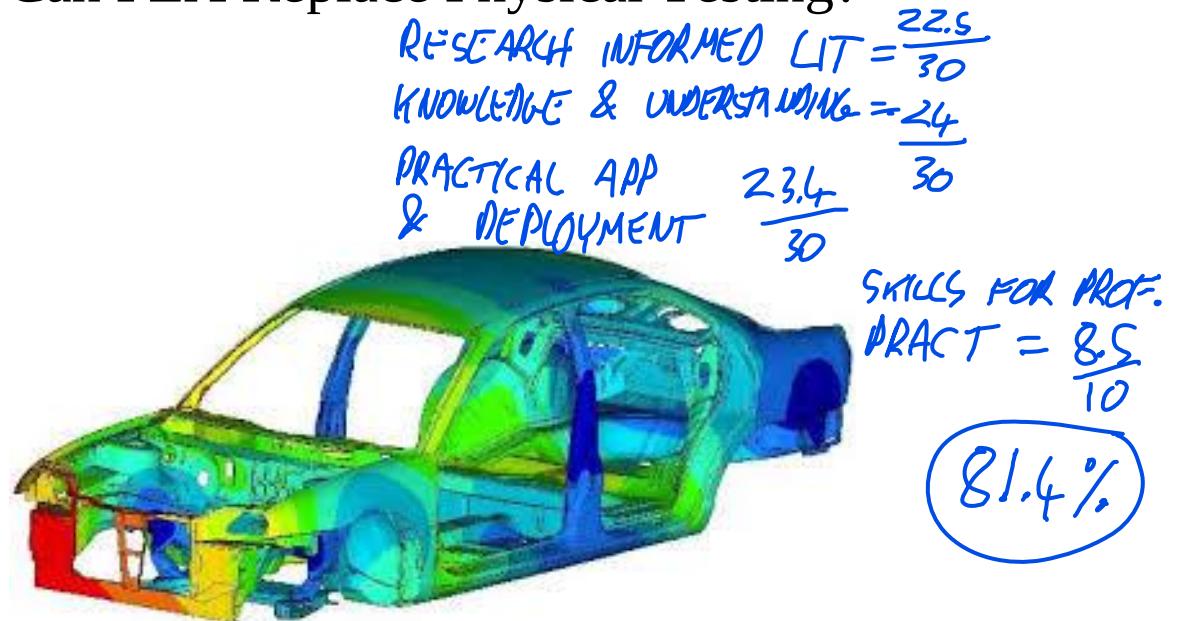


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Can FEA Replace Physical Testing?



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Table of Contents

Table of Contents	i
List of Figures and Tables	i
1Introduction.....	1
1.1Aims.....	1
1.2Objectives	1
2Why do companies typically carryout FE analysis alongside physical testing?	2
2.1Traditional Design Analysis and Validation.....	2
2.2Contemporary CAE Driven Design	4
3FE Model Correlation and Validation.....	6
3.1Why Correlate FE Models?	6
3.2How can FE models be correlated to physical tests?	7
3.2.1Modal analysis	7
3.2.2Strain Gauging	9
3.2.3Other Methods: Dynamic Response, Thermal and Pressure comparison... ..	11
3.3Model Updating	11
4Conclusion: Can (or should) FE Analysis Replace Physical Testing?	12
5References.....	14
6Appendices.....	16
6.1Appendix 1 - Case Study	16
6.2Appendix 2 - Modal Correlation Study Results.....	17

List of Figures and Tables

Figure 1: Pie Chart Showing FEA Market Share By End User 2016 (TechNavio, 2016).....	2
Figure 2: Table of Traditional Design Process Limitations	3
Figure 3: Table of FE Analysis Types (Koutromanos, 2017).....	4
Figure 4: Traditional Design vs FEA Driven Design Diagram (Kurowski, 2011)	4
Figure 5: Table of Benefits of FEA in the Design Process.....	5
Figure 6:: Sleipner Oil Platform Tricell Cross- section (SINTEF , 1992).....	6
Figure 7: Modal Test Correlation Diagram (Schedlinski, et al., 2005).....	8
Figure 8: Summary Of Modal Correlation Results (Schedlinski, et al., 2005).....	9
Figure 9: Altair FE Model Correlation Experiment Results (Guffroy, et al., 2016).....	10
Figure 10: Altair FE Model Correlation experiment Using Strain Gauges (Guffroy, et al., 2016)	10
Figure 11: FE Model Diagram and Dynamic Response Results (Jun Lu, et al., 2017)	11
Figure 12: Costs With and Without FEA (Altair, 2016).....	12
Figure 14: Labelled Body in White (Volvo, 2016).....	15
Figure 15: Results from Modal Correlation Study (Schedlinski, et al., 2005).....	16

1 Introduction

With the advancement of computational resources In recent years, finite element analysis (FEA) has become a mainstay in the techniques used to validate and optimise component designs during the early stages of manufacture. Prior to the proliferation of digital computation of such problems, key design metrics such as; stress, stiffness, and displacement distributions etc, were either calculated by a series of arduous hand calculations or studied using both destructive and non-destructive experimentation. Nowadays, this advancement of computing power, as well as the development of sophisticated FE software, allows engineers to calculate, simulate and validate typical problems including structural analysis & optimisation, impact analysis, vibration & fatigue analysis, fluid dynamics analysis and thermal diffusion problems more quickly than previously achievable. This dissemination and constant evolution of FE techniques in all engineering sectors raises fundamental questions about how we currently test components before they reach production, as well as how we validate FE models going forwards. Arguably, one of the most fundamental questions posed is “can or should FEA replace physical testing?”.

1.1 Aims

This report, by use of case studies and both lecture and research-informed engineering judgement, aims to answer the question “Can or should FEA replace physical testing?”. Although the answer deduced will be specific to the chosen case study, the wider applications of FEA will also be considered throughout in order to form a meaningful discussion.

1.2 Objectives

- Identify a relevant case study around which to base the research and discussion. (***Moved to Appendix 1 to conserve word count for main body***).
- Identify typical FE techniques as well as any physical tests carried out specific to the case study.
- Conduct research and discuss the uses of FEA in industry and how FE analysis may be used alongside physical tests.
- Review how FE models are correlated or validated with physical testing, Particularly how do we ensure an FE model accurately represents the behaviour of a component in the real world.
- Form a meaningful discussion as to whether FEA can ever replace physical testing, considering both the case study and the wider applications of FEA.

2 Why do companies typically carryout FE analysis alongside physical testing?

Modern manufacturers use a combination of numerical, physical and computer-aided analysis during the development of new products, be it to validate a design, optimise time spent in the design process, optimise the design itself or to prove that the product is compliant with regulations and standards. Nowhere is this more true than within the automotive industry. A report by industrial market researchers TechNavio found that the automotive industry was the largest end-user of FEA software in 2016 (TechNavio, 2016). Below is a pie chart of the report's findings;

FEA Market Share By End User (2016)

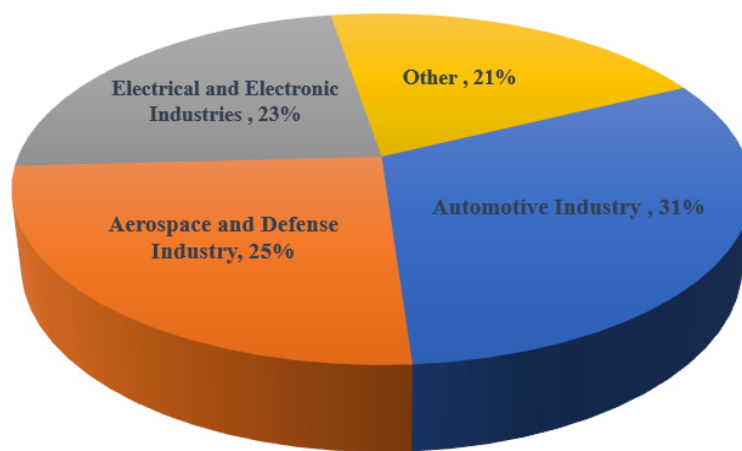


Figure 1: Pie Chart Showing FEA Market Share By End User 2016 (TechNavio, 2016)

2.1 Traditional Design Analysis and Validation

Design validation is the process of ensuring the proposed design sufficiently meets the form, fit and functional requirements outlined in the design success criteria (also known as a statement of requirements). Design success criteria is typically driven by the demands of the consumer, safety standards and regulatory compliance. Put simply, design validation ensures the proposed design will function sufficiently in its intended application (P.G.Maropoulos & D.Ceglarek, 2010).

It is important to define the difference between design validation and FE model validation, as mentioned above, design validation is the process of ensuring a design is sufficient for its intended purpose, whereas FE model validation is the process of ensuring an FE model is an accurate representation of how a given design will respond to loading and environmental conditions in reality (FE model validation is discussed further in chapter 4).

The traditional approach to design validation is the build, test and learn methodology (also known as the Guess, Test and Revise method). This method is an incremental and iterative process in that comprehensive validation of a design typically involves repeated physical

testing of numerous prototype components and assemblies. Using the insight gained from the physical test the proposed design is revisited with the aim of improving the design in order to meet the design success criteria, when this is achieved, the design is said to be validated.

O'Connor (2001) describes that the test and learn methodology has a number of inherent limitations, these have been tabulated below;

Limitations of The Build, Test & Learn Methodology	
Broad Limitations	Description
Number of Prototypes	Multiple prototypes are required during the validation process, which in automotive chassis design, may be costly and take a significant time to manufacture.
	Destructive testing may also require numerous components or assemblies for different loading/ test scenarios.
	Significant tooling costs are also an issue, particularly in prototypes involving cast or pressed components requiring costly dedicated tooling.
	Environmental concerns are also apparent, needless building and destruction of prototypes may be seen as inappropriate in modern manufacturing.
Time spent & Late Discovery of Design Flaws.	As discussed above, this traditional process is both incremental and iterative, large amounts of time may be invested into a design that proves insufficient during physical testing, leading to redesigns.
	Design flaws found late during this process further exacerbate this issue, this results in a loss of competitive advantage with regards to time to market.
Lack of Design Insight.	While this traditional methodology may identify the weaknesses with a proposed design, it does not offer any insight as to why the design failed a given test, or how it should be mitigated against in the next design iteration.
	In complex systems, with inhomogeneities, material nonlinearities and complex geometries, identifying the cause of failure may prove exceedingly difficult and require extensive investigation, further exacerbating the time and monetary costs.
	Often, implementing the build, test and learn method results in the development of a minimally viable product. While the product may meet the success criteria, it is often suboptimal in that the design could be lighter, stronger, cheaper, safer and more robust etc.

Figure 2: Table of Traditional Design Process Limitations (O'Connor, 2001)

In summary, this traditional approach is resource intensive in terms of costs, lead times and design effort. Increased awareness of safety and thus increased complexity in automotive chassis design, combined with competition in a crowded market meant that automotive manufacturers needed to improve efficiencies in the development of new chassis designs. This in turn supplied the demand for the adoption of FE analysis in the industry (Saupan, et al, 2007).

2.2 Contemporary CAE Driven Design

A concurrent approach to Design, analysis and validation is the CAE (also called simulation/FEA) driven design methodology. In CAE driven design, FE Analysis and optimisation are used to synthesize and define the design long before physical prototypes are manufactured, this allows design engineers to gain insight to the functional and performance characteristics using virtual simulations before investing in costly physical prototypes (Altair, 2016). Types of analysis used in CAE driven methods are tabulated below;

FE Analysis Types	
Linear statics	Nonlinear analysis
Dynamic analysis	Fatigue analysis
Computational fluid dynamics	Buckling analysis
Noise vibration and harshness	Thermal analysis
Impact analysis	Mass/stiffness optimisation

Figure 3: Table of FE Analysis Types (Koutromanos, 2017)

The fundamental aim of CAE or FEA driven design is to streamline the design validation process, (using the types of analysis in figure 3) by minimising the number of physical prototypes and testing and thus redesigns by increasing the confidence in the design earlier in the process (see figure 4).

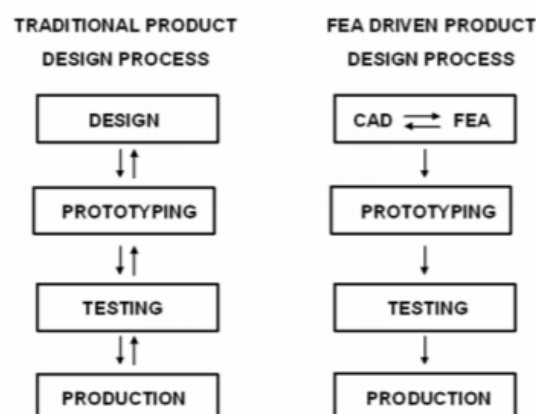


Figure 4: Traditional Design vs FEA Driven Design Diagram (Kurowski, 2011)

Jaguar land rover described in an article published by Altair, that in order to remain competitive in automotive manufacturing, they adopted a FEA driven design approach. JLR described how stringent safety and emissions regulations required them to drive down the weight of their passenger vehicles. As a result, they decided to radically change their chassis fabrication materials from welded steel structures to bonded aluminium variants. The authors described how, historically, this would result in a vast amount of physical testing in order to validate the new construction technique, however, using a FEA driven design, JLR was able to minimise the number of physical tests required and maintain a time to market advantage. The authors discuss how using FEA driven design techniques, they can achieve a “right first time” design

for automotive BIWs. JLR quoted impressive performance characteristics using optimisation methods for stiffness and mass, they noted “The BIW produced by this [FEA Driven] process is twice as stiff as the structure it replaces and only half its mass. The reduced number of iterations and subsequent model builds means development time can be cut to 8 weeks with only 3 analysts. Using more traditional methods takes a larger team of analysts several months and does not guarantee the optimum [design].” (Reed, 2002). Using this “right first time” strategy, physical testing almost becomes a check box exercise before production. In such instances engineers are no longer attempting to gain design insight from such tests but are using them purely for validation of the design and of FE models. Kurowski (2017) discussed the benefits of the CAE driven design process, these are tabulated below;

The benefits of FEA in the Design Process	
Broad Benefits	Description
Reducing Physical Prototypes	The ability to produce rapid virtual prototypes and perform FE analysis early in the design process increases confidence in the proposed design and reduces the dependence on physical testing.
	Design flaws are found earlier in the design process meaning monetary investment in prototypes and tooling is reduced.
	Low cost-to-assurance ratio, multiple test scenarios can be performed on a single model, whereas multiple prototypes may be needed in destructive physical tests.
Reducing Design Process Cycle Time	Time to market advantage due to significantly reduced lead times. In automotive settings this can be a reduction from several months to a matter of weeks.
	Proper implementation of FEA can result in “right first time” designs with significant monetary and time based advantages.
	Lower cycle times allows engineers to develop optimal designs rather than the minimally viable design that merely satisfies the success criteria.
Increased Design Insight	Optimisation methods such as mass, stiffness and topology optimisation enables lighter, stronger, safer, cheaper and more robust designs.
	Rapid feedback (or results) on how small design alterations affect performance.
	Better understanding (and visualisation) of how a component is likely to respond to a much wider array of loading conditions and scenarios than is achievable in physical tests.
	The ability to extrapolate new results by parametric analysis of existing validated models.

Figure 5: Table of Benefits of FEA in the Design Process (Kurowski 2017)

In summary, FE analysis has significant cost and lead time advantages, as well as the ability to not only meet a design success criteria but surpass it by means of optimisation techniques. This poses the question: if using FEA techniques can yield ‘right first time’ designs, what is the purpose of physical testing in modern design? Put simply, there are a series of uncertainties in FEA that require the results of a model to be validated using a method with fewer (or more easily controlled) uncertainties, this is known as model correlation/validation and is discussed further in chapter 3.

3 FE Model Correlation and Validation

The process of correlating Physical testing and FE models is one of the ways in which FE models are validated. A widely accepted definition of FE Model validation is “a method for determining how closely a FE model accurately represents the real-world behaviour of an object with respect to its intended application” (AIAA, 1998). The real-world behaviour of the object is often determined by data collected from physical tests and experimentation. Mayes et al. clearly defined FE model correlation, in their study titled “Model Correlation and Calibration”, as “The process of gaining physical and model insight by observing differences between [FE] models and [physical] tests” (Mayes et al, 2008).

3.1 Why Correlate FE Models?

It is crucially important that design engineers fully understand how a component or assembly is going to respond to a multitude of loading and environmental conditions. Even the most competent FE Analysts may be victim to unforeseen errors within the FE model. R. Miller stated, “An FEA program allows an engineer to make mistakes at a rapid rate of speed.” (Miller, 1981). Some of the typical errors include;

- Discretization Error - insufficient mesh density or poor mesh quality for example.
- Incorrect Boundary Conditions - incorrect loads and under or over-constrained models for example cause falsified results.
- Modelling Error – Oversimplification, incorrect model geometry or material properties etc.
- User Error – typographical errors, wrong units or even using the wrong form of analysis for a given problem.

(Pointer, 2014)

As such, a means of discovering and thus mitigating errors in FE models is required, this is crucial when errors in the FE model, and subsequently the design, may pose a risk to the safety of the consumer, which is particularly prevalent in the automotive, aerospace, civil, medical and defence engineering sectors. Consider the Sleipner-A oil platform disaster in 1991. Extensive FE analysis was conducted on the support structure tricells (Figure 3). However, underestimation of the shear stresses (*underestimated by 47%*) resulted in the insufficient design of the support structure. Subsequently, the support structure collapsed resulting in the sinking of the Sleipner-A oil platform, causing total economic losses of £1.17 billion (*Adjusted for inflation*), fortunately, there were no casualties (SINTEF , 1992).

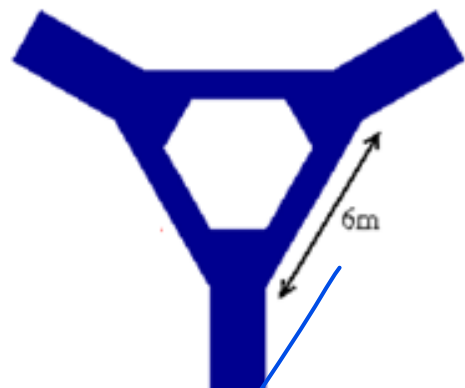


Figure 6:: Sleipner Oil Platform Tricell Cross- section (SINTEF , 1992)

3.2 How can FE models be correlated to physical tests?

For very simple problems, a classic example being linear static analysis of cantilever beams, we can check or validate the FE model numerically by comparing the predicted results, such as the deflection under a given load, with results from traditional hand calculations and engineering judgement (Costen, 2019). The difference (or error) between simple linear static problems solved in FE software and using hand calculations is usually minimal, a general rule of thumb is within 1% is achievable for very basic problems, however, such simplistic problems rarely occur in reality, and when they do, FEA is seldom required.

For more complex analyses, using hand calculations and engineering judgement is not sufficient. In complex problems, a numerical solution may be inaccurate or require significant effort. In some instances, a problem may not have a mathematical solution. Complex FE models may include; Transient/dynamic problems, complex geometries, material nonlinearity and inhomogeneities. As such, experimental or physical correlation is typically required to form a comprehensive and credible validation.

Baker (1992) provided a review of model correlation methodologies, the author explained that a typical approach to FE model correlation involves simulating a physical experiment in the FE model, the FE model is then used to create a series of blind predictions as to the results of the real world test. This process is known as experimental model validation. It is crucially important that the simulated experiment uses the same loading and constraint conditions as the physical test. The results of the physical and simulated tests are compared, the difference between these two sets of results is said to be the error in the FE model (Baker, 1992). Depending upon the outcome of the model correlation procedure, the model is either proven as valid, or updated (or calibrated). Model updating is discussed in chapter 3.3

3.2.1 Modal analysis

Modal analysis is one of the most common model correlation methods used in automotive engineering and design. Modal analysis falls under the study of noise, vibration and harshness (NVH), it identifies the natural frequencies and vibration modes/mode shapes of a given chassis or chassis component. Like any structure, vehicle chassis have a natural resonant frequency. Vibration at the chassis natural frequency may lead to excessive or even violent vibrations, that in turn lead to accelerated damage and fatigue to the chassis components, as well as discomfort to the vehicle occupants.

According to Avitabile (2007) Physical modal analysis involves mechano-vibrational excitation of specific locations on a component using roving hammers, or more commonly, electro-magnetic/pneumatic variants. Sensors are strategically placed on the surface of the component, such as load cell transducers or accelerometers. Non-contact sensors such as laser vibrometers can also be used to measure the frequency response functions (FRF) of the given input, which is recorded using a data acquisition device (Avitabile, 2007). Historically, single input, multiple output (SIMO) methods were used, where multiple measurement points are used to measure the FRF's from a single excitation point. More recently however, multiple input, multiple output (MIMO) methods have provided a more uniform distribution of vibration through the component, and thus yielded preferable results (Silva, 2001). Modal analysis can also be completed in FE software, similar to the physical test method, an input load, of known amplitude and frequency, is incident upon the component. The frequency response is then measured at node locations or using virtual sensors.

Schedlinski et al. (2005) proposed a method for model correlation of an automotive body in white using modal testing. This article is significant in that the authors form a consortium of senior design engineers from major automotive OEM's, including; Porsche, Volkswagen, BMW, DaimlerChrysler (Mercedes) and Audi. The proposed method employed the same broad methodology as reviewed by Baker (1992) (discussed above), both physical and FE based tests are conducted and the results compared in order to determine the error in the FE model.

Below is a diagram of the correlation methodology as proposed by Schedlinski et al.

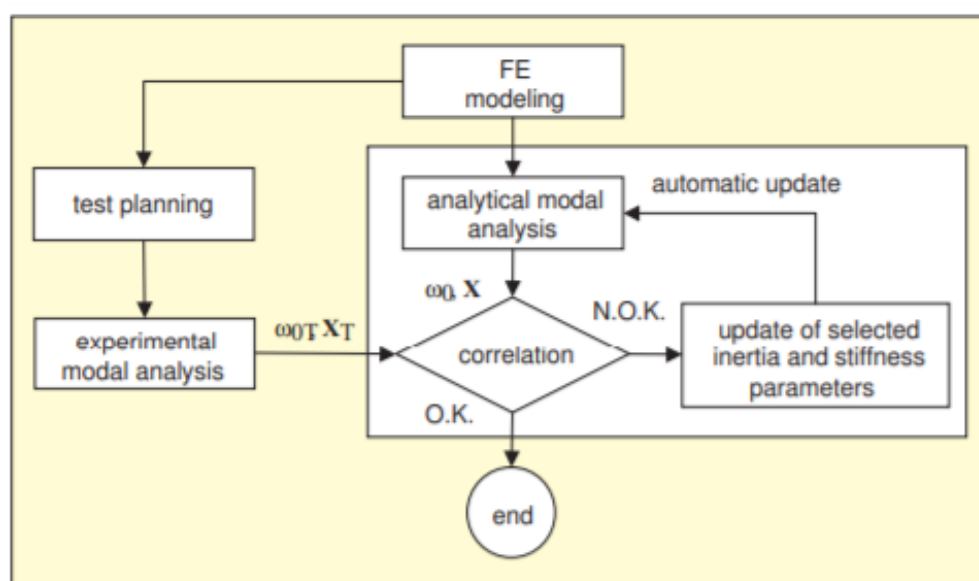


Figure 7: Modal Test Correlation Diagram (Schedlinski, et al., 2005)

Schedlinski et al. discussed the importance of careful consideration and matching of the test set-up procedures in both the FE and physical tests, such as exciting device and sensor locations and constraints etc.

The study used 4 roving hammers and 17 accelerometers placed throughout the BIW to determine the eigen frequencies. The validity of the FE model was determined over 3 iterations, using 2 metrics, the difference between the eigen frequencies from the physical test and the FE model, and the modal assurance criterion number (MAC). Between iterations, the young's modulus values for the BIW components were adjusted with the aim of decreasing the difference between the eigen frequencies and increasing the MAC values.

the results from the study are tabulated below (Full results in appendix 2);

Summary of Modal Correlation Results		
Iteration	Average Δf %	Average MAC %
1	3.20	76.75
2	1.28	86.7
3	1.12	88.18

Figure 8: Summary Of Modal Correlation Results (Schedlinski, et al., 2005)

The study shows that experimental modal analysis can certainly be used to correlate an FE model, and whilst the average deviation was small to begin with, it was decreased by almost two thirds using this correlation methodology.

3.2.2 Strain Gauging

Another form of experimental model validation is strain gauging. Physical Strain Gauging is similar to the modal test method discussed above in that sensors are placed onto the component in order to measure the response to some loading condition. Strain gauging is used to measure stress distributions through a component. Stress analysis of automotive BIW's is one of the fundamental types of analysis in chassis design, it is used in structural integrity and safety analysis, driving dynamics studies including torsional rigidity and stiffness etc and mass optimisation procedures (B.Patil, et al., 2013).

Physical strain gauging involves strategically adhering strain gauges to the surface of a component. A strain gauge uses a conductive foil in a serpentine pattern attached to an insulating backing. A voltage is applied across the strain gauge. An external load (tensile or compressive) is then applied to the component, as the component deforms under load, the strain

gauge deforms also, either expanding or contracting. This deformation changes the cross sectional area and thus the resistance within the strain gauge, as such the magnitude of the induced stress can be inferred (Edwards, 2007).

Strain gauging procedures can also be simulated in FE software using virtual strain gauges. Altair (2016) investigated FE model correlation using the strain gauging methodology. The study used four linear strain gauges placed on an aluminium structure. The test procedure was simulated using virtual strain gauges. Below is an image of the test set-up and the results of both the FE simulation and the physical testing.

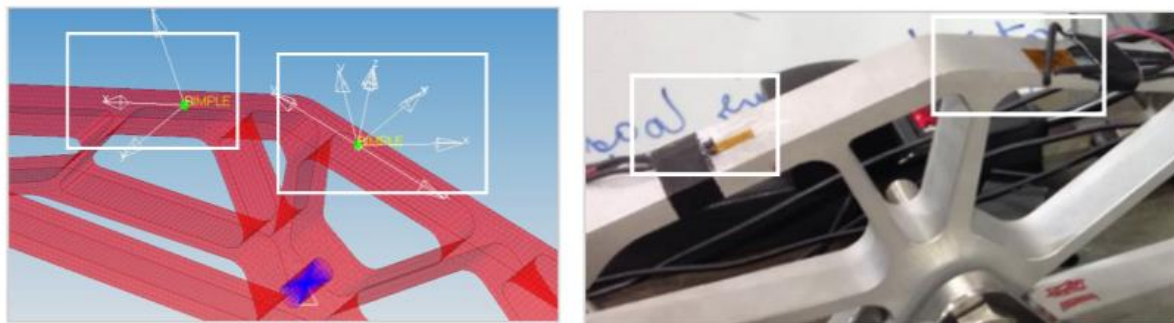


Figure 10: Altair FE Model Correlation experiment Using Strain Gauges (Guffroy, et al., 2016)

Gauge	Strains Measured (in Micro Strain) from the Lab	Strains Measured (in Micro Strain) from the simulation	Deviation
Gauge1	0.087	0.0573	34%
Gauge2	0.271	0.311	15%
Gauge3	0.201	0.175	13%
Gauge4	-0.069	-0.063	9%

Figure 9: Altair FE Model Correlation Experiment Results (Guffroy, et al., 2016)

The study found a maximum deviation of 34% between the FE model and the physical test (see table below). Interestingly in this case, after significant design of experiments (DoE) analysis, the deviation was found to be as a result of the placement of the strain gauge in the physical test scenario. The authors concluded that to avoid such scenarios, strain gauges should not be placed in areas of high stress or deformation (Guffroy, et al., 2016). The study highlights the importance of careful consideration of the set-up of both the physical and simulated tests, it also shows that deviations between physical and simulated test may not be as a result of FE modelling errors but also uncertainties in the physical tests.

3.2.3 Other Methods: Dynamic Response, Thermal and Pressure comparison...
Strain gauging and modal analysis are only two forms of test-analysis correlation methodologies and have been discussed in more detail here as they are the most common procedures used to correlate automotive BIW models with physical tests. There are many other methods used to validate FE models for many different types of components, loading and constraint scenarios etc. Other methods include thermal and pressure comparisons and dynamic response analysis using time dependent loads rather than static loads for example.

Jun Lu et al. Discussed how they successfully used Dynamic response analysis to validate a FE model used for NVH optimisation of a BIW. The test involved simulating engine vibration using a shaker device between 33 and 200Hz. The authors discussed how they used sensitivity analysis to identify the key panels on which to focus the dynamic response analysis. Jun Lu et al. noted that they achieved “right first time” modelling of the BIW and that the model did not require updating after the correlation study, as the maximum error was only 6.99% (Jun Lu, et al., 2017). Below is a diagram of the FE model and the results of the physical and simulated tests.

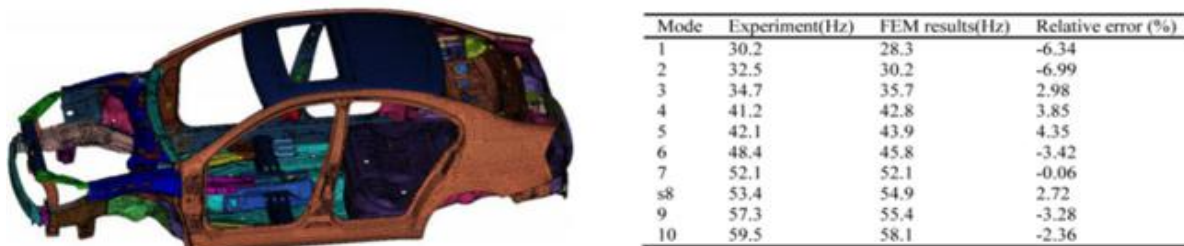


Figure 11: FE Model Diagram and Dynamic Response Results (Jun Lu, et al., 2017)

3.3 Model Updating

Model updating (or calibration) is a process by which alterations are made to the original model in order to bring the results of an FE model test in line with those of the physical test. It is conducted after the results from the FE model and physical tests have been collected, if the disparity between the two sets of results is deemed to be outside of predefined limits, the model requires updating. Friswell & Mottershead (1995) described how model updating typically involves altering material properties, such as mass and stiffness, but can also require changes to the model geometry (particularly joints, welds and edges) or changes to the discretisation method, second order elements or further mesh refinement for example. (Mottershead & Friswell, 1995). Mottershead, Link and Friswell discussed how sensitivity analysis can be used to identify the key parameters that should be adjusted during the model updating procedure. The authors describe how the trial and error approach to updating is no longer feasible in complex models and that sensitivity analysis mitigates this issue (Mottershead, et al., 2011)

4 Conclusion: Can (or should) FE Analysis Replace Physical Testing?

A short answer to the question above is no, it is highly improbable that FE analysis can completely replace physical testing in the automotive industry, or any other industry for that matter. The ever increasing complexity and sophistication of FE models means that it is not feasible to establish confidence in the simulation using hand calculations or engineering judgement alone. It could certainly be argued that to some extent FE analysis has already replaced a large proportion of the physical tests a given company would have to carry out to comprehensively analyse and validate a component design using the traditional build, test and learn methodology, but it is important to realise that physical testing has been reduced and not replaced in this instance.

Major automotive (and many other) OEM's have successfully developed 'Right first time' design procedures by implementing CAE driven design principles in order to streamline and improve efficiencies in the design and development of new vehicle structures. This improved efficiency has been driven by cost, time, and quality objectives (figure 12) and an increased awareness of safety and environmental concerns in automotive design. Despite this 'right first time' philosophy, physical testing has still been required in all instances. Reed (2002), a senior engineer at JLR, described how one only knows that a proposed design was 'right first time' when the Simulation results have been substantiated using some form of physical testing (Reed, 2002).

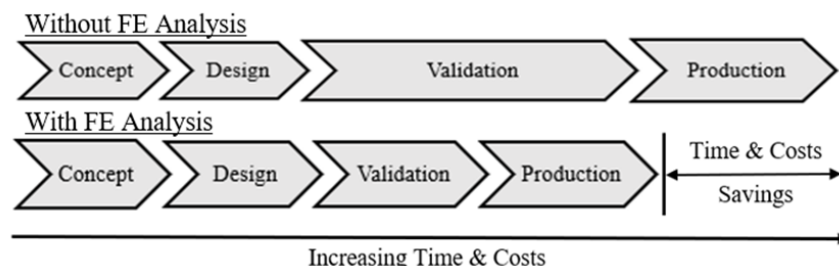


Figure 12: Costs With and Without FEA (Altair, 2016)

While there has been major advancement in FE software in recent years, with developers striving to make FE software easier to use, more intuitive and increase the level of automation in some key tasks, such as mesh generation for example, FE analysis is still a largely manual process, thus the quality and accuracy of a FE model is heavily dependent on the skill, knowledge and sound engineering judgement of the analyst (DePalma, 2011). Gokhale (2018) discusses the importance of realising that even the most competent analysts are susceptible to oversights or unforeseen errors during FE analysis, and as such, a comprehensive verification and validation process is necessary in all instances (Gokhale, 2008).

An important consideration in model validation is the definition of an acceptable level of deviation between the physical and FE results, Baker (1991) suggested that a success criterion of between 2-10% deviation is an achievable benchmark, however, as there is no standard or universally accepted success criterion, this value is susceptible to change. Some may take a more permissive approach and accept a larger range of deviations, while others may be more stringent, ultimately an assessment of the risks and consequences linked to this deviation must be carried out, in a scenario where the safety of the consumer may be put at risk as a result of errors in the FE model, this definition must be studied much more closely, automotive manufacturers tend to take an ALARP (as low as reasonably practicable) approach to risk.

The Physical testing procedure must also be extensively planned and considered. It is important to consider how closely the FE model correlates to the physical test results, but also how closely the physical test simulate the loading and environmental conditions the component is likely to endure in its intended application.

In summary, FEA has the ability to pose a significant advantage in terms of the monetary savings, lead time savings and providing optimal designs that are 'right first time'. It is important that we recognise the limitations to FE analysis and thus use physical validation methods to check and substantiate our analysis wherever possible. While it is impossible to predict how future advances to FE analysis techniques will change this validation methodology, and previous advances have revolutionised the way we currently design products, It is safe to predict that companies, particularly automotive manufacturers, will be performing physical tests alongside FE analysis for the foreseeable future.

EXCELLENT SECONDARY RESEARCH - PARTICULARLY THE USE OF FEA BY INDUSTRY.

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6 Appendices

6.1 Appendix 1 - Case Study

The case study chosen for this review is vehicle structural members used in metal monocoque chassis designs. The metal monocoque chassis is by far the most prominent form of chassis design used in consumer-grade, mass-market automotive manufacturing. A bare monocoque chassis, also known as a body in white (BIW), is an assembly of structural components, such as; front chassis legs, strut towers, front and rear bulkheads, A, B and C pillars, rocker panels, roof rails, cross members, floor panels, door impact beams and front and rear crash bars.

Typical construction materials for these components are high strength steel and aluminium alloys. Joining processes for steel and aluminium chassis components involve resistance spot welding RSW, resistance seam welding, arc welding (MIG/TIG), riveting and more recently adhesive bonding. Below is a labelled diagram of a BIW detailing the construction materials and component locations.

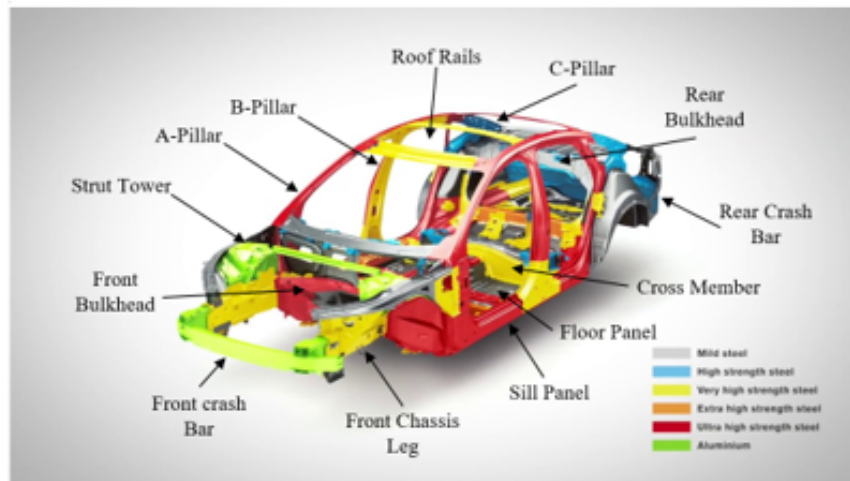


Figure 14: Labelled Body in White (Volvo, 2016)

Finite element analysis of automotive structural members encompasses multiple forms of analysis, including; impact analysis, structural analysis and optimisation, and fatigue and vibration analysis for example. Historically, FE models of BIW's were extensively simplified to decrease the complexity and thus solve time of the model. Features such as welded joints were typical simplifications, BIW's may have upwards of 5000 spot welds. In sophisticated RSW models, each spot weld may have up to 6 degrees of freedom (DoF), resulting in upwards of 30,000 DoF for RSW joints alone. As such, RSW's were simplified or even disregarded in order to decrease the demand on computational resources and thus lower the model solve time. Nowadays, the advancement of computer resources has enabled FE analysts to use more sophisticated and complex models for BIW analysis, with the aim of more closely simulating the real world behaviour of the components in a wide range of loading conditions.

6.2 Appendix 2 - Modal Correlation Study Results

Iteration 1

Table 1. Initial correlation.

No.	EMA ¹	FEA	Δf , %	MAC, %	No.	EMA ¹	FEA	Δf	MAC, %
1	1	7	-7.04	98.24	8	12	18	-3.07	66.41
2	2	8	0.19	87.42	9	13	19	-0.02	72.49
3	3	9	-6.17	63.55	10	14	20	-1.85	86.89
4	5	13	0.83	73.20	11	15	22	1.39	78.18
5	6	11	-11.72	61.13	12	17	24	-0.07	67.88
6	8	14	-3.39	79.49	13	18	26	-1.07	96.49
7	10	15	-6.55	66.51	14	19	27	-1.49	76.60

1) without rigid body modes

Iteration 2

Table 2. Correlation after remodeling.

No.	EMA ¹	FEA	Δf , %	MAC, %	No.	EMA ¹	FEA	Δf	MAC, %
1	1	7	-4.51	98.62	10	11	17	-0.14	68.37
2	2	8	3.01	97.51	11	12	18	-0.57	88.51
3	3	9	-1.49	96.22	12	13	19	0.19	72.25
4	4	10	-0.16	90.12	13	14	20	-1.31	89.43
5	5	11	1.26	90.92	14	15	21	0.83	65.52
6	6	12	0.65	68.55	15	16	22	0.18	66.29
7	7	13	-0.71	59.68	16	17	24	0.48	86.01
8	8	15	0.22	94.88	17	18	25	-0.98	98.19
9	10	14	-6.35	52.61					

1) without rigid body modes

Iteration 3

Table 3. Correlation after computational model updating.

No.	EMA ¹	FEA	Δf , %	MAC, %	No.	EMA ¹	FEA	Δf	MAC, %
1	1	7	-4.35	98.69	10	10	16	0.21	82.22
2	2	8	0.75	97.54	11	11	17	0.09	69.57
3	3	9	-1.49	95.49	12	12	18	-0.90	85.80
4	4	10	1.10	94.38	13	13	19	0.15	75.85
5	5	11	-0.50	93.86	14	14	20	-1.35	92.13
6	6	12	-1.83	65.05	15	15	22	1.49	98.63
7	7	13	-2.67	90.49	16	17	24	0.85	85.47
8	8	14	-1.26	95.39	17	18	25	-0.71	98.09
9	9	15	-1.55	80.52					

1) without rigid body modes

Figure 15: Results from Modal Correlation Study (Schedlinski, et al., 2005)