A CASE STUDY OF FATIGUE DAMAGE ANALYSIS OF THE CONDENSER-COMPRESSOR CONNECTING TUBE OF A TRUCK'S AIR CONDITIONING SYSTEM

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ABSTRACT

This paper presents a fatigue damage analysis of the metallic tube that connects the compressor and the condenser in a truck's air conditioning system. During an accelerated durability test performed with a truck in a proving track, fatigue failure was detected in this component. Then, in order to observe the component's mechanical behaviour in greater detail and learn more about the failure, new tests were conducted. In these tests, a fresh part was instrumented with strain gauges to estimate the damage required for the component to endure 100% of the intended operation time (approximately 10 years of vehicle usage). The measurements from the strain gauges were analysed using the strain-life fatigue method associated with the Rainflow counting technique and the Palmgren-Miner rule to compute the damage. The strain-life approach employed here was based on the Coffin-Manson-Basquin formula, with the Morrow mean stress correction. The objective of the damage estimation is to provide guidance for future design changes aimed at increasing the component's lifetime.

KEYWORDS: *Failure Analysis, Accelerated Testing, Fatigue, Damage, Strain Gauge*

I. INTRODUCTION

Durability is a critical aspect of a vehicle component design, especially in the case of commercial trucks. These heavy-duty vehicles are subjected to demanding operational conditions, carrying substantial loads and enduring long-distance travels [1, 2]. Ensuring the reliability and longevity of truck components is essential to avoid premature failures, reduce downtime, and enhance the safety of everyone involved.

To assess the durability of a truck's components, engineers typically simulate the actual operating conditions of the vehicle through testing, along with the use of analytical and numerical techniques to draw conclusions and take action. This analysis encompasses aspects such as material selection, fatigue life prediction, and the evaluation of different load scenarios. Understanding how various factors influence the durability of components is vital for truck manufacturers to improve their designs and enhance the overall performance and reliability of their vehicles and corresponding components.

Accelerated testing is a useful methodology employed to assess vehicular durability efficiently and cost-effectively. This methodology aims to simulate years of real-world usage in a shorter timeframe by exposing the components to higher loads and more severe environmental conditions than those experienced in operating conditions. This provokes a faster degradation process that aids to reveal potential failure modes, critical stress points and understanding key aspects of the component durability.

The insights gained from accelerated testing enable engineers to optimize designs, identify potential issues and develop robust solutions [3-6].

One area of particular interest in durability analysis is the study of material fatigue. Fatigue failure occurs when a component is subjected to cycling loading, provoking repeated stresses that are below its ultimate strength but leading to the initiation and propagation of cracks, ultimately resulting in failure [7-9]. Understanding the fatigue behaviour of materials is crucial in determining the service life of truck components and predicting failure modes.

The use of strain gauges and other sensing technologies has become commonplace to monitor in-service loads and gather data for durability analysis [10, 11]. Strain gauges are mounted on critical components to measure the strains and stresses experienced during various operational conditions. The collected data is then used to assess, for instance, the fatigue life of the components and validate simulation models.

Numerous studies have been conducted to improve the reliability and performance of truck components, particularly in terms of their durability, with a focus on fatigue failure. Components such as axles, engine parts, chassis, and suspension systems are subjected to high repeated loads and stresses during operation, making them susceptible to fatigue failure. The following works are referenced [12-14], among others, related to the fatigue analysis of truck's components, each of one using a different methodology.

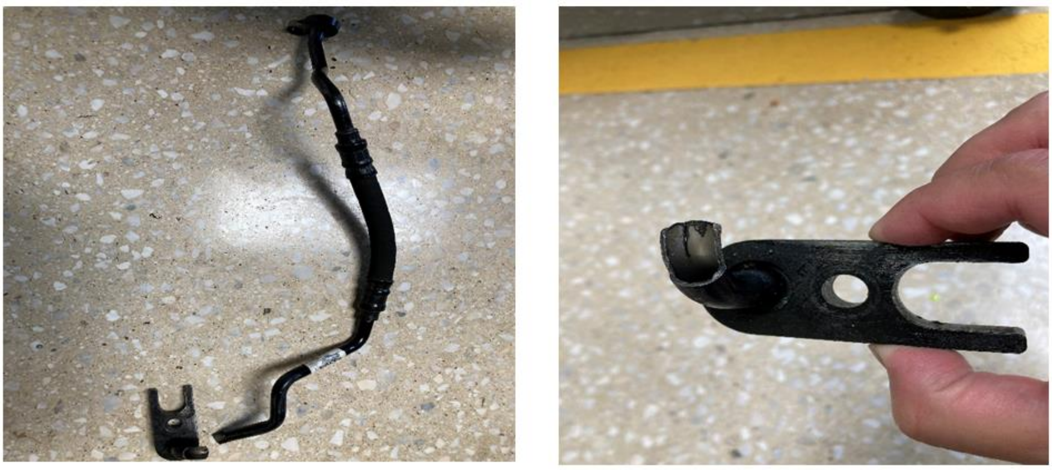
Within this context is inserted the present study, which aims to estimate the fatigue damage of the metal tube connecting the compressor and the condenser of an air-conditioning system of a truck. We utilize a specific methodology explained throughout the text.

The remainder of the text is organized as follows. Section II presents the problem definition, the damage model and the employed methodology. The results are presented in Section III and the main conclusions drawn from the study are presented in Section IV.

II. PROBLEM DEFINITION, DAMAGE MODEL AND METHODOLOGY

2.1. Problem Definition

In an accelerated durability test carried out on a medium heavy-duty 4×2 tractor truck, failure due to fatigue was found in a metal tube connecting the air conditioning compressor and its condenser after about 23% of the complete test (113 over 500 cycles). The rupture occurred where the tube has a 90º change, as shown in Figure 1. Then, new accelerated tests were conducted, where a fresh part was instrumented with strain gauges. The measurements from the strain gauges, in combination with the strain-life fatigue method and the Palmgren-Miner rule were employed to estimate the damage required for the component to withstand 100% of the intended operation time.



(a) (b)

Figure 1. Condenser-compressor connecting tube failure: (a) overview and (b) detail of the broken region

2. 2. Strain-Life Model and Fatigue Damage

In this study, the strain-life (ε-N) fatigue model is used to compute the damage. This model utilizes the standard strain-life method, known as the Coffin-Manson-Basquin formula, with the Morrow mean stress correction. In this model, the relationship between the strain amplitude (ε_a) and the corresponding number of cycles to failure (N_f) is given by:

$$\varepsilon_a = \frac{\left(\sigma_f{}' - \sigma_m\right)}{E}\left(2N_f\right)^b + \varepsilon_f{}'\left(2N_f\right)^c \tag{1}$$

where E is the Young's modulus, $\sigma_f{}'$ is the fatigue strength coefficient, b is the fatigue strength exponent, $\varepsilon_f{}'$ is the fatigue ductility coefficient and c is the fatigue ductility exponent of the material, and σ_m is the mean stress.

Rainflow counting method in combination with Palmgren–Miner linear rule are used to compute cumulative damage D, which is given by

$$D = \sum_{i=1}^{n} \frac{N_i}{N_{fi}} \tag{2}$$

where n is the number of loading blocks, N_i is the number of applied cycles and N_{fi} is the number of constant strain amplitude cycles to failure for block i. The failure of the component is usually considered when the total damage reaches the value of one (D = 1).
In order to be concise, Rainflow method is not discussed here. Interested readers can refer to [7, 15] for detailed explanation.

2.3. Methodology

The accelerated tests with the fresh part were conducted at the proving ground of Volvo Trucks Brazil in Curitiba city. The tests involved subjecting the part to events with previously correlated severity, as shown in Figure 2. The part underwent a pre-established number of service cycles, following the Volvo test procedure. The procedure required the tests to be performed with controlled speeds for each event and under the following conditions:

- Vehicle loaded, running clockwise;
- Vehicle loaded, running counterclockwise;
- Vehicle unloaded, running clockwise;
- Vehicle unloaded, running counterclockwise.

Figure 2. Test track (source: Google Maps)

The sensors (strain gauges) were mounted on the component in a region close to where the previous failure had been detected, as shown in Figure 3.

Before conducting the tests on the track, the strain related to the part assembly was measured, and it was then added to the strains measured during the track tests for the calculation of the damage.

Figure 3. Rosette strain gauge attached to the interested region

The signals measured by the strain gauges were acquired by the Dewesoft signal conditioner, shown in Figure 4. Subsequently, the data were analysed using the nCode software, which calculated the life and damage of the component following equations (1) and (2). Figure 5 presents a flowchart of the calculations performed by nCode.

Figure 4. Dewesoft data acquisition module

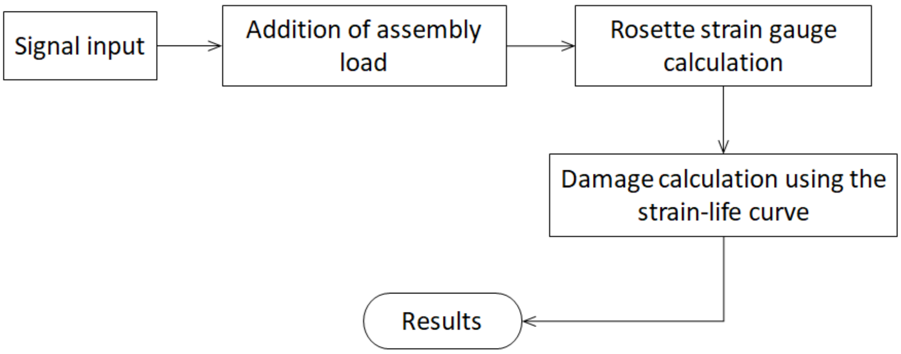


Figure 5. Calculation flowchart

The flowchart consists of the following steps:

- Signal input: In this step, strain signals acquired during the measurement are inserted, totalling one test cycle;
- Addition of assembly load: A constant strain value, due to the assembly load, are included in the damage calculation;
- Rosette strain gauge calculation: The signals from the three gauges are combined to calculate the principal strains and stresses;
- Damage calculation: The strain vs. number of cycles curve is obtained, and damage is extracted for each test condition.
- Results: The damage value for a respective number of repetitions is presented.

This calculation flow was employed for each of the running conditions of the proving ground, and the corresponding damages were appropriately summed, as explained in the Results section.

The tube is made of steel, which the properties are presented in Table 1.

Table 1. Material properties used for performing the calculation.

Property (unit)	Value
Young's modulus (MPa)	206.3×10^3
Yield strength (MPa)	220
Ultimate tensile strength (MPa)	373
Elastic Poisson's ratio (-)	0.3
Plastic Poisson's ratio (-)	0.55
Fatigue strength coefficient (MPa)	662
Fatigue strength exponent (-)	-0.101
Fatigue ductility coefficient (-)	0.218
Fatigue ductility exponent (-)	-0.473
Cyclic strength coefficient (MPa)	916
Cyclic strain hardening exponent (-)	0.214

III. Results

After applying the methodology described in Section II, the damage is calculated for approximately one test cycle. Table 2 displays damage results for each of the test conditions.

Table 2. Damage results values for each of the test conditions.

Condition	Damage
Vehicle loaded, running clockwise	0.00185857
Vehicle loaded, running counterclockwise	0.00157569
Vehicle unloaded, running clockwise	0.00180128
Vehicle unloaded, running counterclockwise	0.00185712

By considering the number of laps of each condition with respect to Volvo's internal accelerated endurance test procedure, it is possible to estimate the total damage to reach 113 cycles (the accumulated number of cycles that the component withstood before its failure): 0.19720158.

Different than what was stated in Subsection 2.2, the component failed with a total damage lower than "1". This discrepancy could be attributed to variations in the manufacturing process, assembly procedure, geometric dimensions and, most importantly, material specification. These factors can influence the material properties that are considered in the damage calculation.

IV. Conclusions

Even though the calculated damage value until the component failure was lower than "1", it provides a reference to rely upon. In this way, for the material properties employed in this analysis, the revised total damage limit is 0.19720158.

Thus, this methodology could serve as an alternative for durability validation in comparison to a long lead time and expensive complete vehicle endurance test.

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