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Can FEA replace physical testing?

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1 Introduction

This report will address three questions, the first being 'Why do companies typically carry out FE analysis alongside physical testing?', secondly 'How does a physical test correlate to an FE study?' and finally 'Could or should Fe analysis replace physical testing?'. All these questions will be answered through detailed research, analysis of prior case studies and a logical educated approach. Finite Element Analysis (hereafter FEA), is the process of simulating components or assemblies for the purpose of analysis using the finite element method. FEA enables engineers to recreate physical phenomena that a part would normally undergo, for the optimization of the design process. (TWI, 2019) The case study selected to complete this report is entitled, 'Modelling, Design and Analysis of Heavy Vehicle Chassis for the Effects of Various Stress Distributions'. (Dhandapani, 2012) This case study will be used as a real-world example to add context to this report's findings. The case study is a report about the static stress and fatigue life span of a heavy dump truck chassis. The report also uses an experimental and validation approach.

2 Why do companies typically carry out FE analysis alongside physical testing?

2.1 Traditional Techniques/Iterative

Iterative design is a cyclic approach to design, the designer can revisit any part of the cycle in the pursuit of perfection or continual improvement. Iterative design requires many iterations of various stages, such as frequent testing, materials testing, prototype testing and design evaluation. A typical design cycle can be seen below in Figure one. This approach has many advantages and can lead to an excellent end product.

- This method leads to rapid resolution of misunderstandings within a project team and heightened clarity early on.
- User feedback is used to meet requirements.
- It builds client relationships as they are involved at various stages rather than purely at the end.
- Development teams receive validation that their work is value added.
- Regular testing provides a strong performance framework.
- It incorporates lessons learned into the final product.
- Stakeholders get a better progression view between iterations.

(Interaction Design Foundation, 2020)

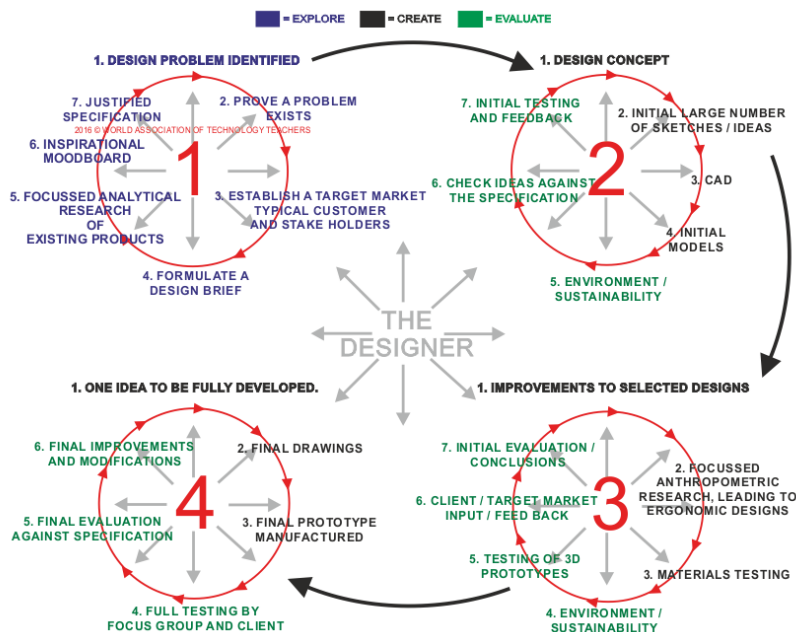


Figure 1 (Ryan, 2016)

Following on from the iterative method, earlier FE modelling methods also followed a similar process with numerous iterations. Prior to modern developments in computing, FE modelling would consist of, progression from a computer aided design straight to prototype manufacture and functional physical testing. If any design weaknesses or defects were detected during the prototype testing phase, then there would be a redesign and additional prototyping phase. This would go on until all design criterion and or standards were adequately met, sometimes with numerous prototype phases.

2.2 Modern FEA Techniques/CAE

CAE or computer aided engineering describes the entire product engineering process from design to virtual testing and incorporating the planning of manufacture. CAE takes things to the next level; it not only allows for the design of a product but allows for virtual testing of the physical properties before the need for a prototype. Most commonly Finite Element Analysis is used within the CAE umbrella. With the readily available high-powered computing, the design cycle cost and time are greatly reduced. The CAE Design process is used prevalently across most industries, aerospace, automotive, consumer, biomedical, defence, energy etc. (Simscale, 2019) There are several reasons CAE has come to the forefront of development techniques; new and inspiring designs, products with better quality e.g. lighter due to the material efficiency and a faster design cycle with fewer trial and error runs.

In order to enable a better level of confidence in an FE model there are several types of analysis, as shown below.

- Linear static analysis
- Fatigue analysis
- Nonlinear analysis
- Optimization
- Dynamic analysis
- CFD analysis
- Buckling analysis
- Crash analysis
- Thermal analysis
- NVH analysis (Brancheau & Goelke, 2019)

These analyses exist to validate the FE model and to ensure the streamlining of the entire design process. This entire approach can be found within the case study attached in the appendices. The case study pertains to the FE modelling of a dump truck chassis. The

report follows a typical CAE type analysis, CAD design, meshing, load analysis, redesign of model and finally physical testing with validation.

In answer to the question posed by this chapter, then FE analysis is carried out alongside physical testing in order to streamline their design cycles. FE reduces the amount of research and development costs incurred by numerous prototype phases. Not only are costs reduced but the amount of time it takes to get the product to market are significantly reduced. As well as FE performs in this respect, the model still needs validation and verification and as such will lead to more iterations between the CAD modelling and virtual testing phases. In comparison to traditional design cycles, a few extra virtual phases improve over the multiple prototype phases typically associated with older techniques.

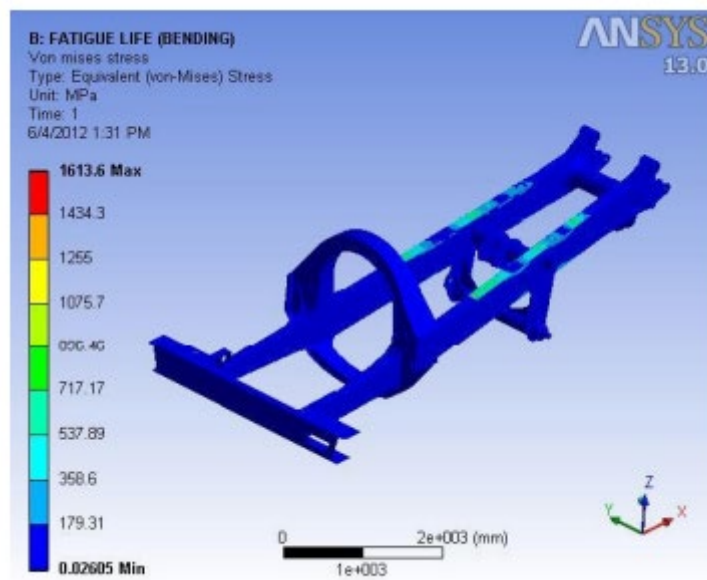


Figure 2 FEA Model of Case study Chassis (Dhandapani, 2012)

3 How are FE models correlated to physical tests?

3.1 Strain Gauge Testing

The principal physical testing carried out in the attached case study, was strain gauge testing, used to determine the stresses and strains acting on the chassis and also the fatigue strength.

A strain gauge is a sensor with resistance that varies with applied force, essentially it converts force, pressure tension weight etc, into an electrical resistance, that can be measured and quantified. When forces are applied to a stationary objects, stress and strain are the consequence. Stress being the internal resistance and strain the displacement or deformation that occurs. As the name suggests the strain gauge measures strain, the deformation of the object. Strain consists of tensile and compressive strain, tensile is denoted by a positive sign and compression a negative. Therefore, strain gauges can measure contraction or expansion. Strain within a body are caused either by external forces or an internal effect. Under certain conditions the external influence can be derived and measured from the strain gauge readings. In experimental stress analysis, the strain values on the surface of a body art used to measure the internal stress and to also state the safety and endurance of the component. Transducers can be designed to measure the outside forces or other values, such as moments, pressures, accelerations, displacements or vibrations. A transducer generally contains a pressure sensitive diaphragm with an attached strain gauge. (Omega, 2020)

In the context of the case study, going from FEA model shown in Figure 2 to the following Figures that measure the physical tests in comparison to the FEA results.



Figure 3 Experimental Setup (Dhandapani, 2012)

Figure 3 shows the experimental setup in the case study, four 50-100 tonne hydraulic actuators were attached to the front (left and right) and also the rear (left and right). In order to simulate the real world rear body and payload that would generally act upon the chassis, 50 tonnes is the accepted payload. This setup is then used to measure the fatigue life of the chassis.

Equipment used for testing.

- 4 x 100 tonne hydraulic actuators
- Portal reaction frames
- 210 bar hydraulic power pack
- 4 channel actuator controllers
- Strain gauges

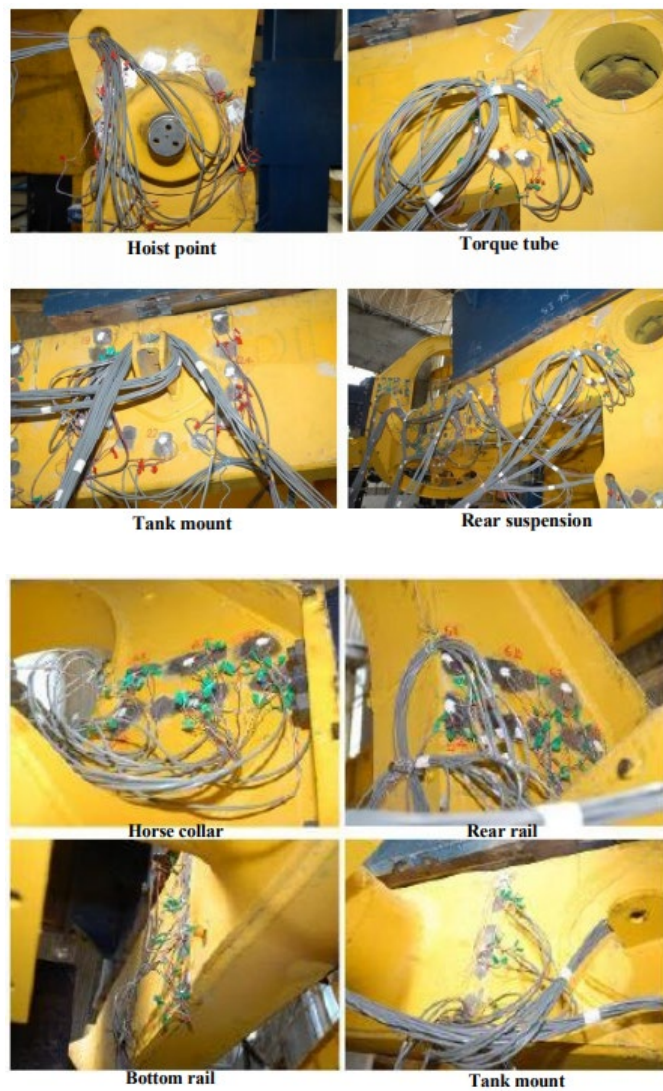




Figure 4 Strain Gauges Fitted to Critical Areas (Dhandapani, 2012)

The strain gauges were fitted to the critical areas that were highlighted in the FE analysis. Uni directional strain gauges were used where the direction of the forces was known, in the unsure areas tri directional strain gauges were fitted. The gauges are rosette and were bonded to the chassis with an epoxy resin, five hundred strain gauges were used in total. The areas around joints or welds were identified as potential weaknesses as well as pivot points or suspension mounts.

Load Distribution on the Chassis for Fatigue Test		
	kg	N
Pay load	54500	5,34,645
NVW	43500	4,26,735
Maximum GVW	98000	9,61,380
BENDING LOAD CASE		
Front Suspension Load (F1v)		1,60,230
Front Suspension Load (F2v)		1,60,230
Rear Suspension Load (F3v)		3,20,460
Rear Suspension Load (F4v)		3,20,460
TORSION (LEFT RAMP LOAD CASE)		
Front Suspension Load (F1v)		0
Front Suspension Load (F2v)		3,20,460
Rear Suspension Load (F3v)		1,60,230
Rear Suspension Load (F2v)		4,80,690
TORSION (RIGHT RAMP LOAD CASE)		
Front Suspension Load (F1v)		3,20,460
Front Suspension Load (F2v)		0
Rear Suspension Load (F3v)		4,80,690
Rear Suspension Load (F4v)		1,60,230

Figure 5 Table of Loads Applied to the Chassis

The loads applied in Figure 5 were applied sequentially at 0%, 30%, 70% and 100%. Vertical loads were applied to the front and rear suspension mounts and torsion was applied to the main chassis body.

Strain gauges locations	Experimental stress values (MPa)	Analytical stress values (MPa)	Difference
1	-7.16	-10.33	3.17
2	4.21	-8.22	4.21
3	11.47	17.47	-6.00
4	-16.15	-11.09	-5.06
5	9.63	12.18	-2.55
6	11.99	9.55	2.44
7	-52.64	-55.14	2.5
8	-37.61	-48.44	10.83
9	30.61	32.83	-2.22
10	44.99	43.52	1.47
11	-64.91	-60.09	-4.82
12	-54.12	-59.03	4.91
13	-35.58	-41.07	5.49
14	54.57	53.43	1.14
15	-74.48	-76.66	2.18
16	-26.63	-26.8	0.17
17	48.13	-50.08	-1.95
18	66.01	68.08	-2.07
19	-81.33	-85.84	4.51
20	-51.38	-53.49	2.11
21	31.24	-38.22	-6.98
22	57.08	52.12	4.96
23	49.19	51.34	-2.15
24	-29.37	-27.83	-1.54
25	-82.47	-73.26	-9.21
26	6.11	9.04	-2.93
27	19.81	21.24	-1.43
28	-5.95	3.41	-9.36
29	-9.21	-10.78	1.57
30	-2.06	-3.74	1.68
31	12.07	9.63	2.44

Strain gauges locations	Experimental stress values (MPa)	Analytical stress values (MPa)	Difference
32	2.5	-1.48	3.98
33	3.85	4.06	-0.21
34	-15.62	11.03	-26.65
35	-7.74	8.43	-16.17
36	8.62	9.7	-1.08
37	-177.4	-172.3	-2.7
38	52.38	-44.69	7.69
39	10.42	23.37	-12.95
40	110.3	97.83	12.47
41	-66.15	71.98	5.83
42	-16.88	15.38	-32.26
43	62.83	-64.71	-1.88
44	3.63	-2.17	5.8
45	-2.23	-2.41	0.18
46	-2.41	2.53	-4.94
47	-115.7	-117.6	1.9
48	-52.66	-42.51	-10.15
49	28.86	29.64	-0.78
50	137.2	130.08	18.12
51	-130.2	-142.49	12.29
52	34.7	30.26	4.44
53	134.8	129.81	4.99
54	-138	-139.72	1.72
55	-29.1	-35.31	6.21
56	66.24	57.81	8.43
57	117.9	101.18	16.72
58	121.9	-126.89	-4.99
59	21.5	37.75	-16.25
60	127.4	155.11	-27.71
61	19.42	-18.46	0.96
62	-9.02	-10.53	1.51
63	-14.95	-15.36	0.41
64	20.57	-19.18	1.39
65	-17.93	-10.24	-7.69
66	18.59	15.56	3.03

Figure 6 Physical test results Vs FEA results (Dhandapani, 2012)

The results shown in Figure 6 show that in general the FEA results are fairly close to the physical tests, with a certain margin of error. There are some cases in the results that show a distinct departure from a margin of error and these areas on the chassis should be studied and tested further to ascertain the reason behind the difference in tests and FEA.

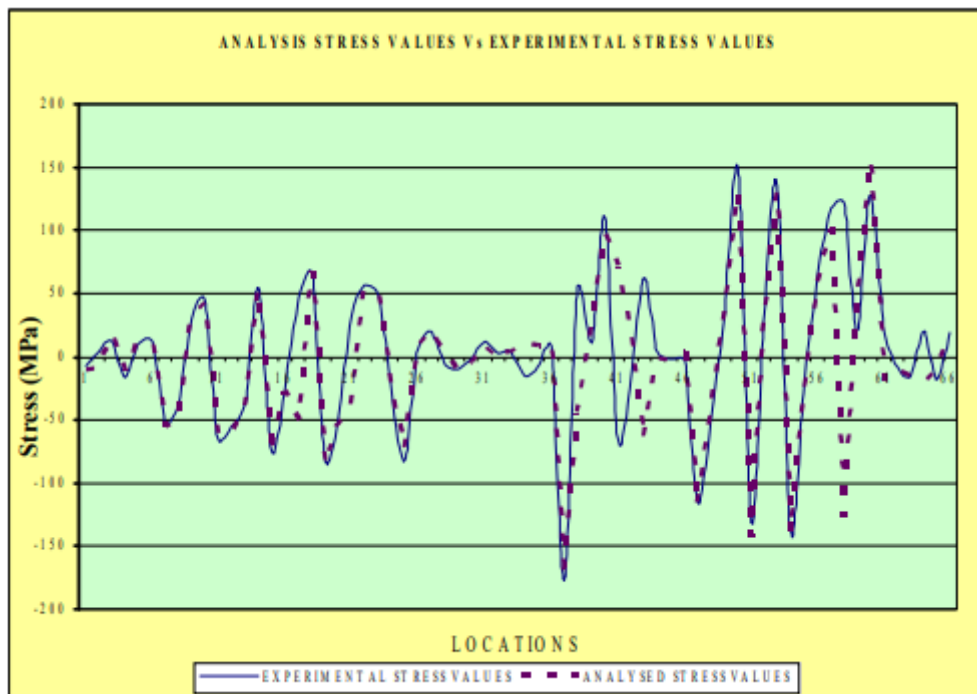


Figure 7 Graph Depicting Figure 6 Results (Dhandapani, 2012)

The comparison graph in Figure 7 makes visualisation of the numbers easier to digest, you can particularly see where the chassis didn't act as the FEA suggested. In particular between locations 56 and 61.

3.2 Other Physical Testing Methods

3.2.1 Modal analysis

Modal analysis studies the dynamic properties of a structure or part, these being frequency, damping and mode shapes. This can be achieved in several ways, through the medium of FE Analysis or experimentally. This is advantageous as there is a recurring theme underlying within this report. That FEA needs to be experimentally validated in order for the results to have any degree of confidence. Essentially a vibration force is applied to the structure and then the response of the system is measured. Different methods can be used for different structures, a simple structure might be tested with a simple hammer test. The structure is struck with a hammer and measured at a different point by the attached sensors to the hammer device. As the structure becomes more complicated the method used also becomes more complex. There are mechanical shakers that can be set to different

frequencies, set to a pattern of frequencies to measure different responses or white noise settings that is completely random. The sensors used to measure response are either accelerometers or force transducers. The data recorded from the vibration and response, is fed to a dynamic signal analyser. A dynamic signal analyser interprets the data using a frequency response function. (Zhao, 2017)

While initially modal analysis was an aerodynamic application, in recent times it has permeated into all engineering fields, automotive, bio engineering, aerospace, medicine and science. (Zhao, 2017)

In answer to the question posed in this section, there are many ways in which FE analysis can be correlated to physical test. The strain gauge method as detailed above was of particular interest as it was the principal method used in the case study. Modal analysis was also briefly covered as an easily quantified method used to correlate FEA with physical tests. There are further methods but due to the need for conciseness these will just be mentioned here.

- Dynamic Response: similar to modal analysis
 - Drop test: a component is dropped to see the response of the system
 - Crash test: used in automotive predominantly
 - Impact tests
- 

The strain gauge method as shown in the case study shows how the FEA model was carried from modelling to FEA testing and then through to experimental testing. After physical testing the FEA results were validated using the actual experimental data and quantified into a clear result.

4 Conclusion

4.1 Can or Should FE Analysis Ever Replace Physical Testing?

Currently FE analysis has reduced the cost, amount of prototype phases and the time involved in modern design cycles, more so where CAE has been implemented. Should it completely replace physical testing, no it should not. That is not to say that at some point in the future where FEA and computing power has developed to a greater extent that it couldn't at that point.

When validating FEA there are several types of errors inherent within the process that can affect the accuracy of the analysis.

Modelling errors, due to simplification of real-world factors.

- For instance, the wrong geometric description has been used, the loading used is symmetric but should be antisymmetric.
- The incorrect material properties have been defined, like Poisson's ratio etc.
- The definition of the load, like simplifying complex loads as one load.
- The boundary conditions, forgetting to fix part of the geometry or even using incorrect boundary conditions can give bad results.
- The wrong type of analysis.

The type of analysis covers a multitude of sins, does the material act linearly or non-linearly? Is the geometry linear? Are contacts defined with or without friction? Does buckling occur? Is the problem time dependant or steady state? All these have the potential to throw a spanner in the works.

Discretization errors within the creation of the mesh.

- Which type of element should be used? In 2D should we use plane stress or plane strain?
- Mesh density, how fine should the mesh be to create accurate results without investing too much time.
- What order should the elements be? First order tetrahedral or second order tetrahedral?

First order tetrahedral elements perform well within linear materials, whereas second order tetrahedral elements are better with elastic materials as they show deformation easily but at a cost of computation and time.

Numerical errors within the FEA.

- Integration errors due to Gauss integration can lead to numerical instabilities. (exact integrations provide a structure that is too stiff)
- Rounding errors, caused when adding or subtracting either very large or very small numbers.
- Matrix conditioning errors.

(Murad, 2019)

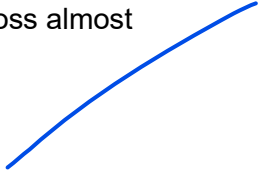
Most of the aforementioned errors are human related errors, they are made because of several reasons but essentially at the fault of the user. Whether there is a lack of understanding on the part of the user, mathematically, engineering or to do with physics. This lack of understanding can greatly affect FE analysis outcomes and the confidence in its accuracy. There's an adage within the FEA community, "bad data in equals bad data out" though the use of bad could be substituted for an expletive.

Take for example, a simple steel strut, in this case the consequent modelling and FE analysis would be very easy to validate. The stresses and strains acting under a certain load are easily derived with hand calculations, with a very good degree of accuracy. Therefore, the FEA study can be validated by the hand calculations with certainty and the accuracy is easily ascertained. Whereas with a more complex component or more complex set of loading conditions or even both consecutively, a lack of understanding in any way can lead to an incorrect analysis. For instance, a load is applied vertically but a lateral force isn't modelled as it wasn't expected or thought of, then the FEA is out of sync with reality.

In the context of the case study in the appendices, the FE analysis on the whole acts within reasonable confines of the physical tests. There are a few instances shown on Figure 7 where the FEA swerves from the experimental results. This is because the loads applied to the chassis are more than expected and concentrated at certain points of the prototype. This leads to the material being pushed past the elastic limit and becoming permanently deformed. The solver used for the case study was setup for linear characteristics and once the material becomes nonlinear the FEA results start to divert from the experimental results. In this case the chassis was then redesigned with further strengthened components to withstand the actual loads expected. This further proves the point that physical tests are essential, if the chassis went straight out into the world from FEA there could have been extreme failures under normal operating conditions.

In conclusion, with the amount of errors that are possible within FEA then physical validation is an essential part of a product design cycle. Some companies are striving for a right first-time approach to CAE and are making great strides towards a reduction of costs and time.

Their procedures are improving with time as CAE becomes more efficient with more data and historical experimental data, but physical tests are still carried out. Another aspect to consider is the standards that are applied to any product, in the automotive industry there are stringent road safety standards that have to be met. Physical testing plays a massive part in the meeting of these types of standards. Such standards are applied across almost all consumer products.



5 Appendices

5.1 Case study Link

<https://shodhganga.inflibnet.ac.in/handle/10603/17023> (Dhandapani, 2012)

GOOD SUMMARY OF THE CASE STUDY & HOW CORRELATION WAS ASSESSED. YOU HAVE USED THIS WELL TO ADDRESS THE BRIEF.

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