

BACHELORS DEGREE ASSIGNMENT SPECIFICATION

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declare that this assignment is all my own work and that I have acknowledged all materials used from the published or unpublished works of other people.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

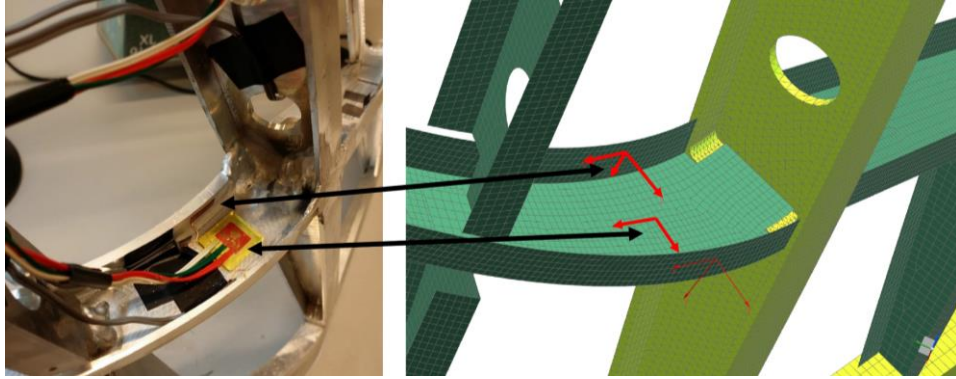
Learning Outcomes tested (from module syllabus)	Assessment Criteria To achieve each outcome a student must demonstrate the ability to:
Demonstrate an ability to analyse a range of engineering problems using advanced stress analysis principles.	

- 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	18.6
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	17.4
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	18.4
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

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)		60.9 %
	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.

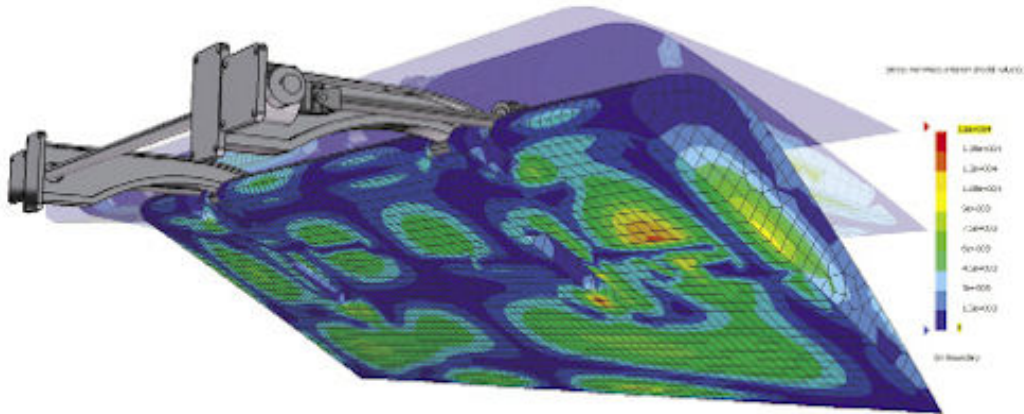
Common Assessment Criteria Applied	Level of Achievement						
	REFER		3 rd	2:2	2:1	1 st	1 st
	OUTRIGHT FAIL	UNSATISFACTORY	SATISFACTORY	GOOD	VERY GOOD	EXCELLENT	EXCEPTIONAL
1. Research-informed Literature	0-29% ☐	30-39% ☐	40-49% ☐	50-59% ☐	60-69% ☐	70-79% ☐	80-100% ☐
2. Knowledge and Understanding of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



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David



ADVANCED FEA AND STRESS ANALYSIS M6X00420

Can FEA replace physical testing?

Abstract

This report will examine the advances in Finite Element Analysis and compare with traditional testing methods in a case study format.

USE PAST
TENSE

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Introduction:

The purpose of this report is to carry out a case study type analysis on the role of Finite Element Method (F.E.M) testing of engineering products in a modern related industry. The study will look at how the use of F.E.M is implemented when testing components within an industry of the candidate's choice and how these methods compare with more traditional, physical testing methods or even how they are used in conjunction. In this instance, a study of the aerospace industry will be carried out as it is the author's belief that this industry has the most developed F.E modelling infrastructure in place and also relies on findings from simulations in many areas of the design and validation process' more so than most other engineering industries.

Further discussion will include, how a physical test may be correlated to a F.E model by deciphering what type of analysis may be necessary, how the model is bound and loaded methods and equipment required for physical testing and methods of correlating between physical and simulation.

To conclude the report, further discussion on whether physical testing of components can be phased out completely from the design process will ensue, with considerations to some of the items raised in the previous section explored in further detail.

1. Why companies use F.E.A alongside physical testing:

As mentioned previously, this study will be analysing the aerospace industry and their use of finite element testing, as this industry has been at the forefront of computer simulated testing since the very early days of this process, namely with Boeing in the early 1960's albeit using very simplified models and basic elements to identify load paths through materials. (Abbey, 2014)

15 YEARS OLD. Nowadays, the aerospace industry relies on the results of F.E testing heavily in the design process of aircraft and their associated components, this reliance can be attributed to the fact that the strive for lighter, stronger and more economical aircraft is in high demand in the modern world and in order to achieve this, more and more manufacturers are utilizing composite materials for their designs. (Peeters P.M., 2005). The use of composites poses an issue when it comes to physical testing in the aerospace sector due to the complexity of the fibre construction. This area has been studied extensively in aircraft design, particularly in relation to modelling of wings and fuselage components that may encounter bird strikes or tool damage to the laminate layers during manufacture or transport, or indeed in flight.

Studies carried out by Myler and Farook (Umar Farook, 2016) have used finite element method to predict the possibility of delamination of composite materials when encountering a strike from a blunt object, utilizing Abaqus™ software to non-linearly analyse the components and determine their failure modes. The ability to perform these simulations is invaluable in this instance, as physical testing of the impact strains would be extremely difficult in these complex materials due to their orthotropic and quasi-brittle nature.

The results of their study concluded that the simulated model could accurately predict laminate failure based on Hashin's failure criteria, hence highlighting the credibility of the F.E simulation in relation to composite materials.

Conversely, physical testing of components is still widely used in the aerospace industry due to the demand for impeccable safety of aircraft and strict regulations imposed by transport authorities worldwide.

These physical tests must be carried out on the composite materials to determine the flexural and compressive stresses encountered by the components in order to validate simulated data in these areas, as these properties cannot be predicted from empirical tensile properties (ZwickRoell, 2013).

In order to perform the required testing and meet international standards, new testing equipment has been developed, specifically for the purpose of testing composite materials whereby a 9-component stress tensor is utilized to account for the material complexity and provides greater accuracy in results.

ZwickRoell's Modular Testing System for Fiber Reinforced Composites: 21 Types of Test, 115 Standards, 320°C of Temperature Range!



Figure 1: ZwickRoell composite test machinery. (ZwickRoell, 2013)

Another area that F.E analysis is used in aerospace, is in the analysis of air-crash investigations. Many accidents in the past have utilized the power of these analyses to find the cause of a failure of an aircraft component due to fatigue or abnormal loading due to contact with an object.

Most notably in the case of the MH370 mystery, where a suspected piece of debris from the flight was recovered from the ocean, part of a flaperon. When the damage was inspected, investigators had to determine if the part had fallen from a supposed height of 5000ft, the aircraft's last known altitude or was it still attached to the plane as it made contact with the surface of the ocean? By creating an FEA simulation of both scenarios, including wave movements, tides and the projected flight path of the aileron from this altitude, engineers were able to ascertain that the aileron was in fact still intact as the plane struck the ocean, it was also possible to determine the position of the aileron from the damage incurred and although the mystery remains unsolved, some light was shed on the final movements of the aircraft as a result of these findings, suggesting that the aircraft may have been ditched.

This process was also used in the case of American Airlines flight 587 and actually resulted in the cause of the accident being established by using the F.E data, along with flight data recorder data to recreate the static and dynamic loads encountered by a failed mounting lug on a vertical stabiliser, which was subsequently physically tested in the laboratory and conclusively proved the failure mode as a cleavage-tension failure at the mounting lug holes on the composite stabiliser structure. (Griffioen, 2009)

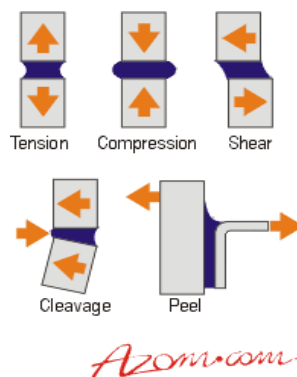


Figure 2: Example of cleavage tension failure, shown bottom left of image. (AZ of materials, 2001)

2. How a physical test may be correlated to an F.E model:

When attempting to correlate or validate F.E models, the procedure can be split into two distinct areas, linear and non-linear. (Harish, 2019) (neglecting thermal, buckling, NVH etc. for the purposes of this section). Each of these areas of analysis has a critical impact on the validity of the results from the F.E test and will directly affect how they correlate with the physical test.

2a. Linear Analysis:

In a static or quasi-static linear analysis, the stiffness matrix will not change when loaded, loads are applied gradually and the accelerations within the system considered negligible, (i.e. displacement/time) and the results will only display as a comparison of values for stress encountered vs. U.T.S or yield stress (Altair University, 2015). Generally, linear static analyses will deal with small deformations.

For dynamic linear analysis, a system exhibiting simple harmonic motion could be considered, as the mass in the system will oscillate linearly as a function of force applied and spring stiffness.

2b. Non-linear Analysis:

Non-linear analysis should be considered in a material sense when materials are expected to exceed their yield strength, whereby they encounter plastic deformation and the stiffness matrix alters, the F.E analysis must account for this change in stiffness iteratively in order to yield favourable results.

Consideration must also be given to geometry of the part being analysed non-linearly as large changes in geometry will also affect the results of a study as the material deforms. (Altair University, 2015). Non-linear analysis can be useful in analysing crash safety evaluations using software such as Altair Radioss.

With dynamic non-linear systems, the response of a system can be found analytically by implementing differential equations, this can be performed in an F.E analysis and provides a good benchmark for expected response that would be difficult to replicate experimentally.

Correlation:

In the first instance, a physical experiment may be carried out on a material or a structure, whereby the estimated loads are applied to the structure and a variety of tests performed to determine stress, strain and deformation. Specialist equipment is required such as, strain gauges and load cells that measure these parameters accurately, and naturally the test machinery itself that can apply the necessary loading, whether it be compressive, tensile, shear or bending amongst many others.

Using classical analytical methods, a simplified model of the structure can be assessed quickly and conclusively and will generally provide 100% accurate results for the simplified structure, this is useful for linear static studies and can be compared with the prototype physical test results to determine validity.

The numerical results from the F.E model can then be compared to both previous methods to then ascertain validity also. Generally, in the first instance F.E results will not correlate with experimental or analytical and will require reconfiguration of the model parameters, boundary conditions, mesh quality and determination of local stress concentrations (Proulx, 2011).

It is suggested that correlation within 10-15% between experimental and F.E.A models is considered successful. (Altair University, 2015)

As an aside relating to aerospace:

2c. Modal Analysis:

In the case of the aerospace industry, modal analysis is an extremely important aspect of F.E.A, as this area is often used to determine the aerodynamic response of aircraft structures in a given frequency range. Modal analysis is used to determine phenomena such as “flutter” on aerodynamic surfaces that may result in a loss of dynamic stability in the aircraft due to wind-shear or other unexpected factors affecting the dynamics of the aircraft structure. (V. Quaranta, 2013) Vibration can also be modelled using modal analysis, again particularly useful in aircraft engines where resonance could prove fatal. Rigorous standards exist for these analyses and several levels of validation are required to correlate F.E models in this procedure.

To correlate modal F.E analyses, physical experiments are set up that excite the component or structure using a modal shaker device and measure its response at its natural frequencies, by means of accelerometers fixed to the structure. This also determines the mode-shapes and damping co-efficient for the particular frequency. The F.E model is then created, and the same loads and boundary conditions applied within the software and results compared regarding deflection and comparison of mode-shapes. (Crystal Instruments, 2016)

If results are found not to be in agreeance, it is possible to adjust the mass (inertia) of the component, redesign the model and/or increase or decrease the stiffness of the material thus allowing correlation for a particular mode.

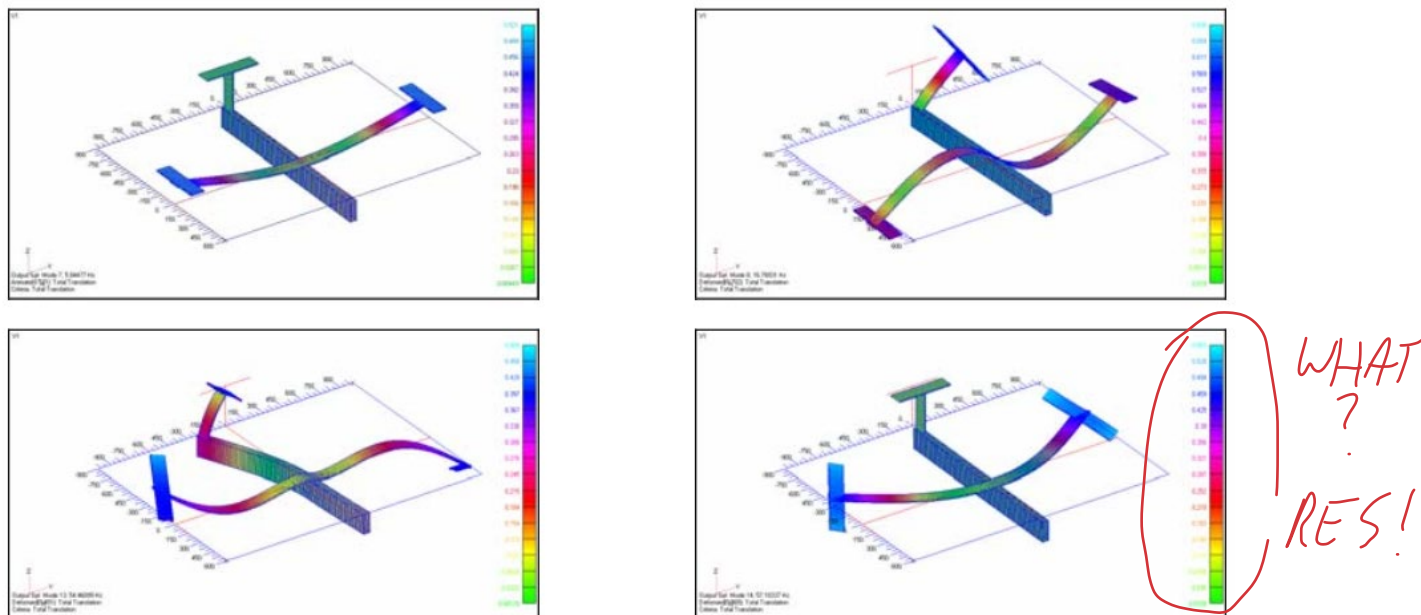


Figure 3: Modal analysis of aerospace structure F.E model. (I. Mendoza-Muñoz, 2015)

3. Feasibility of F.E testing replacing Physical testing:

At the current time, we are not yet at a stage where F.E simulations can fully replace physical testing. Many advances have been made in this field, but the requirement is still there to physically test components and materials in order to provide certification and conformity to standards. This is of particular concern in the aerospace industry as previously discussed.

Possible methods of moving towards complete reliance on simulation results are in practice today, with many aspects of simulation being relied on fully, particularly in the areas of CFD and crash testing. As an example, the Jaguar XE was fully modelled and certified with a co-efficient of drag of 0.26 without a single prototype being built. (Vyas, 2015).

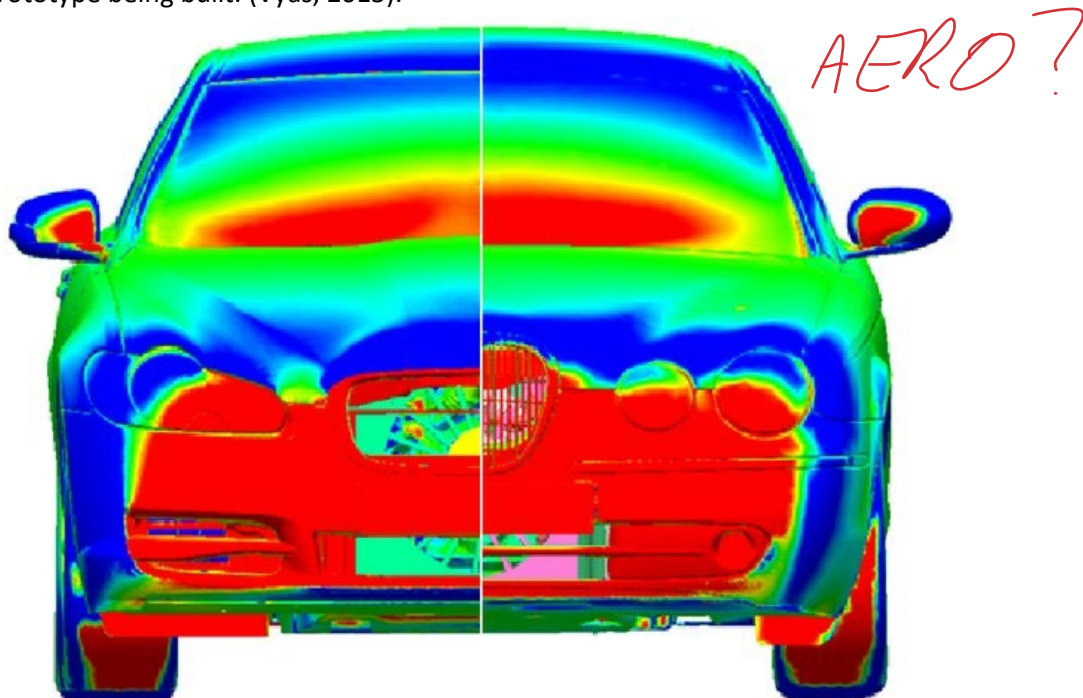


Figure 4: Jaguar XE and S-type CFD comparison. (Gaylard, 2008)

This process resulted in massive cost benefits in the development of the vehicle by making the requirement for wind tunnel testing and clay modelling etc. obsolete. (Schweinsberg, 2015). It is estimated that more reliance in these areas could save car manufactures between \$3-10 billion per year in the United States alone.

The advent of exa-scale computing is providing a platform by which many environmental considerations can be included in global F.E models thus providing a more robust picture of loading, boundary and environmental conditions, this is made possible by the huge computing power available through cloud computing with up to 10^{18} calculations being performed per second.

This also leads on to the development of software based measurement devices, such as virtual strain gauges, developed by companies such as Altair (Virtual Gauge Director) and nCode becoming more commonplace in the automotive and aerospace industries, whereby a virtual strain gauge is placed in the F.E model at the same position as a physical gauge would be on the real-life counterpart. This would

eliminate the requirement for a physical test in various applications by allowing correlation of previously collected data and again, could result in massive time and cost benefits for manufacturers.

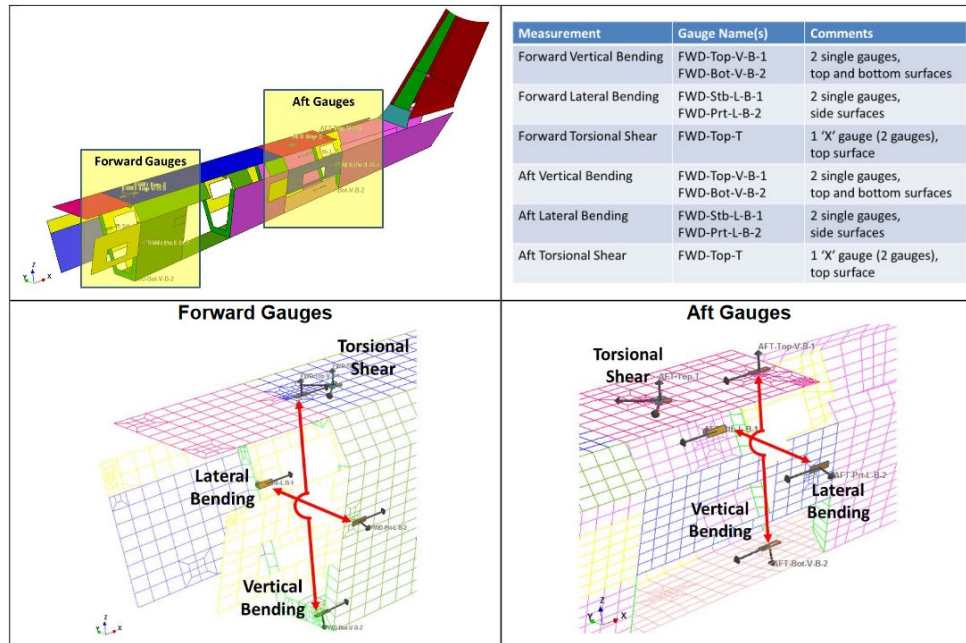


Figure 5: Placement of virtual strain gauges on Helicopter tail structure F.E model. (R. J. Plaskitt, 2013)

Although still expensive technology, this is a game changer for industry as it provides greater corroboration with materials and structures non-linear behaviour when encountered by a real-world scenario, and also can iteratively model F.E at the macro-scale and cellular automata at the mesa and micro-scales as proposed by Shterenlikht et al. (Anton Shterenlikht, 2017) to predict crack propagation in composite materials.

As this technology becomes cheaper and more readily available it is possible that we could see a shift towards full simulation capability and reliance within the next 10-25 years, provided the same rate of progression follows.

An area that is also important in the simulation field is Verification, Validation and Uncertainty Quantification (VVUQ), this is a framework designed to assess the credibility of simulations by ensuring that correlation is met by verifying mathematical models with F.E, validating the model against real world scenarios and applying comparisons between physical and experimental results to understand uncertainties in the simulation. These frameworks are currently supported by the ASME and provide clarification in credibility of simulation results if VVUQ policies are adhered to. (American Society of Mechanical Engineers, 2020).

This is a step in the right direction to provide reliable, repeatable and accurate standards in the simulation and modelling industries and when further developed could see a marked increase in the use of standalone F.E.A methods becoming widespread in industry, coupled with the aforementioned practices.

Conclusion: *REALLY?*

This report has conclusively discussed the various reasons why companies, in particular aerospace companies use finite element methods in parallel with traditional physical test methods in the design of their components and structures. These methods allow for greater understanding of the dynamic loads encountered by said components, in a flight environment that would be difficult to replicate with physical testing, being the main point. It also allows for a greater understanding of the product lifecycle and a more detailed fatigue analysis which is prevalent in the industry due to the cyclical environment in which it operates.

Various methods of analysis have been discussed and practices which are commonly used to correlate them within industry. This has also touched on some of the equipment required and specialist methods undertaken in the aerospace industry, although only brief discussion has commenced regarding these methods, it does give a basic insight as to how the results may be correlated as the entire field may be a little outside the scope of this report.

To answer the question of whether or not F.E testing can replace physical testing, as previously mentioned the most likely answer is no, at the moment there is still a lot of reliance on physical experiments to verify and calibrate the F.E models, if the VVUQ framework is adhered to however, and the implementation of extremely powerful processing, there may be a paradigm shift towards full reliance on simulated results in the near future.

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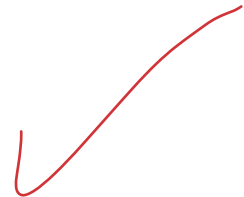
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Appendix:

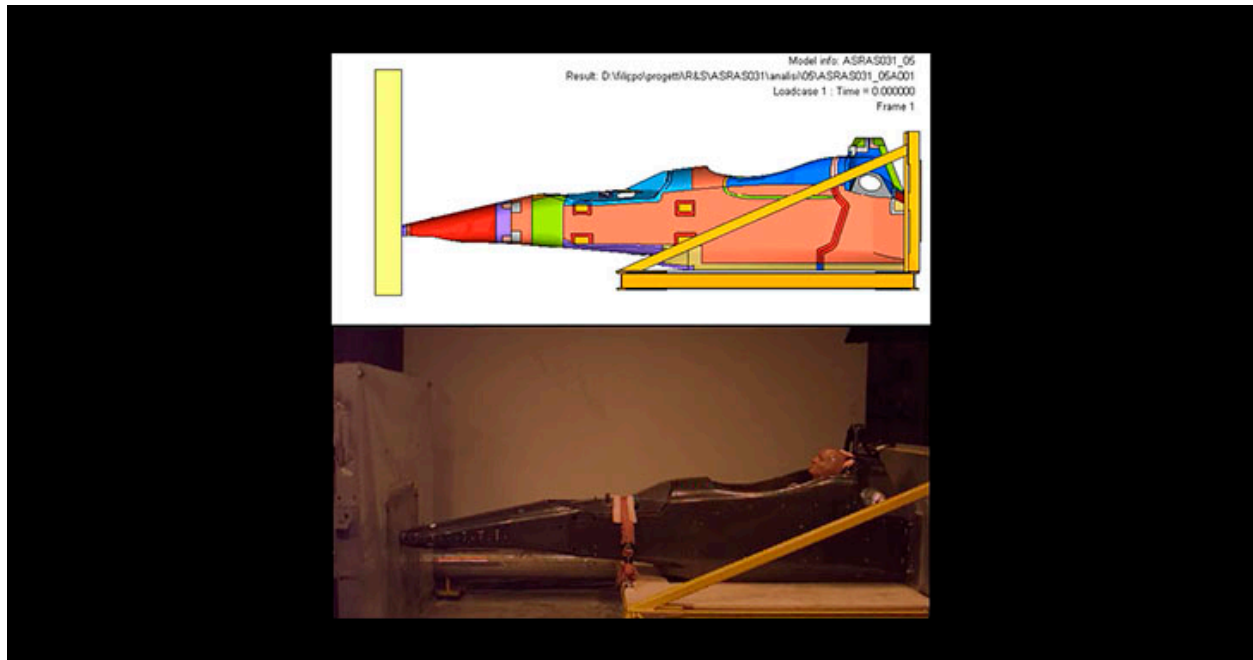


Figure 6: Radioss crash test F.E model and physical crash test.

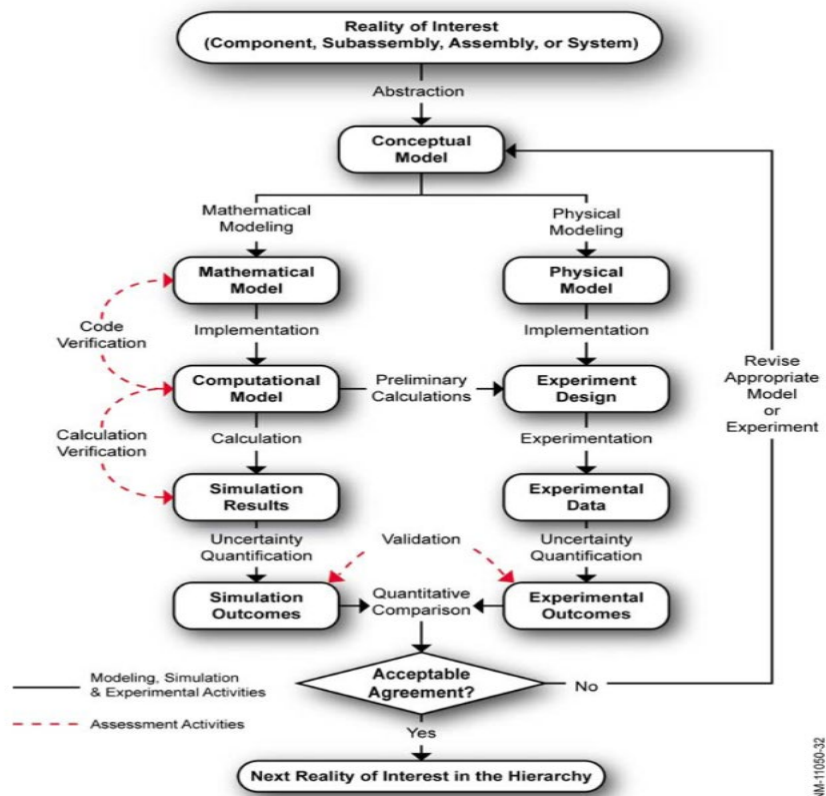


Figure 7: VVUQ flowchart

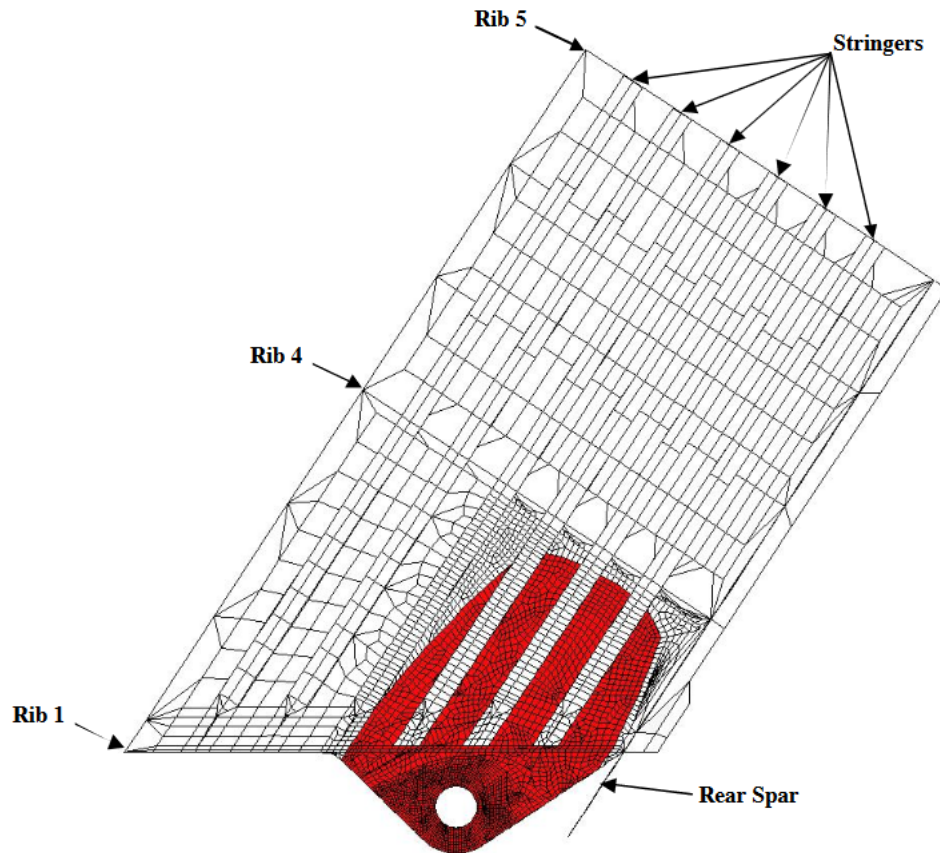


Figure 8: Section of rudder NASTRAN FEA model from American Airlines flight 587.

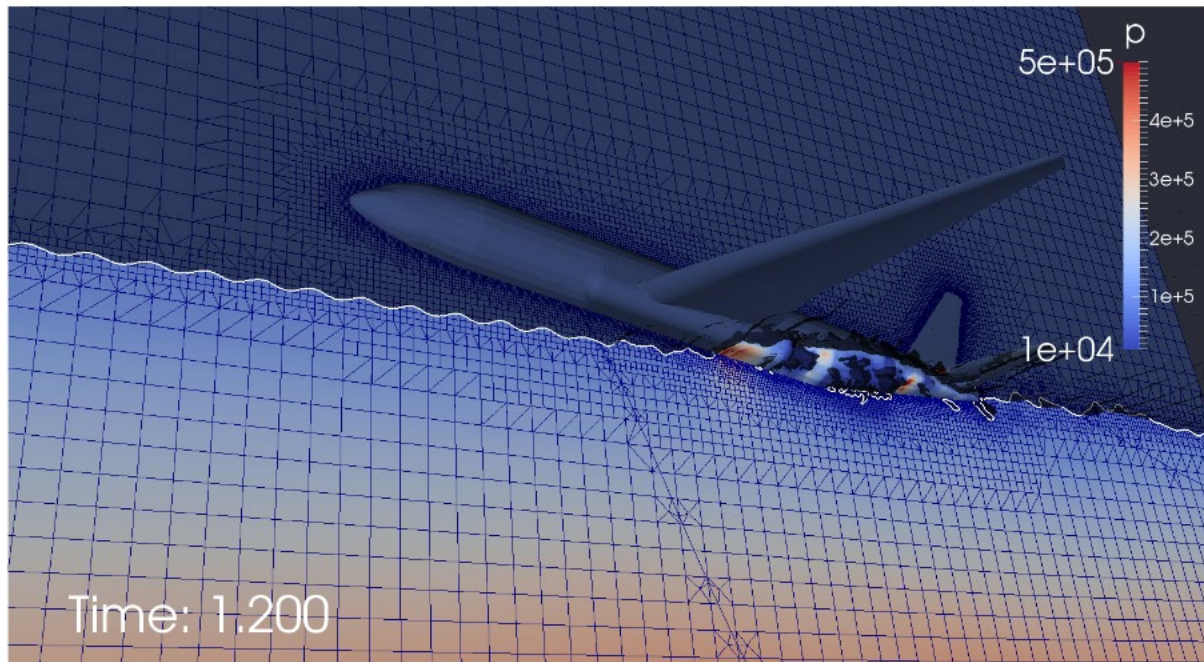


Figure 9: Study into MH370 mystery, modelling of Gliding water entry.

A REVIEW OF FEA TECHNOLOGY ISSUES CONFRONTING THE AEROSPACE INDUSTRY

Table 2: Aerospace requirements - theme Durability and Life Extension

#	Engineering analysis requirement	SoP	PL	TRL	Remarks
1	Failure mechanisms of fibre reinforced composite materials	-	-	7	
2	Fracture mechanics/fracture control	4	6	8	
3	Crack propagation and residual strength	4	6	8	More than 15 years of co-operation between ESA and NASA for the development of relevant methodologies and numerical tools, e.g. NASGRO and ESACRACK.
4	Damage/damage tolerance	3	5	3-8	Extension to non-metallic materials and elastic-plastic conditions needed.
5	Support maintenance and upgrades of legacy aircraft - life cycle >30 years	4	6	6	Needs for data integrity and standardisation, long term archiving.
6	Assessment of structural damage: dents, de-laminations, etc.	3	5	7	
7	Determination of stress-intensity-factors (SIF)	-	-	7	FE and BE.
8	P-element method	-	-	8	Tools PROBE, StressCheck and NASTRAN used at ESA.
9	Linking FEM and BEM	-	-	6	Fluid-structure interaction.
10	Integration of tools for structural analysis and life (cycle) analysis, in particular w.r.t. geometry, loads, material property databases, probabilistic analysis	-	8	4	
11	Modelling and assessment of residual stress (due to welding, moulding, casting, etc.)	3	5	5	
12	Modelling and assessment of welds	3	4	4	

Figure 10: Conference proceedings from FENET discussing tech. requirements in Aerospace. 2005