

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

Student name:	EVANS	Student P number:	
Programme:	BEng Automotive and Manufacturing streams		
Module:	Advanced Stress Analysis & FEA	Module Level (4, 5, 6):	6
Module code:	M6X00420	Contribution to Overall Module Assessment (%):	50 %
Lecturer:	Kelvin Lake	Internal Verifier:	Rob Goodson
Assignment Title:	Can FEA replace physical testing?	Assignment No (x of x):	1 OF 1
Hand Out Date:	25/02/2020	Submission deadline:	29/03/2020

Referencing:	In the main body of your submission you must give credit to authors on whose research your work is based. Append to your submission a reference list that indicates the books, articles, etc. that you have read or quoted in order to complete this assignment (e.g. for books: surname of author and initials, year of publication, <u>title of book</u> , edition, publisher: place of publication).			
Disclosure:	I declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people. All references have been duly cited.			
Student's Signature:	<i>Assignments will not be accepted without a signature here</i>	Date:		
Turnitin: Lecturer to tick to indicate if an electronic version of the assignment must be submitted to Turnitin. Note: the Turnitin version is the primary submission and acts as a receipt for the student. Penalties for late submission: Up to four weeks late, maximum mark of 40%. Over four weeks late, Refer. Only Year Tutors and the Programme Director may grant an extension.			YES	✓
			NO	

Learning Outcomes tested (from module syllabus)	Assessment Criteria To achieve each outcome a student must demonstrate the ability to:
Demonstrate an ability to analyse a range of engineering problems using advanced stress analysis principles.	

- DO NOT put this form into Turnitin or it will match many similarities with other students' submissions.

TASK DESCRIPTION

This assignment explores FEA and the role that it plays in product development. It is expected that the student will research this topic (referencing any sources used, using Harvard or Vancouver).

GUIDANCE FOR STUDENTS IN THE COMPLETION OF TASKS



The above image shows a component undergoing physical testing and the corresponding FE model. Your task for this assignment is to discuss the following;

1. Why companies typically carryout FE analysis alongside physical testing.
2. How a physical test may be correlated to an FE model.
3. If you think that FE analysis can (or should) ever replace physical testing.

In order to do this, you should consider a case study and use this to discuss the above tasks.

This report should be 3000 words long and should be submitted via moodle

STRUCTURAL SECTION MARKING CRITERIA AND STUDENT FEEDBACK

This section details the assessment criteria. The *extent* to which these are demonstrated by you determines your mark. The marks available for each criterion are shown. Lecturers will use the space provided to comment on the achievement of the task(s), including those areas in which you have performed well and areas that would benefit from development/improvement.

Common Assessment Criteria Applied	Marks available	Marks awarded
1. Research-informed Literature Extent of research and/or own reading, selection of credible sources, application of appropriate referencing conventions.		
(Assessed in point 1)	30	21
2. Knowledge and Understanding of Subject Extent of knowledge and understanding of concepts and underlying principles associated with the discipline.		
(Assessed in point 2)	30	20.4
3. Analysis Analysis, evaluation and synthesis; logic, argument and judgement; analytical reflection; organisation of ideas and evidence		
(N/A)	0	
4. Practical Application and Deployment Deployment of methods, materials, tools and techniques; application of concepts; formulation of innovative and creative solutions to solve problems.		
(Assessed in point 3)	30	20.7
5. Skills for Professional Practice Attributes in professional practice: individual and collaborative working; deployment of appropriate media; presentation and organisation.		
(Assessed in report presentation and structure)	10	7.3

Assignment Mark Overall (Assessment marks are subject to ratification at the Exam Board. These comments and marks are to give feedback on module work and are for guidance only until they are confirmed.)	Late Submission Penalties (tick if appropriate)		69.4%
	Up to one-week late		
	Over one week late		

COMMON ASSESSMENT AND MARKING CRITERIA

	OUTRIGHT FAIL	UNSATISFACTORY	SATISFACTORY	GOOD	VERY GOOD	EXCELLENT	EXCEPTIONAL
Assessment Criteria	0-29%	30-39%*	40-49%	50-59%	60-69%	70-79%	80-100%
1. Research-informed Literature Extent of research and/or own reading, selection of credible sources, application of appropriate referencing conventions	Little or no evidence of reading. Views and findings unsupported and non-authoritative. Referencing conventions largely ignored.	Poor evidence of reading and/or of reliance on inappropriate sources, and/or indiscriminate use of sources. Referencing conventions used inconsistently.	References to a limited range of mostly relevant sources. Some omissions and minor errors. Referencing conventions evident though not always applied consistently.	Inclusion of a range of research-informed literature, including sources retrieved independently. Referencing conventions mostly consistently applied.	Inclusion of a wide range of research-informed literature, including sources retrieved independently. Selection of relevant and credible sources. Very good use of referencing conventions, consistently applied.	A comprehensive range of research informed literature embedded in the work. Excellent selection of relevant and credible sources. High-level referencing skills, consistently applied.	Outstanding knowledge of research-informed literature embedded in the work. Outstanding selection of relevant and credible sources. High-level referencing skills consistently and professionally applied.
2. Knowledge and Understanding of Subject Extent of knowledge and understanding of concepts and underlying principles associated with the discipline.	Major gaps in knowledge and understanding of material at this level. Substantial inaccuracies.	Gaps in knowledge, with only superficial understanding. Some significant inaccuracies.	Evidence of basic knowledge and understanding of the relevant concepts and underlying principles.	Knowledge is accurate with a good understanding of the field of study.	Knowledge is extensive. Exhibits understanding of the breadth and depth of established views.	Excellent knowledge and understanding of the main concepts and key theories. Clear awareness of challenges to established views and the limitations of the knowledge base.	Highly detailed knowledge and understanding of the main theories/concepts, and a critical awareness of the ambiguities and limitations of knowledge.
3. Analysis Analysis, evaluation and synthesis; logic, argument and judgement; analytical reflection; organisation of ideas and evidence	Unsubstantiated generalisations, made without use of any credible evidence. Lack of logic, leading to unsupportable/missing conclusions. Lack of any attempt to analyse, synthesise or evaluate.	Some evidence of analytical intellectual skills, but for the most part descriptive. Ideas/findings sometimes illogical and contradictory. Generalised statements made with scant evidence. Conclusions lack relevance.	Evidence of some logical, analytical thinking and some attempts to synthesise, albeit with some weaknesses. Some evidence to support findings/ views, but evidence not consistently interpreted. Some relevant conclusions and recommendations, where relevant	Evidence of some logical, analytical thinking and synthesis. Can analyse new and/or abstract data and situations without guidance. An emerging awareness of different stances and ability to use evidence to support the argument. Valid conclusions and recommendations, where relevant	Sound, logical, analytical thinking; synthesis and evaluation. Ability to devise and sustain persuasive arguments, and to review the reliability, validity & significance of evidence. Ability to communicate ideas and evidence accurately and convincingly. Sound, convincing conclusions / recommendations.	Thoroughly logical work, supported by evaluated evidence. High quality analysis, developed independently or through effective collaboration. Ability to investigate contradictory information and identify reasons for contradictions. Strong, persuasive, conclusions, justifiable recommendations.	Exceptional work; judiciously selected and evaluated evidence. Very high quality analysis, developed independently or through effective collaboration. Ability to investigate contradictory information and identify reasons for contradictions. Highly persuasive conclusions
4. Practical Application and Deployment Effective deployment of appropriate methods, materials, tools and techniques; extent of skill demonstrated in the application of concepts to a variety of processes and/or contexts; formulation of innovative and creative solutions to solve problems.	Limited or no use of methods, materials, tools and/or techniques. Little or no appreciation of the context of the application.	Rudimentary application of methods, materials, tools and/or techniques but without consideration and competence. Flawed appreciation of the context of the application.	An adequate awareness and mostly appropriate application of well established methods, materials, tools and/or techniques. Basic appreciation of the context of the application.	A good and appropriate application of standard methods, materials, tools and/or techniques. Good appreciation of the context of the application, with some use of examples, where relevant.	A very good application of a range of methods, materials, tools and/or techniques. Very good consideration of the context of the application, with perceptive use of examples, where relevant. Evidence of some innovation and creativity.	An advanced application of a range of methods, materials, tools and/or techniques. The context of the application is well considered, with extensive use of relevant examples. Application and deployment extend beyond established conventions. Innovation and creativity evident throughout.	Outstanding levels of application and deployment skills. Assimilation and development of cutting edge processes and techniques.
5. Skills for Professional Practice Demonstrates attributes expected in professional practice including: individual initiative and collaborative working; deployment of appropriate media to communicate (including written and oral); clarity and effectiveness in presentation and organisation.	Communication media is inappropriate or misapplied. Little or no evidence of autonomy in the completion of tasks. Work is poorly structured and/or largely incoherent.	Media is poorly designed and/or not suitable for the audience. Poor independent or collaborative initiative. Work lacks structure, organisation, and/or coherence	Can communicate in a suitable format but with some room for improvement. Can work as part of a team, but with limited involvement in group activities. Work lacks coherence in places and could be better structured.	Can communicate effectively in a suitable format, but may have minor errors. Can work effectively as part of a team, with clear contribution to group activities. Mostly coherent work and is in a suitable structure.	Can communicate well, confidently and consistently in a suitable format. Can work very well as part of a team, with very good contribution to group activities. Work is coherent and fluent and is well structured and organised.	Can communicate professionally and, confidently in a suitable format. Can work professionally within a team, showing leadership skills as appropriate, managing conflict and meeting obligations. Work is coherent, very fluent and is presented professionally.	Can communicate with an exceptionally high level of professionalism. Can work exceptionally well and professionally within a team, showing advanced leadership skills. Work is exceptionally coherent, very fluent and is presented professionally.

Student Self Evaluation Form

Student name:		Student P number:	
Programme:		Year of programme	
Assignment Title:			

This section repeats in brief the common assessment criteria detailed on previous pages. The *extent* to which these are demonstrated by you determines your mark. Using these criteria, tick the box that best indicates the level of achievement you feel you have achieved with regard to each of them.

Common Assessment Criteria Applied	Level of Achievement						
	REFER		3 rd	2:2	2:1	1 st	1 st
	OUTRIGHT FAIL	UNSATISFACTORY	SATISFACTORY	GOOD	VERY GOOD	EXCELLENT	EXCEPTIONAL
1. Research-informed Literature	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐
2. Knowledge and Understanding of Subject	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐
3. Analysis	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐
4. Practical Application and Deployment	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐
5. Skills for Professional Practice	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐

PLEASE COMMENT ON AREAS IN WHICH YOU FEEL THAT YOU HAVE PERFORMED WELL	PLEASE COMMENT ON AREAS YOU FEEL THAT YOU NEED TO DEVELOP

Student's Name		Date	
Student's Signature			



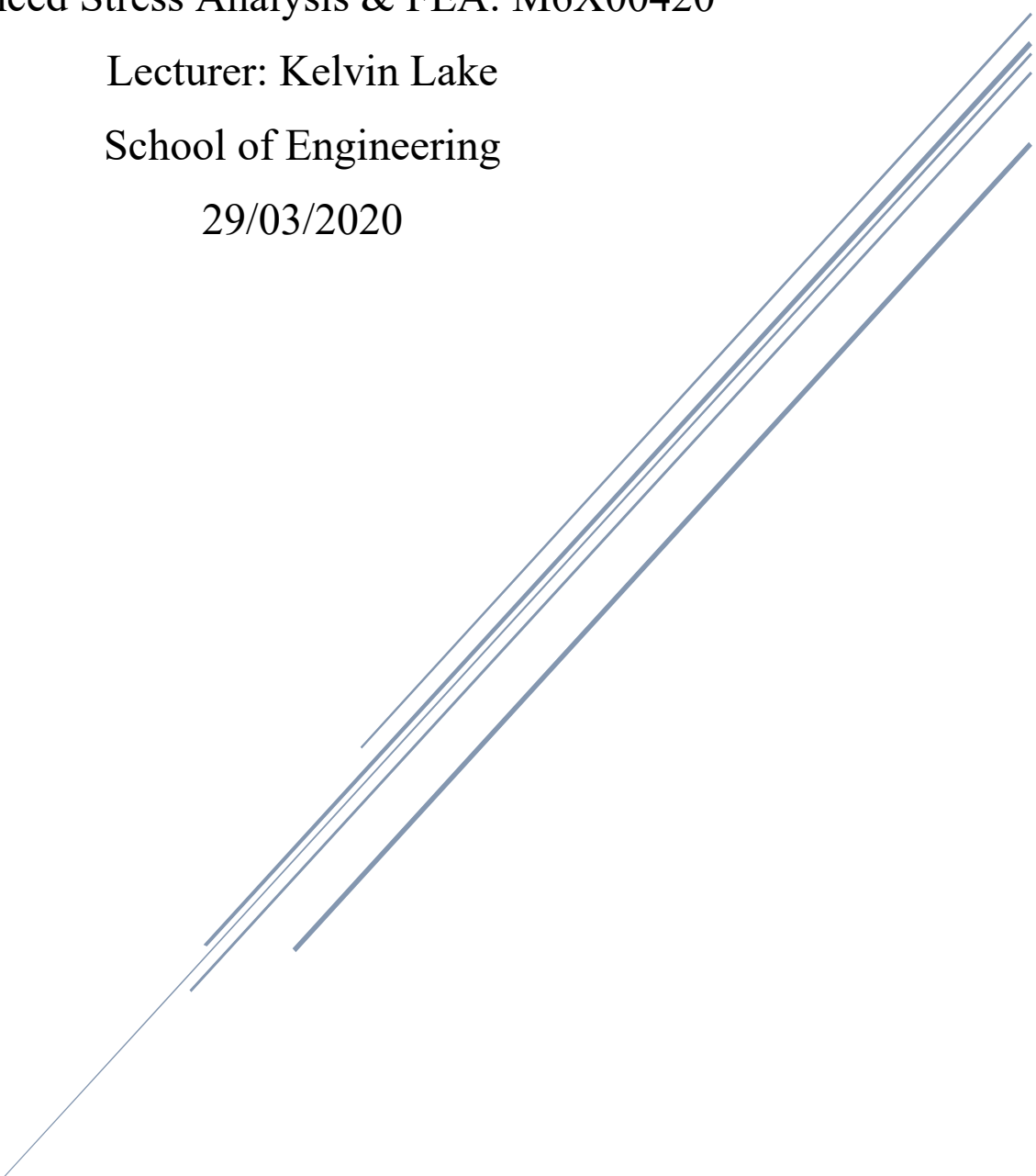
CAN FEA REPLACE PHYSICAL TESTING FOR TURBINE BLADES? A CASE STUDY

Author: Sion Evans (P150600)
Advanced Stress Analysis & FEA: M6X00420

Lecturer: Kelvin Lake

School of Engineering

29/03/2020



Abstract

With continuing increase of strain on resources as the population and quality of life increases, development of simulation techniques could prove astronomically beneficial if they are able to replace physical testing in the manufacturing industry. This paper aims to describe the FEA process and its correlation with physical testing at this date and then determine whether it is possible or should be possible. The literature reviewed in this report clearly described FEA as an extension of physical testing that has already shown to improve our understanding of physical systems as well as reduce prototyping and physical testing. However, it was found that FEA is limited to such qualities at this stage of human technological capabilities, and it is not yet possible, if ever, to replace physical testing completely.

Figure 1 Turbine blade structure (Decker, 2019).....	3
Figure 2. The standard FEA process (Gokhale, 2019)	4
Figure 3. 1 st and 2 nd order tetrahedral solid elements before and after deformation (SimScale, 2016)5	
Figure 4. Examples of element types used in FEA analysis (Rahul, 2018)	6
Figure 5. Stress distribution visuals along a turbine blade (Mourad Nachtane, 2018)	6
Figure 6. Full-scale testing apparatus of turbine blades (Bin Yang, 2013).....	8
Figure 7. Schematic diagram of various non-linear analysis applications (Gokhale, 2019).....	12

$Ku = P$	Equation 1. Static load equation	10
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Graph 1. Graph displaying the linear and non-linear components of material behaviour (Gokhale, 2019).	11
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Nomenclature

FEA = Finite Element Analysis

PDE = Partial differential equation

CAD = Computer Aided Design

K = Stiffness Matrix

u = Displacement

P = Vector of loads

Contents

Abstract.....	1
1. Introduction	3
2. Numerical Simulation.....	4
2.1 What is FEA	4
2.2 The FEA Procedure.....	4
2.2 i) Modelling/ Pre-processing.....	5
2.2 ii) Solution.	6
2.2 iii) Post-Processing.	6
3. Why Turbine Blade Manufacturing Companies Use FEA.....	7
4. Correlation Between Physical Testing and FEA of Turbine Blades.	8
4.1 Static Testing.....	8
4.2 Fatigue Testing.....	9
4.3 Modal Testing.	9
Non-Destructive Testing (NDT)	9
4.4 Correlation with FEA.	10
5.Limitations of FE-Simulations.	12
6. Can FEA Replace Physical Testing?	13
7. Future possibilities	13
8. References.	14
Appendix A.....	16

1. Introduction

The size and commercial production of wind turbines has continued to grow to a point where it can compete with fossil fuels. Currently, the largest installed turbine has a capacity to generate 12MW of energy with a blade diameter of 220m (GE Renewable Energy, 2020) with 142 TWh global energy contribution coming from wind in 2018 (BP, 2019). As the magnitude of the blade size is increasing, as to is the recurring issue of blade fatigue. Turbine blades are subjected to intermittent loading conditions caused by inertial accelerating loads, gravity and turbulent wind flow. Resulting in flapwise and edgewise direction loads that deform the blade and have the potential to cause catastrophic failure (Othman Al-Khudairi, 2017). To predict failure events and mitigate solutions to the design and development of such blades physical tests and analysis takes place. Such tests may include but are not limited to static testing, modal testing, fatigue testing and none-destructive testing. This can be done physically with experimental methods, analytical methods or through numerical simulations.

Numerical techniques are mathematical models that use computers to solve governing partial differential equations otherwise extremely difficult for humans to calculate. As computers improved over the years to become the super computers currently available today, as to did the efficiency, accuracy and applicability of numerical techniques. There are four types, Boundary Element Method, Finite Volume Method, Finite Difference Method and Finite Element Method. FEM is known to outperform other numerical models for structural approximations and solving complex transient PDE's over complex domains (Gokhale, 2019). FEA was developed by engineers in various industries to address structural mechanics problems. Earliest mathematical papers on FEA can be found as early as the analytical studies made by Schellbach [1851] with Courant [1943] being the first to introduce triangular and rectangular 'finite elements' (Stein, 2014). However, real life applications didn't start till the rise of the computers with the first papers submitted by Topp, Turner, Martic and Clough (1955) with groundwork for further developments in FEA submitted by Strang & Fix (1973) (SIMSCALE, 2020). To today's date where FEA has become a well-established integrated tool for design and development manufacturing processes across a range of industry.

Prior to simulation engineers depended on empirical information from laboratory's scaled up to industry level for the development of a product (Date, 2005). This paper aims to describe the FEM procedure, use published literature to address its current correlation with physical testing and finally determine whether an FEA model can completely replace physical testing for wind turbine blades. The structure of a turbine blade can be seen in [Fig. 1] with a full description in the appendix.

GOOD INTRO.
GOOD CONTEXTUALISATION

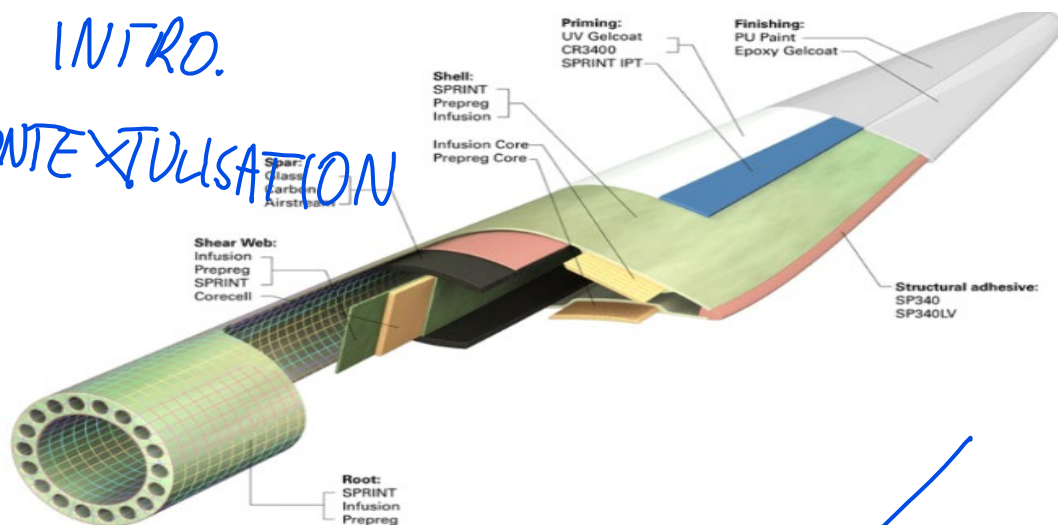


Figure 1 Turbine blade structure (Decker, 2019)

2. Numerical Simulation

2.1 What is FEA

FEA is a name given to any simulation that uses the Finite Element Method (FEM) to quantify and understand physical phenomena, such as wave propagation, thermal transport and structural/fluid behaviour. The FEM does this by describing complicated partial differential equations (PDEs) otherwise impossible without computers. PDEs are discretized and represented by an array of nodes where unknown values are approximated, usually polynomial (SIMSCALE, 2020). Multiple computer software packages are used across industry, some include SOLIDWORKS, Auto-CAD, CATIA. There is not any clear indication that any particular software is better than another, the decision on which software to apply the model is typically down to the preference of the user (Gokhale, 2019).

2.2 The FEA Procedure

The FEA procedure takes place in three main stages, the procedure is divided into, modelling, solution and visualization as illustrated in [Fig. 1].

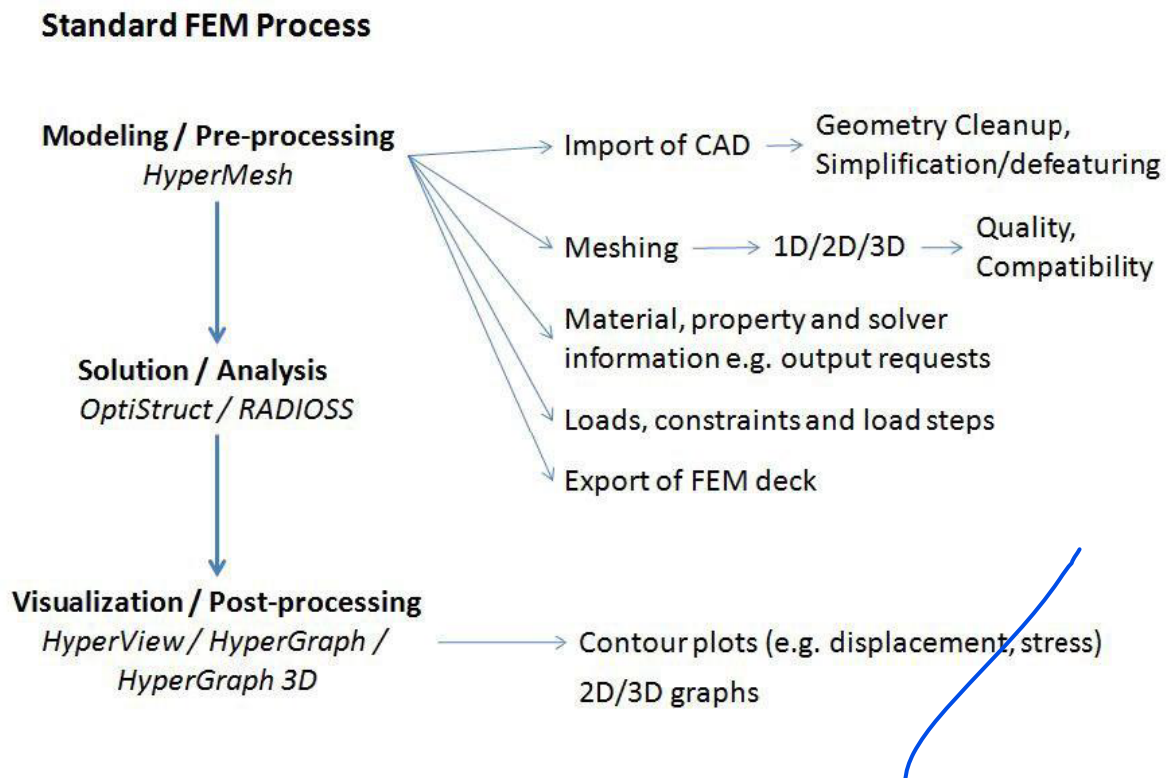


Figure 2. The standard FEA process (Gokhale, 2019)

2.2 i) Modelling/ Pre-processing.

At the beginning of FEA simulation a CAD geometry is imported into the pre-processor. This is where the geometry is cleaned up to remove issues such as broken surfaces, un-stitched surfaces, redundant surfaces and any other issues (Onwubolu, 2013). Issues such as these can cause complications in the meshing procedure further along the process, so it is crucial that everything is straightened out before moving forward with the procedure.

Once an appropriate geometry is acquired, the creation of the mesh can begin. The mesh is built up with an array of elements built up from nodes. Nodes are single points within a programme that contain material and structural data, they are connected by lines to create an element and eventually a mesh (Date, 2005). It is through this medium, approximations are made. Therefore the number and quality of the elements directly affects the accuracy of the results, and subsequently the computational time of the simulation. A mesh can consist of various element types as illustrated in [Fig. 3], the most commonly used elements are 1D Beam elements, 2D Shell elements and 3D Solid elements (Gokhale, 2019). The mesh set-up is the most crucial part of any numerical model, if little or no time goes into element and mesh set-up, the whole simulation is compromised.

The majority of parts analysed using FEA simulations utilize a 3D, solid element model to define the boundaries surrounding the part. This is typically the industry standard as it produces more accurate results than a 1 or 2D element mesh (Gokhale, 2019). Solid elements have 3 degrees of freedom per node but can have a different number of nodes depending on which order (1st or 2nd) of the element. As shown in [Fig. 2], a first order tetrahedron has four flat faces and vertices, with 4 connecting nodes. The second-order tetrahedron has four flat faces with 10 nodes including the 4 vertices and mid-points of its edges (Onwubolu, 2013).

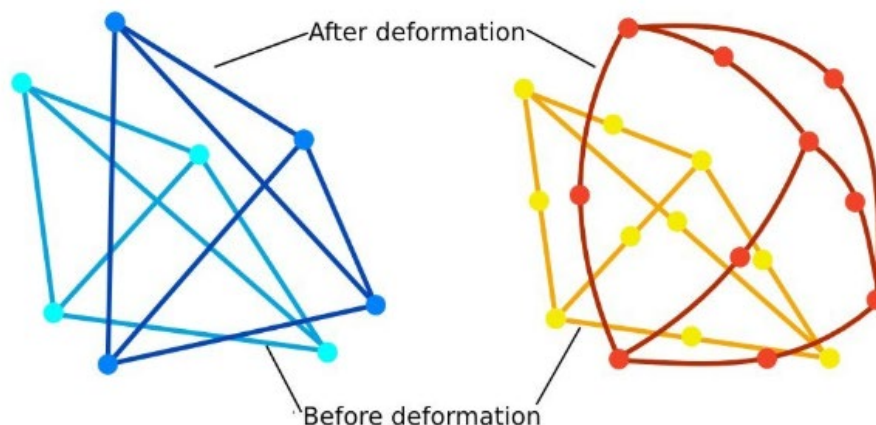


Figure 3. 1st and 2nd order tetrahedral solid elements before and after deformation (SimScale, 2016)

A shell element is a triangle consisting of 3 nodes with 6 degrees of freedom. Typically considered less accurate than a solid mesh, however in some particular cases containing thin-walled parts, i.e. sheet metal parts, a shell mesh is preferred for its low computational cost and solve speed and widely used across the turbine blade manufacturing industry (Aaron Miller, 2013; F.M. Jensen, 2006; Othman Al-Khudairi, 2017). 1D beam elements are typically used to create structural members as the reduced number of nodes and elements is desirable for their minimal impact of computational cost (Onwubolu, 2013).

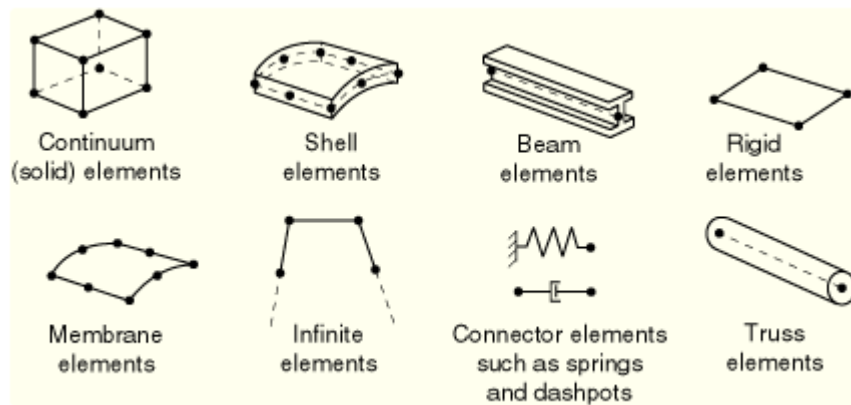


Figure 4. Examples of element types used in FEA analysis (Rahul, 2018)

Following the completion of the mesh, material and property information is assigned to the elements. Solver information, Loads and constraints are then inserted to replicate the conditions under which the product must be tested before progressing to the next stage of development.

2.2 ii) Solution.

This part of the process is where the FEA software provides a solution to the conditions set by the user, by solving the constituent governing equations. Any issues with the model will prompt the software to display an error. Some examples of errors include invalid material properties, poor element quality and insufficiently constrained model.

2.2 iii) Post-Processing.

Finally following a successful solve, the post-processing package is where visualisations of the parameter being analysed, e.g stress, strain, deformation, is illustrated to the designers. Many conclusions are drawn from this process, where the behaviour of the product being tested can be visualised in ways impossible to do in real life applications, expanding the knowledge of the engineers working with a particular product (REF). An example of this can be seen in [Fig. 4]

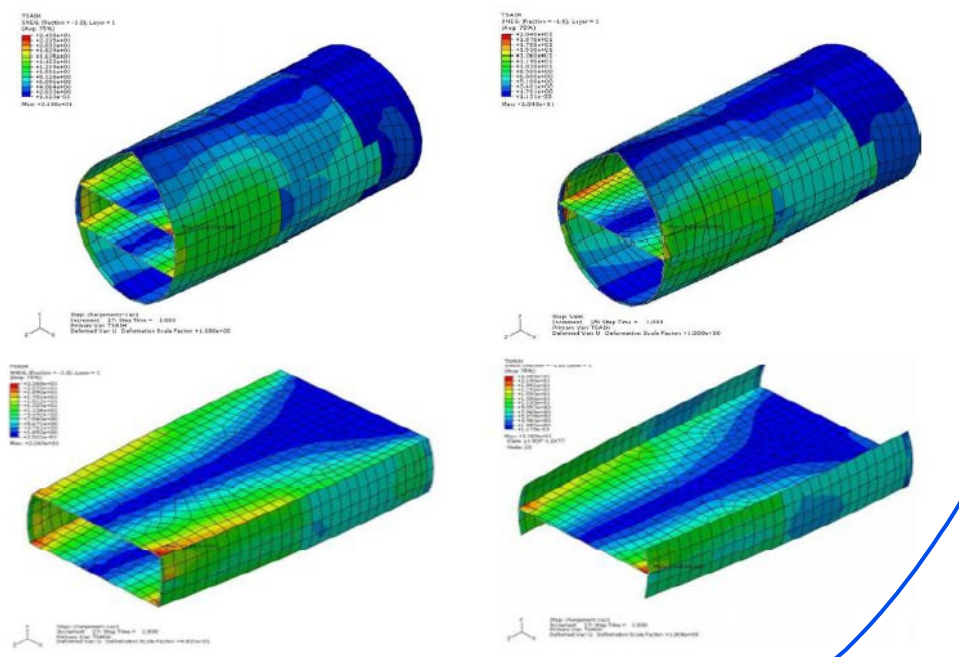


Figure 5. Stress distribution visuals along a turbine blade (Mourad Nachtane, 2018)

3. Why Turbine Blade Manufacturing Companies Use FEA.

As wind turbine technology has developed the size of the turbines has exponentially grown to as large as the Haliade-X 12 MW offshore turbine with a turbine diameter of 220m (GE Renewable Energy, 2019). Determining the blade envelope on aerodynamic performance alone is no longer practical, there is now a requirement to consider the structure of the blade much earlier in the design process, as the structural concerns have become a more dominant design criterion (Thomas D. Ashwill, 2003). FEA is the primary numerical tool used by blade manufacturing companies to carry out structural analysis in the design and development process (Nitin Tenguria, 2011). Its proficiency is recognised worldwide as it provides a range of advantages over traditional testing methodologies, resulting in increased productivity and revenue, two desirable outcomes all companies wish to ascertain. Advantages include but may not be limited to:

Comprehensive result sets – FEA can generate a physical response of the system at any location, particularly those that cannot be captured by a physical section analysis. An example of this can be seen in full blade shell modelling, where second-order layered shell elements are used to model non-beam behaviours like cross-sectional warping (Thomas D. Ashwill, 2003).

Optimal use of a model – Once calibrated of FEA several failure modes namely critical failure, fatigue due to gravity, acceleration or cyclic loading can be done using the same model. Through numerical simulation complex load cases that represent actual wind flow can be analysed (Anon., 2011), a big advantage over full-scale tests that can only impose idealized loads. Setting up an FEA model is much more practical than setting up physical apparatus to test for each failure mode individually.

Increased Accuracy and Insight into critical design & physical testing parameters – Traditionally, ideas were sketched up, developed into prototypes and manufactured before testing could take place, only to find certain parameters had been overlooked (REF). FEA allows for simultaneous calculations and visualization of physical parameters. As a result, designers can accurately simulate critical test conditions and gain a more advanced knowledge of where and how failures occur.

An example of this can be seen in the works of (F.M. Jensen, 2006) where a 34m wind turbine blade has been tested in flapwise bending till collapse. A non-linear FEA was employed and compared with measurements taken and showed that delamination of the outer skin was the initial failure, followed by delamination buckling and a complete collapse. Without the post-processing features of FEA, the origin of the delamination buckling would be very difficult to determine.

Virtual Prototyping - FEA simulation has allowed initial designs to be virtually created and analysed in hours, compared with the days or weeks it would take for a physical prototype, saving time and money. Scholars and manufacturers use FEA to virtual prototypes to investigate a fatigue analysis of various materials and designs that reduce blade weight and subsequent gravitational fatigue loads (Aaron Miller, 2013). Composite fiberglass blades cost as much as \$9-11 per kg, with a typical 1.5 MW turbine blade weighing roughly 216 kg (Composite World, 2008). Without the use of FEA simulation software physical prototypes would cost so much time and money the technology would most likely not be feasible, especially whilst trying to compete with the oil and gas energy industry.

4. Correlation Between Physical Testing and FEA of Turbine Blades.

This section aims to briefly describe physical testing processes and how they correlate to FEA. During operation the blade is aerodynamically loaded in the flapwise direction and gravitationally loaded in the edgewise direction, which increase with blade size (Othman Al-Khudairi, 2017). A paper by (Mourad Nachtane, 2018) identified and studied the critical loads of a turbine blade, which can be written as:

1. Wind loading.
2. Bending loading.
3. Buckling loading.
4. Centrifugal loading.
5. Gravity loading.

The Mechanical property testing of such blades is essential for the safe-guarding and quality assurance of the technology. Such property tests are measured under individual or combinations of tensile, compressive and shear loads, this is done through static, fatigue and modal testing (Bin Yang, 2013). This can be done through full-scale testing where idealised conditions are set and strain gauges sensors and accelerometers collect relevant data, as seen in [Fig. 4]. This section aims to briefly describe physical testing process and identify the correlation with FEA.

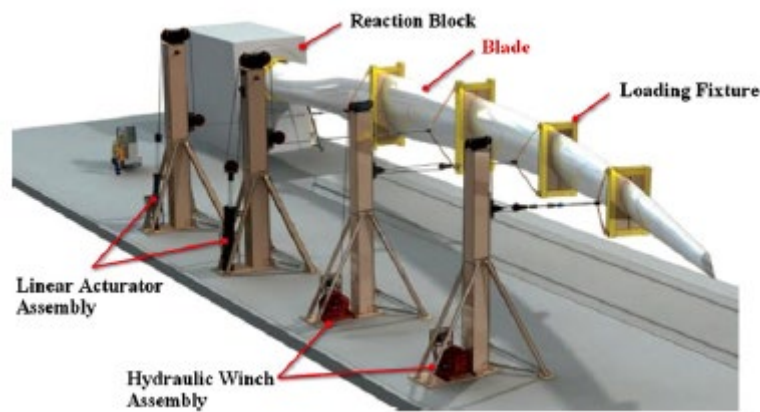


Figure 6. Full-scale testing apparatus of turbine blades (Bin Yang, 2013)

4.1 Static Testing.

In experimental static testing loads are unidirectionally applied to the blade to determine the ultimate strength. This is done to ensure blade and tower collisions to not take place and determine a blades ability to withstand excessive cyclic loads caused by transient storm conditions. The test methodology being a choice of destructive or none-destructive testing. Such test can take form in many ways depending on the size of the blade, multiple techniques can be seen in a review of turbine testing technologies reported in (Bin Yang, 2013).

4.2 Fatigue Testing.

Blades are subjected to highly irregular loading conditions caused by gravity, turbulent wind flow and inertial loading during acceleration of the turbine. Fatigue testing is open to determine failure mode and fatigue strength of the blade, in particular fatigue at attachment regions, such as the root attachment of the blades and rotor. The technique of doing such a test is down to inhouse industry standards with variation between one company and another (Thomas D. Ashwill, 2003) There are multiple laboratories worldwide that have developed their own methods for fatigue testing as can be seen in the work of (P.R. Greaves, 2012).

4.3 Modal Testing.

Modal analysis is carried out to determine the dynamic characteristics of structural element at resonance (TARTIBU, 2015). Turbine blades have become more flexible as they have grown, creating potential instability problems. Determining the modal parameters is crucial for determining the blades reliability as the resonant properties of the blades are influenced by the physical geometry properties.

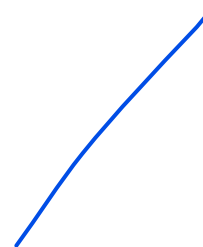
The modal analysis is accomplished through a number of experimental techniques where the dynamic properties are characterised into the following modal parameters:

- Modal frequency.
- Damping factor.
- Mode shape

Modal frequency analysis is performed by exciting the blade at a fixed point in a fixed direction, using an impact hammer and electrodynamic shaker. Accelerations are measured at various cross-sections along the blade using accelerometers.

Non-Destructive Testing (NDT)

The field of NDT is also used on turbine blades, typically used inspection rather than full-scale structural analysis. Some techniques include vibration analysis, thermography, X-ray imaging, in acoustic emission testing and ultrasonic techniques. Although it is typically used for inspection, some techniques can cross over to the development and design stages of blade manufacturing. A comprehensive description of the following techniques has been published in the works of (R. Raišutis, 2008; Bin Yang, 2013).



4.4 Correlation with FEA.

At today's date in FEA is used as an extension of physical testing the gain comprehensive understanding of the governing physical principles. When referring to the correlation between FEA and physical testing, it is the types of analysis used in FEA and the application within the wind industry that is of interest. This section aims to briefly describe certain analysis types that are associated with the physical tests above. As submitted in the FEA Altair Guidelines (Gokhale, 2019), the FEA model has a range of analysis capability including:

- | | |
|---------------------------|---------------------|
| 1. Linear static analysis | 6. Fatigue analysis |
| 2. Nonlinear analysis | 7. Optimization |
| 3. Dynamic analysis | 8. CFD analysis |
| 4. Buckling analysis | 9. Crash analysis |
| 5. Thermal analysis | 10. NVH analysis |

The following analysis capabilities are practically applied in the manufacturing industry, particularly in product design and existing product development. Allowing engineers to accurately simulate and approximate solutions cheaper than traditional methods and with more visualisation of theoretical internal stresses (Onwubolu, 2013). It is used as a tool to ensure that new and existing products meet economic and physical specifications and determine allowable modifications required to overcome any problems permitting it from.

Linear static analysis is the most popular analysis type used in an FE-simulation, where the elastic modulus is taken to be constant and the material behaviour is represented by a straight line through the origin, later broken into solid pieces as it succeeds the ultimate stress (Gokhale, 2019). It is typically used as an extension of static and fatigue testing for wind turbine blades, examples of its correlation are published in the works of (Aaron Miller, 2013; Othman Al-Khudairi, 2017). FE models are typical to be built of simple 2D shell elements where the static load is solved using [Eq. 1] following the static force and equilibrium conditions that applies to static analysis.

$$Ku = P$$

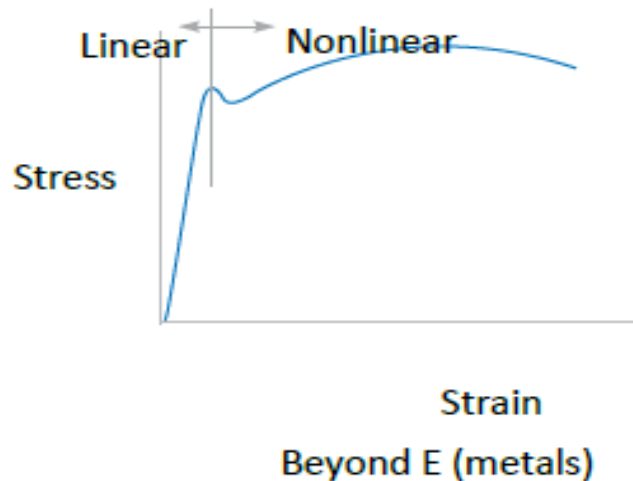
Equation 1. Static load equation

K = Stiffness Matrix

u = Displacement

P = Vector of loads

Non-linear analysis is also used in fatigue testing, it is associated with non-linear elastic, viscoelastic and elastoplastic material behaviour where the force vs displacement curve is polynomial [Graph. 1]. It is used to deal with true stress and strain where stiffness is a function of displacement (Gokhale, 2019). Its applications can be seen in [Fig. 5], although its typical function is to analyse local deformations with a more complex sophisticated mesh made up of solid 3D elements, in place of the global shell elements system that fails to accurately simulate this phenomena. As discussed in the works of (Nitin Tenguria, 2011; F.M. Jensen, 2006).



Graph 1. Graph displaying the linear and non-linear components of material behaviour (Gokhale, 2019).

Non-linear analysis typically correlates to critical loading analysis due to its accurate prediction of material properties after succeeding ultimate stress. This FEA is used to discuss significant damage behaviour and knowledge of complex structural behaviour and can be seen in the critical load analysis work submitted by (Mourad Nachtane, 2018). A comprehensive description of other non-linear applications can be found in the work of (Altair REF).

Other analysis types such as fatigue, dynamic, acoustic, thermal and response spectrum also apply to static and fatigue testing also to modal testing. In all cases FE-simulation is used as an extension of the physical test to gain otherwise unavailable insight to phenomena that takes places during cyclic, transient, shear and compressive loads that a blade is subjected to. An officially validated modal can take the place of most of the physical test, especially in the early development stages with regards to modal testing for blade material and geometry selection. NVH analysis capabilities of FEA are typically used in the design process of turbine blades as noise pollution from wind turbine is an old age issue with negative public perception potentially damaging the development of the wind energy industry.

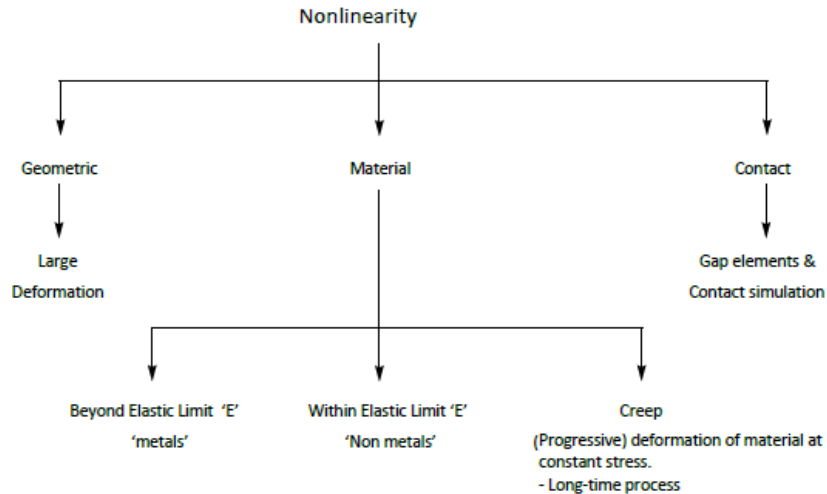


Figure 7. Schematic diagram of various non-linear analysis applications (Gokhale, 2019)

5. Limitations of FE-Simulations.

FE-simulation is not without its limits and is subjected to a range of errors and uncertainties holding it back. The uncertainty in FEA and all numerical simulations can be categorised into numerical uncertainty and physical uncertainty.

Difficulties arise when applying an FE-model to a full-scale test. In the case of a full scale turbine blade test, high tolerances in the manufacturing process creates empty spaces and variation in geometrical details that validated models do not recognise, thus creating errors and uncertainties in the numerical results (F.M. Jensen, 2006). Difficulties also arise in attempting to predict local deformations with globalised 2D shell mesh where inaccuracies leave uncertainty of results. A solid 3D mesh can be used to simulate such local deformation however, little work has been done on the integration of both mesh types so actual test data is required for identifying localised deformations that require a more sophisticated 3D solid mesh (Nitin Tenguria, 2011).

Additionally, physical uncertainties can be found in boundary and initial conditions, geometry details, loads and material properties (Dascotte, 2004). Variables such as temperature, load level and frequency can affect each of these physical properties through changing how the material is affected, making it difficult to realistically simulate this change. The numerical uncertainties can be accumulated by several variables, such as:

- Lack of system understanding, and vague physical process data can lead to conceptual modelling uncertainties.
- The choice of element type, level of geometrical detail and mesh density can lead to discretization uncertainties. Additionally, errors accumulated in the discretization process occur leading to differences in result sets found using the same FE-model (Dascotte, 2004). Tolerances, convergence, integration step and rounding number also lead to solution errors and uncertainties. A paper submitted by the centre for predictive engineering and computing sciences presents a method for estimating the previously discussed errors, it can be found in the work of (Todd A. Oliver, 2014).
- The wrong utilization of the software and input programming errors are examples of human errors leading to numerical simulations.

6. Can FEA Replace Physical Testing?

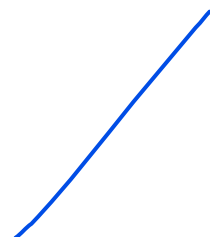
The aim of this paper was to discuss the FEA process, the correlation this has with physical testing and to determine whether FE-simulation could, or should, completely replace physical testing. It is clear across all literature that numerical modelling, including FEA, has continued to improve to a point today where design, meshing, analysis, and postprocessing comes highly integrated and automated alongside physical testing. It continues to be used across industry as a reliable tool to improve the accuracy, efficiency, cost and analysis of not only turbine blade, but all manufacturing processes.

This world is of finite resources, with exponentially growing population and need for raw materials, the longevity of humankind is at risk and the sustainability of our processes are of great importance. Through the creation of a simulated world capable of realistically representing underlying physical properties, the limitations of a finite world would be no more and new the possibilities of an infinite simulated world would be revealed and serve a great purpose for mankind. However, as perfect as that sounds it is currently more of a science-fiction fantasy than it is a possibility. Numerical simulation has dramatically reduced the need for a range of physical testing apparatus and processes, reducing the use of materials and subsequently reducing cost. Unfortunately, that is all it is limited to with current technological capabilities. Without the validation of numerical models through imperial measurement and physical testing as they are currently based on nominal values for input.

It is clear from the works of scholars and engineers surrounding FEM that it is not yet at a stage where it can completely replace physical testing for turbine blade manufacturing. In some cases physical testing is even required by law where national standards for German certification body requires a full scale static and fatigue testing before being certified for use (Thomas D. Ashwill, 2003). Contradictory to replacing physical testing, some scholars suggest more testing is needed to improve the efficiency and accuracy of FE-modelling through the analysis of test data to determine probability distribution function and their properties (Dascotte, 2004). This work highlights an important point as validating a single simulation from a single test only reveals a small picture if the scatter of the input test data is not considered.

7. Future possibilities

This paper is limited only to the FEA capabilities with regards to turbine blade manufacturing. Further investigation into whether certain niche products have the capability of being physically tested and manufactured completely through simulation. The sheer size and health risk of wind turbines make it much more difficult for this to be possible. Additionally, more physical testing is desirable to build up a vast range of physical data to improve the probabilistic nature of numerical modelling by improving the accuracy of inputted data obtained by collecting more physical test results.



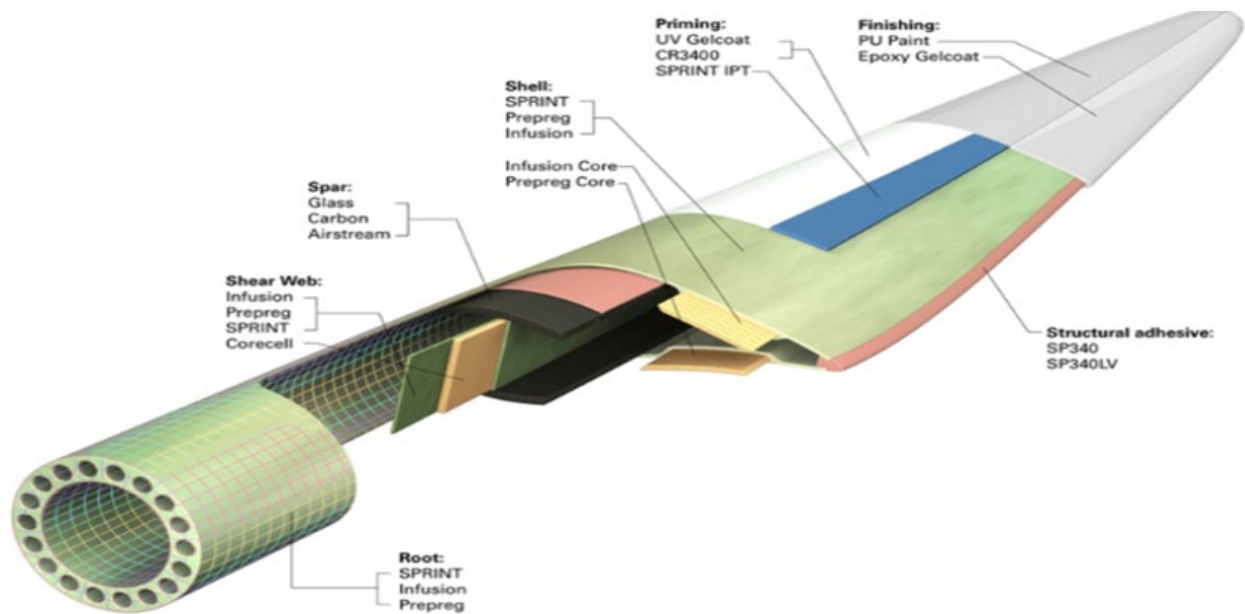
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Appendix A.

Wind turbine blades are the component used to harvest kinetic energy in the prevailing wind and transfer it to the rotor to generate mechanical torque which is later used to generate electricity. The blades function by harvesting the lift-component of the wind through using aerofoil technology. Through using such technology wind velocity is encouraged to accelerate over the top of the aerofoil creating low velocity below the profile and generating lift. The blade is generally tapered from a thick profile near the joint to the rotor to a narrow profile near the blade tip to increase the tip speed ratio and maximise lifting capacity. Typical structural architecture for wind turbine blades. The spar cap is a relatively thick laminate with primarily unidirectional fibres to carry the flapwise bending loads. Blade skins are typically double-bias or triaxial fibreglass, with balsa or foam core used as needed for buckling resistance. Historically, wind turbine blades have been constructed using either all-fibreglass laminate or, in a few cases, fibreglass construction with selective use of carbon for local reinforcement. For blade sizes up to 30 m the most common manufacturing approach has been an open mould with wet lay-up. The most notable exception to that approach is Vestas Wind Systems, which has a long history of using prepreg fibreglass in its blade manufacturing process as described by (Thomas D. Ashwill, 2003).



GOOD CASE STUDY USED TO CONTEXTUALISE YOUR REPORT WELL.
HOWEVER YOU COULD HAVE DISCUSSED THE IMPACT THAT FEA HAS ON
THE DESIGN PROCESS FURTHER.