Using Simulation to Identify Loads Contributing to a Structural Durability Failure of an Engine Component

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***Abstract**: Honda engines undergo severe testing for evaluation of performance and durability. This paper focuses on a structural durability failure of a steel tube press-fit into an aluminum casting installed on an engine. While the engine is operating, the assembly experiences complex load conditions including modal excitation, high acceleration, as well as, forces and moments caused by system deformation. Traditionally, these loads cannot be measured without completely changing the system. This makes determining a root cause difficult. Therefore, True-Load was used in conjunction with measured strain data to calculate the transient behavior of the loads acting on the components and the stresses experienced by the tube. Analysis of this information allowed the loading conditions driving the failure to be identified. This provided direction for future design iterations.*

***Keywords**: Abaqus, Durability, Engine, Frequency, Modal, Powertrain, and True-Load*

1. Introduction

In the automotive industry, powertrain systems are subject to extreme test conditions intended to mimic or exceed any reasonable load expected from a customer. During development, engine tests are conducted on a dynamometer to evaluate several metrics, including performance, emissions, and durability. In many cases, a system or component may fail to meet predetermined criteria or experience an unexpected failure mode. When such problems present themselves, finite element analysis (FEA) serves as an excellent tool for root cause analysis and aid to set direction for resolving the issue. Knowing the appropriate boundary and load conditions for FEA is key for completing a thorough root cause analysis.

Loads influencing a component are easily identified when engineering knowledge is used to create a free body diagram. Unfortunately, in many situations it is impossible to know the magnitude of the respective loads. Therefore, engineers must resort to assumption, experience, and iterative analysis to determine the magnitude of the loads input for FEA and judge reasons driving a failure. This process can be difficult, costly, and, in some instances impossible.

Powertrain systems experience a wide range of loads, most of which are dynamic and usually act simultaneously on the involved components. The severity of these loads will vary with engine speed and potentially excite components at their natural frequencies, ultimately, increasing the amplitude of the load. Modal excitations create a high-cycle load condition leading to structural fatigue concerns. Structural failure because of high-cycle fatigue can be especially difficult to diagnose.

Excessive cyclic strain was obvious when a steel tube press-fit into an aluminum cast engine component failed during a development test. Strains in this tube are caused by a combination of loads including; modal excitations at resonant frequencies, high acceleration, as well as, forces and moments induced by deflection of mating parts. The complexity of the loading makes it very difficult to identify the loads driving the failure mode. Therefore, the magnitude and transient behavior of each load must be established to determine their influence on the part and help engineers diagnose the issue.

Abaqus/CAE and True-Load, when used in conjunction with testing, offer a toolset to allow engineers to conduct FEA and calculate load magnitudes respectively. Abaqus/CAE lets engineers build and solve finite element models with numerous loads and load types. True-Load uses FEA results from perturbation load cases and measured strain values to calculate an appropriate load magnitude for all the loads included in the perturbation step. True-Load also automatically conducts verification by comparing the calculated strains to measured strains and provides a correlation plot. This information equips engineers with the information needed to conduct a proper root cause analysis and offers confidence that their conclusions are accurate.

A root cause analysis for loads driving the failure of a press-fit tube are discussed throughout the remainder of this paper. Starting with a background describing the details of the issue, followed by methodology for the True-Load analysis, and concluding with a discussion regarding the findings of the study. Both Abaqus/CAE and True-Load proved to be valuable assets, providing engineers with an appropriate direction to resolve the durability issue.

2. Background

A fluid leak was observed during development testing. Cracking of steel tube was determined to be the source of this leak. The failing tube is press-fit into an aluminum cast component installed on an engine. While operating at high engine speeds this tube cracked and became completely detached from the assembly. The crack occurred in a compression bead near the joint between the tube and the casting. Images of the assembly, the failure, and the tube are shown in Figure 1. The circled bead in the bottom image of Figure 1 is where the crack occurs. In several tests the crack initialized in the portion opposite of the bend, the star in Figure 1 shows the rough location. The complexity of the assembly and the dynamic nature of the loading make it difficult to model the component in FEA with the proper loading. Therefore, True-Load was used to recreate the transient loads, including accelerations and the modal excitations. This allowed for the most influential loads to be determined and aid in setting a direction to resolve the problem.

Figure 1: Installed tube (left), Cracked tube (right), Press-fit tube (bottom)

3. Methodology

In today's world with access to large amounts of computational power it is completely feasible to create a model of the entire engine, transmission, and dyno. However, building a model of this sort is time consuming and computationally expensive. Typically, engineers do not have the luxury of time when trying to root cause a failure. For this reason, simpler less expensive models are desired. Abaqus/CAE coupled with True-Load allows engineers to build simpler component level models while maintaining confidence in their accuracy. A table outlining the advantages and disadvantages to a full scale model and a component level model is shown in Table 1.

For this project a FEA model of the engine component was created using Abaqus/CAE. Using this approach reduced model build time, decreased solve time, and with True-Load correlated the model to test conditions. To further reduce computational cost; the model was simplified with rigid bolts, distributing elements for connected masses, and a cut section of the mating parts. Several loads were defined for this component. Forces and moments were applied to one of the mounting faces to account for induced deflections. Body accelerations in X, Y, and Z directions were added to account for gross vibrations. The model was also constrained in all degrees of freedom on the cut faces of the mating parts. In addition to these load cases, a modal perturbation step was used to find the first six mode shapes. The FEA solution for this model was then used as an input for True-Load Pre-test.

Table 1: Advantages/Disadvantages of modeling methods

	Advantages	**Disadvantages**
Full Scale Model	-Less Assumptions	-High Build Time -High Solve Time -High Complexity
Component Level Model	-Low Build Time -Low Solve Time -Low complexity	-Many Assumptions

True-Load Pre-test calculated strain gauge locations based on the strain fields predicted for the solved load cases. A total of 24 gauge locations were calculated to maintain the appropriate gauge to load case ratio of 1.5 or higher. An instrumented physical part, with gauges in these locations, was used to take measurements for several engine sweeps. The sampling frequency was set to 6000 Hz to capture high frequency effects. The strain signal and the gauge locations on the failing tube are shown in Figure 2. To identify resonance, a frequency analyses for the strain signals was completed and compared to the frequencies predicted by FEA. The frequency analysis for gauge 7 shows high peak amplitudes at frequencies consistent with mode 4 and 5 predicted by FEA (see Figure 3). Thus, highlighting modal excitations as an area of concern.

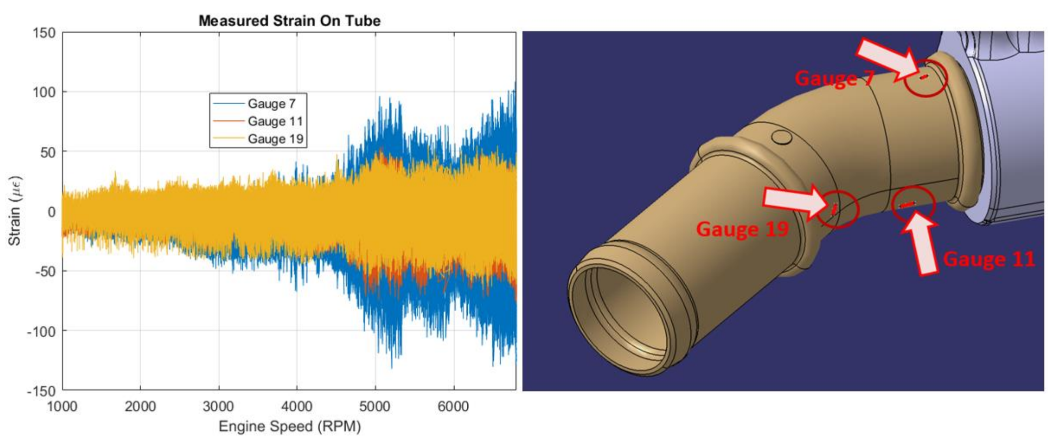

Figure 2: Measured strain and gauge locations on the failing tube

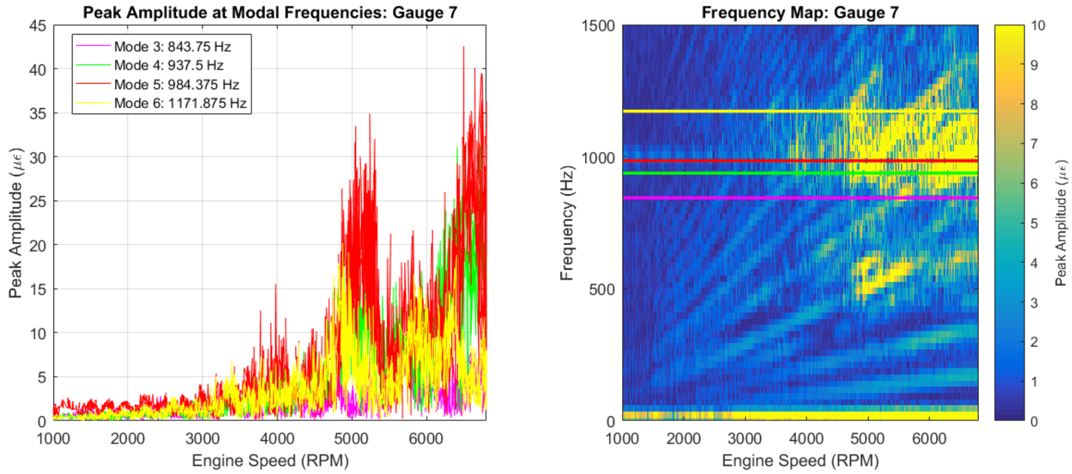

Figure 3: Frequency analysis for gauge 7

True-Load Post-Test, the gauge locations, and the measured strains were used to calculate the magnitude of the loads acting on the assembly. To do this True-Load simulates a strain field based on scaled strains from the perturbation load cases and attempts to correlate the simulated strains to the strain measurements. The overall correlation, including all the gauges, for the simulated strain and the test measurements is shown in the left image of Figure 4. A slope of one is desirable for this plot. It can be seen that the slope of the overall data is trending toward one but is very scattered. Therefore, in order to provide higher confidence in the True-Load results the strain correlation was reviewed for the gauges placed on the failing tube. The right image of Figure 4 shows the correlation for gauge 7, the gauge closest to the failure. This correlation shows a very good strain correlation, providing confidence in the results for the tube in question.

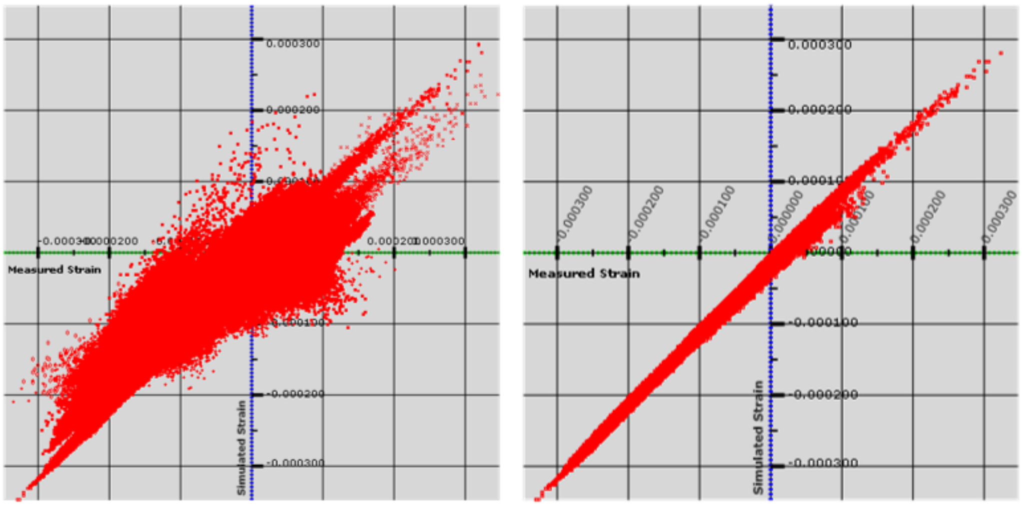

Figure 4: Overall strain correlation (left) and gauge 7 strain correlation (right)

Focus was placed on the modal contributions calculated by True-Load. Only the first six mode shapes were considered for the True-Load calculations. The modal contribution factors calculated for a single engine sweep are shown in Figure 5, Figure 6, and Figure 7. True-Load calculates mode 1, mode 4, and mode 5 as the highest contributing modal excitations. This correlates with the analysis shown in Figure 3. Mode 1 was not highlighted in this frequency analysis, therefore, this frequency is more important for strains of the overall assembly but not the tube itself. This information was used to study the stress amplitudes of the tube.

True-Load was used to calculate peak stress values for elements of the tube. This highlighted the peak stress location on its inner and outer surfaces. The stress contours are shown in Figure 8. These contours are a compilation of the maximum stress values over the entire transient event. From the contours, the element with the largest stress value was selected for a frequency analysis.

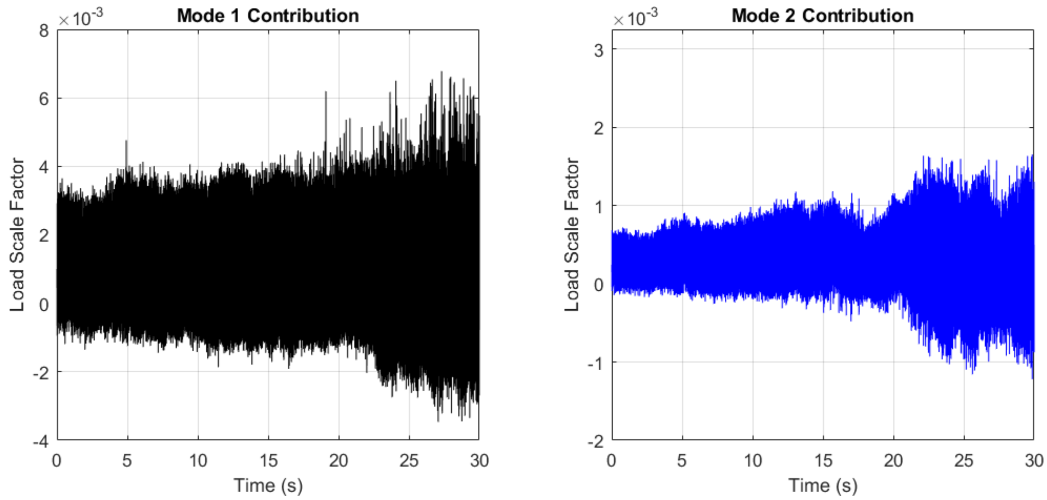

Figure 5: Mode 1 (left) and Mode 2 (right) contribution factors

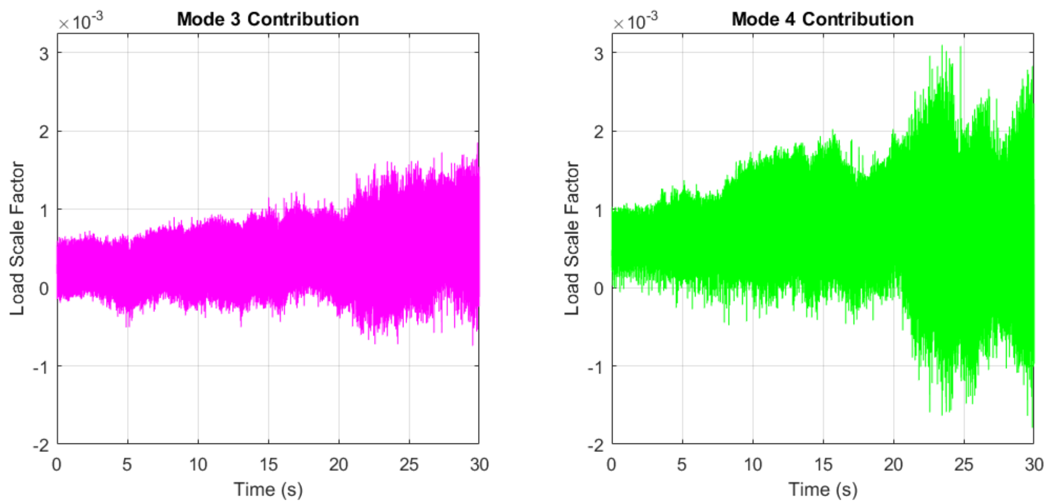

Figure 6: Mode 3 (left) and Mode 4 (right) contribution factors

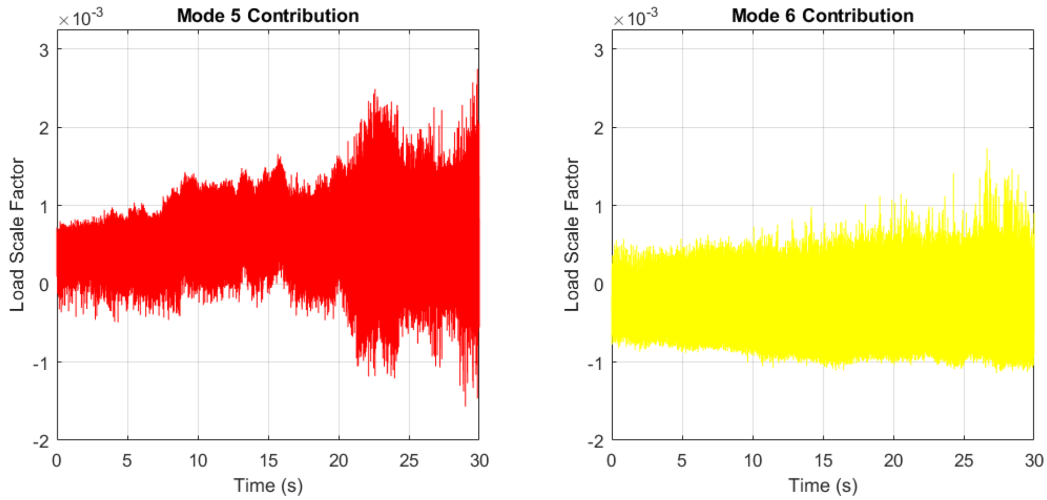

Figure 7: Mode 5 (left) and Mode 6 (right) contribution factors

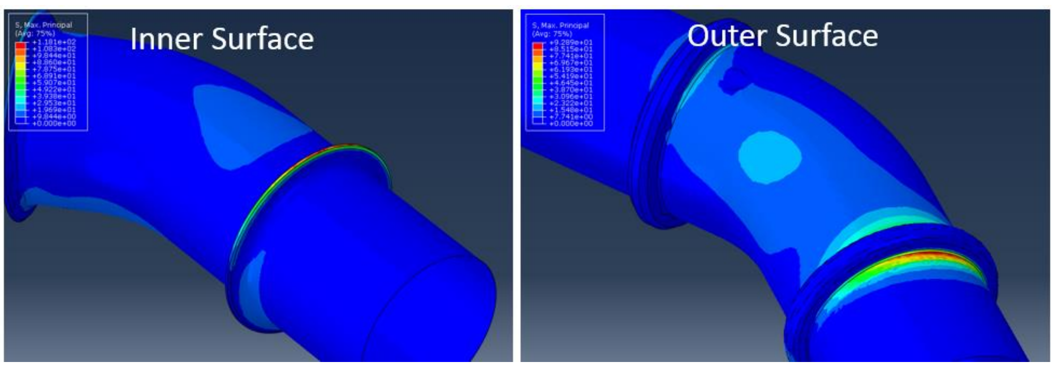

Figure 8: True-Load maximum stress calculation

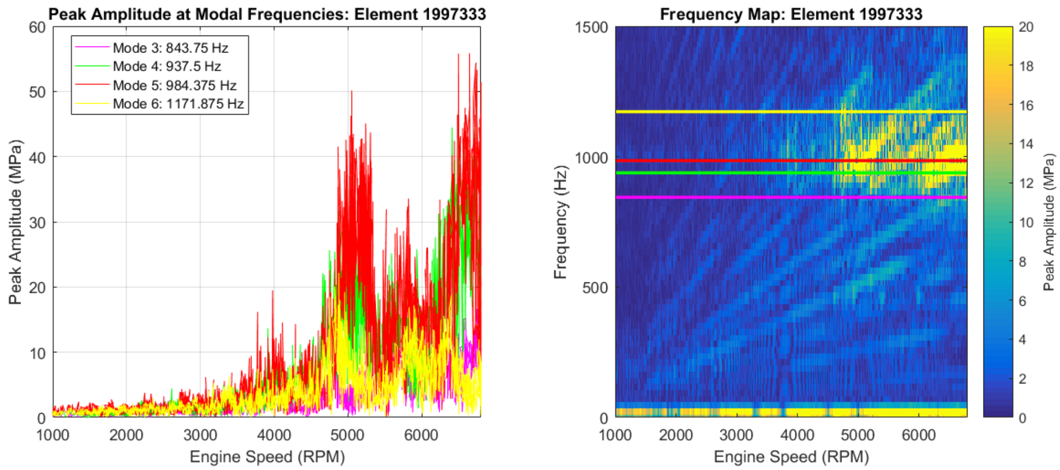

Figure 9: Baseline frequency analysis of high stress element of tube

Principal stress values for the max stress element were calculated at each step in the engine sweep. This calculation included all of the scaled load functions calculated by the initial True-Load correlation. A frequency analysis of this stress signal was completed and is shown in Figure 9. As expected, the image shows high peak amplitudes for the frequencies of mode 4 and mode 5.

To understand how load functions from mode 4 and mode 5 influenced the stress amplitude of the tube, True-Load was used to create an event without these modal excitations. This was done by excluding the modal contribution loads for modes 4 and 5 from the stress calculation. A frequency analysis of the updated stress signal was completed and shown in Figure 10. The images in this figure, when compared to the original, show how the stress amplitudes are reduced when strains from these modes are excluded.

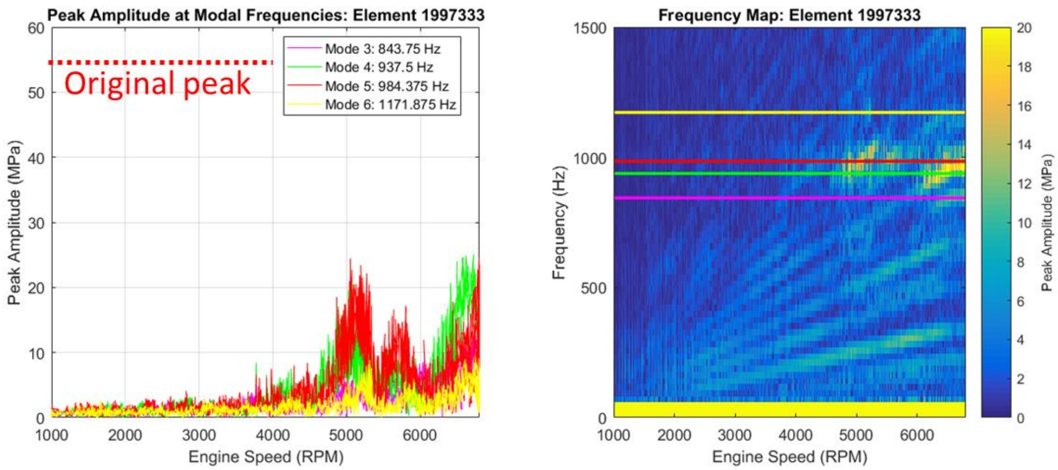

Figure 10: Frequency analysis of high stress element with loading from mode 4 and mode 5 removed

4. Conclusions

The modal loading predicted by Abaqus/CAE and True-Load would have been very difficult to achieve using traditional analysis methods. The results produced clearly highlighted which mode shapes were most influential to the stress in the failing tube. It also allowed an understanding of the stress amplitudes if loads from these modes were removed. True-Load also predicted the highest stresses to occur in a location similar to crack initialization. This, along with good correlation plots, allowed confidence in the results and provided engineers with a clear direction to resolve the issue.

With the information provided by this analysis, engineers can alter the design of the assembly to raise the frequencies of modes 4 and 5 or change the shape of the tube to be more durable. In either case loads provided by True-Load can be used to conduct iterations involving these design changes. Therefore, when a design solution is finalized, engineers will have confidence that the changes will resolve the issues.