). It is also assumed that the installation phase of the blade is a weather-restricted marine operation which is mostly the case. The entire installation phase of the blade is considered to be a point of no return (PAN), meaning that once the blade is lifted, the operation cannot be reversed back (Fig. 1). The operational limits can be derived for each sub-operation based on structural damage criteria with relevant impact regions mentioned. The final operational limit for blade installation is the minimum value derived for all the three sub-operations.

Step 1: Stochastic global response analysis of the installation system with the lifted blade: The first step involves the stochastic global response analysis of the installation system with the lifted blade for a chosen sea state. Sea state parameters (Hs, Tp, and Uw) are used , and relationship between the environmental conditions and impact velocity are determined (Fig. 5). Finally, for a given sea state, the extreme value distribution of the impact velocity is obtained. This distribution will be used in connection with the structural impact analysis of blade to determine the distribution of damage energy.

Step 2: Nonlinear structural analysis of the blade model: This is an independent step in which, a nonlinear time domain impact analysis (damage assessment study) is performed on a finite element model of a blade. Different random impact velocities (Analysis 2a) are considered and threshold velocity of impact below which there are no damages developed in the blade are determined. Further, a deterministic relation between damage energy and impact velocity post the threshold value (Fig. 5) are established. The approach where the operational limit are derived based on the threshold value is called ND (No damage) approach where as the approach involving the operational limit obtained based on some level of acceptable damages in the blade is called DT (Damage tolerance) approach (Fig. 5). In order to consider the later approach, which facilitate in extending the operational limits, residual strength analyses on the damaged blade are performed (Analysis 2b). Finally, a deterministic relation between damage in the blade and its residual ultimate post impact strength are determined.

Step 3: Assessment of operational limit: The stochastic nature of the environmental condition implies that for any given sea state, the impact velocity, the blade damage and the residual strength would have a distribution and are linked with each other from the relationship obtained from previous steps. The allowable environmental conditions are the conditions that will lead to the same exceedance probability which is considered as a standard 10^{-4} for unmanned structure. For ND (No damage approach), the exceedance probability is estimated by considering an acceptable limit of the threshold value of impact velocity and for DT (damage tolerance) approach the exceedance probability is estimated based on allowable strength reduction, say 5%, from the distribution of residual strength obtained from previous step. The sea state parameters for which the exceedance probability is less than 10^{-4} is considered allowable.

3 Case Study

The present paper illustrate the above mentioned methodology for the *sub-operation 2* of the blade installation (Fig. 7). A case study is considered where the DTU 10 MW blade [16] suffers an impact with the tower at its tip region (60 m from root, along the leading edge) while being lifted. It is assumed that the blade is lifted in a turbulent wind with zero degree pitch angle at an installation height of 119 m using a jack-up crane vessel. The reason for choosing this section of the blade as the impact region is because this region has the least laminate thickness (18 mm, Fig. 11) along the leading edge. This is expected to be more sensitive to impact damage for the same level of impact energy compared to the other regions. The turbulent wind chosen for installation in the case study has a mean wind speed of 10 m/s at the hub height of the turbine with turbulence intensity of 15.72%. The complete illustration of the explicit response-based methodology based on damage tolerance (DT) approach is out of the scope of this paper and the paper focuses on the estimating whether the chosen turbulent wind with Uw = 10 m/s is safe for blade installation based on a ND (No damage) approach.

4 Analysis, Results and Discussion

As per the methodology, the first step is the stochastic dynamic motion response analysis of the installation system (Fig. 5). Steady state time domain simulations were carried out by coupled Aero-Hydro-Mechanical code, i.e., SIMO-Aero [3] to calculate the dynamic characteristics of blade motion during installation. The installation system includes a crane vessel, the blade to be installed, yoke and the hook modelled as rigid body (Fig. 6). A simplified nonlinear spring model was used to model the tugger lines under constant tension control. In this study, the target mean tension in the tugger lines is 80 kN. SIMO-Aero accounts for hydrodynamics of the installation vessel, mechanical couplings between bodies in the system and

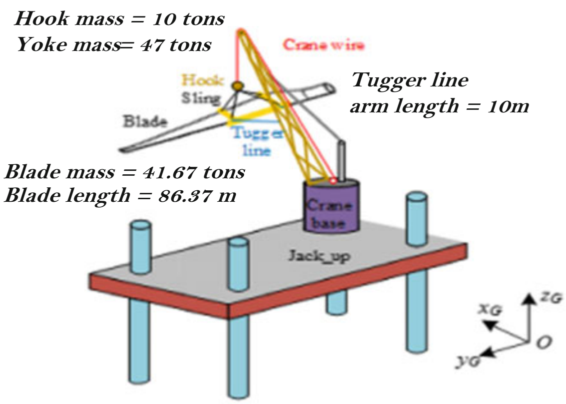

Fig. 6 Global response analysis of the installation system using SIMO-Aero [3]

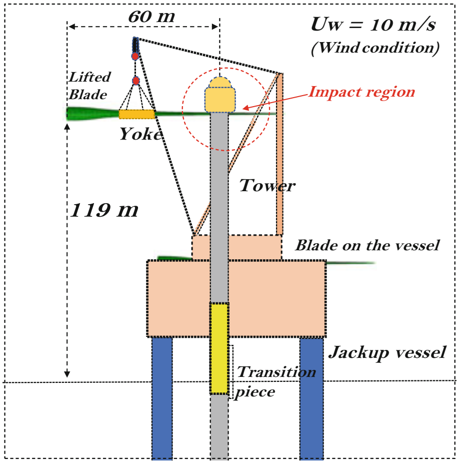

Fig. 7 Case study-sub-operation 2 of the installation phase

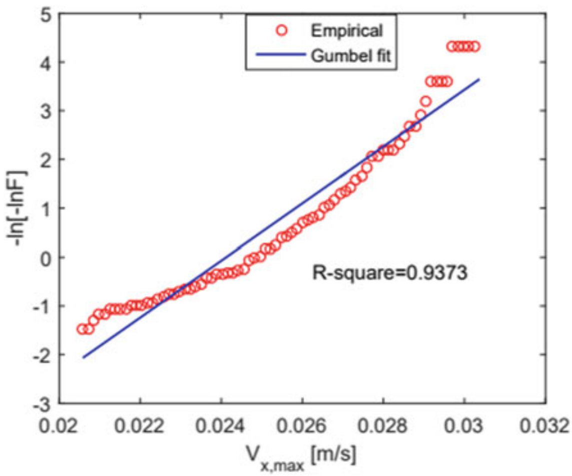

Fig. 8 Data fitting: Gumbel probability paper ($\mu = 0.0241$ and $\beta = 0.0017$)

aerodynamics of the lifted blade. Moreover, it was assumed that the jack-up vessel was rigidly sited on the seabed without any motion (Hydro module was unchecked). Details regarding the lift wire and slings could be found in [3]. A set of 30 steady state time domain simulations were run in turbulent wind conditions (Uw = 10 m/s, Iz = 15.72%) to get the characteristics of the impact velocity. Each simulation has a duration of 1100 s with the first 100 s removed to exclude transient effect. The total duration of data was 30,000 s. It was found that the motion of the blade is dominating in the x-direction and thus this velocity was chosen for further study. The maximum velocity (Vx) in each 500 s (60 data points) were selected for extreme distribution analysis and were fitted to Gumbel probability plot which showed good fit (Fig. 8). The parameters for the distribution were further estimated based on method of moments and is reported as ($\mu = 0.0241$ and $\beta = 0.0017$). Figure 9 shows the

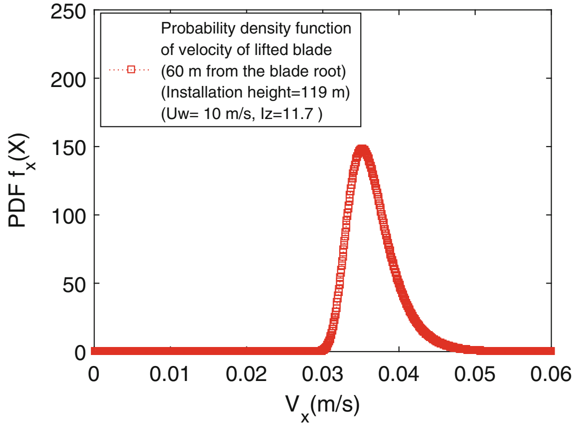

Fig. 9 EVD of impact velocity of the blade

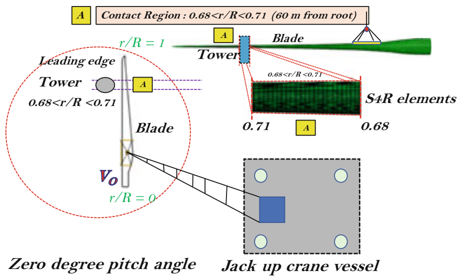

Fig. 10 Impact scenario and contact region considered for damage analysis (bird view)

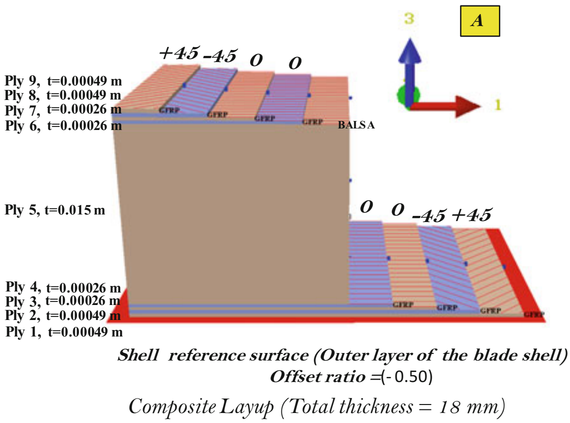

Fig. 11 Composite layup at the contact region $[+45/-45/0_2/\text{Balsa}]_s$

extreme value probability density function (PDF) for the impact velocity of the blade based on the above parameters for the particular chosen wind condition. These distributions connects stochastic analysis with the deterministic analysis.

After the distribution of the characteristics of the motion of the lifted blade is obtained, the next step is the nonlinear time domain impact analysis of the blade. Figures 10 and 11 shows the contact scenario (bird view) and the composite layup

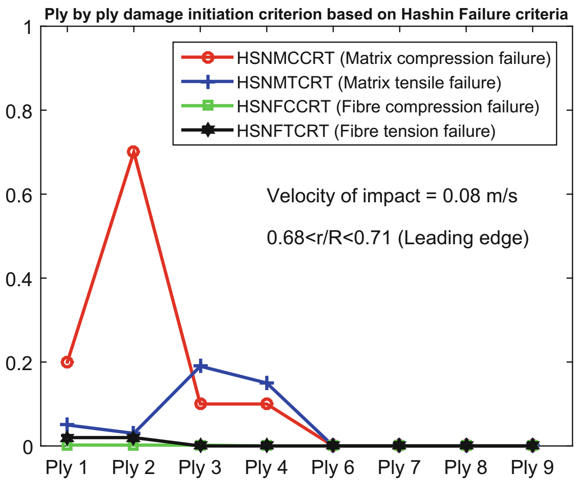

Fig. 12 Ply by Ply Hashin failure criterion 0.08 m/s (no damage initiation)

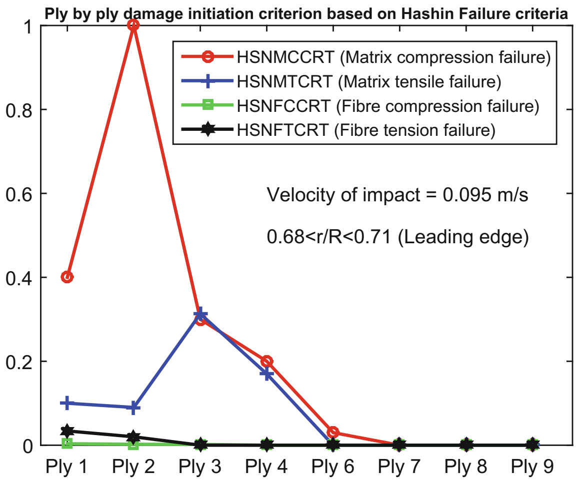

Fig. 13 Ply by Ply Hashin failure criterion 0.095 m/s (damage initiation)

respectively for the impact location (A, $0.68 < r/R < 0.71$) for the structural analysis in Abaqus/Explicit environment. The numerical modelling details for the blade along with the damage criteria and the nonlinear material and contact formulation implemented in this study can be found in [5].

The first step for this damage assessment study (Analysis 2a) is to find the threshold velocity of impact below which there is no initiation of damage in the blade. The blade was given initial velocity of impact starting with extremely low value. It can be seen that for the case of 0.08 m/s, none of the ply in the laminate has reached Hashin failure criterion equal to one (Fig. 12). This indicates that the damage initiation criteria has not been met and there was no damage in the blade which is consistent with the results for the damage energy presented in Fig. 14. However, for the case of 0.095

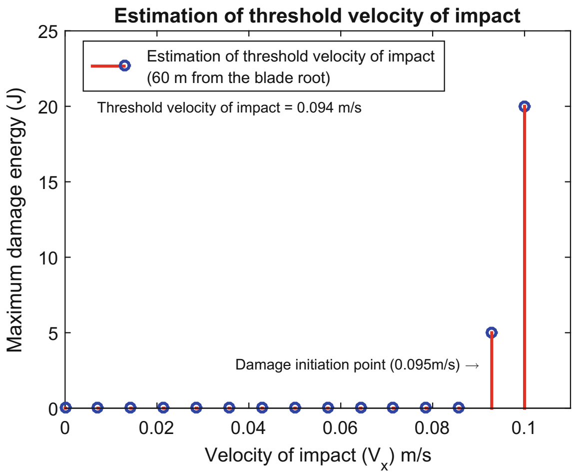

Fig. 14 Estimation of threshold velocity of impact (no damage approach)

m/s, Ply no. 2 (Fig. 13) has HSNMCCRT (matrix compression failure) criterion equal to one which confirms our understanding that the damage has initiated in the blade and there is development of damage energy as shown in Fig. 14. From the above discussion it can be said that the damage threshold velocity would lie somewhere below 0.095 m/s (Fig. 14). From further analysis, it was found that 0.094 m/s is the threshold velocity of impact and any impact velocity above it would initiate the damage. The threshold velocity of impact obtained from this study (0.094 m/s) can now be utilized to calculate the operational limit based on estimation of exceedance probability explained before. It was found that the exceedance probability calculated based on this threshold value from the extreme value distribution (Fig. 9) is of the order 10^{-6} and was much less than the acceptable limit of 10^{-4}. Thus from this observation, it can be said that the average mean wind speed of 10 m/s is safe for blade installation from structural damage perspective when no damage (ND) approach (i.e., allowing no damage in the blade even after impact and setting a limit before initiation of damage onsets) is used.

Further, in order to utilize the damage tolerance approach, it is important to estimate the dependency of damage energy with impact velocity post the threshold level. Nonlinear structural analysis of the blade, as discussed in step 2 in Sect. 2, was conducted with different impact velocities ranging from 0.1 to 4 m/s. The maximum values of damage energy developed in the blade for all impact velocities were obtained through suitable damage models which are presented as red-dotted points in Fig. 15. To reveal the dependency of damage energy with velocity, the red dotted points are further fitted using both first and second order polynomials, which are shown in Fig. 15 as well. After the relation between damage energy and impact velocity is determined ($638.14V_x^2 + 914V_x$), the distribution of damage energy can be obtained from the extreme value distribution of the velocity (Vx) obtained from Step 1 (stochastic analysis) by transformation of variables. However, one important

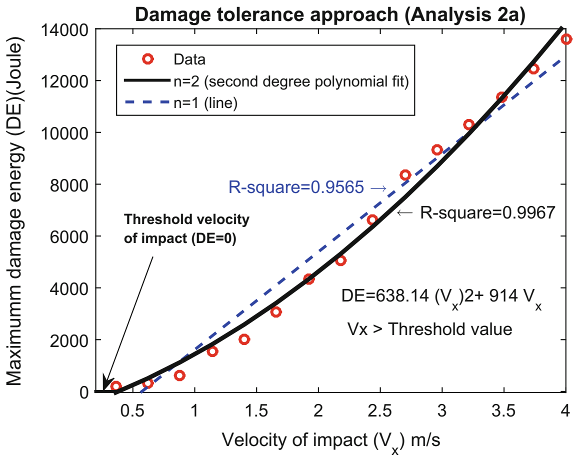

Fig. 15 Estimation of dependency of damage energy with the velocity of impact post damage threshold velocity (damage tolerance approach)

note to consider here is that the relation between the distribution of damage energy and impact velocity is dependent on the composite layup, details for the numerical model and will also vary with the choice of blade and thus require a broader statistical distribution utilizing large laminate layup sequences. This can be quite challenging as limited number of reference blades are available in research domain. Moreover, the reference blades, for, e.g., DTU 10 MW, are non-existing blades and do not correspond to practical blades used in industry. Alternatively, an experimental investigation on the blade would give some real time reference data to compare. Again, such an approach is important especially when the industry plans to go into deeper water and would require floating vessel to install the blade which could present these accidental impact events with a higher impact velocity, above the threshold level, as they will be influenced by wave-induced motion.

5 Conclusions

This paper presented a novel explicit structural response-based methodology to investigate the operational limit for the single-blade installation by emphasizing the importance of structural safety of the blade under accidental loads. The methodology maps the stochastic motion analysis of the installation system with different choices of pitch angle for the lifted blade with the deterministic structural impact analysis at different blade sections and finally calculates the operational limit. The methodology broadly mentions two different categories for calculation of such limits. The first category involves the No damage (ND) approach where the operational limits are calculated based on threshold impact velocity with no damage allowed in the blade. Another category is based on the damage tolerance (DT) approach which involves the utilization of post impact residual strength of the blade and can be applied further when the industry plans to extend its operational limit. The paper illustrates the mentioned methodology based on ND approach for the DTU 10 MW blade model lifted horizontally with jack-up crane vessel for zero-degree pitch angle under mean wind speed of 10 m/s which impacts the tip region of the leading edge of the blade. It was found that the blade was safe to install from structural safety perspective in such a wind condition given that the characteristic response were below the threshold level to cause any damage in the blade.

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