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REAR SUSPENSION DAMPER SUPPORT VIRTUAL DURABILITY AND LOAD RECONSTRUCTION

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Abstract. *Reliability is essential at commercial vehicles development: crucial for brand reputation and to avoid financial losses due to inoperative machinery. Vehicle suspension purpose is absorbing track roughness and ensure a comfortable and safe ride. The damper is an essential component of this system and its support must withstand typical loads, especially impacts, since the efforts are proportional to event velocity. The aim of this work is predict rear damper support life at one durability missions of product's validation plan: Rough Road. The loads histories are crucial for reliable durability result and were reconstructed from strain measurements at strategic point, optimized to assure correlation between virtual and experimental results.*

Keywords: *Load reconstruction, Failure probability, CAE, Fatigue, Pseudoinverse*

1 INTRODUCTION

During trucks nominal operation it is subjected to wide range of different mission profiles generating loads from variety sources such as brakes, power train and, most important for the damper support, object of this study, from the track. According to fatigue theory, Lalanne (2002), the damage produced by the loads are accumulated during all vehicle's lifetime. Depending on the operation condition, damage can achieve critical level that will result in cracks and, at least, unpredicted stop maintenance. Particularly refereed to the damper support, a failure during vehicle travel can lead to handling loss and severe accidents with injury risk either for occupants or pedestrians.

To assure product quality and reliability it is mandatory to define representative validation missions according with vehicle application. One of the most broaden mission, part of validation, is denominated Rough Road. It is a non-controlled off road circuit, with wide kind of obstacles: irregular track surface, cattle cross, holes, climbs and velocity variability due to track layout.

Product development engineering was coupled with experimental data acquisition and virtual tools to compose three solid legs for robust design achievement. The steps are detailed at section 4. The approach offers reliable result, is time saving and is a key concept for global product development.

2 REAR SUSPENSION DAMPER

The rear primary suspension of the specific light truck object of study is composed by parabolic leaf springs, anchored by two supports, and one telescopic damper. Figure 01 presents the original damper support, with 2.12kg.

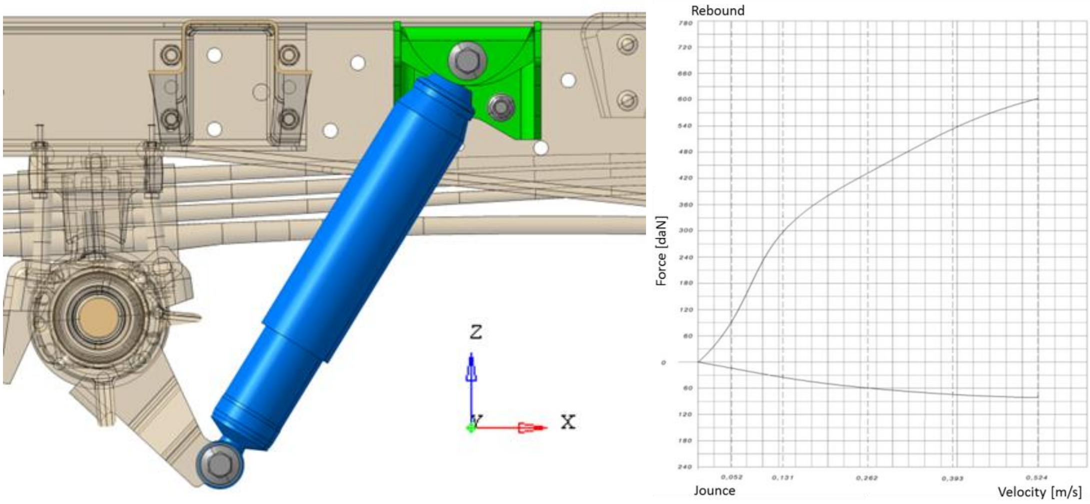


Figure 01. Original damper support and its force curve (max. 6kN)

The forces produced by the damper of course related to vehicle's travel mission profile and are proportional to its piston velocity and direction according to bounce or rebound movement. Figure 02 also presents this relation and states maximum value of 6kN.

The damper support was originally designed with four seam welds which areas of particular interest, since it is a potential failure area depending on weld repeatability and quality. Figure 02 presents support's seam welds and the failure detected during Rough Road durability mission. From fracture marks carefully analysis it is possible to predict the crack initiation point, at the seam weld bead.

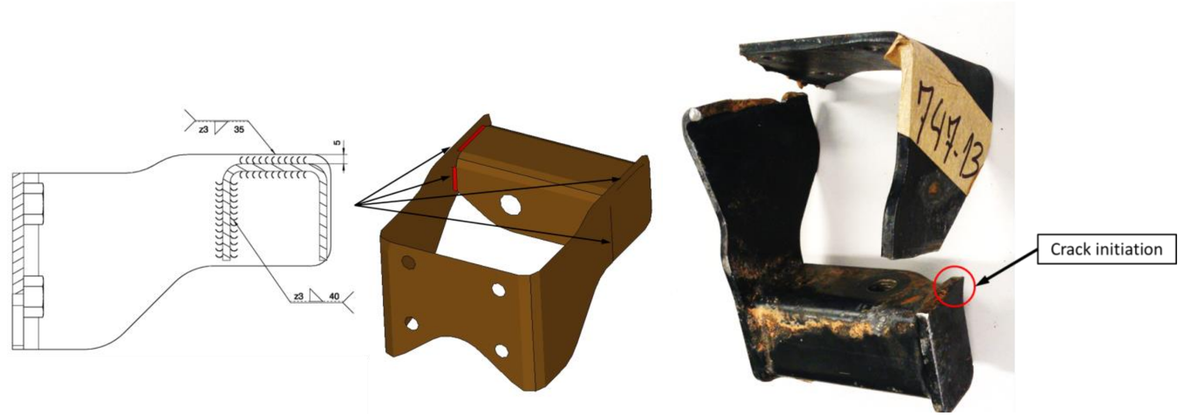


Figure 02. Failure mode detected during Rough Road mission: crack initiated at seam weld bead

The principal concern about seam weld durability is generally a concern during components design and validation, since its life varies widely depending on manufacturing process quality and repeatability. A specific durability curve (SN) was considered to assess weld durability first to correlate with experimental failure and then to predict component's life during concept development phase, avoiding time and money waste with prototype procurement and physical validation.

The first performed virtual analysis was a static analysis with concentrated loads decomposed equally between damper actuation directions, showed that longitudinal efforts (along X axis) induce stresses 10 times higher than vertical loads (along Z axis). Figure 03 presents the max. principal stress, the most significant parameter for component's fatigue life, on both conditions.

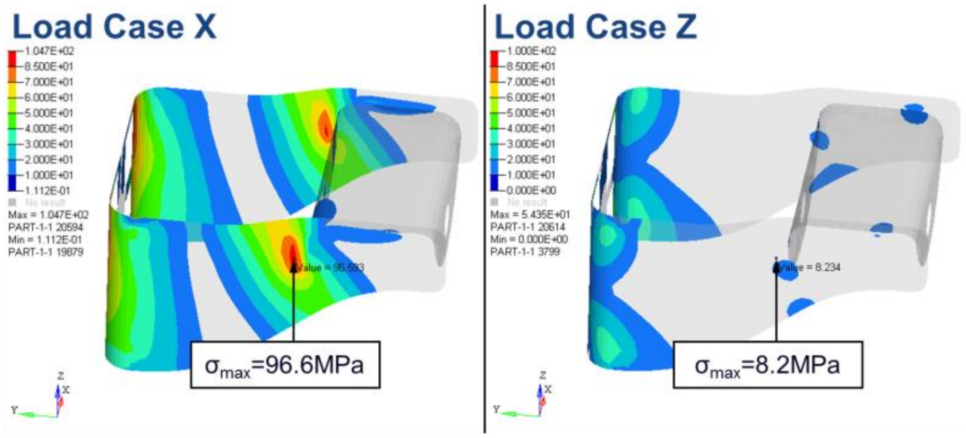


Figure 03. Stress sensitivity between loads cases in longitudinal (X) and vertical (Z) directions

The strain gauge positions were defined based on the strain field of this both load cases: X and Z directions.

3 FATIGUE THEORY & CALCULATION

According to Lee, et. al. (2005), fatigue is a localized damage process of a component produced by cyclic loading. It is the result of the cumulative process consisting of crack initiation, propagation, and final fracture of a component. During cyclic loading, localized plastic deformation may occur at the highest stress site. This plastic deformation induces permanent damage to the component and a crack develops. As the component experiences an increasing number of loading cycles, the length of the crack (damage) increases. After a certain number of cycles, the crack will cause the component to fail (separate).

In general, it has been observed that the fatigue process involves the following stages: (1) crack nucleation, (2) short crack growth, (3) long crack growth, and (4) final fracture. Cracks start on the localized shear plane at or near high stress concentrations, such as persistent slip bands, inclusions, porosity, or discontinuities. The localized shear plane usually occurs at the surface or within grain boundaries.

In engineering applications, the amount of component life spent on crack nucleation and short crack growth is usually called the crack initiation period, whereas the component life spent during long crack growth is called the crack propagation period. An exact definition of the transition period from initiation to propagation is usually not possible.

Typically, the crack initiation period accounts for most of the fatigue life of a component made of steels, particularly in the high-cycle fatigue regime (approximately >10,000 cycles). In the low-cycle fatigue regime (approximately <10,000 cycles), most of the fatigue life is spent on crack propagation.

Once a crack has formed or complete failure has occurred, the surface of a fatigue failure can be inspected. A bending or axial fatigue failure generally leaves behind clamshell or beach markings. The name for these markings comes from the appearance of the surface. An illustration of these markings is shown in Figure 04.

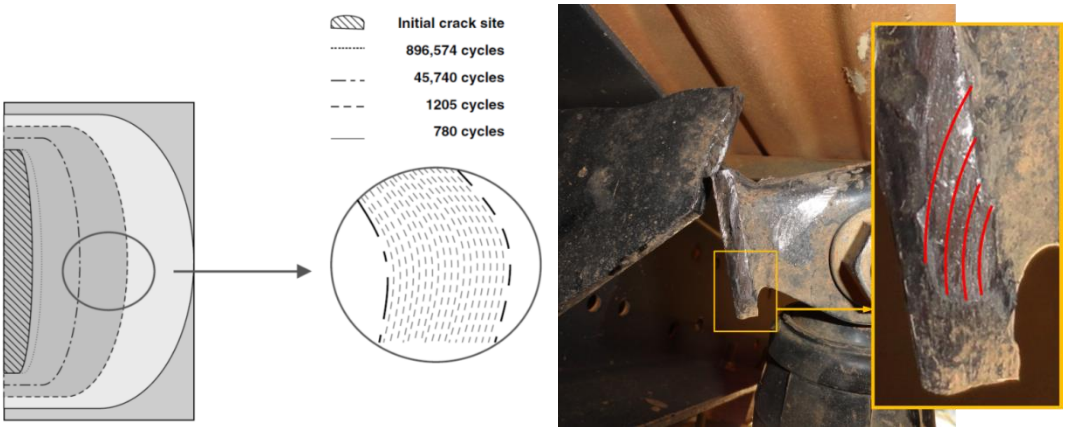


Figure 04. Fracture surface beach marks at the seam weld root of the failed part

There are three commonly used methods: the stress-life (S-N) method, the strain-life (ε-N) method, and the *Linear Elastic Fracture Mechanics* (LEFM). For seam welds S-N method was considered. For all other areas (ε-N) approach was the chosen one due to its enhanced precision.

The British Standard BS 7608 (2014) was adopted as reference for SN curve for the welded regions.

3.1 Cycle Counting & Rainflow

Lee, et. al. (2005) indicates, that fatigue damage is strongly associated with the cycle ratio, $n_i/N_{i,f}$, where n_i and $N_{i,f}$ are, respectively, the number of applied stress and/or strain cycles and the fatigue life at a combination of stress and/or strain amplitude and mean stress levels. The fatigue life, $N_{i,f}$, can be obtained from baseline fatigue data generated from constant-amplitude loading tests.

In Figure 5, one complete stress cycle in a time domain is related to a closed hysteresis loop in the local stress–strain coordinate and consists of two reversals. The reversal can be described as the event of unloading or loading.

Over the years, cycle counting methods such as level crossing, peak-valley, and range counting have been commonly used and improved for minimizing errors during extraction of the cycles number in a complex loading history. The three-point cycle counting, which is a variation form rainflow originally develop by Matsuishi and Endo (1968), was the choice for durability analysis of this work. As per the SAE standards, it uses three consecutive points in a load-time history to determine whether a cycle is formed. Figure 5 shows the rules that identify the two possible closed cycles in a stress time history.

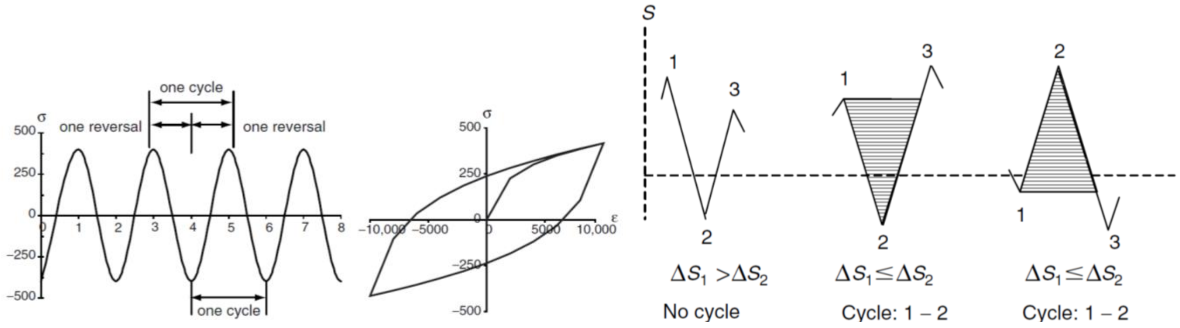


Figure 5. Three point rules for rainflow cycle counting

The three-point cycle counting method requires that the stress time history be rearranged so that it contains only the peaks and valleys and it starts with either the highest peak or the lowest valley, whichever is greater in absolute magnitude. Then, the cycle identification rule is applied to check every three consecutive points from the beginning until a closed loop is defined. The two points forming the cycle are discarded and the remaining points are connected to each other. This procedure is repeated from the beginning until the remaining data are exhausted.

4 LOADS RECONSTRUCTION

Finite Element Analysis (FEA) is widely used in the design of product. While the Finite Element Analysis methodology has become much more sophisticated in recent years giving analysis greater fidelity in their models in terms of geometric representation, the analyst still needs to provide the model with loading information.

Reliable loads, relative to product's application is decisive for durability life prediction. Therefore, a key aspect of this work is to transform the evaluated component: damper support, into a load cell. It was accomplished throughout strategically placement of 5 strain gauges. The methodology is based on Hooke's law and elasticity theory. The process could be arranged in the following steps:

1. identify appropriate load cases according with component nominal operation. In the specific case of the assessed damper support two loads conditions were considered: vertical (Z axis direction) and longitudinal (X axis direction) forces;

2. the expected strains at the part are determined aided by a Finite Elements Analysis (FEA);

3. measure the real strains at the part during appropriate durability missions, according with product vocation. Specifically for automotive industry, this is a strategical step and must be aligned with market demand in order to develop a lean and robust product. Highway, city and off road are general examples of completely different tracks, each one with its own characteristic. The final validation mission can be composed by any combination i.e. 10% highway + 50% city + 40% off road of the vehicle missions;

4. make the inverse path of step 2: from the measured strains, determine true loads magnitude for each considered condition.

The applicability of the approach outlined by Dhingra-Hunter (2003) requires the structure to behave linearly under the event of interest. In addition, and most importantly, the strain response can be thought of as being proportional to the applied load, Hooke's law. With these conditions being satisfied, a general expression may be written representing this proportionality:

$$\varepsilon \cdot C^{-1} = F \tag{7}$$

[ε] is the strain matrix. Generally, the measured samples are stored along lines and the columns relative to each gauge.

The term [C] is called sensitivity matrix and will have dimensions of n loads by m gauges. It is the proportionality factor between strains and force level ($\varepsilon = F \cdot C$). Since in great majority of situations the number of load cases (n) is different from the number of strain gauges (m), the matrix C is not square. Therefore, it's inverse must be computed through Moore-Penrose pseudoinverse matrix generalization.

4.1 Matrix pseudoinverse

As proposed by Laub A. J. (2011), consider the case of $A \in R_r^{mxn}$. Every $A \in R_r^{mxn}$ has a pseudoinverse and, moreover, the pseudoinverse, denoted $A^+ \in R_r^{mxn}$, is unique. A purely algebraic characterization of A^+ is given in the next theorem proved by Penrose (1956).

Theorem: Let $A \in R_r^{mxn}$. Then $G = A^+$ if and only if:

P1. $A \cdot G \cdot A = A$

P2. $G \cdot A \cdot G = G$

P3. $(A \cdot G)^T = A \cdot G$

P4. $(G \cdot A)^T = G \cdot A$

Furthermore, A^+ always exists and is unique.

Note that the above theorem is not constructive. But it does provide a checkable criterion, i.e., given a matrix G that purports to be the pseudoinverse of A, one need simply verify the four Penrose conditions (P1)–(P4) above. This verification is often relatively straightforward.

The characterization of A^+ was independently developed by E. H. Moore (1920), Arne Bjerhammar (1951) and Roger Penrose (1955). We refer to this as the "limit definition of the pseudoinverse."

Theorem: Let $A \in R_r^{mxn}$. Then

$$A^+ = \lim_{\delta \to 0} (A^T \cdot A + \delta^2 \cdot I)^{-1} \cdot A^T$$

In particular, when A has linearly independent columns (and therefore matrix $A^* \cdot A$ is invertible), A^+ can be computed as:

$$A^+ = (A^* A)^{-1} \cdot A^*$$

When A has linearly independent rows (matrix $A \cdot A^*$ is invertible), A^+ can be computed as:

$$A^+ = A^* \cdot (A \cdot A^*)^{-1}$$

4.2 Instrumented Points

The instrument positions are defined aided by static virtual analysis, that allow to recognize sensitive areas to each investigated load case. In case of damper support: X and Z directions. The points are presented at Figure 6.

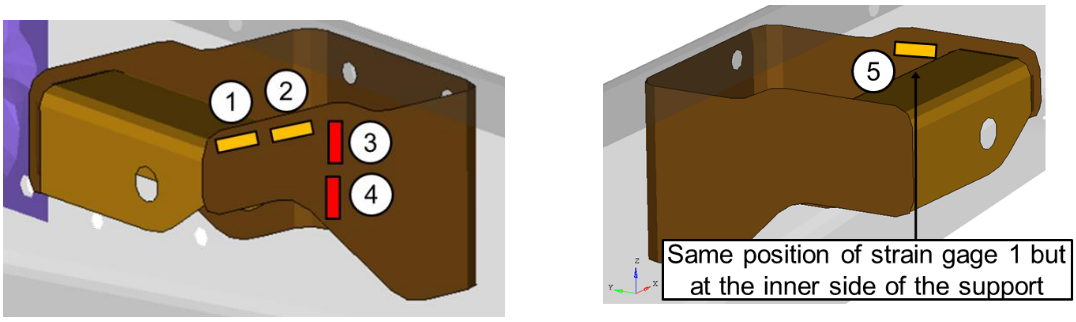


Figure 6. Instrument points position at the developed damper support

The stability of [C] is dependent upon the inverse of the dot product of the strain matrix. A nearly infinite number of configurations of the [C] matrix exist, but there are a limited number of [C] matrices that behave "well". "Well" behaving [C] matrices will be relatively insensitive to signal noise and gauge placement accuracy. In accordance with Dhingra (2003) recommendation, there lays the importance to optimize instrument position to maximize correlation indexes.

5 DURABILITY RESULTS

5.1 Failure Probability

Fatigue life data exhibit widely scattered results because of inherent microstructural inhomogeneity in the materials properties, differences in the surface and the test conditions of each specimen, and other factors. Therefore, statistical approach is mandatory, either for determine test procedure, number of samples as well as interpret results and SN curve, Nakazawa an Kodama (1987).

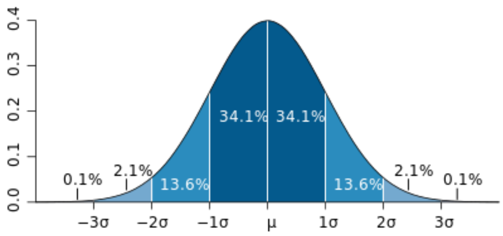
The results are presented in terms of failure probability. The concept is inherent to the considered durability SN (or εN) curve. They are determined from reliability of Wöhler tests, where constant-amplitude stress cycles is imposed until specimen failure. The test is repeated for different amplitudes, always registering the number of cycles material could resist. As remembered by Lee, et. al. (2005), these kind of tests were named in honor to railway engineer August Wöhler, who has first investigated those material parameters between 1852 and 1870.

The distribution of fatigue lives is assumed to be a log-normal, that is, a Normal or Gauss distribution of the logarithm of the fatigue life, nCode (2013). This probability density function is only depended from distribution standard deviation (σ) and average (μ):

$$\emptyset(x) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} e^{-\frac{(x-\mu)^2}{2 \cdot \sigma^2}}$$

Specifically for seam weld, the life variability is wide. British Standard BS 7608 (2014) previews a durability life varying around 20 times within $\pm 3\sigma$ interval. The material discontinuities are intense and, sometimes, bead notches and stress concentrations can be perceived by a naked eye. Specifically for the analyzed component, at the particular considered mission: Rough Road, which is a severe track, with bumps, holes, impacts, the failure is almost a certainty. Figure 7 summarizes the durability results.

Part	Mission	Failure Probability Risk [%]
Original support	Rough Road	**97.8**



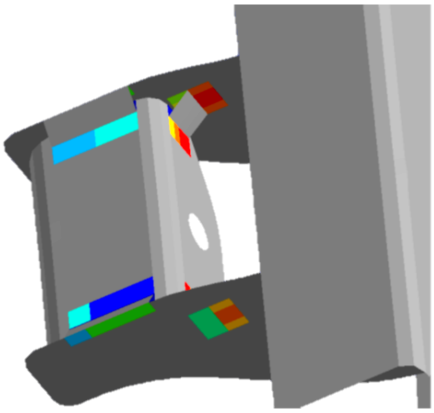


Figure 7. Predicted life considering material and seam weld structural variability

5.2 Correlation

The Figure 8 presents the correlation between measured strains and calculated results at special track and Rough Road missions, respectively.

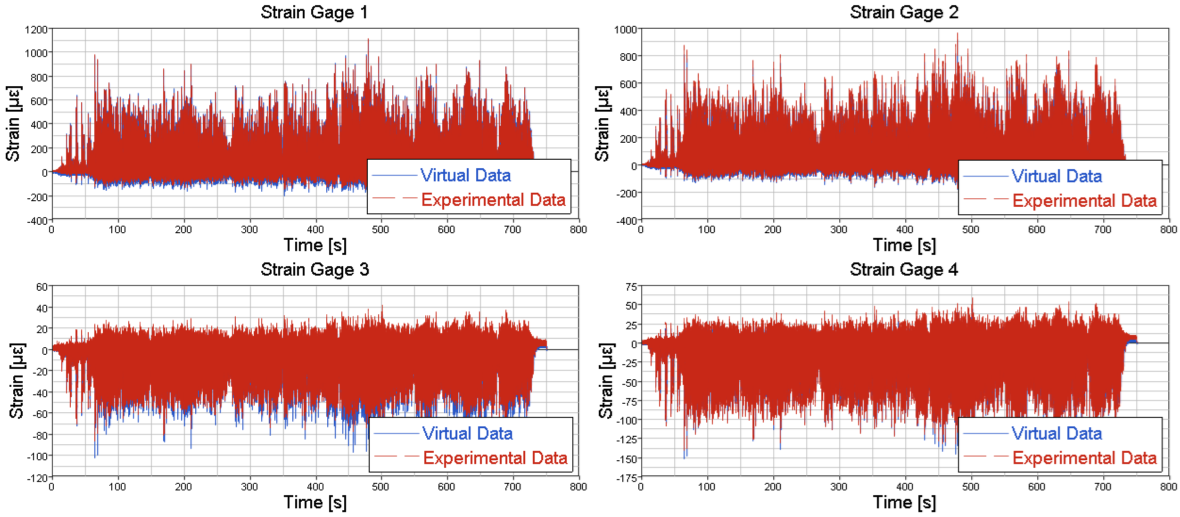


Figure 8. Correlation between virtual and measured strain at Rough Road mission

The comparison proves that load reconstruction technic is truly able to measure real loads and can be applied in any structures that operate linearly in nominal operation, becoming its own load transducer through proper management of FEA results and strain data collection.

6 CONCLUSIONS

The component is not appropriate to withstand Rough Road durability mission. The predicted failure risk is 97.8%, id est, a rupture is very likely to happen before test target.

Load reconstruction maximize the contribution of numerical methods for product development. It contributes to precisely determine the operational loads time history, which is, aside with material properties, a crucial parameters for component's durability. Only understanding the real loads is possible to reach a lean and reliable design, key aspects of any successful product in a competitive market.

The predicted results are consistently correlated with empirical data. The same critical point was observed as well as the stress/strain level and time history were equivalent to the measured values.

The proposed approach can be also used to build a consistent data base with diverse measurements relative to the wide load cases and mission conditions experienced by the vehicle (or its components) during their life. This knowledge could offer a new perspective to review or build standards and specifications indeed in accordance with broad global requirements. The data base is also an important reference to implement any required design modification motivated by any reasons. For instance, but not only: fulfill manufacturing process limitations or material replacement due to commercial market restrictions, develop a production for a particular application or either to benefit from a cost reduction opportunities.

Due to poor repeatability, especially manual operated seam welds must be avoided at risk of premature failure, since a wide component's durability life variation is expected. As general guideline, any weld should be avoided saving one manufacturing operation and increasing component reliability.

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