

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

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declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people.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

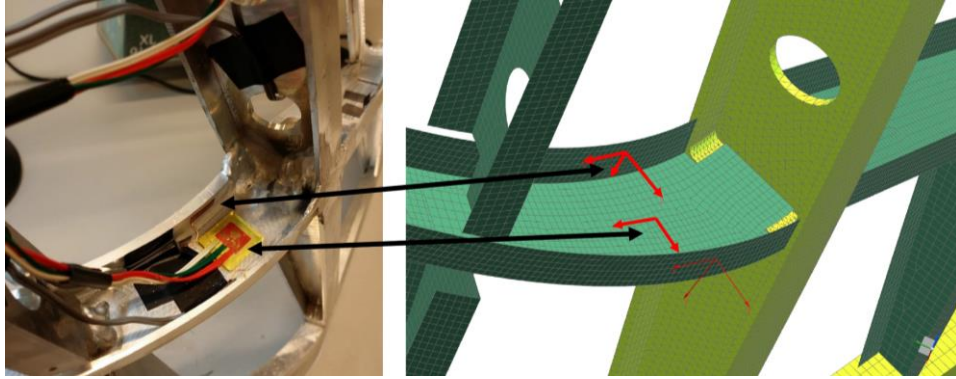
Learning Outcomes tested (from module syllabus)	Assessment Criteria To achieve each outcome a student must demonstrate the ability to:
Demonstrate an ability to analyse a range of engineering problems using advanced stress analysis principles.	

- 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	20.1
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	19.5
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	6.6

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)		66.6 %
	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

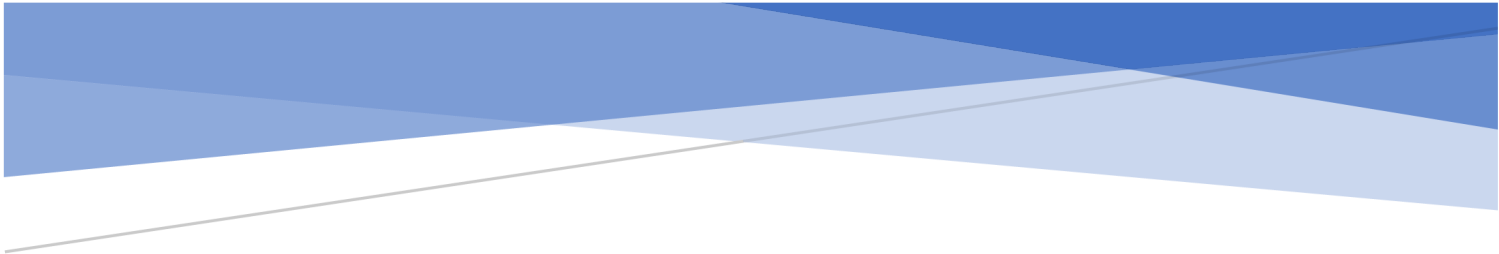
Student name:		Student P number:	
Programme:		Year of programme	
Assignment Title:			

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			



SHOULD FINITE ELEMENT ANALYSIS REPLACE PHYSICAL TESTING?

An investigation into finite element analysis and its
correlation to physical testing

Abstract

An investigation into the necessity for finite element analysis and computer aided engineering utilizing comparison of case studies as a form of research.

Joseph Ieuan Woodhouse-Thomas

Jthomas.151048@student.uwtsd.ac.uk

Contents

Introduction	1
Introduction to stress analysis	2
FEA testing	2
Physical Testing	3
Why do companies typically carry out FEA alongside physical testing?	4
How does a physical test correlate to FEA?	5
Can or should FEA ever replace physical testing?	6
Conclusion	8
Bibliography	9
Figure 1 - Example of FEA results	2
Figure 2 - Four-point bend set up (Wagner, 2010)	4
Figure 3 - Force Vs. Displacement Graph	7
Figure 4 - Spring stiffness correlation	7

Introduction

The following report aims to answer 3 questions concerning finite element analysis (FEA). The first being, why do companies typically carry out FEA alongside physical testing? Following this, how does a physical test correlate to a FEA? And finally, can or should FEA replace physical testing?

A variation of case studies have been considered to further understand the need for FEA. The first case study researches a simulation and physical experiment to refine the FEA model currently being used and validate the findings.

The following test investigates a CAD related FEA experiment using a diesel engines V8 crankshaft, and the effects of the torsional loads from the torque caused by the combustion forces and bending moments caused by a combination of the combustion forces and the inertia forces produced by the engine speed.

The final case study is an experiment investigating into road holding methods on large vehicles. The investigation examines the FEA and physical testing of leaf springs, and a comparison of these methods, with the aim to validate and further develop the simulation model with considerations to the criteria necessary when designing suspension systems.

Introduction to stress analysis

FEA testing

There are three methods to undertaking engineering problems, these are:

- Analytical method – A traditional approach with 100% accurate results, however, only viable for basic problems like cantilever and simple supported beams.
- Numerical method – The numerical method gives a mathematical representation. Within this method, assumptions must be made towards the model. This method is applicable even when a physical model is not produced, however different software offers different advantages and disadvantages, and the results cannot be taken as 100% correct.
- Experimental method – The experimental method uses real-life measurements however is very time consuming, even if small iteration is to be made, the numerical method is far quicker.

Finite element analysis (FEA) is the simulation of any physical phenomenon using a numerical technique called finite element method (FEM) (Simscale, 2020). Used by engineers worldwide, FEA reduces the design process by allowing the user to simulate tests without manufacturing a physical component. FEM uses nodes to calculate stress and strain, a node is a co-ordinate location in space where the degrees of freedom (DOF) are defined. For mechanical application, the location of the node displaces and the change in displacement is used to calculate the necessary results.

Not all the elements of a specimen have 6 DOFs, the number of nodes is dependant on the element type and group of elements. The element type can be 1D, 2D or 3D, the group that element is between thin shell, plane stress, membrane, and plane stress.

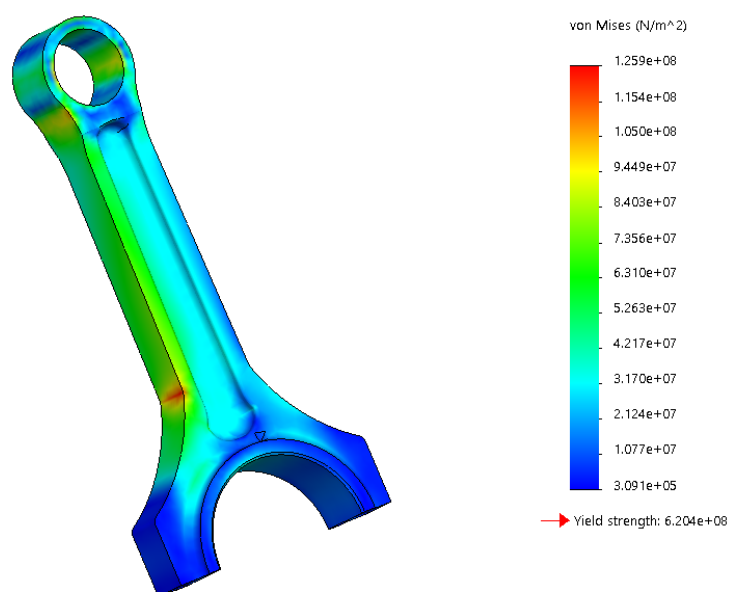


Figure 1 - Example of FEA results

The above figure shows an example of the results found when carrying out an FEA study. The key on the right-hand side of the figure shows the amounts of stress being put through the component within this frame of the study, the key is colour co-ordinated, and provides the yielding point of the material if it is exceeded.

There are numerous types of finite element analysis for different types of applications.

- Linear static analysis is less realistic than non-linear, and all forces act on the part must be equal
- Non-linear static analysis is more realistic but takes longer to solve.
- Dynamic analysis is split into two areas. One being free, and due to natural frequencies, the second is forced and is in response to external excitation, such as road activity in a car.
- Buckling analysis is only applicable for comprehensive loads on slender beams and sheet metal parts.
- Thermal analysis corresponds with conduction, convection and radiation.
- Fatigue analysis relates to the life of a component, and its durability.
- Optimisation analysis correlates to the study of topology, topography, size and shape to make improvements to the component.
- Crash analysis is heavily used in the automotive industry as it relates to the safety of the passengers and how the vehicle performs in an incident.
- Computation fluid dynamics (CFD) considers the fluid mechanics of a system, involving fluid motion and fluid at rest (Altair).

Physical Testing

Physical testing can be described as a trial and improve method of development. Physical tests use strain gauges to find the stresses and forces acting on a component of a system. In a circumstance where FEA is unavailable the only way to seek failure in a component is by producing the specimen and field testing it, this comes with its advantages and disadvantages.

The advantages come in the form of certainty and reliability in the work being carried out. Cancelling out any odd scenarios or questionable cases where a part has broken or even lasted un-explainable longer than anticipated, a physical test will give reliable results to tests being undertaken. For that reason, field testing would seem like the ideal method to carry out any development in products and parts.

However, at this time with the computer software available, field testing is considered inefficient to a certain extent. Whereas an FEA run will take a day or two, max, a field test can take up to weeks to organise, alongside the need to manufacture the specimen being analysed every time it is necessary to make an adaptation (Wen, 2011).

INFORMAL!

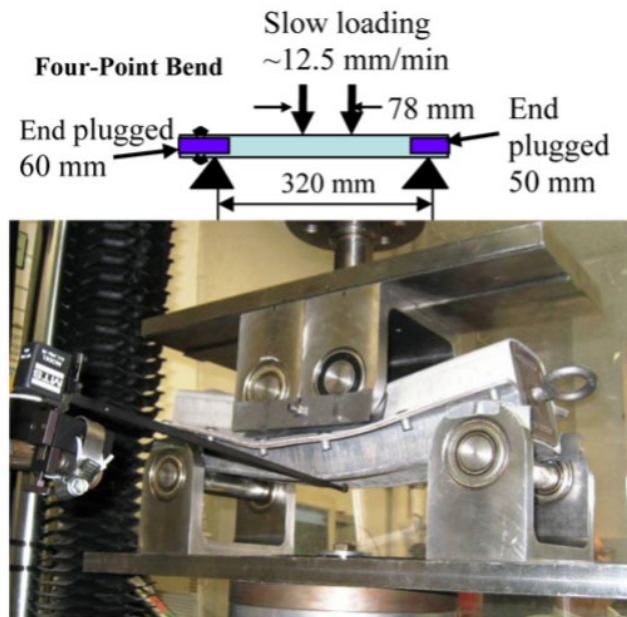


Figure 2 - Four-point bend set up (Wagner, 2010)

Wagner (2010) discusses a quasi-static axial compression test using a range of materials. Another disadvantage of physical testing comes in the form of costing, whereas a computer simulation can show results of any chosen metal, wood, or plastic, the engineer is forced to purchase necessary metals for an experiment, and this can increase costing dramatically if the procedure doesn't commence smoothly.

Why do companies typically carry out FEA alongside physical testing?

Pozolo (1999) writes of a case study where a trailer on the front of a trailer is put under two different experiments. The first being a FEA motion simulation of a trailer drawbar and frame that had been created to simulate the predicted outcome using ABAQUS standard FEA program. Within this motion simulation the point loads had been rigidly constrained, and located at the vertical centre of gravity.

In addition to this, a physical test was undertaken with a fully loaded trailer that was tested using strain gauges at an army testing ground. The data was collected over 30 second intervals on random proportions of test courses.

The initial results of the motion simulation showed 8.3% under prediction in comparison to the field testing. With the end goal to improve the safety factor of the trailers mounting point, the motion simulations load points were better located and refined for more accuracy.

The reason for carrying out the motion simulation alongside the physical testing is to improve the simulated results and gain a greater understanding of the loads and strains acting on the trailer while undertaking the simulation. This combination of motion simulation and physical testing assists the

engineers when troubleshooting to reduce the time in the design process (Prathamesh J. Baikerilkar, 2017).

Although the motion simulation, with the correct constraints and boundary conditions, provided results similar to the field testing, there were scenarios in which the FEA study was unable to re-make.

Furthermore, by combining the capabilities of the analytical techniques such as the FEA study and the physical testing together, the design, prototype and testing process time was significantly reduced, alongside the changes made to the motion simulation being beneficial towards using the FEA model in future investigations.

To conclude and answer the initial question, a company will benefit significantly from utilising finite element analysis alongside physical testing to save time, money and resources throughout the development and production of parts and components, moreover, FEA gives the engineer the ability to jump leaps through the early stages of a project and gain a general understanding of the stresses through a part before it has even been considered into manufacturing.

How does a physical test correlate to FEA?

An FEA models' accuracy is greatly dependant on the boundary conditions set when building the motion simulation/ static simulation. These boundary conditions consist of:

- Appropriate application of load bearing faces is crucial within motion simulation, without appropriate allocation of loads the system is unaware to forces being implemented, and therefore ignores them.
- Correct and accurate mates are an essential role to the motion simulation as it prevents any faults or errors in the system while contributing real-life elements.
- Contacts between parts in an assembly create collisions in a motion simulation if applicable, which present inaccuracies and problems to be solved, rather than the study being intangible and idealistic.
- Changing the frame rates to increased frames per second increases accuracy in data but consequently also increases run time, a certain amount of compromise is therefore necessary (Underwood, 1989).
- Operation speed, such as engine speed, can also affect the running time of a scenario, thus the need for compromise is, once again, essential (Trovey, 2002).
- Considering gravity in a situation adds realistic measures when gathering data.
- Material allocation is a very important step in conducting a motion simulation especially when the setting is based on an engine in real life conditions (Peterson, 2008).
- The materials of the components possess different masses depending on the density and this can differ the results significantly.
- Accounting for frictional losses increases the precision within the experiment, thus providing more accurate results (Polycarpou, 2006).

- Mesh size makes a large difference to the intricacy of the area it is allocated to, however, like other areas of the conditions, it adds a significant amount of time to the overall run.

Sergio Gradella Villalva (2010) writes of a case study using a computer aided engineering (CAE) simulation in comparison to an experimental real-life test. The tests were carried out using a crankshaft from a diesel V8 configuration.

Within the experiment, bending and torsional loads were implemented on the components to achieve a direct comparison to the FEA results and the experimental testing. When testing with a torsional strain gauge, the comparative difference came to 4.52% between the FEA and physical model. The investigation then followed on to test the bending moment of the specimen, the results presented a 1% difference in deviation between the two methods.

This case study shows a very similar correlation between the two tests, however this resemblance comes at a price of time on the behalf of the simulation side. Due to the boundary conditions and requirement for similarity, the simulation runs take a large amount more time (Roszkos, 2019). This, however, is still a lot shorter than if the specimen had to be manufactured as it would take up more time to produce it than to simulate (Hongfeng Ma, 2019).

Therefore, the correlation between physical testing and FEA testing can be seen from this review of the case study investigated. The results show a small difference in magnitude of stress; however, the trend of stress is identical between the two methods.

Sergio Gradella Villalva (2010) concludes that the positives that can be drawn from the study are the FEA findings can be utilised to develop the products further, however, physical test will still need to be undertaken to validate the fatigue life of the specimen.

Can or should FEA ever replace physical testing?

To answer this question, a case study considering leaf springs has been researched to gain a thorough understanding of the outcomes and requirements when simulating an FEA study. Tank (2017) writes of the suspension system needing to:

- Maintain the correct vehicle ride height.
- Reduce the effort of implemented forces produced by the road.
- Assure the wheel alignment is correct.
- Support the vehicle's stability while in use.
- Keeping the maximum amount of friction between the tyre and the road.
- Assure that implemented change in direction is controlled.

To simulate the leaf springs it is first essential to perform hand calculations to determine the correct value of spring stiffness for the vehicle. It is also necessary to calculate the amount of preload implemented on the system before commencing in a test. Following this the amount of damping being

used adds reality factors to the simulation, if the damping rates are incorrect then the values produced by the FEA study will be inaccurate.

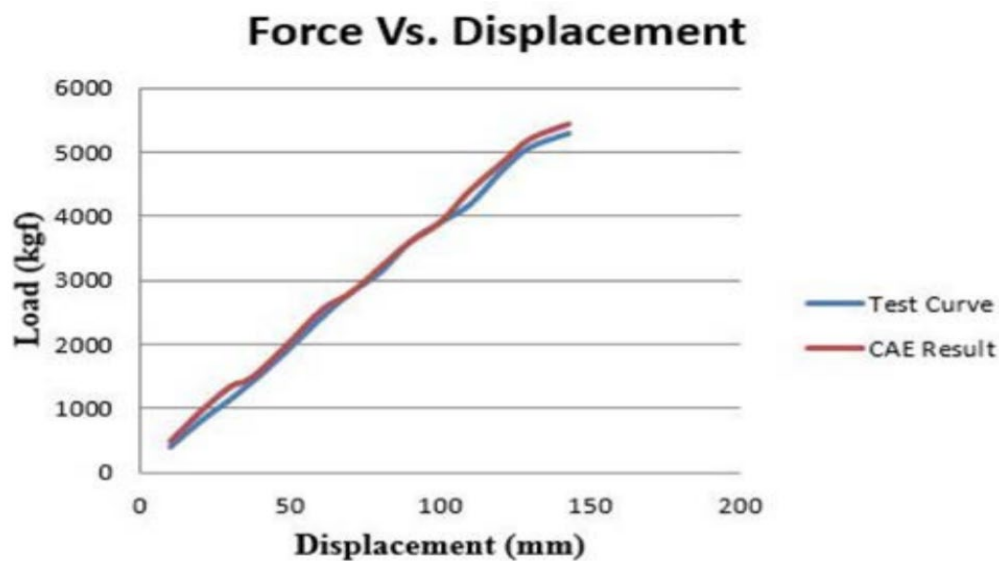


Figure 3 - Force Vs. Displacement Graph

The results show a similar displacement when the load is implemented onto the leaf speings in a simulated and rig test situation.

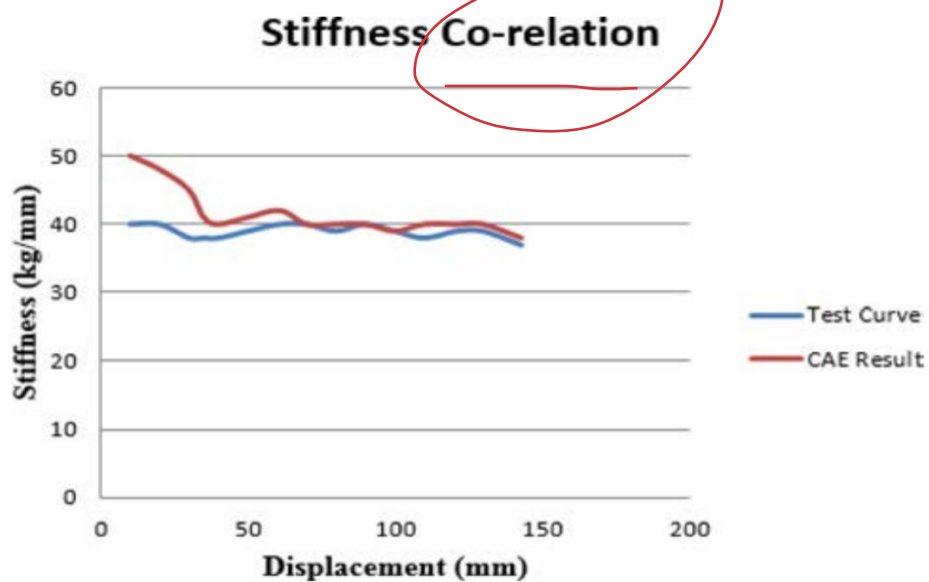


Figure 4 - Spring stiffness correlation

The correlation shown by figure 4 presernt far different results to that of figure 3, whereas the displacement shows small amounts of deflection within its findings, the stiffness of the leaf springs

between the two methods are very different, this can produce un-realistic results and therefore lead an investigation in the wrong direction if only utilising FEA until a final model is produced.

That said, with correct loads being implemented and further investigation into the characteristics of the leaf spring being simulated, correct and accurate results can be obtained. The biggest downfall to any simulating is the user, therefore, precision and attention must be taken into every allocation of boundary condition and load on the specimen.

With the increasing age of computers doing more and more at increasing rates it is easy to pass by details that may jeopardize a simulation, Van Dyke (2015) discussed the dangers in modern FEA when using programmes such as when allocating materials, mesh sizing and the general question of what assumptions the software being used is making. *AND.....*

In relation to the question in hand, the development of computer aided engineering is quickly becoming more involved within the engineering industry. With the increasing amount of change facing the automotive side of industry, large amounts of tests and simulations are being undertaken to win the race to development. However, the need for physical testing is still a necessity over a large amount of the engineering world, from fatigue testing to final designs being validated. Therefore, FEA should not replace physical testing completely, at this point in time, but, continue to assist engineers in making the design process more cost effective and time efficient (Hemez, 1998).

Conclusion

The initial case study showed a trailer undertaking physical tests and FEA experiments, the report wrote of an iterative approach to refining the difference between the two techniques of testing to learn more about the abilities in the FEA software. The findings proved that an open approach to using both FEA and physical testing sped up the process.

The following case presented an experiment into the FEA and physical testing of a crankshaft on a V8 diesel. The consensus drawn from this study was that the boundary conditions in which the FEA simulation is put under makes the biggest difference to outcome of the results, therefore showing that the main contribution towards inaccuracies when conducting an FEA study is the operator.

The final case explains the case study utilising a leaf spring. The results held many similarities between the FEA and physical testing when comparing the force and displacement, however large disparities became apparent when the spring stiffness was considered over the course of the test. With that said, many inaccuracies can come from this and the results may be incorrect.

In conclusion, all three case studies presented positive and negative feedback from both the physical and finite element testing, the FEA testing does decrease the time taken to find the basics of an engineering product however the results show deflections from the physical testing and the user is the main participant, whereas physical testing provides better and more significant results, therefore, the design process is greatly prolonged because of this.

Bibliography

- Altair. (n.d.). *Practical Aspect of Finite Element Simulation*. Altair University.
- Dyke, D. V. (2015). *Dangers of modern FEA*. Portland, Oregon: OVGO.
- Hemez, F. M. (1998). *Test-Analysis Correlation and Finite Element Model updating for nonlinear, transient dynamics*.
- Hongfeng Ma, J. W. (2019). Fatigue redesign of failed sub frame using stress measuring, FEA and British Standard 7608. *Engineering Failure Analysis*, 103-114.
- Peterson, J. (2008). *Finite Element Analysis of Carbon Fiber Composite Ripping Using ABAQUS*. tigerprints.
- Polycarpou, A. C. (2006). *Introduction to the Finite Element Method in Electromagnetics*. Retrieved from IEEE Xplore: <https://ieeexplore-ieee-org.ezproxy.uwtsd.ac.uk/document/6812584>
- Pozolo, M. J. (1999). *Using Modeling and simulation for failure analysis*. Michigan: SAE.
- Prathamesh J. Baikerikar, C. J. (2017). Comparison of As-Built FEA Simulations and Experimental Results for Additively Manufactured Dogbone Geometries . *ASME Digital Collection*, 14.
- Roszkos, C. S. (2019). Static and dynamic analyses of aluminum foam geometric models using the homogenization procedure and the FEA. *Composites Part B: Engineering*, 361 - 374.
- Sergio Gradella Villalva, E. G. (2010). *Correlation between CAE and Experimental Fatigue bench tests for automotive Crankshafts*. Brasil: SAE.
- Simscale. (2020). *What is FEA?* Retrieved from Simscale: <https://www.simscale.com/docs/content/simwiki/fea/whatisfea.html>
- Tank, S. K. (2017). *CAE Methodology of Leaf Spring Suspension and Its*. SAE.
- Trovey, M. (2002). Concept design CAD for the automotive industry. *Journal of engineering design*, 5 - 18.
- Underwood, J. .. (1989). *Applications and Limitations of Finite Element Analysis To Armament Components*. New York.
- Wagner, D. A. (2010). *FEA Predictions and Test Results from Magnesium Beams in Bending and Axial Compression*. SAE International.
- Wen, J. (2011). *Strength Prediction of Bumper by Correlating FEA with Test*. SAE International.