

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

Student name:	FOXTON	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I declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people.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:	Assignments will not be accepted without a signature here	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

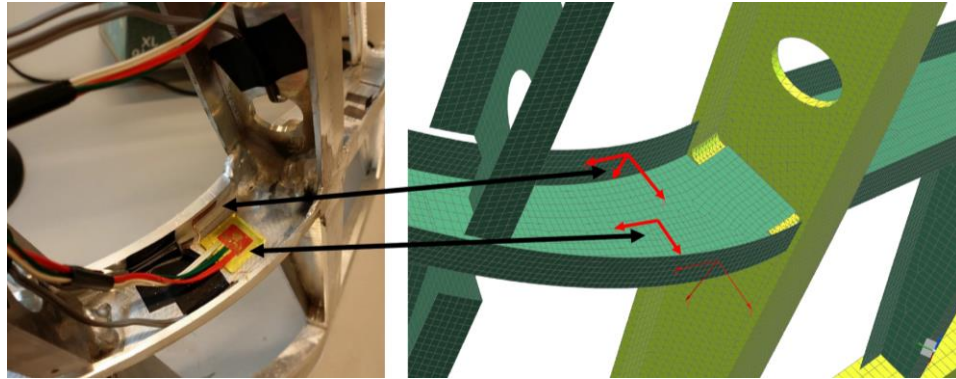
Learning Outcomes tested (from module syllabus)	Assessment Criteria To achieve each outcome a student must demonstrate the ability to:
Demonstrate an ability to analyse a range of engineering problems using advanced stress analysis principles.	

- 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	20.4
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	20.1
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	6.8

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)		68	%
	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			

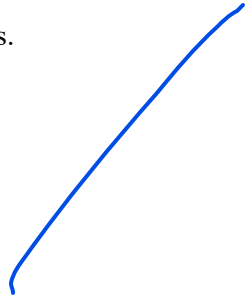
The role of FEA and physical testing for first-stage gas turbine blades

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1 Abstract

Structural health monitoring plays a large part in determining the remaining lifetime of the monocrystalline gas turbine blades that can cost tens of thousands of pounds to manufacture. The monitoring of creep deflection and crack formation/propagation have large impacts of the remaining lifetime of gas turbine blades and while there are many creep models that can predict the lifetime of a blade through the Finite Element Method, the long lifetime and high stress nature of gas turbine blades means that unforeseen circumstances i.e. machinery failure, can lead to heavily reduced blade lifetime. The pairing of SHM (Structural health monitoring) and FEA (Finite Element Analysis) allows for possible active systems that will use SHM to detect cracks and measure creep deformation and feed that information into an FEA package to give an updated lifetime prediction and fatigue characteristics.



GOOD CONTEXTUALISATION

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3 The role of FEA and physical testing for first-stage gas turbine blades

Understanding the mechanical limits of a part or product that has to withstand a state of high mechanical stress at a point in its lifetime has clear implications on the design, development and maintenance of that part allowing for improvements to be made to make a product stronger, safer, lighter and less material intensive as well as providing the ability to understand why something has failed in the design. Until 1964 understanding mechanical limits of a part was limited to physical testing (ESRD, 2014) and to fully understand the mechanical failure point of a part, the part must be permanently or plastically deformed; this testing cycle calls for a highly iterative design strategy that is not only costly in terms of the materials used, but the time taken to develop a product to its maximum potential. The use of computational methods allows for testing of mechanical structures without using physical prototypes, most notably, FEA (Finite Element Analysis). In 1964 the first FEA program was developed by NASA known as NASTRAN (NASA STRuctural ANalysis) built with the intention of designing more efficient space vehicles (NASA, 2012). Today FEA serves 3 main purposes: Informing initial design choices, validating a design and understanding why a given design may have failed. Looking at the Energy generation sector and the move towards renewables; there are no better examples of high mechanical stress cases than in gas turbines, which will help bridge the gap between heavy fossil fuels and renewable technologies providing a consistent baseload of power to manage the inconsistencies of renewables while large scale energy storage is developed to the scale it needs to be.

3.1 Gas power generation

Gas power generation is split into 3 main sections: compression, combustion and turbine generation, the most efficient simple cycle turbines only operate at 40% efficiency with exhaust gasses still at 600°C therefore, most gas power plants utilise a combined cycle system where heat is recovered from the exhaust gasses and used in steam power generation (Wartsila, 2013).

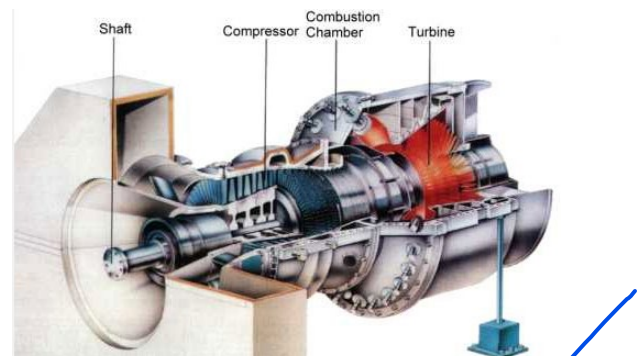


Figure 1 – Diagram of standard simple cycle gas turbine (Wartsila, 2013)

As the compressed air is combusted it makes first contact with the high pressure or first-stage turbine section which operates at 1600°C while rotating at 3000 rpm (Atefi, et al., 2010). A comparatively small 50MW gas turbine sold by Siemens AG costs around \$17 million, therefore, the cost of failure is enormous for these turbines which range up to 600MW (POWERWEB, 2016). Having the ability to fully understand the mechanical structure of a part allows for reduced failure risk. This report will investigate the uses of FEA for gas turbine blades and the role physical testing still plays.

4 Current uses of FEA with Physical Testing in industry

4.1 Material property requirements

With most gas turbine blades have an operational lifetime in the order of tens of thousands of hours, being able to sustain high stress loading, long term, is a key requirement of the blades. Mechanical creep describes the time-dependant deformation at high temperatures and constant stress (French, 1991) and is one of the key mechanical properties of turbine blades in determining the useful life remaining in a blade. Creep is usually caused by grain sliding which changes depending on alloy choice and casting process (Peng, et al., 2015). Creep of a gas turbine can lead to a shifted centre of mass affecting the stresses at the root of the blade as well as elongation at the tip leading to possible collision with the turbine housing (Patel, et al., 2015). This sustained cyclic stress can be described by the materials low-cycle fatigue characteristics; which is defined by the number of cycles a material is operating higher than the endurance limit of that material and is usually accepted to be in the order of 10^4 to 10^5 cycles (Parida, 2001).

As gas turbines become more efficient, they are able to burn gas at higher temperatures resulting in higher turbine inlet temperatures; To handle higher temperatures, gas turbine blades are often air cooled, this variable temperature means the structure is at high risk of Oxidation, Hot Corrosion and Thermal Fatigue (Peng, et al., 2015). These properties will be a point of focus when investigating the use of FEA and Physical testing for gas turbine blades.

4.2 Benefits of FEA

The first benefits of FEA occur in the development of a new blade. While the form design of a blade is largely dictated by its aerodynamic properties aided by CFD simulations; the value of FEA for gas turbine blades cannot be understated with relation to the material properties (Design World, 2009). As previously mentioned, creep damage is one of the leading factors when determining the remaining life of a turbine blade. Using various creep models within FEA packages; estimations into a blades useful life can be determined which ensures that a blade is being used for an optimal amount of time while not presenting a risk of damage to the turbine (Mazur, et al., 2011). Having this analytical tool ultimately lowers costs of operation for the turbine as the expensive blades are operated to their optimal lifetime and blade damage is less likely to occur.

Due to the operating stresses and temperatures of gas turbine blades, alloying is used to enhance creep strength and thermal fatigue properties; most notably, Nickel based superalloys. With high Ni gamma phase content comes very high creep strength but very low ductility (Peng, et al., 2015), meaning they are very brittle. This makes the material and the manufacturing process expensive. Being able to test a large variety of alloy combinations within FEA packages to determine an ideal material for the blades, heavily reduces costs, alleviating some of the financial pressure of the prototyping stage and making the time to reach a final product shorter.

One of the main points of stress concentration that is not dictated by its aerodynamic properties is the ‘root’ of the blade, the point a blade connects the rim of a turbine. The static loading a turbine root is subjected to is ideal for FEM optimization allowing for development of turbine roots with optimised stress distributions (Tan, et al., 2015). Figure 2 shows how an FE Model is meshed for blade root optimisation.

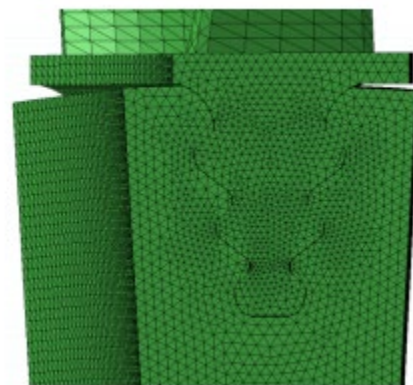


Figure 2 – Meshing structure of gas turbine fir-tree root for design optimisation (Tan, et al., 2015)

4.3 Benefits of Physical Testing

Being able to predict and estimate the lifetime of a blade is useful however, due to the long operational time of a blade there is no way a software package could simulate the micro discrepancies in oscillation/vibration and corrosion through decreased fuel quality and possible mechanical failure in the turbine rotor hub; these residual stresses, lead to a reduction in a blades resistance to fatigue (known as fretting fatigue) which can lead to the early propagation of cracks and eventually failure of a blade (Patel, et al., 2015). This type of failure is not predictable by any FE model due to its circumstantial variance; using various forms of non-destructive testing, early crack formation can be detected which allows for an updated model of the useful lifetime of a blade (Pitkanen, 2001). This type of monitoring is known as structural health monitoring (SHM) and is often taken real time allowing for a level of blade structural health analysis that could not be achieved using FEM simulation.

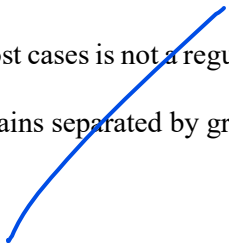
4.4 How FEA and Physical Testing work together

Independently, FEA and Physical testing provide useful analytical tools to determine structure, material properties and fault analysis. However, when combined become even more useful. As the material properties of a blade change, whether that is through creep (deformation), fretting fatigue or thermal fatigue; having the ability to update the yield stresses and remaining allowable deformation allows for the FE models to stay relevant. As previously mentioned, without this combination, FE models would quickly become outdated due to its inability to model residual stresses which contribute so heavily to a blade's lifetime.

5 Correlation FE Models and Physical testing correlate

5.1 Material property correlation

Ensuring a model developed within an FE study matches the physical model is fundamental to the validity of the simulated results and with gas turbine blades operating near maximum operating tolerance it is vital that the mechanical properties of the blade are predictable, however, the nature of metallic structures does not lend itself to fully predictable mechanical properties. As metals cool from molten state to solid state at its freezing point, the metal forms a crystalline structure, which in most cases is not a regular structure but is rather a group of small crystals with varying alignment known as grains separated by grain



boundaries, within the crystalline structure the metal can also form dislocations as the bonds do not align correctly (Subramaniam, 2009). The resulting material does not exhibit fully predictable mechanical properties with the grain boundaries providing a foundation for early mechanical yield under high stress, this is the primary cause of creep within turbine blades. To combat this Rolls-Royce and other companies use advanced casting processes to produce a monocrystalline metallic structure (Wahl & Harris, 1996). This process heavily improves creep strength and makes for a more predictable metallic structure. This consistency makes the case for FEA stronger as a turbine blades monocrystalline structure allows for linear creep characteristics making for easier simulation when applied to the FE Model.

5.2 Model vs Experimental correlation

With blades costing an estimated \$10,000 to produce (Eng, 2018) and most blade fatigue occurring over the course of tens of thousands of hours, classic destructive testing which usually applies force over a matter of minutes, does not provide a particularly useful set of data for companies that are testing the stress characteristics of the blades. This does not mean physical testing does not play a role in the development of blades. NDT (Non-Destructive Testing) can provide useful analytical information to validate FE Models and to provide a more practical set of data for the lifetime of the blades.

5.2.1 In situ testing

A select group of FEA packages offer material creep simulation and is broken down into 3 major sections illustrated by the graph shown in Figure 3; Primary creep is describes the initial and very sharp increase in creep strain over a short amount of time said to occur in the first hour of the load being applied. Secondary creep is a more gradual increase in creep strain over the longest amount of time, this relatively

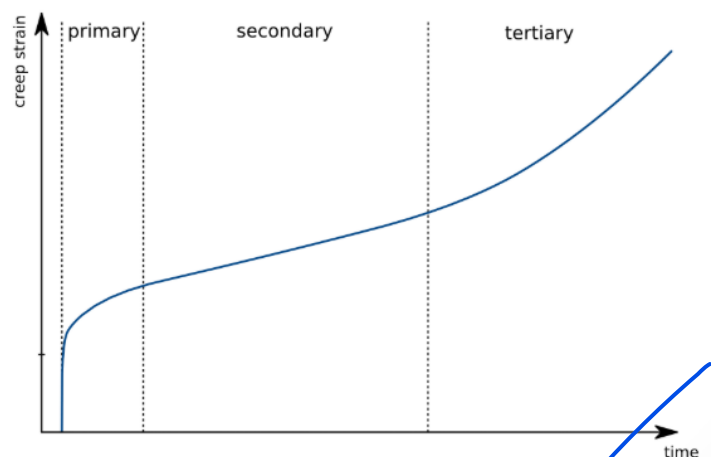


Figure 3 – Graph showing 3 main stages of creep strain with respect to a change in time

linear increase in creep strain is where most of the consideration lies when observing a creep model. Tertiary creep is the final steep increase in creep strain until failure of the part. Being able to constantly monitor a gas turbine blade as it operates, allows for the creep models to be updated to be able to predict remaining part life. The usage of creep model and in-situ monitoring means unforeseen variation in stress can be accounted for i.e. internal vibration (SIMSCALE, 2020).

5.2.2 Crack Detection

Infrared monitoring:

Infrared imaging uses heat energy to observe patterns on the surface of a blade. Gas turbine blades are equipped with an extensive channel system of air cooling which allows the blades to operate above their theoretical maximum temperature, this does however make thermo-visual analysis more complicated for the detection of possible cracks. When observing the images produced by the infrared camera there are clear patterns that can be observed. Gradual heating gradient radiating from the cooling points clearly indicates temperature change due to cooling, however sharp localised heating has the possibility to indicate the formation of a crack. As a crack forms the shear stresses around that crack point are focused causing a localised heating point on the blade (Meola, et al., 2008). This early crack formation detection can be used in conjunction with FEA packages that can simulate crack propagation, which will aid in re-estimating the remaining lifetime of the part.

Radiography:

Just in the same way radiography is used to identify deformities in bone structure, as radioactive material decays, different materials have better ability to block radiation which is then received by a sensor and produces an image which gives a clear image of the internal structure of a gas turbine blade. While Infrared thermography allows to pinpoint the corner point of the cracks based on local thermal increase due to increased localised stress, Radiographic scanning allows the form of the crack to be identified. Once a crack is identified there are many fatigue based FEA programs that will predict remaining lifetime till failure. Similarly, to infrared monitoring it is important for cooling channels not to be mistaken for possible failures.

5.2.3 Creep Detection

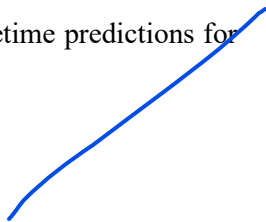
Tip timing method:

Tip timing often uses a simple 1D ultrasound sensor to observe when a blade is passing over the sensor. A theoretical time can be calculated which can estimate the time a blade should take to pass the sensor, it can then be compared to the practical measurement from the sensor to have a real time graph of any timed difference, if timing difference between expected and measured is detected, it is indicated that the blade may have become misaligned, if the time between expected and measured changes more than the rest, that part has suffered vibration. Vibration can lead to decreased lifetime and increased creep deflection; this increase in deformation can be quantified and used in conjunction with FEA based creep models to give an updated estimate to the parts lifetime.

6 The future of FEA and physical testing

FEA is proven to be a very powerful tool to maximise the cost effectiveness of gas turbine blades. While independently FEA and Physical testing do prove to be useful assets for gas turbine blades and their lifetimes; FEA provides allows for predictions about creep characteristics and the linear stress characteristics, but due to the long lifetime at prolonged stresses, many of the failure modes of gas turbine blades are due to unforeseen stresses i.e. vibration, objects, bad fuel mixtures and synchronisation issues. Therefore, when real time measurements (Structural Health Monitoring) are taken, conclusions about crack propagation and unforeseen creep deflection can be observed and used in crack based FEA simulation to estimate how and when the blade will fail allowing for an updated lifetime estimate to maximise the lifetime of the expensive blades without putting the machine at risk of damage through a failed part.

Research has been done into the use of coupling Structural Health Monitoring with Finite Element Analysis for an updated model of the lifetime prediction for Wind Turbine structure (Hartmann, et al., 2011), this technology has very useful implications for SHM of gas turbine blades with the prospects of providing an autonomous extraction of data and update the predictions to gain a live set of lifetime predictions for each blade.



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[Accessed 13th March 2020].

INTERESTING REPORT.
AN OBVIOUS DRAWBACK OF PHYSICAL TESTING FOR FATIGUE IS THE AMOUNT OF TIME THAT THE TEST TAKES, USING FEA SIGNIFICANTLY REDUCES THE TIME TO DEVELOP A PRODUCT.
YOU COULD HAVE DISCUSSED THIS FURTHER & RELATED IT TO MORE APPLICATIONS TO ADD TO YOUR REPORT.