

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

Student name:	HOPKINS	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I declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people.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	✓
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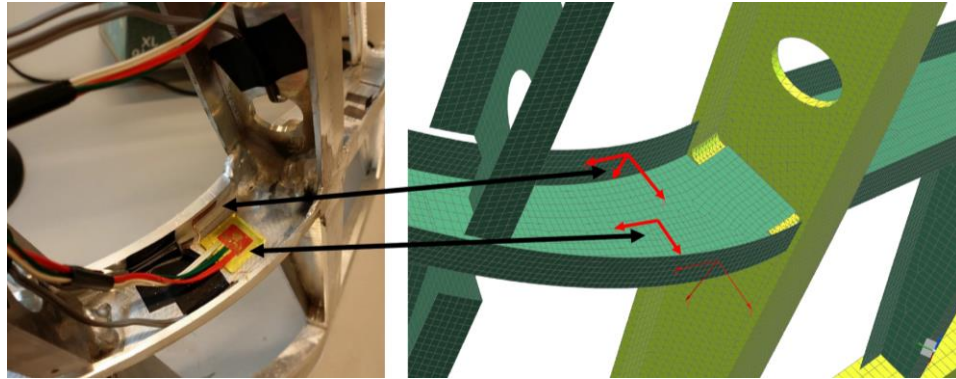
Learning Outcomes tested (from module syllabus)	Assessment Criteria To achieve each outcome a student must demonstrate the ability to:
Demonstrate an ability to analyse a range of engineering problems using advanced stress analysis principles.	

- 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	20,7
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	6,5

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)		67,1 %
	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			



*University of Wales Trinity
Saint David - School of
Engineering*

Can FEA replace physical testing?

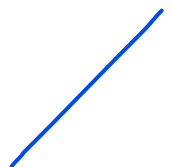
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2 Introduction

Finite Element Analysis (FEA) is a Computer Aided Engineering (CAE) method that can simulate many physical effects including structural analysis, fluid flow, thermal flow, vibration analysis and fatigue.

‘Finite element analysis (FEA) is a computerised method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects.’

(Autodesk, n.d.)

FEA is a useful CAE tool as it can lower the cost of a products development by reducing expensive physical testing and the number of physical prototypes manufactured. FEA can also decrease development times and can lead to a higher performance product with greater durability.

According to COMSOL (2017), the laws of physics can be expressed in mathematical models; and the foundation of the FEA software is formed from different conservation laws. The Finite Element Method (FEM) is used to discretize the mathematical model, resulting in corresponding numerical models. The numerical models are then solved, and the results analysed.

Since the finite element method subdivides the large geometry into a number of smaller finite elements, the results are only an approximation. In industry, the FEA results need to be verified and validated, to ensure accurate FEA results as interpolation occurs between nodes.

‘Since the calculations are done on a mesh, rather than the entirety of a physical object, it means that some interpolation needs to occur between the points.’

(English, 2019)

The aim of this report is to discuss why companies typically carry out FEA alongside physical testing, how a physical test may be correlated to a finite element model, and finally, to answer whether FEA can, or should, ever replace physical testing.

This report will consider a linear-static case study titled;

‘How well does a linear static finite element analysis predict measured strains from a nuclear package tie-down system during rail transportation?’

(Cummings, et al., 2018)

This study investigates how the predicted and measured strains correlate on a tie-down system for a rail bed. The tie-down system is designed to secure a 99.7 ton nuclear package and must endure everyday operation and ensure package safety is not compromised during an impact. See *Appendix 9.1* and *9.2* for details of the tie-down system and *Appendix 9.4* for results.

3 Why companies typically carry out physical testing alongside finite element analysis?

FEA is often used when developing components in the early stages of the design process. FEA and topology optimization are used in CAE-led design and can reduce development time greatly over CAD-led design. FEA testing can be used on a wide range of designs, using almost any combination of loads, constraints and materials.

'It is possible to generate a simulation of any design concept and to determine its real-world behaviour under almost any imaginable environments, therefore allowing the concept to be refined prior to the creation of drawings.' (OZ-Tac Engineering, n.d.)

When designing a component FEA can identify any weaknesses in the design more effectively than practical testing. FEA studies are quick and easy to set up, and many studies can be performed inexpensively. FEA is useful in the design stages, as large changes can be implemented and tested on the design in a short space of time.

'Physical prototype testing is limited to the conditions of the test. FEA can vary loading, material and restraints over a wide range of alternatives at low costs.' (King, 2018)

If physical models were being tested, then a new prototype would need to be manufactured for each design tested. Considering the case study, if several physical tie-down systems were destroyed during testing, this would be very expensive. The main structural members of the tie-down system are constructed from welded high strength stainless steel beams and the design features phosphor bronze trunnion bushes. A mixture of partial and full penetration butt welds are used during construction, and where possible the welds are double sided. The time to manufacture new tie-down systems would be longer in comparison to developing an FE model.

Components are primarily designed to function below the material's elastic limit therefore, linear-static analysis is used. Linear-static analysis is quicker to solve compared to non-linear static. Non-linear studies are beneficial, however, as components can be tested to failure identifying areas of weakness. FEA is cheaper than practical testing, therefore, prototypes are only used at the later stages of the design process, where the FEA results require validating.

Since FEA relies on the geometry being represented by a finite number of elements, the results are always an approximation and need validating.

'The biggest challenge in FEA is validation, carefully chosen and closely monitored physical tests that confirm whether or not physical reality and virtual reality line up.'

(Thornton, 2011)

The accuracy of the FEA output will entirely depend on the validity of the inputs. Provided that the boundary conditions accurately define the problem, accurate results can be obtained. The validity of FEA results can be measured by comparing the results to hand calculations, or physical testing.

'Hand calculations should also be used to validate FEA results to determine the accuracy of the model.'

(Emmetcosten, 2019)

For complex geometries or non-linear studies calculations are often too difficult to complete by hand, therefore, physical testing is required. Physical testing is regularly used in motorsport and automotive applications since parts often have complex geometries and loading scenarios. However, using both hand calculations and physical testing ensures higher confidence in the FEA results. By conducting physical testing alongside FEA, the results can be compared to ensure correlation.

'The final step in verifying your model is to build a testing prototype in order to validate your model against real-world results.'

(Emmetcosten, 2019)

Physical testing is also important as a lot of the information required to set up the FEA study is strongly based on physical testing. Material properties are found from physical testing, and therefore, it is not only used for validating FEA results. Linear analysis requires the Young's Modulus and Poisson's ratio of the material, and non-linear analysis additionally requires the stress-strain curve. These are only found from practical testing, normally determined by a standard tensile test.

'Be aware however that most of the information you include in FEA (material models/parameters values etc.) is strongly based on physical tests. You can't "discover" Young Modulus with FEA. Such parameters have to be tested and then implemented.'

(EnterFEA, n.d.)

The output of an FEA study is only as good as the input of the boundary conditions, therefore, engineering judgement is required when setting up a study. Setting up a FEA study using an experienced FEA engineer is vital, as there are many boundary conditions where errors can be made.

Even an experienced engineer can make errors, therefore, validation is important for accurate results.

Linear analysis is often used for studies where only elastic deformation is considered; however, non-linear analysis is better at simulating stress concentrations. Stress concentrations are very small areas with high stress. Stress concentrations often are observed at areas with a sudden change in geometry. The stresses can be above yield at these stress concentrations and therefore, create a sudden increase in stress.

'Because of this sudden increase, linear FEA is not accurate at predicting effects in these stress concentrations.'

(Penner, n.d.)

An experiment was conducted by Sparta Designing Solutions to show how stress concentrations affect the structure as a whole. Static FE analysis was performed and compared to practical testing. It was observed that

'...for a linear analysis there is an allowable size of stress concentration that will not affect the overall strength of the component, depending on the loading case.'

(Penner, n.d.)

Since non-linear analysis will give the same results as linear analysis below the yield stress of the material, it can be beneficial to use non-linear analysis. Physical testing, however, will ensure that the stress concentrations are not inaccurately interpreted.

ALL QUOTES !

YOUR INPUT ?

4 How a physical test may be correlated to a finite element model?

4.1 CAD model

Since FEA is a balance of accuracy against time, the CAD models are often simplified for quicker solve times. Since the aim of the study is for the results to converge in the shortest amount of time, removing unnecessary features is important.

'In simulation, a simplified solution is often chosen in order to save time and expense.'

(Dietsche & Reif, 2018)

Often there are features in the geometry which will not affect the analysis; therefore, they can be removed to simplify the study. Also, by simplifying the model the FEA results can be validated by comparing to theory, which always considers simple models.

'Another reason to simplify the CAD model is to get a model more easy to compare with Theory, because theory always considers very simple models. If the model used from the beginning is very complex, there is no way to validate and compare results with theory.'

(Rusu, 2013)

Small faces and edges can lead to a bad mesh, which can increase time for convergence. Often CAE software includes simplification features which will identify areas of the design that can be simplified and will implement the changes to the model.

The geometry should be checked for:

- *Free edges*
- *Scar lines*
- *Duplicate surfaces*
- *Small fillets*
- *Small holes*
- *Beads*
- *Intersection of parts (assembly of components)*

(Altair Univerisity, 2014)

These features can often be removed before analysis. In the case study, the keep plate bolts, and bolt holes were removed from the tie-down system FE model. They were difficult to mesh and did not affect the analysis (see *Plate 1*).

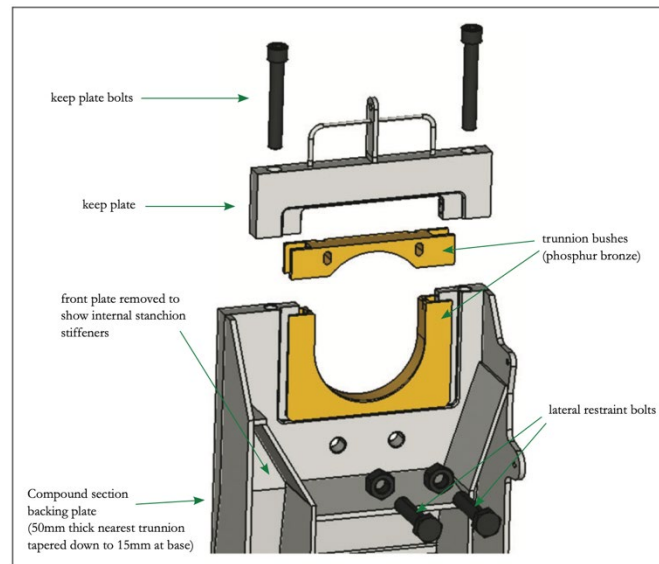


Plate 1 - Upper part of stanchion with trunnion bushing

4.2 Mesh

Since FEA relies on discretization of the complex geometry, mesh selection is important. Firstly, the type of elements needs to be chosen. For 3D geometries these include; tetrahedra, bricks, prisms and pyramids (see *Plate 2*). Each element type has advantages and disadvantages.

‘For some applications, quadrilateral and hexahedral meshes offer more accurate interpolation and approximation.’

(Shewchuk, 2012)

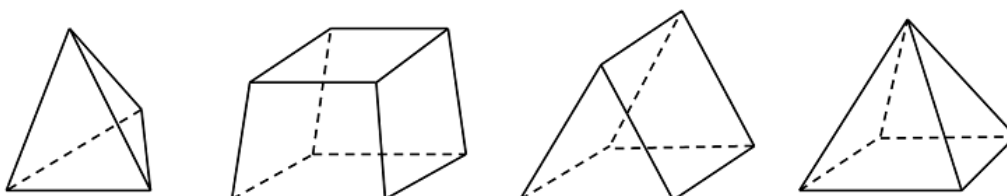


Plate 2 - Element types for three-dimensional geometries (Frei, 2013)

These element types can either be linear or higher-order elements. Linear elements mean there are only nodes in the corners of the element. Higher-order elements have nodes in the corners and have additional mid sided nodes on the edges of the element. A linear tetrahedral is much less accurate than a higher-order alternative, as calculations are worked out at the nodes. A tetrahedral element with four nodes is a popular element, however, their accuracy is low.

'When it comes to performance they are terrible.' (Skotny, 2019)

During the tie-down system study, the dummy package was meshed with four-node tetrahedral elements, and the tie-down was meshed with a mixture of eight-node brick elements and four-node shell elements (see *Plate 3* and 7). The interacting parts were meshed with finer solid elements. A total of 568,416 elements were used.

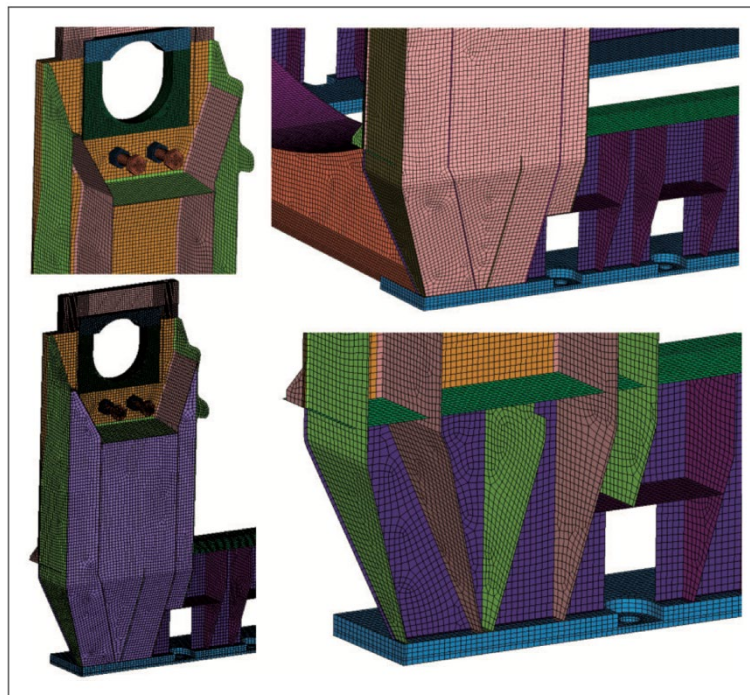


Plate 3 - Details of the tie-down system mesh

Mesh generation also needs to be considered. SolidWorks simulation's default mesher, the standard mesh uses the Voronoi-Delaunay algorithm which aims to maximise the angle of each triangle or tetrahedra. This method minimises the chance of producing elements with a high aspect ratio. The mesh needs to be as fine as possible in important areas of the geometry but can be coarser where the geometry has less effect on the results. Areas with stress concentrations need a fine mesh, as stress averaging will occur between elements, and a coarse mesh will result in large differences between neighbouring elements. By performing studies initially with a coarse mesh, areas of high

stress can be found, and refinements made to the mesh in those areas. Using a smaller element size will improve accuracy, however, it can also produce elements with a high aspect ratio. Mesh details need to be analysed before selecting the mesh, as elements with high aspect ratio can cause a large discretization error.

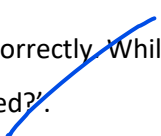
'Elements with large angles can cause a large discretization error; the solution yielded by a numerical method such as the finite element method may be far less accurate than the method would normally promise.' (Shewchuk, 1999)

According to AutoDesk (2017), the maximum recommended aspect ratio for any study is fifty. A good mesh will include nearly all of its elements with an aspect ratio of below three.

'A good mesh will, however, have nearly all of its elements with a small aspect ratio or a value less than 3.' (Petrock, 2017)

Adaptive mesh refinement should also be performed. According to Frei (2013), these can only be used with tetrahedral elements. There are two types; H-refinement and P-refinement. Both methods iteratively change the mesh until the change in strain energy between each iteration is within the prescribed accuracy. The H-refinement method iteratively increases the number of elements in areas of high stress. The P-refinement increases the element order in areas of high stress. Mesh convergence tests are important as they indicate the maximum element size where the results have started to converge.

4.3 Boundary condition

The boundary conditions of some models can be difficult to set up correctly. Whilst defining loads, questions need to be asked like 'is the load instantly or slowly applied?'. 

It is easy to over constrain a model during FEA. For many studies the fixed constraint or a Rigid Body Element (RBE) is used. This constrains the point in 6 Degrees Of Freedom (6 D.O.F) and assumes the point is infinitely stiff, which is hardly the case in real-world solutions. During the tie-down system study, *'...the tie-down bolts are omitted and the entire lower surface of the bottom flange of the longitudinal beams is constrained.'*

This meant that the structure was over-constrained, however, sensitivity analysis showed that alternative methods produced minor differences in structural response.

Contacts can be especially difficult to define for large models. During the creation of the tie-down system, a hybrid shell and brick element mesh had to be connected for the stanchion components. There was a disparity in nodal DOF for the two element types, therefore, a row of shell elements was added between the components. This meant that predicted stresses and strain at this location were likely inaccurate.

4.4 Material properties

The Young's modulus varies with temperature, therefore, the temperature at which the analysis is performed will need to be considered. If a temperature change occurs during the physical test, then dynamic analysis must be performed. For an isotropic material like aluminium, the FEA software will assume that the material is homogeneous, with no structural discontinuities.

'A material which has a uniform structure throughout without any flaws or discontinuities is termed a homogeneous material.' (Hearn, 1997, p. 3)

Material production grades needs to be considered when conducting FEA. Manufacturing defects often lead to differences to the material property in different locations.

4.5 Type of analysis

In linear-static analysis many assumptions are made during the study. The solver assumes that the material behaves linearly and obeys Hooke's law until the elastic limit. This is in fact incorrect, the material behaves linearly until the limit of proportionality, and from here to the elastic limit does not obey Hooke's law. It also assumes small deformations and that load doesn't change magnitude or direction. The solver also assumes the loads are slowly applied. It can be difficult to determine if linear or non-linear analysis should be performed.

4.6 Computer aided engineering correlation tools



HBM Prencia have developed CAE tools to increase confidence in comparing simulation and measured practical testing results. They have developed virtual strain gauge, virtual sensor, strain gage positioning and loads reconstruction. The aim of these tools is to minimise the need to run costly experiments.

'This evolving technology has led engineers as well as managers to challenge how they can better correlate Finite Element predictions (FEA) and test results to minimize the need to run costly repeated experiments.'

(HBM Prencia, n.d.)

The virtual strain gauge HBM Prencia have developed allows the user to position a virtual strain gauge in the FE model which will output strain histories from the dynamic simulation. This data and physical test data can then be compared to ensure correlation (see *Plate 4*).

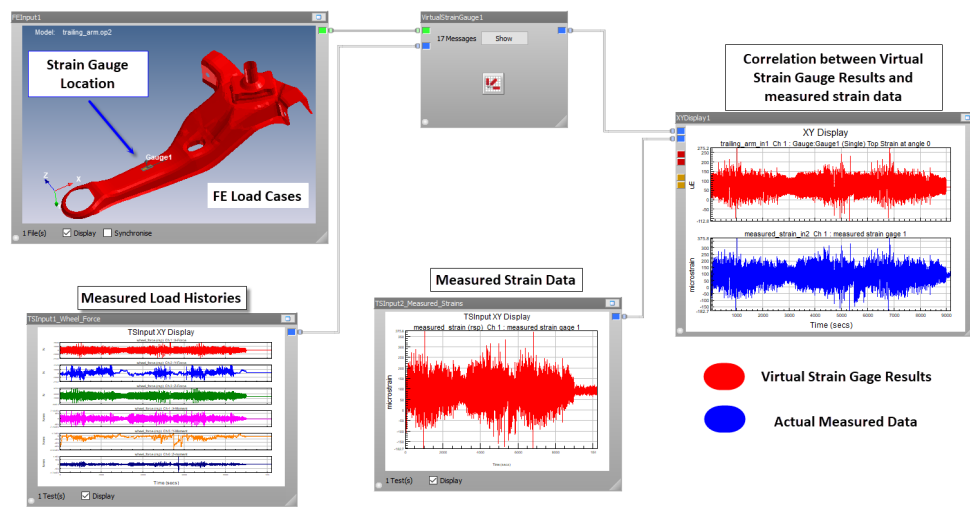


Plate 4 - Virtual strain gauge (HBM Prencia, n.d.)

The virtual sensor can be positioned on the FE model and will output uniaxial or triaxial displacement time histories which can be compared to real test data. These correlation tools are important as they can reduce the number of physical tests conducted.

5 Can finite element analysis replace physical testing?

As software's continue to improve, the likelihood of FEA replacing physical testing in some fields is increasing. Computational power is increasing at a rapid rate, allowing superior FEA software to be produced. FEA has already decreased the amount of physical testing performed in industry, however, it likely won't replace it.

Currently FEA cannot completely replace physical testing. Where human safety is involved, physical testing is critical, and will likely never get replaced by FEA.

'The physical tests are critical for credible analyses.' (Thornton, 2011)

In reference to the case study, if physical testing was not conducted on the tie-down system and the FEA results didn't correlate to physical testing, this could lead to a failure. If the tie-down system failed during operation, then a package of nuclear waste could be spilled causing catastrophic consequences. Also, if a design fault was found after putting the tie-down system into production, it would have to be recalled, costing the company hundreds of thousands or even millions of pounds. It would be much more beneficial to spend more time and money verifying the FEA results to mitigate the possibility of a faulty product going into production.

Since there are so many different variables in real-world conditions, the FEA software will never be able to perfectly simulate real-world studies.

'Virtual testing with FEA saves money and time by reducing the amount of physical testing, but it doesn't always completely eliminate it. Virtual models have limitations since they cannot always completely simulate real physical conditions, so they might not be able to completely replace physical-prototype testing.' (King, 2018)

Errors are possible in physical testing; however, it represents real-life scenarios much more reliably than FEA. According to Murad (2019), errors in FEA can be categorised into three main sections;

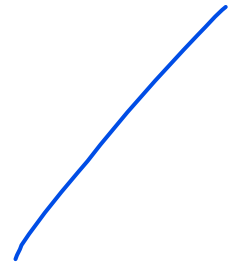
- Modelling errors due to simplifications
- Discretization errors due to the creation of a mesh
- Numerical errors of the solution from

6 Conclusion

This report highlights how vital FEA is in industry, however, it also highlights the importance of validation and verification. Careful analysis of FEA results are required to verify its accuracy. Since FEA is a computational method, one cannot solely rely on FEA results without ensuring they correlate with real-world tests. To ensure correlation to real-world solutions the FEA results need to be compared to physical tests or at the very least hand calculations.

Correlating physical tests and FE models are becoming easier with new computational correlation tools. As technology progresses it will become easier to correlate predicted and measured results.

Despite FEA often producing accurate results, it will likely never replace physical testing. There are so many potential areas for errors to arise in FEA, therefore, boundary conditions and material properties must be carefully selected during analysis. To reduce uncertainty of the results comparisons to physical tests are imperative.



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9 Appendix

9.1 Major components and features of the rail wagon, package and tie-down system

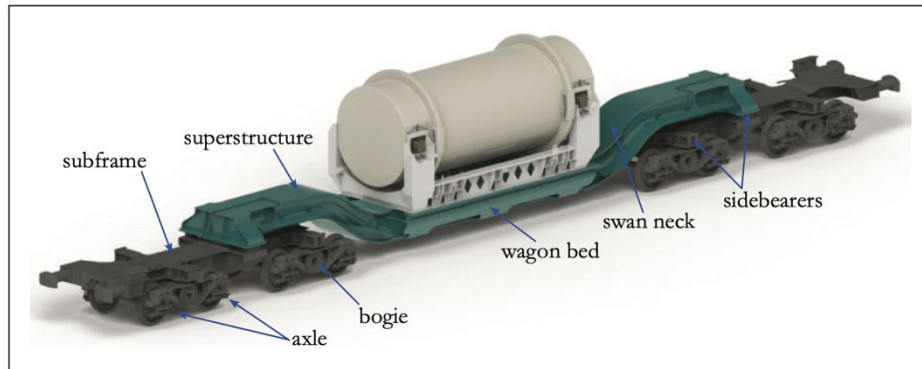


Plate 5 - Major components and features of the rail wagon, package and tie-down system

9.2 Details of the rail tie-down system

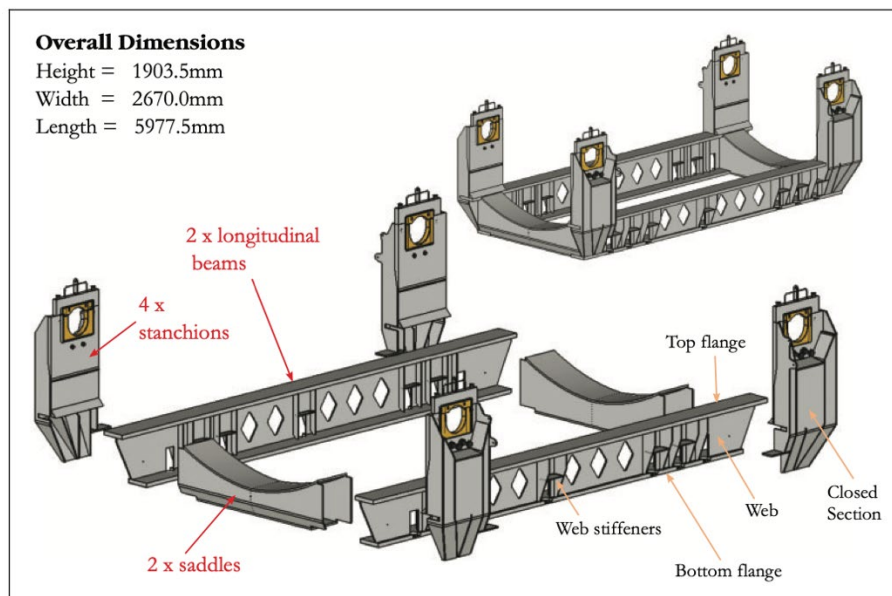


Plate 6 - Details and specifications of the tie-down system

9.3 Rail tie-down system FE model with dummy package

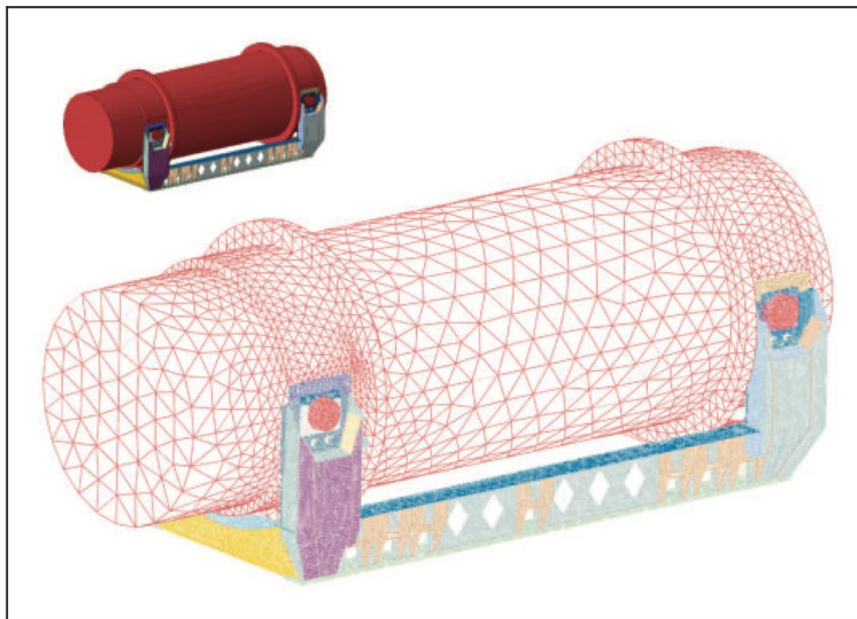


Plate 7 - Tie-down system and dummy package meshed FE model

9.4 Results

'Cummings et al. described methods for filtering measured accelerations during a rail journey of a 99.7 t nuclear package. They estimated quasi-static accelerations for comparison with the current design parameters. In the present study, dynamic acceleration and strain data are systematically passed through a low-pass filter, whilst varying its cut-off frequency between 1 and 100Hz. The filtered triaxial acceleration time histories are used to scale the results of a linear static finite element model (FEM) at specific elements in the model corresponding to strain gauge locations. The scaled vertical, lateral and longitudinal accelerations are then summed to calculate strain time histories. The calculated strain time histories are compared with actual measurements.'

(Cummings, et al., 2018)

Virtual strain gauges were added to the FE model in the same locations as the strain gauges from the practical testing.

'A 30min section of the measurements during the journey was low-pass filtered with a fourth order, forward-backward, Butterworth filter. Strain time histories were calculated using the

filtered accelerations measured at the base end stanchion. This process was repeated for 28 different filter cut-off frequencies 1–20 Hz in 1 Hz increments and 20–100 Hz in 10 Hz increments.' (Cummings, et al., 2018)

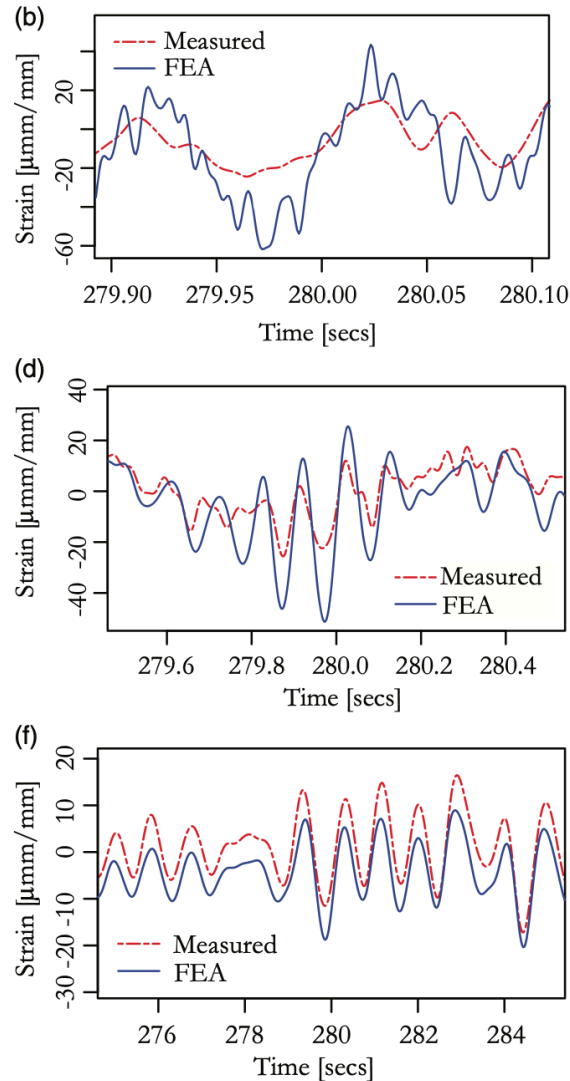


Plate 8 - Predicted and measured tie-down system strain results

- (b) – Time history slice with low-pass filter cut-off frequency – 100Hz
- (d) - Time history slice with low-pass filter cut-off frequency – 20Hz
- (f) - Time history slice with low-pass filter cut-off frequency – 2Hz

The results show good correlation of the predicted and measured strains (see *Plate 8*). The results show how using a lower cut-off frequency, the FEA results are more accurate. At higher frequencies a linear relationship between the acceleration and strains does not exist. According to Cummings, et

al. (2018), the linear FE model over predicts the strains because it does not include the inertial dynamic effects. A dynamic analysis would have led to superior predicted results for this study.