

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

Student name:	OKE	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I declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people.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	18.9
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	19.5
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	18.9
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	6.4

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)		63.7 %
	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 unsupported/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			



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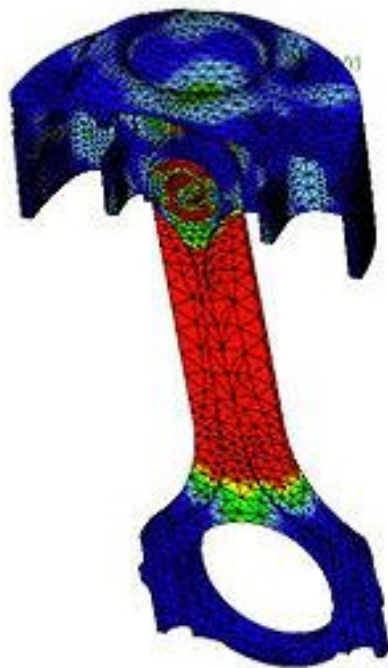
Can FEA replace physical testing?

Advanced Stress Analysis and FEA (M6X00420)

Student: Alex Oke (PI51012)

Lecturer: Kelvin Lake

Due Date: 26/04/2020



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I Introduction

Finite Element Analysis (FEA) is the simulation of any physical objects operating scenarios using a method called the Finite Element Method (FEM). This is a numerical technique used by engineers in order to reduce the number of iterations during prototyping, accelerate the design process and improve the quality of the final product in a shorter time span.

To understand any physical object scenario, mathematical processes such as Partial Differential Equations are used to quantify all forms of structural, thermal or fluid behaviour during simulations. Over the last two decades, the FEA has become the primary numerical technique for allowing computers to solve these equations efficiently. These equations are also used to solve the physics applied and engineering phenomena occurring during all types of different load scenarios, thus enabling a fast computation of stresses and strains.

The solution provided from FEA approximates the real result which is given by physical testing. This approximation allows for engineers to identify stress concentrations, areas of the design which are failing due to object geometry and areas which have excess material thus allowing for design and mass optimisation in the context of a reciprocating engine connecting rod as a case study.

In Altair's Design Approach, a product concept optimisation step is implemented prior to the initial CAD design, thus allowing for a conceived design to be proposed early on in the design process.

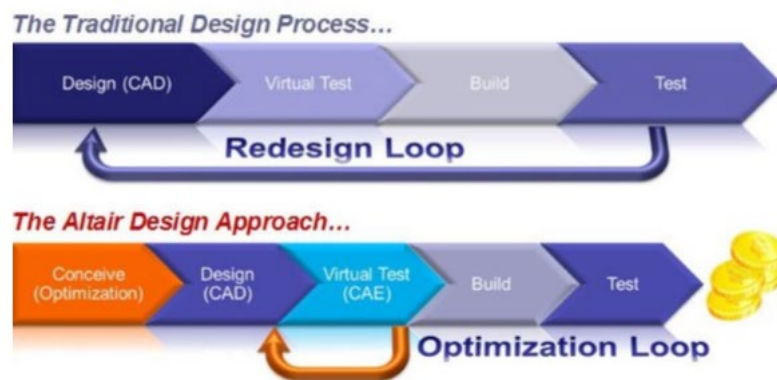


Figure 1 The Altair Design Approach compared to The Traditional Design Process

I.1 Aims of this report

- To show why companies carry out FE analysis alongside physical testing.
- Explain how physical testing is correlated to an FE model.
- Discuss the feasibility, positives and negatives of FEA completion with no physical testing.

2 4-Stroke Combustion Engine Connecting Rod Case Study

2.1 Brief Description

GOOD
CONTEXTUALIZATION

A combustion engine with a reciprocating piston and that is part of the full crank mechanism is shown in Figure 2. The prominent component converting reciprocating to rotational motion is the connecting rod attached at one end to the piston and at the opposite end the crankshaft.

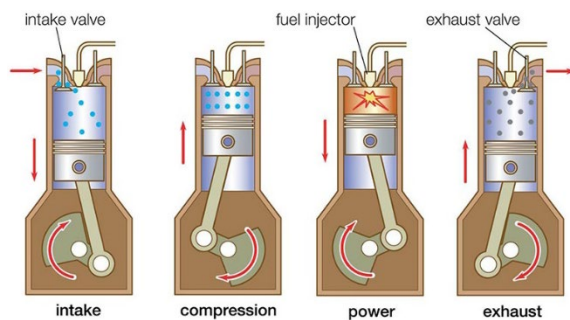


Figure 3 4-Stroke Combustion Engine Cycle

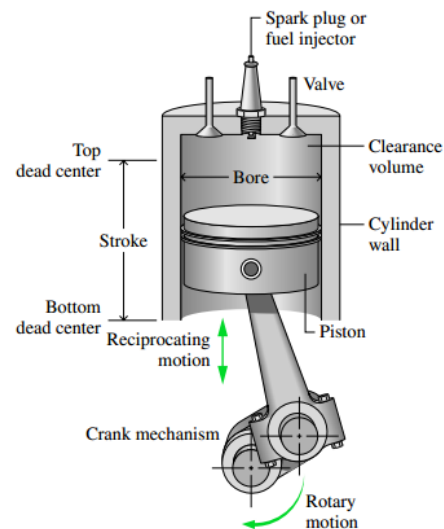


Figure 2 Crank Mechanism Diagram (Patidar, Penn State University, 2017)

2.2 Connecting Rod Loading Scenarios

Throughout 720° of crank rotation which represents a complete 4-stroke cycle in a combustion engine, there are 2 extreme load cases which are considered during the design process. The 4-stroke cycle is illustrated in Figure 3. During the power stroke, peak cylinder pressure occurs from combustion thus putting the connecting rod under a compressive load. The extreme second load case is a tensile load which the rod experiences when the reciprocating assembly's mass is trying to stretch the rod at exhaust top dead centre. To calculate these loads, see Equation 1 and Equation 2 below:

2.2.1.1 Inertia force causing tension in rod

Equation 1 Inertia Force

$$\text{Inertia Force} = \text{Reciprocating Mass} \cdot \text{Piston Acceleration}$$

2.2.1.2 Gas Force causing compression in rod

Equation 2 Gas Force

$$\text{Gas Force} = \text{Cylinder Pressure} \cdot \left(\frac{\pi \cdot \text{Cylinder Bore}^2}{4} \right)$$

2.3 Errors During Load Calculations

Gas force can be incorrect from a cylinder pressure sensor which may not be correctly calibrated or not correctly installed, therefore resulting in a cylinder pressure being too high or low, causing the compressive force applied in an FEA model to be too high or low. Using a force which is too low for the connecting rod will result in a cross-sectional area in the shank of a connecting rod which buckles under the combustion pressure, if the force is too high then the connecting rod will be over engineered with too much re-enforcement and mass.

Whilst defining the maximum Inertia force, the kinematic formulation of the crank mechanism is considered and used to calculate piston acceleration. The mass of the reciprocating assembly must be measured accurately otherwise this force will not be represented correctly as piston acceleration and reciprocating mass are the only two inputs possible of introducing errors.

2.4 CP Carrillo & PANKL

CP Carrillo are a connecting rod and piston design and manufacturing company operating in the USA since 1963. Finding their process of designing using FEA correlated with real testing has proved something of a challenge for the author as this is a well-guarded secret. An example of the full FE model used with a stress plot is illustrated in Figure 4.

The parent company of CP is PANKL Racing Systems situated in Austria who specialise in developing and manufacturing engine and drivetrain components such as connecting rods and piston for race cars, motorcycles and various high-performance vehicles including the aerospace industry. Both CP and PANKL rely heavily on computer generated models of their components to ascertain the stress, strain and displacement.

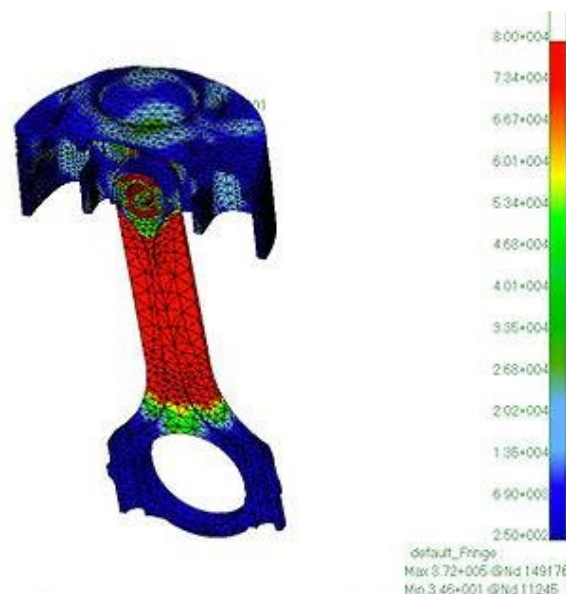


Figure 4 CP Carrillo Connecting Rod FEA Example (CP Carrillo, 2019)

“An essential part of the development process is the Finite Element Analysis of our components, for which PANKL Racing uses a proprietary method. By fine-tuning the individual components, we are able to guarantee an optimised result with regard to performance characteristics and reliability” (PANKL, 2019). This statement given on their website informs the author they are using FEA to develop their product further to enhance vehicle performance as opposed to the financial benefit the majority of the automotive industry is targeting.

PANKL state that to provide preliminary results to the customer during the development process, they utilise state of the art physical testing in the form of tensile, compression and ovalisation test beds. This testing is to provide early results of design iterations along with fatigue and friction analysis which they carry out on all components before signing off.

According to Brett Becker who discusses the new 2000hp capable BoostLine connecting rods manufactured by Wiseco in a blog on Speed News, “the company performed significant testing of the finished product, but also initially through finite element analysis” (Becker B, 2007). Brett goes on to say that when designing a connecting rod for a new application requiring a heavier or lower load than a current design, they can make small adjustments to the FEA simulation to enable the delivery of a conceived idea early on.

2.5 Physical Testing Correlated to FEA

A study carried out by Matthew Powell exploring connecting rod design using composite materials, states that Matthew modelled the rod in Solidworks and completed an FEA in Siemens FEmap with loads calculated from the extreme load cases stated in section 2.2. To ensure the material properties used in the FEA are correct and accurate to yield useful results, carbon fibre coupons were tested in a Denison test machine. Without testing the exact material being used the FEA results will vary from what the author is expecting from hand calculation for stress, strain and displacement.

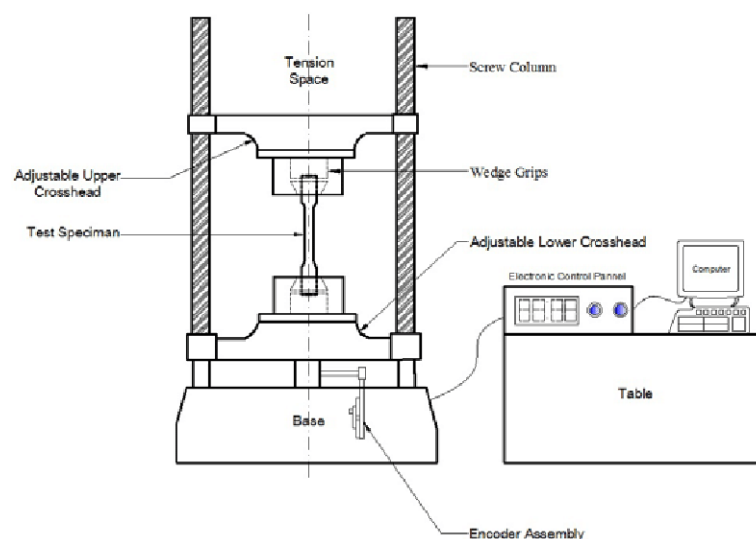


Figure 5 Tensile test machine schematic diagram (Chellamuthu, 2012)

To validate a tensile FEA scenario for the connecting rod, a Tensometer as illustrated in Figure 5 is used to examine the rod shank displacement in the Y-axis. This test is carried out using the same force applied in the FE model for continuity. For validation of the compressive FEA test, the same process is used as the tensile test but with the machine in compressive direction using a sensor to record the force applied, a DTI gauge for the displacement of the rod and a strain gauge for the strain.

As stated by E.J. Hearn in his 2nd book on Mechanics and Materials, the use of FEM and mathematically calculated stresses is acceptable for an engineer to adopt when working with materials and components that are the regular output of that manufacturer, however, when a new material or object geometry is required, this no longer allows the engineer to rely on past knowledge of solutions and therefore requires a new approach by using a set of already established physical validation techniques used to this day. These techniques used as opposed to the theoretical procedures FEA is governed by include brittle lacquer and strain gauges.

In a paper published by Sourabh Jain and many other available literature sources to the reader documenting the methods used to validate computational methods, the comparison of results from FEA with hand calculations and strain gauges are the predominant way of correlating a physical test to the computational methods used. The author has not come across any available literature suggesting brittle lacquers are used in the correlation to this day, however as mentioned in section 2.4, these are well guarded trade secrets.

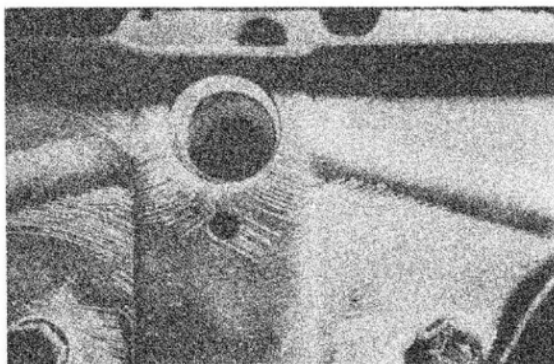


Figure 8 Brittle lacquer crack pattern showing the stress concentrations on an engine block (Magnaflux Corporation)



Figure 7 Connecting Rod with strain gauge attached to I-beam shank section (Micro-Measurements, 2018)

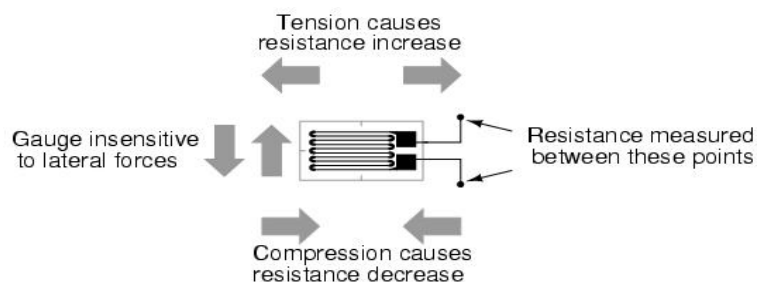


Figure 6 Strain gauge schematic diagram (Vignesh, 2018)

3 Finite Element Mesh Influence on Correlation

From the authors experience from a previous study there are factors of meshing which can have a large impact on how the results compare with physical testing outcomes. The number of elements which are being used must follow a simple rule to enable the true behaviour of a part with complicated geometry through its neutral axis. This rule is to have at least 3 elements across a face on the objects geometry to obtain a compressive and tensile force either side of the neutral axis as displayed in

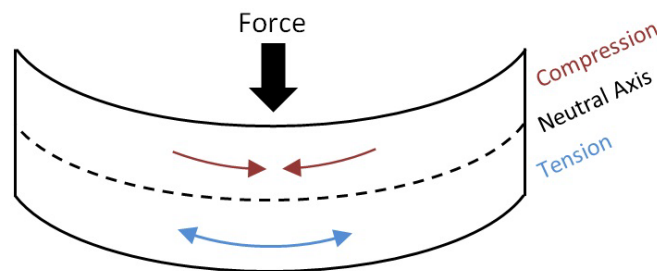


Figure 9 Three stress areas of definition (Palas, 2015)

In Altair's guide to the practical aspects of FEA, it is noted that the size of mesh elements can be selected by many different contributing factors dependant on the scenario, object geometry and its boundary conditions.

Element size selection can be governed by one or a combination of the following constraints presented to the engineer:

- **Based on previous experience** (Where good correlation has been found with same type of FEA scenario simulation and FEM used)
- **Time limited** (With less time available to the design engineer, the mesh size may need to be smaller in order to reduce computing ^{TIME} time and effort)
- **Hardware limited** (This is at the discretion of the engineer to understand the element node quality and size which can be used within their means)
- **Type of analysis** (If only deflection/displacement is being studied and not the stress so importantly, then a lower element size can be used for a beam of rectangular section)

These constraints when choosing an element solution to go with can effect also the results which the engineer yields to compare and correlate with real results therefore this is paramount it must be understood prior to attempting multiple FEA's and time consuming iterative changes to the FEM used if the correlation is not within a permitted acceptable error percentage.

4 FEA Without Physical Testing

4.1 Feasibility

To complete an FEA without correlating the results to a physical test can be done, however the implications of this can be costly further down the line, this can be simply put into perspective by referring to the original design process in Figure 1 which consists of a repeated loop of iterations until the component is correct. In the context of a connecting rod, the physical testing can be neglected when the engineer has many years of experience in FEA of a specific type of connecting rod for only a specific type of application, the engineer must also know which FEM to use and how to set-up the model with the correct mesh and boundary constraints. Only when the engineer in question has completed and successfully manufactured connecting rods for a specific purpose can they neglect the physical testing correlation, thus assuming their FEA is correct.

In the event of a different material being selected for the connecting-rod, which is a common reason for new designs, the engineer will need to adapt his FEA model and the objects geometry will undoubtedly change therefore yielding naturally different results. With a different material used, the Young's Modulus of the material will most likely change as observed in multiple pieces of literature. Therefore, the change in elastic material properties will result in a varied displacement result for the shank of a connecting rod which will not correlate with previous experiments, thus requiring physical testing to be completed for FEA validation.

Taking into consideration the connecting rod is not under a specified load in all engines from varying combustion pressures and engine rotational speeds, the load which these rods will change depending on application therefore resulting in a different set of results for a higher or lower load applied.

4.2 Positives

- Some physical testing can be destructive therefore an initial cost reduction.
- If only FEA is used as a virtual testing method, it can reduce time spent on physical testing.
- For the shank of the connecting rod it can be assumed that the results yielded are most likely to be acceptable. *-SO WHY DO IT?*

4.3 Negatives

- Can lead to the end product not completing its duty life cycle due to inaccurate un-correlated FEA results.
- Propagation of cracks in the connecting rod without an adequate physical test to correlate with is going to cause time lost in re-iterative designing the component and running FEA tests which in itself cost time for an employer or self-employed engineer.

5 Conclusion

To conclude this research report discussing whether FEA should replace physical testing, the author would like to re-iterate that removing the physical testing can be done to a certain extent, but it is highly dependant on the many different forms of product design the FEA will be used for.

In the context once again of a connecting rod, the loading which the connecting rod is subject to is changing depending on its application, this is the primary reason for changing the connecting rod in the first place, therefore it cannot be removed in the sense of critical engine components which will cost the customer a lot in repairs. Not only limited to the loading, the material properties may change in order to reduce the mass of the rod or in the event of a connecting rod requiring a higher Young's Modulus in order to reduce rod shank displacement causing catastrophic engine component contact. Any of these changes to the design must be physically tested as this will logically change the results produced by any FEM used.

The costs of completing FEA without correlation can far outweigh those which are saved in negating the physical tests. Therefore, in the opinion of the author the discussion brings the final outcome that physical testing is currently necessary in the development and design of high-end connecting rods and in general any critical engine part which could cause such damage as it would.

In other applications of product design such as in the context of a chair leg, there are lots of previous studies to suggest that this is not as critical as such engine components. Therefore, it can be completed using FEA with no correlation as long as the engineer designing the chair leg has completed a correlated FEA before and uses the same finite element method as previously used.

GOOD CASE STUDY THAT
YOU HAVE RELATED WELL TO
FIRST PRINCIPLES.

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