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Can FEA Replace Physical Testing?

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MODEL A

MODEL B

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1 Introduction

This report talks in detail about what can be achieved with today's FEMs, in the context of design optimisation of ICE connecting rod and components surrounding it.

Author also talks about few methods which can be applied to the physical test correlation, which helps with FEA model validation.

Lastly, author makes a case against the replacement of physical testing with FEA, describes why physical testing is so important and what undesirable consequences the lack of physical testing may have on a company.

2 The Importance of FEA

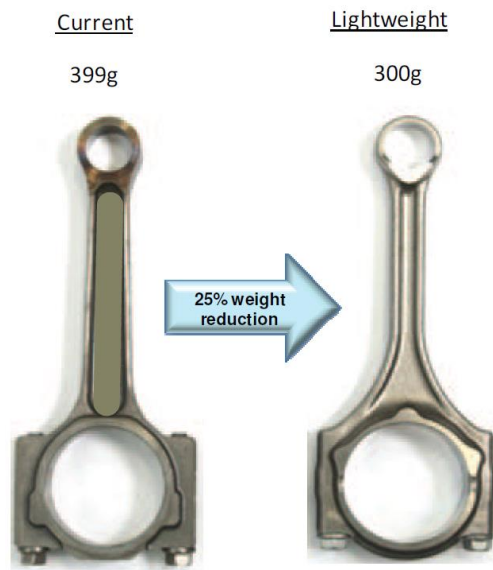


Figure 2-1: Connecting Rod, Results of FEA Optimization (MATHEUS DOS SANTOS FERREIRA, 2013)

Finite Element Analysis (FEA) is frequently carried out alongside physical testing in the design process. Physical testing is usually carried out for two purposes: 1) FEA model validation, 2) final design testing & evaluation. The use of physical testing is always minimized as much as possible due to the inherent costs, not only materialistic but also time related, associated with the production of the required physical prototype, as well as the testing equipment, required personnel etc. This was very apparent in author's research as many sources have shown the physical testing chapters to always be the shortest, showing what author could only describe as 'neglect'. Author's research has shown a clear dependability and trust of engineers in their FEA software packages.

FEA, of which there are 10 types (Lake, 2020), is used to optimize physical designs. This is due to the relatively low costs associated with the design creation and testing. More recently, the increase of affordability of computational power, allowed engineers to improve design processes, one of which is to generate topology based on the design case, as oppose to the previous 'traditional' create, test, improve cycle. These strategies allow for the creation of even more advanced designs while keeping the costs affordable.

Naturally, the same design processes are applied when designing Internal Combustion Engine (ICE) components, such as connecting rods. Connecting rod, as shown in Figure 2-1, is a pin jointed beam which connects the engine's crankshaft to the reciprocating assembly, which consist of gudgeon pin, piston and piston rings.

Due to the extremely complicated loads, which not only consist of stresses associated with the cylinder gas forces and assembly inertias, but also thermal and shear forces, all of which are very dynamic due to the nature of the crankshaft system, as well as all of the processes occurring around the connecting rod (combustion, coolant flow, oil to structure interaction etc.), the 'classical' 0-Dimensional beam theory which is often based on empiricism, is very much not suitable for this design case. As such, the only alternative to FEA are the physical trials which aim to build empiricist solutions, which naturally are incredibly inefficient and as a result, not applicable in 21st century.

As Figure 2-1 has shown, FEA is used to optimise the connecting rod's mass, while retaining acceptable FSF (Fatigue Safety Factor)/ reliability. This is because lighter connecting rod will decrease inertias, reducing bearing and crankshaft loads as well as the wasted engine torque which is required to accelerate 'bottom end' assembly. This results in better fuel consumption.

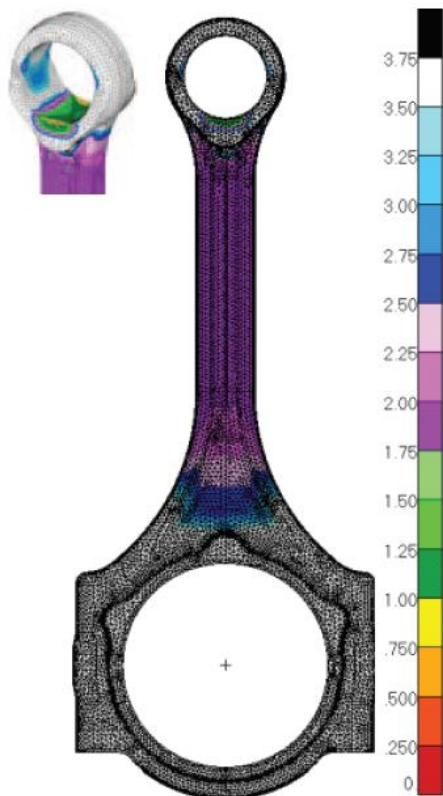


Figure 2-2: FEA Results of Maximum Engine Torque (MATHEUS DOS SANTOS FERREIRA, 2013)

All of these factors are extremely important to today's vehicle manufacturers, since their product sales are directly affected.

Furthermore, FEA allows for computation of parameters which would be impractical to measure in real life, for example: the maximum engine torque distribution, as shown in Figure 2-2. This ability allows engineers to carry out more detailed analysis, which aids to further understand the problem and as a result, help the engineer to make a much better decision regarding the design.

Also, modern FEA software packages allow for the consideration of multiple interactive systems, such as: connecting rod and crankshaft shown in Figure 2-5 or connecting rod big end bearings shown in Figure 2-3.

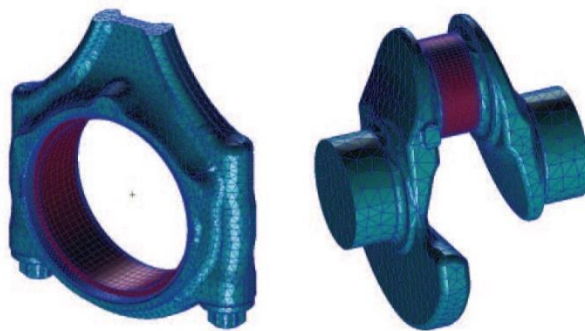


Figure 2-5: Connecting Rod Big End & Crankshaft Models (MATHEUS DOS SANTOS FERREIRA, 2013)

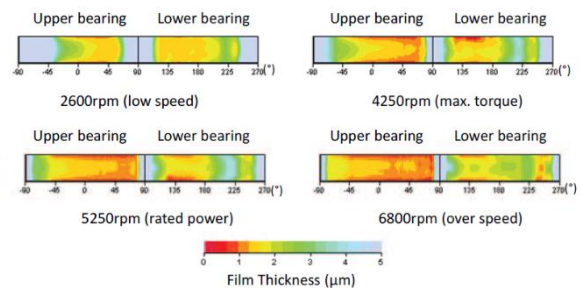


Figure 2-3: Oil Thickness History Maps (MATHEUS DOS SANTOS FERREIRA, 2013)

The fusion of these interactive systems allows for consideration of the dynamic effects which other components in the assembly have on the component being designed. Naturally, this improves the design capability as more factors are considered, many of which were previously an afterthought, due to the design and testing costs as well as the design importance of the connecting rod itself.

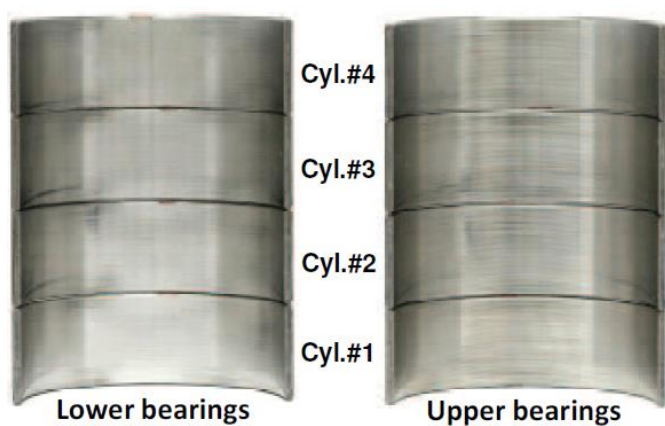


Figure 2-4: Connecting Rod Bearings After 300 Hour Endurance Test (MATHEUS DOS SANTOS FERREIRA, 2013)

Figure 2-4 shows that due to the bearing model incorporation, the big end bearings installed on the new connecting rod design had very good wear, after 300-hour endurance test. This means that not only the new connecting rod design allowed for better performance of a

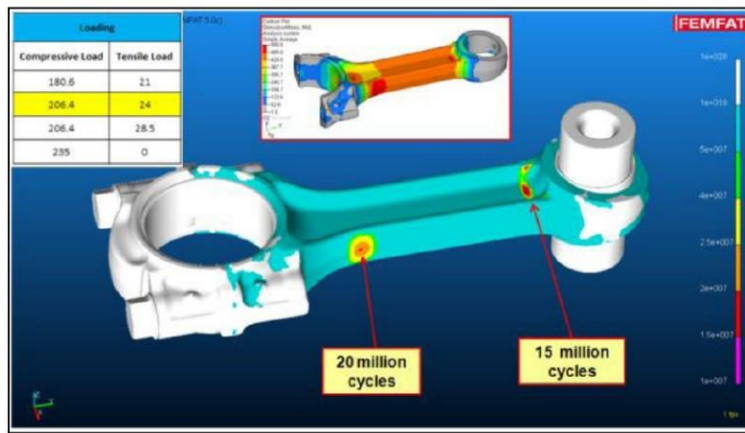


Figure 2-6: Fatigue Life Evaluation (Suresh Kumar Kandreegula, 2016)

separate component but also due to initial success, further design iterations and testing weren't required, saving enormous amount of time and finances which could be spent on other design aspects, allowing for even more improved and as a result, efficient design: performance value divided by cost of the design.

Lastly, as the connecting rods operate inside production ICEs, the reliability is crucial. As Figure 2-6 shows, FEA also allows for the simulation of fatigue. This is important as fatigue failure of such component cannot occur before the end of life cycle of the product, otherwise the manufacturer is going to lose money, either directly via warranty or indirectly via loss of reputation. Fatigue testing is carried out physically on a special rig over very long period of time, due to the enormously high expected life cycle of the connecting rod, about 10^9 cycles (McDonald, 2019). Naturally, such physical testing is too time consuming to allow iterative design cycle. Therefore, FEA is used to determine the fatigue concentrations and the expected local fatigue failure cycle. This allows engineers to improve the identified fatigue regions and ensure the likelihood of success of the expensive life cycle test.

3 Physical Test Correlation

The objective of correlating the FEA results to a physical test is to validate the FEA model, so that the engineer can be confident in two aspects: 1) the time spent on design optimisation won't be wasted as the FEA model is predicting the real life results to good enough accuracy, so that the results of the simulation can be analysed and improved upon. 2) The final design will deliver the performance as designed, meaning that the further investment of the prototype and physical testing is worth-while.

There are many ways to correlate the results of physical testing, the methods are always tailored to the design case that is being considered. However, the most common physical test consists of the use of strain gauges, which will measure the local strain magnitude typically over time. Though it is most common for physical tests to be static due to the inherently lower complications compared to dynamic tests, making the accuracy and analysis of static tests much better, which means that the time aspect is usually not considered.

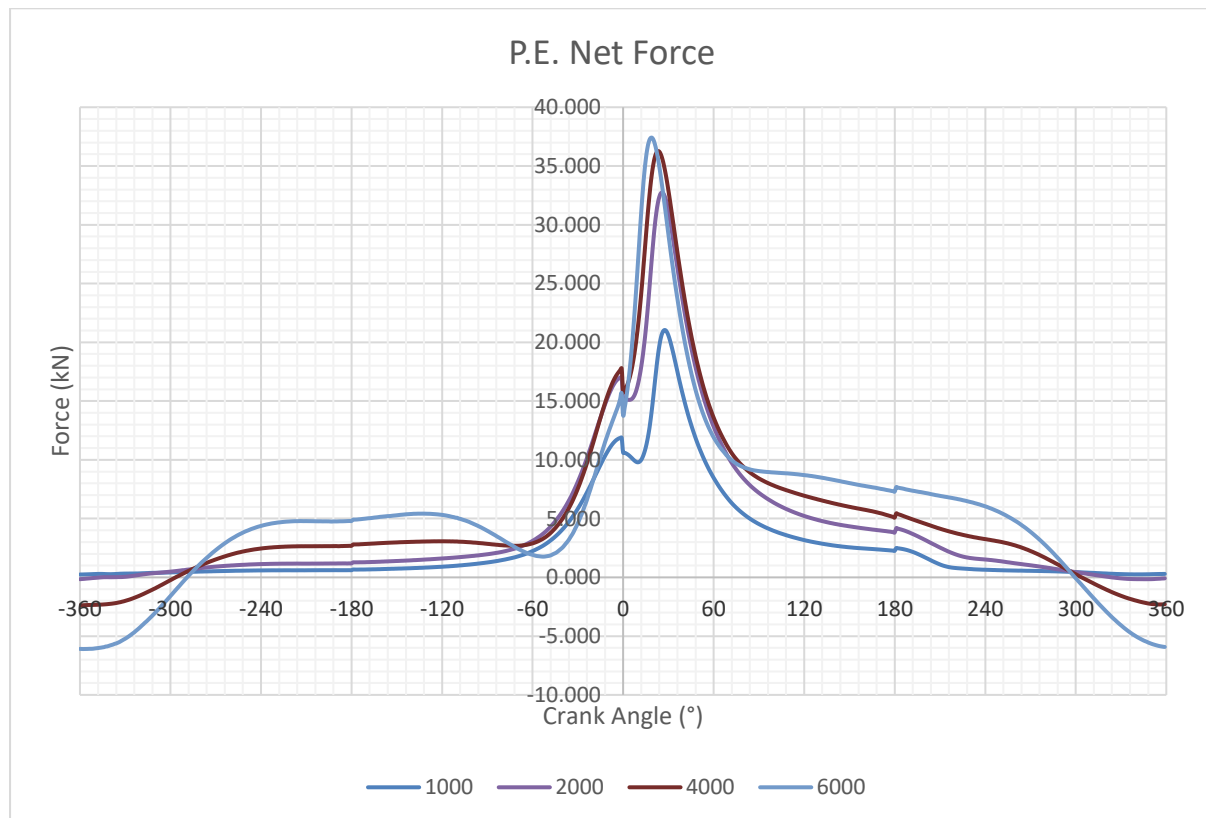


Figure 3-1: Production Engine Net Connecting Rod Shank Force as Function of Crank Angle

Due to the complicated environment that the connecting rod is in a typical 4 stroke engine, normally only two design scenarios are considered: 1) around TDC (Top Dead Centre) on expansion stroke, due to the highest compressive force caused by combustion. 2) around TDC exhaust stroke due to the highest tensile force due to lack of inertia opposing forces. This is shown in Figure 3-1, which shows instantaneous connecting rod forces as function of crank angle at various engine rpm, which author created for report: "Con-Rod Accelerations, Forces & Displacements".

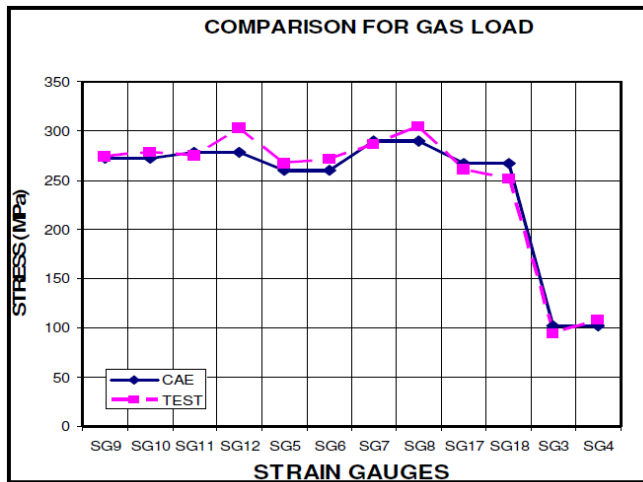


Figure 12.a: Comparison of CAE and TEST results.

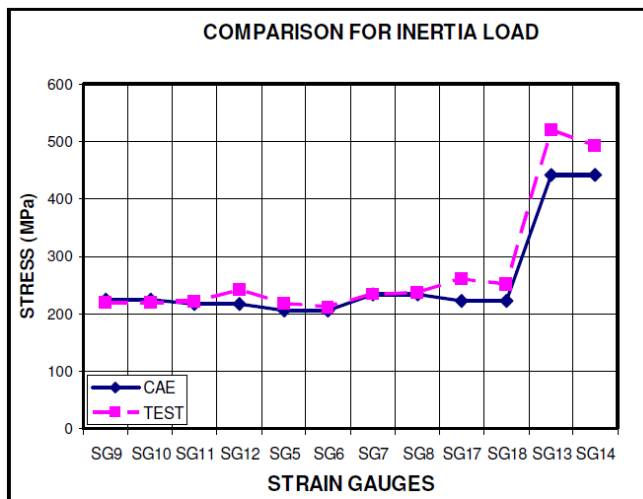


Figure 12.b: Comparison of CAE and TEST results.

Figure 3-2: Connecting Rod Physical Test - Gas Load & Inertia Load Strain Gauge to Simulation Comparison (Abhijit Londhe, 2009)

Figure 3-2 shows the comparison of the static stress magnitudes between the values which were recorded via several strain gauges and the simulation, in maximum compressive and tensile cases, caused by combustion and inertia respectively.

The first correlation which can be done is the assessment of the overall profile, e.g. does the simulation show the same behaviour as the physical test? In Figure 3-2, it is clear that strain gauges 9 through 18 show very similar magnitudes, however, the strain gauge pair of 3,4 and 13,14, show magnitudes which are about 2 times bigger and smaller as the other magnitudes, in tensile and compressive loading respectfully. Since the behaviour of the simulation agrees with the test, it is likely that the boundary conditions of the simulation as well as other 'setup' conditions such as mesh, have been most likely correctly created.

Second correlation which can be done is the assessment of the polarity, e.g. when real life data shows a positive absolute increase of magnitude, does the simulation predict positive or negative?

This usually is also used to determine the validity of the boundary conditions, since polarity inaccuracy are usually caused by incorrect direction of loading, e.g. compressive where it should be tensile and vice-versa. A good graphical representation of polarity is a graph which

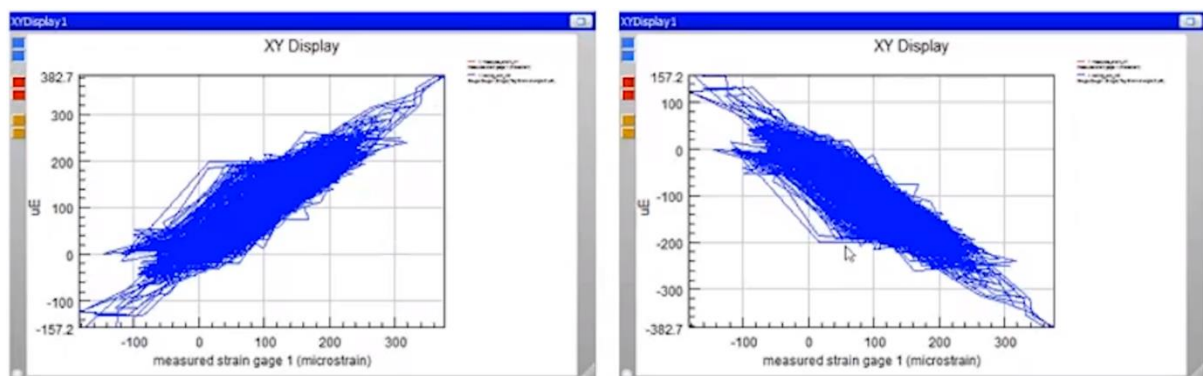


Figure 3-3: Data Polarity Plots (Presencia, 2018)

plots two data sets against each other, as shown in Figure 3-3, as then the positive directly proportional line will indicate a good polarity correlation. Additionally, such graph can also be used to show skewness/ model bias towards either over or under prediction.

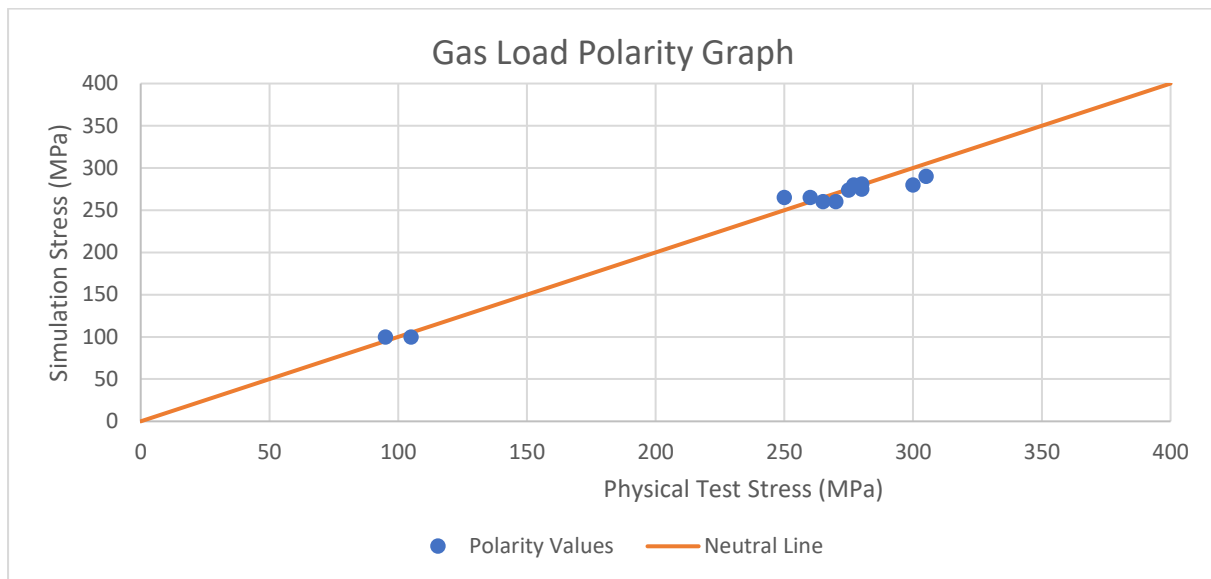


Figure 3-4: Gas Load Polarity

Figure 3-4 shows the polarity graph author created based on the values read from Figure 3-2. It shows the polarity to be very good since all data points occur very closely to the neutral line, it also shows the simulation to be biased towards underpredicting since most data points fall under the neutral line.

Another correlation which can be done is the assessment of the absolute values, e.g. how accurate each data point is compared to physical testing. To show this, author has created Figure 3-5 which shows the inaccuracy of the simulation at each strain gauge location.

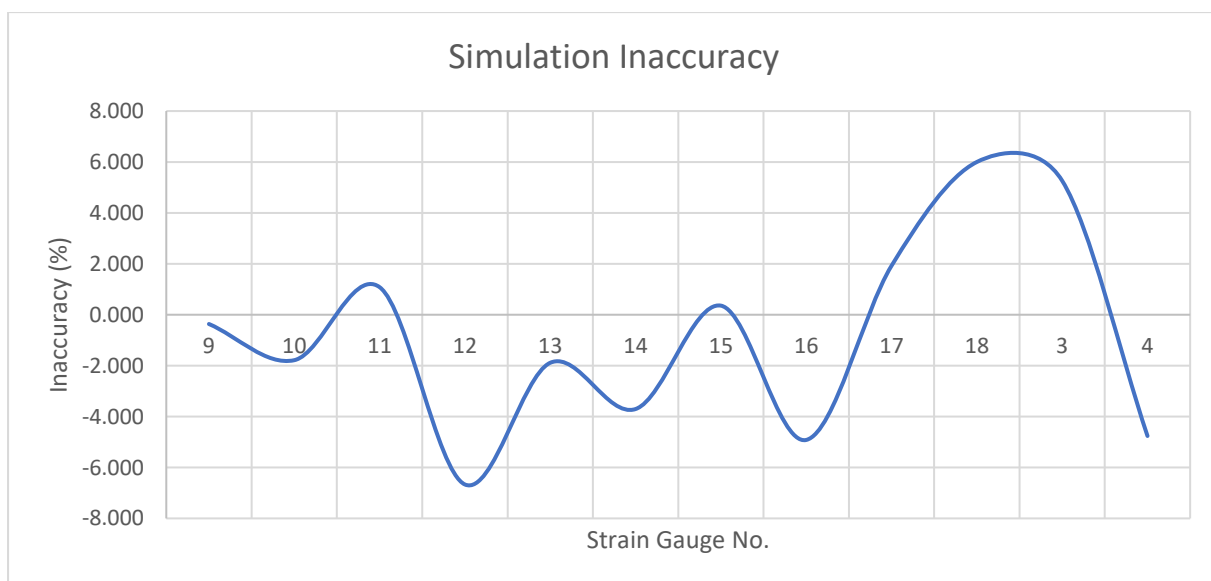


Figure 3-5: Simulation Inaccuracy

Based on the results shown in Figure 3-5, it is clear that the overall accuracy of the model is $\pm 6\%$, which is respectable. It is also showing that the majority of data points are in fact under predicting, just as in Figure 3-4, however, it also shows that nearly all over predicted values have inaccuracy very close to the $\pm 6\%$ tolerance. Therefore, this correlation is not only useful to determine model accuracy but also to create a deeper understanding of why the accuracy is at certain level and how it can be improved, since the most severe local inaccuracies can be individually studied to determine either, local problems such as coarse mesh, or global issues such as model restraining etc.

4 Should Finite Element Analysis Replace Physical Testing?

As it has already been mentioned in The Importance of FEA chapter, FEA especially when incorporated into CAE (Computer Aided Engineering), is a tool which when correctly applied, can enable engineer to develop better optimised design, which is the objective of every engineer.

However, FEA cannot and should not ever be used on its own as it is impossible to perfectly simulate anything, to do so engineers would have to develop models which operate on quantum and planet size at the same time, as it is right now, we are struggling to get molecular sized models right on their own.

The reason why such a complicated model is be required to truly ‘replace’ physical testing is because real life is equally complicated. An FEA model which doesn’t replicate real life perfectly is not able to replace physical testing as such model doesn’t account for every factor which the component might encounter in real life. Furthermore, even if such model existed and was readily available, it doesn’t mean that the case study has been correctly setup by the user. Therefore, even a ‘perfect’ model can very easily calculate very unrealistic results.

As previously shown in Figure 2-3 and Figure 2-4, when correctly applied, FEA can improve the performance of components in real life. However, for FEA to do so, the model used must be valid, e.g. the model accurately represents and agrees with real life, as without validation work carried out before design optimisation, it is impossible to be confident that what software shows will also happen in real life, where it actually matters.

Author believes it is crucial to remember that any FEA method is just an estimation tool which is and most likely never will be perfect due to the complexity of real life. This is why ‘safety factors’ are employed; they allow engineers to account for lack of confidence in their FEA method.

Test sequence	Load amplitude (kN)	No of cycles completed	F.O.S
1	57.73	Run out	1.25
2	58.26	Run out	1.24
3	60.11	Run out	1.20
4	61.96	Run out	1.17
5	63.82	Run out	1.13
6	66.98	Run out	1.08
8	69.75	Run out	1.04
7	72.51	Failed at shoulder	0.96
9	72.51	Failed at shoulder	0.96
10	71.13	Failed at shoulder	1.00

Figure 4-1: Fatigue Safety Test Results (Abhijit Londhe, 2009)

Physical Test Correlation chapter has shown that FEA accuracy of about +/-6% can be achieved, once validation has been carried out. This means that in real life 6% bigger or smaller stress can occur anywhere in the tested local regions, this could potentially be even bigger in other untested localized regions, which is another reason to test the component physically. This is why physical testing is carried out at the very end of the design process. Figure 4-1 shows the results of load testing of the same connecting rod as in Figure 3-2. It shows that the connecting rod has failed when the designed load (Factor of Safety 1.00) was applied. However, it didn’t fail when 4% lower load was applied

instead, which is within the +/-6% model accuracy. If that connecting rod hasn't been physically tested and went into mass production, then the manufacturer which assembled engines with those connecting rods would lose astonishing amounts of money, both directly and probably even more indirectly, as the connecting rods would be failing and they would have to be replaced with a stronger component, which would also cost money to develop and produce.

Locations	Test data		CAE	% of Correlation
	Strain	Stress (Mpa)	Stress (Mpa)	
1	1.57E-03	329	350	94.00
2	1.83E-03	384	400	96.00
3	1.36E-03	286	300	95.33

Figure 4-3: Connecting Rod Physical Test Data Correlation

Sample No.	Cover Factor	Test Loading (KN)		Target no. of Cycles	Completed test cycles (million)	CAE (million)
		Stress (Mpa)	Stress (Mpa)			
1	1.4	180.6	21	5 million/Specimen	10	-
2	1.6	206.4	24		10	15
3	1.6/1.9	206.4	28.5		10	-
4	1.82/0	235	0		10	12
5	1.82/0	235	0		10	-

Note : VECV testing machine capacity 10 million cycles.

Figure 4-2: Optimised Connecting Rod Fatigue Testing

Figure 2-6, which is +6%. Figure 4-2 shows the results of the fatigue physical testing, which all of connecting rod specimens have completed successfully, although the test did not carry-on to the CAE designed limits. This shows that even though the same FEM accuracies in Figure 4-1 and Figure 4-3 were achieved, the desired outcome wasn't achieved in Figure 4-1, which shows how crucial physical testing is.

Sometimes it could be tempting to not carry out physical testing to reduce the time and financial expenses. This most commonly happens when an engineer has become very confident in their FEM (Finite Element Method) due to very good results from the previous project, for example: Figure 4-3 shows the FEA model accuracy of the connecting rod shown in

5 Conclusion

It is very apparent to the author that FEA, especially when applied to CAE, is a very powerful tool which can yield extremely well optimised and diverse designs at relatively low costs.

However, all of the FEA models/ cases must be validated before and after the design optimisation, as this ensures the FEA results to be realistic, making the analysis of further designs worthwhile. The final physical test is also crucial, since it allows the analysis of the component's behaviour in real life, which is where the component will be used in.

6 References

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