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PROPOSAL OF A METHODOLOGY TO USE PHYSIC MEASUREMENTS AS FEEDBACK LOOPS IN COMPUTER-AIDED ENGINEERING ANALYSIS

PROPOSTA DE METODOLOGIA PARA USAR MEDIÇÕES REAIS NA REALIMENTAÇÃO DE ANÁLISES DE ENGENHARIA AUXILIADA POR COMPUTADOR

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ABSTRACT
Within a new scenario in the product development cycle, led by an integrated and synchronized task approach, the combination of testing and simulation is a visible tendency even on the design stage of a component. In this regard, the main objective of this paper is to propose a methodology of how real (physic) measurements can be used as feedback loops in computer-aided engineering (CAE) analysis. For this purpose, a truck's suspension component, instrumented with strain gauges on its hotspots, has been tested in a proving ground track located in Brazil. Using an existing durability commercial software, virtual strain gauges have been placed in the component's finite element model and, with the measured forces inputs, theirs results were compared to the correspondents gauges on the real component. In the case study presented, the proposed methodology reduced the average error of simulation damage results from 58% to 30% on the tested component. This result suggests that this method is capable to offer good enhancements in CAE virtual analysis, providing calibrated finite elements models and consequently more reliable virtual verifications.
Keywords: Computer-aided engineering, Strain gauges, Finite element analysis, Real measurements.

RESUMO
Em um novo cenário no ciclo de desenvolvimento de produto, caracterizado por uma abordagem sincronizada de atividades, a combinação de testes físicos e simulação é uma tendência observada até mesmo nas fases inicias de concepção de um componente. Dessa forma, o objetivo deste trabalho é propor uma metodologia de como medições reais (físicas) podem ser usadas na realimentação de análises de engenharia auxiliada por computador. Para isto, um componente da suspensão de um caminhão, instrumentado em seus pontos de maior tensão mecânica, foi testado em um campo de provas situado no Brasil. Usando um software comercial de durabilidade, extensômetros virtuais foram posicionados no modelo de elementos finitos do componente e, com as entradas de forças medidas, os seus resultados foram comparados aos dos sensores reais, instrumentados na peça física. No estudo de caso apresentado, a metodologia proposta reduziu o erro médio dos resultados numéricos de dano de 58% para 30% no componente testado. Tal resultado sugere que a metodologia proposta é capaz de proporcionar melhoras significativas em atividades de simulação, disponibilizando modelos numéricos calibrados e consequentemente verificações virtuais mais confiáveis.
Palavras-chave: engenharia auxiliada por computador, extensômetros, análise de elementos finitos, medições reais.

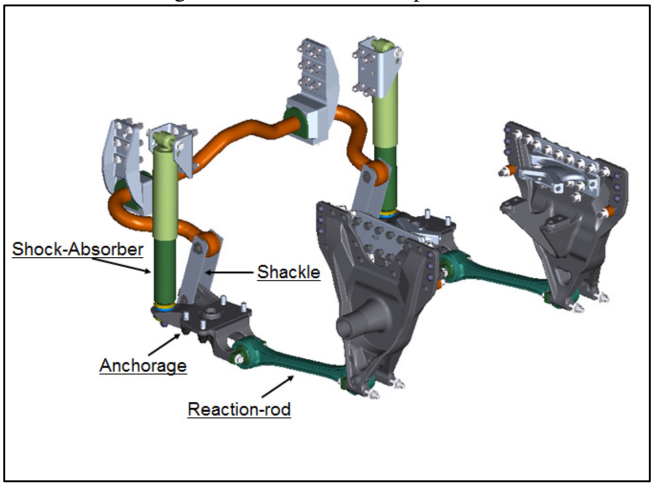
1 – INTRODUCTION

One of the primary objectives, and also a big challenge, on the automotive industry is to offer high quality and low cost products, aspects that impact directly in market share and customer satisfaction (SHIH *et al.*, 1998; WEN, 2008). In this concern, product development and manufacturing organizations are moving from the traditional design-build-test cycle to an integrated and synchronized task approach, led by upfront planning, analysis and simulation, supported by reliable field test data (MILBUM, 2004). One visible trend in the product development cycle is the wide spread of computer-aided-engineering (CAE), like the finite element analysis (FEA) in the automotive industry (SHIH *et al.*, 1998). Even though FEA has demonstrated to accelerate the development cycle, some difficulties in its accuracy are still a constraint in the use of this technique (WEN, 2007; SHIH *et al.*, 1998), as assumptions and simplifications are necessary. In this regard, finite element (FE) model calibration is necessary for securing modelling accuracy, including model assumptions and parameters (WEN, 2007).

The literature presents some researches regarding virtual models calibration applied to railway vehicles (RIBEIRO *et al.*, 2013) and also to structural components, such as bridges (ZHANG, CHANG and CHANG, 2001; SIPPLE and SANAYEI, 2014; WANG, LI and LI, 2010). These works present study cases of how vibration measurements can be used as feedback loops in CAE analysis, similar to what is proposed by Abrahamsson and Kammer (2015) using frequency responses.

The main objective of this paper is to present a methodology to calibrate finite element models based on real strain test data. Using an existing durability commercial software, a correlation between real and virtual strain gauges data has been used to verify a FE model accuracy and to calibrate its parameters until an equivalency with the real component behaviour is established. Although the proposed methodology is presented as a case study of a truck's rear suspension anchorage, it can be extended to others components/analyses.

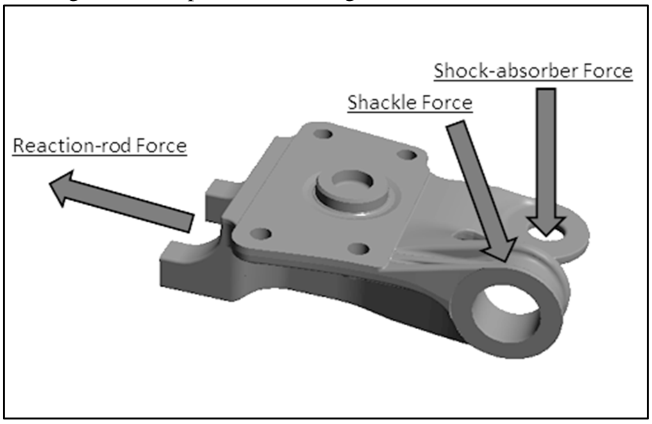
Figure 1 – Truck's rear suspension



This anchorage, indicated in Figure 1, is subjected to three different load cases (Figure 2):

1. Shock-absorber force: damping force due to shock-absorber jounce and rebound conditions.
2. Reaction-rod force: axle horizontal movements and braking maneuvers.
3. Shackle force: sway bar rolling maneuvers and vertical axle motion.

Figure 2 – Suspension anchorage: FE model and load cases



1.1 Boundaries and assumptions

Due to the several variables in the domain of real and virtual testing, some assumptions had to be made and some boundaries were established for this study:

1. Even if measurements errors can occur, it is assumed that the measured results are the correct ones to represent the real behavior of the anchorage.
2. The variable that was used to calibrate the FE model in this case study was the force input. Though material properties, boundary conditions and mesh quality influence in the results, these parameters were assumed to be adequate and were not evaluated in this analysis.
3. As the proposed methodology is based on the linear portion of the stress-strain curve (elastic region), it is assumed that no plastic deformation occurs on the component under study.

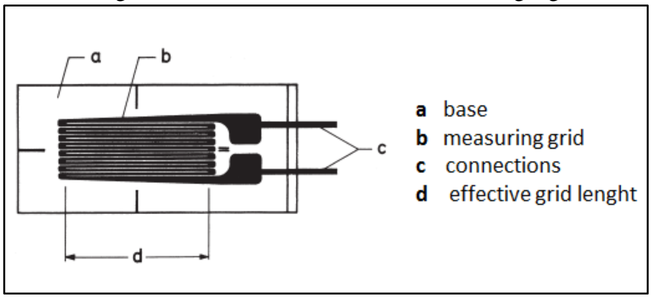
1.2 Background: Metal-foil strain gauge

The metal-foil strain gauges (Figure 3), also identified as metal-foil resistance strain gauges, are sensors composed by a thin resistive foil, fixed on an electrical insulation material - usually polyamide or epoxy-phenolic resin – called base (ANDOLFATO, CAMACHO and DE BRITO, 2004).

The main advantages and characteristics of the metal-foil strain gauges are (LIMA; ROCHA NETO; LIMA, 2008):

– High precision and linearity;
– Low cost and weight;
– Good dynamic and static response;

Figure 3 – Illustration of a metal-foil strain gauge



Adapted from: HOFFMAN, 2012.

The working principle of this strain gauge is based on the fact that all electrical conductors change their resistance when elongated (GALINA, 2003). This characteristic is stated in the second Ohm's Law, which relates the resistance (R) of a conductor to its length (L), cross-sectional area (A) and resistivity (ρ) as in Equation (1).

$$R = \frac{\rho \cdot L}{A} \quad (1)$$

Considering a generic elongation in an electrical conductor, the Equation (1) can be rewritten as Equation (2):

$$\frac{\Delta R}{R} = \frac{k \cdot \Delta L}{L} \quad (2)$$

Where the factor k is defined as the sensitivity of the strain gauge, corresponding to a constant that varies with the resistivityof the material used. Its value varies between 2 and 4, and shall not be related to the magnitude of the measured strain(ANDOLFATO, CAMACHO and DE BRITO, 2004; GALINA, 2003).

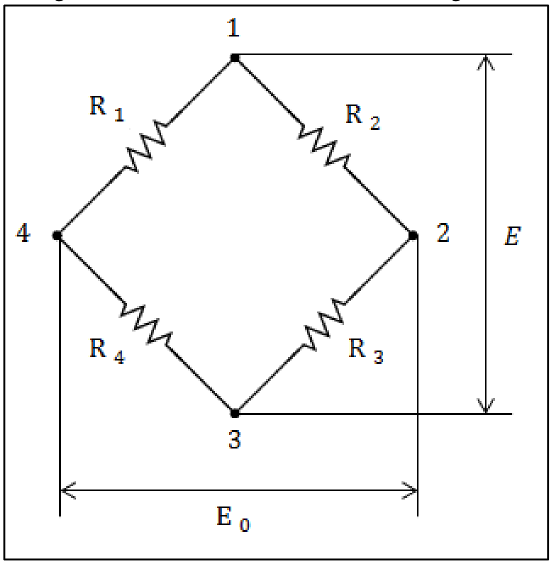
Equation (3) is obtained considering that the giving strain is measured as the total elongation per unit length of material:

$$\frac{\Delta R}{R} = k \cdot \varepsilon \quad (3)$$

The Equation 3 indicates that the magnitude of the measured strain (ε) is proportional to a relative change in the resistance, which is the working principle of this type of sensor.

As the strain gauge resistance changes, the strain results are computed through the electric circuit of a Wheatstone bridge (Figure 4). This is mainly due to the capacity of this circuit to detect small changes in resistance, to allow temperature compensation and also voltage adjustment (AMOROS, 2008).

Figure 4 – Illustration of a Wheatstone bridge circuit

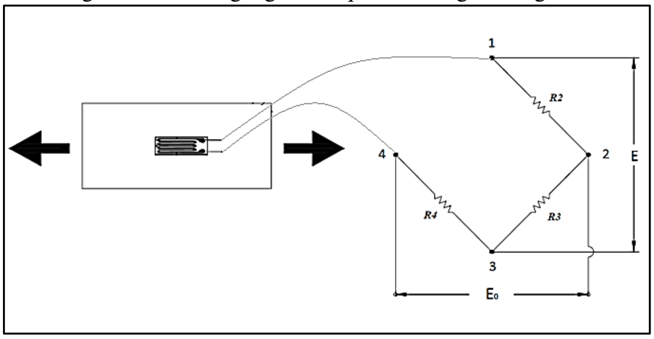


Adapted from: AMOROS, 2008.

The Wheatstone bridge consists of four resistive arms (R1, R2, R3 and R4) connected to a supply voltage, where each arm can be connected to one or more strain gauges (RODRIGUES, 2012).

Several arrangements of strain gauges and resistances are possible in this circuit (¼ bridge, ½ symmetric / asymmetric bridge and full bridge), each one with a specific application. The Figure 5 illustrates the quarter-bridge arrangement, the same used in this methodology.

Figure 5 – Strain gauge with quarter-bridge arrangement



Adapted from: ANDOLFATO, CAMACHO and DE BRITO, 2004.

Finally, the result is obtained by associating the strain to an electrical signal, which subsequently will be conditioned in a data acquisition system (SILVA and ASSIS, 2012).

2 – METHODOLOGY

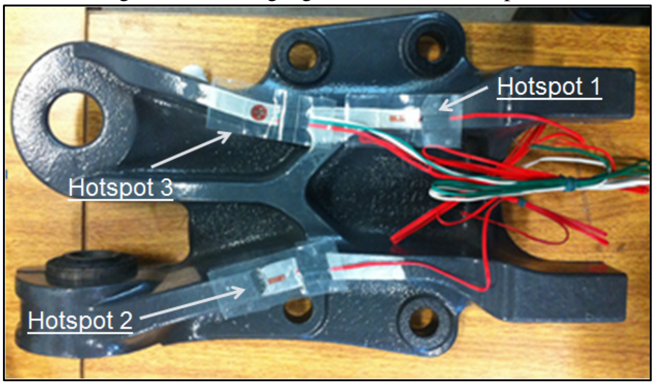
In order to develop a method to calibrate numeric models based on real measurements, the virtual strain gauge tool in nCode Designlife™ 10.0 had been used to compare test and simulation results. An automate process was created where real data is used as a feedback loop in CAE force inputs, so the simulation outputs would converge to the measured ones.

2.1 Anchorage instrumentation

By applying unitary forces in each one of the load cases, the strain hotspots were revealed in the component's model. As illustrated in Figure 7, the hotspots 1, 2 and 3 are respectively due to the reaction-rod, shackle and shock-absorber forces.

Based on this, the real part was instrumented with strain gauges on each one of these three hotspots, as indicated in Figure 6.

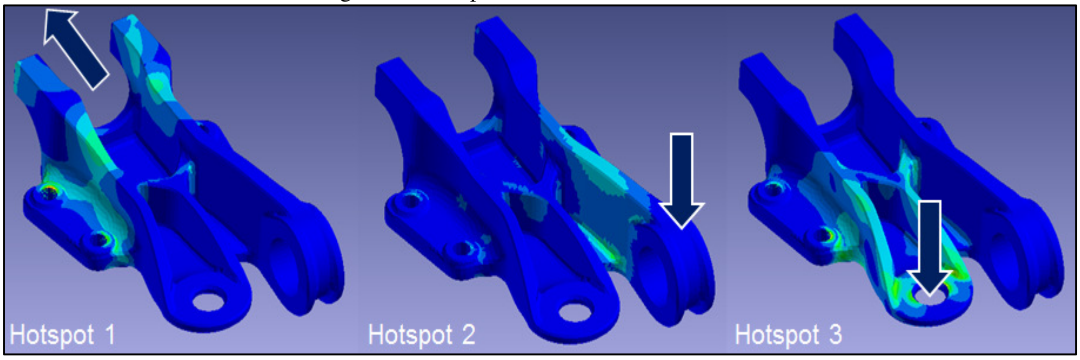
Figure 6 – Strain gauges on the strain hotspots



2.2 Force inputs

Besides the strain values on the suspension anchorage, the dynamic forces for each load case were also measured. While the reaction-rod and the shackle were used as load cells, the damping force was calculated based on the shock-absorber velocity, as detailed as follow.

Figure 7 – Hotspot detection on the FE model



2.2.1 Reaction-rod and shackle forces

Both reaction-rod and shackle were instrumented with two strain gauges each (half-bridge configuration for traction/compression only). With a hydraulic actuator and a load cell, a tensile test (Figures 8 and 9) was performed in order to correlate the microstrain values (uε) with the applied load (kN).

Figures 8 and 9 – Tensile test: reaction-rod and shackle

In Figures 10 and 11 are presented the graphs of the correlation (calibration) between force and micro-strain value on the reaction-rod and on the shackle, respectively.

Figure 10 – Reaction-rod: force-deformation curve

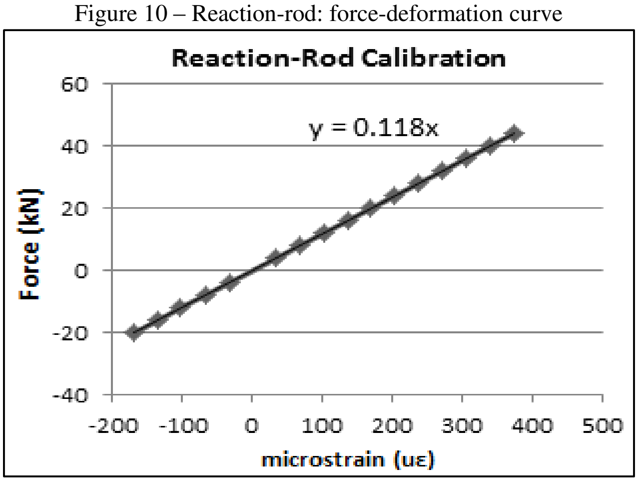
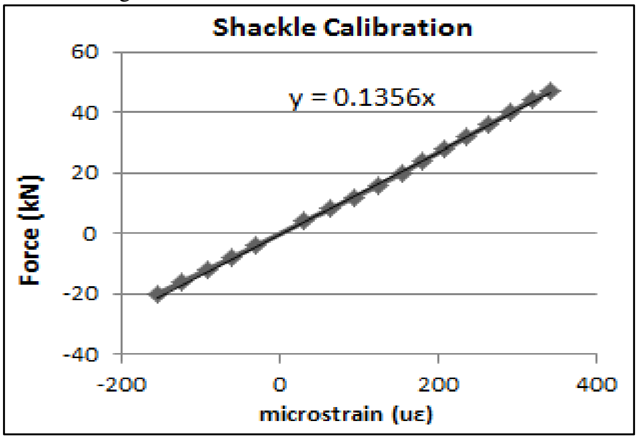


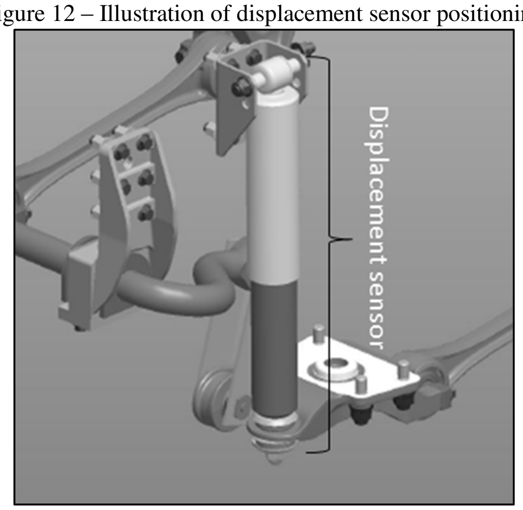
Figure 11 – Shackle: force-deformation curve



2.2.2 Shock-absorber force

The damping force was calculated based on the shock-absorber velocity. For this reason, a displacement sensor (LVDT – Linear Variable Differential Transformer) was placed in the extremities of the shock-absorber, as illustrated in Figure 12.

Figure 12 – Illustration of displacement sensor positioning

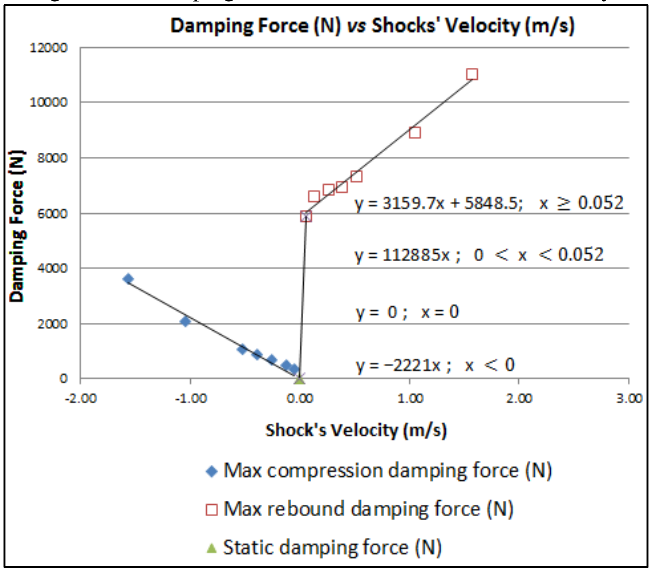


With the measured displacement, the shock-absorber velocity was calculated by derivating the LVDT lecture in the time domain as in Equation (4):

$$\vartheta_{shock-absorber} = \frac{d(LVDT\ lecture)}{dt} \quad (4)$$

Finnaly, the shock-absorber force was obtained using the supplier's experimental curve of damping force – velocity, shown in Figure 13.

Figure 13 – Damping force versus shocker-absorber velocity

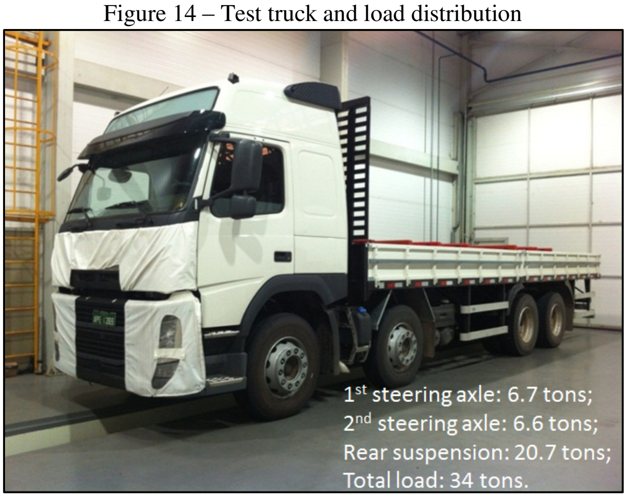


The equations presented in Figure 13 indicate how the experimental data were parameterized (nonlinearities were avoided by linear reformulations).

2.3 Data acquisition: Vehicle conditions, test track and maneuvers

For the measurements, the instrumented components were assembled in an 8 x 2 (4 axles – 1 driven) rigid truck (Figure 14) with technical load (34 tons).

Figure 14 – Test truck and load distribution

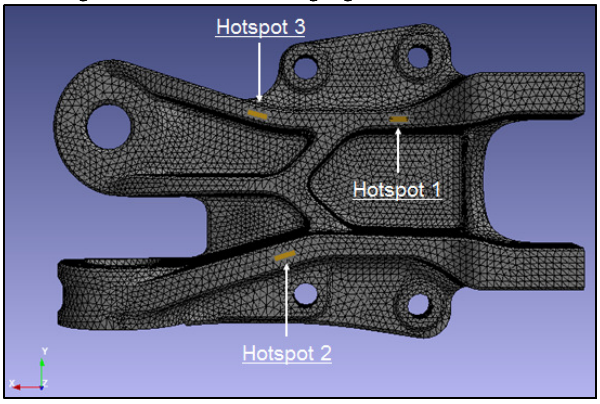


The data acquisitions were performed in a proving ground located in Brazil, following a standard procedure of an endurance test. The test code included several manoeuvres (e.g. braking, lane changing) and events, such as: washboard, cobblestones, Belgian blocks, pot holes, speed bumps and off-road track.

2.4 Virtual strain gages and FE calibration

Using nCode DesignLife™ 10.0, virtual strain gauges were positioned on the FE model in corresponding locations of the real ones, as shown in Figure 15.

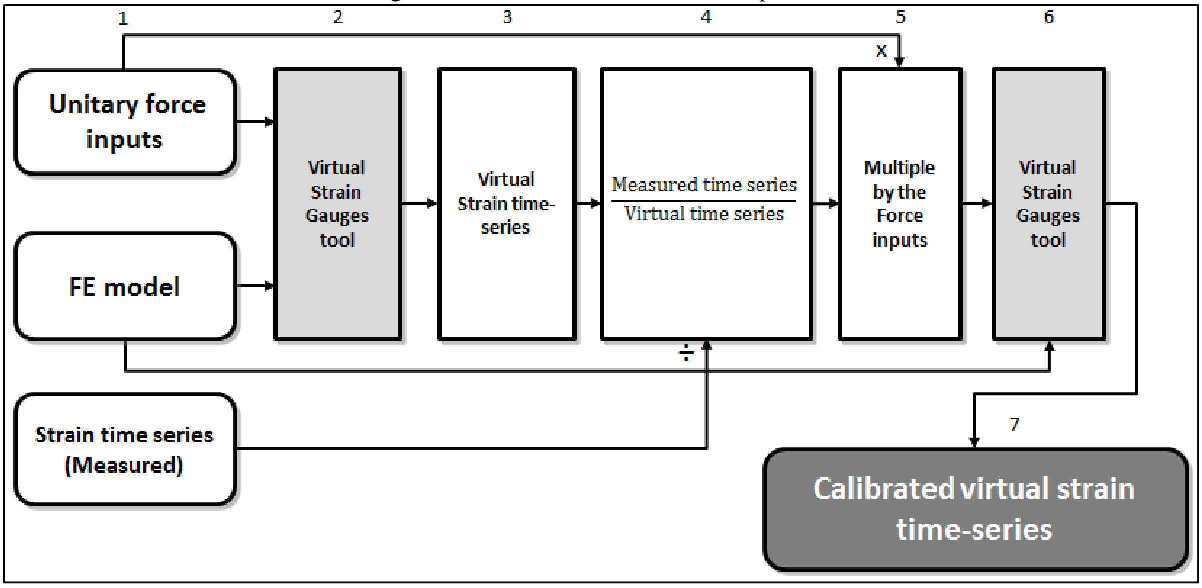
Figure 15 – Virtual strain gauges on the FE model



This virtual strain gauge stool, based on force inputs, enables stress or strain to be extracted from an FE model, recreating a time series channel for each gauge.

Based on it, a process was developed in order to calibrate the virtual model and obtain a virtual output closer to the measured one in the test procedure. The steps of this process, based on the calibration of the force inputs, are presented in the flowchart in Figure 16.

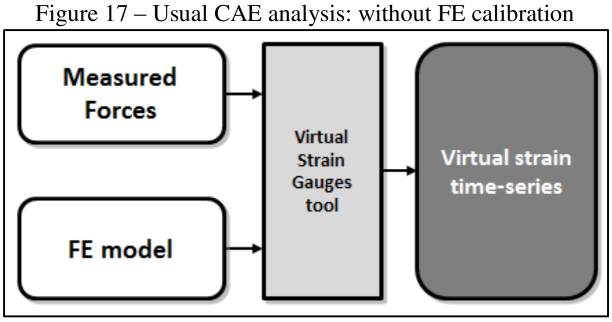
Figure 16 – Flowchart of FE calibration process



Basically, by first comparing virtual and real gauges results, this method calculates floating coefficients (step 4) on the time series for each strain channel. These coefficients are used to calibrate the input forces on the FE model (step 5), as feedback loops in the virtual strain gauges tool, so that virtual and real results are expected to converge in the end of the process (step 7). In sum, the main idea of the proposed methodology is to obtain virtual forces inputs so virtual results come closer to the measured ones. It is important to highlight that for the unitary force inputs, in step 1, a unit such as kiloNewton (kN) should be considered in order to avoid values close to zero on the equation divisor in step 4. Also, it is important that these unitary loads (one for each load case) present the same length and sample rate of the measured time signal (so the division and multiplication in step 4 and 5, respectively, are possible). In the given example, a constant time signal of 1 kN was used as a unitary force input for each one of the three hotspots.

In order to evaluate the method effectiveness, the obtained results were compared to the ones that would be obtained in a usual CAE analysis, without this calibration method, using the measured forces and the FE model as illustrated in Figure 17.

Figure 17 – Usual CAE analysis: without FE calibration



Although the measured forces are experimental results and they are assumed to be physically correct, their outputs (strain time-series) are expected to diverge from the real ones. This difference is presumed to be due the FE model simplifications and parameters. Therefore, the proposed methodology of updating the forces is used as an artifice so the virtual results can converge to the real ones (in other words, the input forces are updated – inside the loop – to compensate modeling errors).

3 – RESULTS AND ANALYSIS

The results presented below are essentially a comparison between real and virtual results (before and after the model calibration).

Using a Fast Fourier Transform (FFT) algorithm, a frequency spectrum analysis was carried out for each time series data, which proved to be a good approach to check the evolution on the results accuracy. The comparative amplitude spectrums, shown in the Figures 18 to 20, were calculated using Hanning window and Peak Hold averaging method.

In addition, from the complete strain time-series of the results (real, virtual, calibrated), a level crossing analysis was performed, which also demonstrated to be an effective method to compare the outputs.

These two analyses, frequency spectrum and level crossing, were chosen due to the fact that they allow a good comprehension of the signals behavior and magnitude. Although the strain time-series can also be compared, the differences between these signals are not so evident, mainly due to the signal length.

Figure 18 – Level crossing and frequency spectrum analysis: results comparison for Hotspot 1

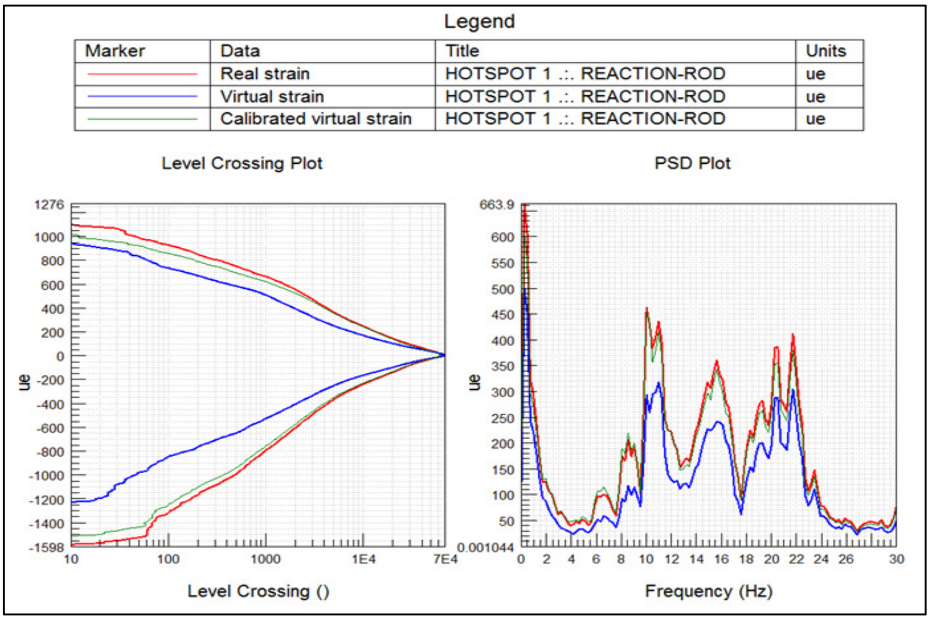


Figure 19 – Level crossing and frequency spectrum analysis: results comparison for Hotspot 2

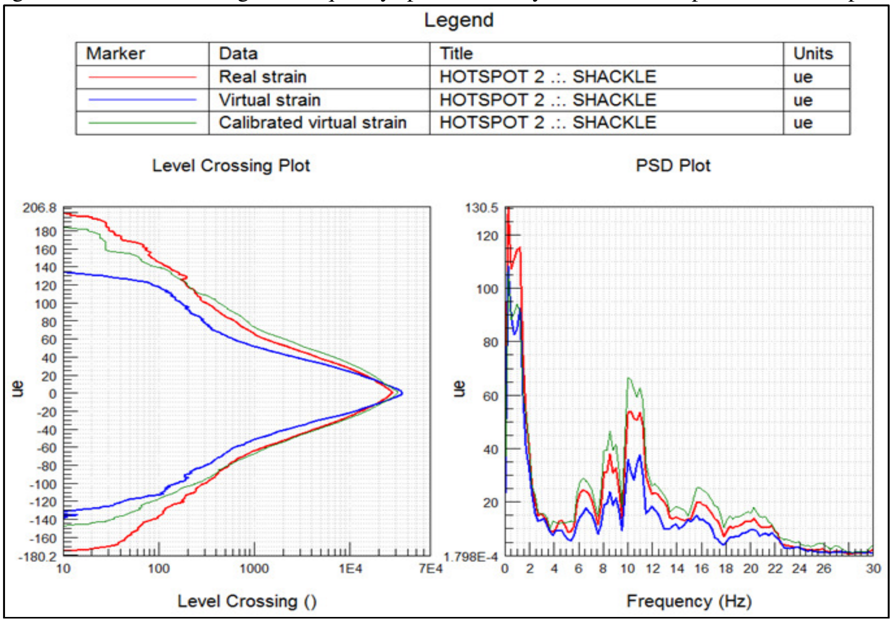
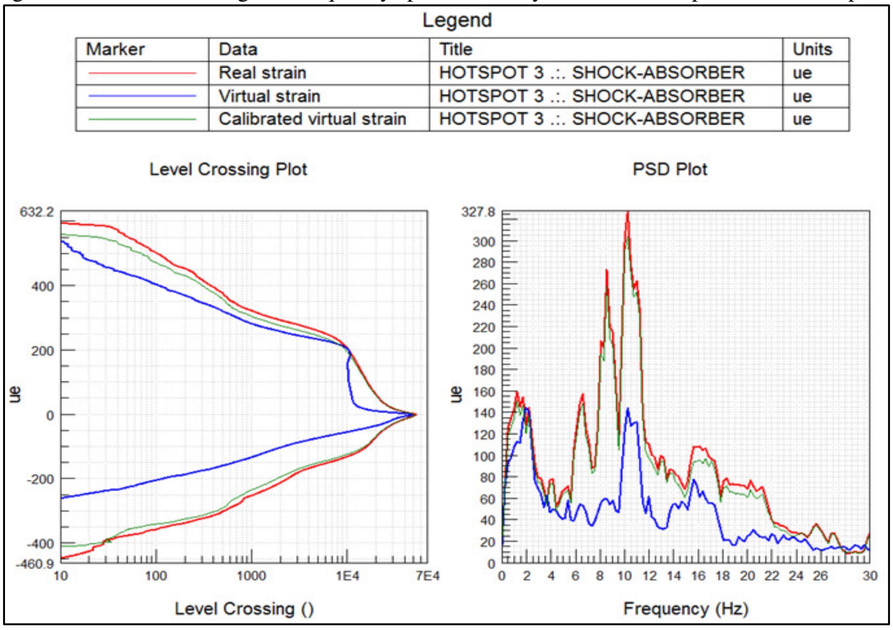


Figure 20 – Level crossing and frequency spectrum analysis: results comparison for Hotspot 3



As it can be visually noted from the frequency spectrum and level crossing analysis, the virtual outputs presented more accurate results (closer to the measured ones) when the analysis was processed through the proposed methodology (in a calibrated finite element model). Even if some small discrepancy can still be noted after this process, the improvements on the results are clear.

In order to quantify this enhancement in the simulation results, a relative damage analysis was performed. Using the measured results as reference, the relative damage of the simulation outputs (original and calibrated model) have been calculated using a theoretical S-N curve. Although some discrepancy from the real data can still be noted, this methodology reduced the error of simulation damage results from 58% to 30% (average on the three hotspots – Table 1).

Table 1 – Relative damage deviation from measured results

Hotspot	Virtual Strain (Error %)	Calibrated virtual strain (Error %)
A	58.20	31.43
B	47.28	33.01
C	69.30	24.72
Average	58.26	29.72

This enhancement in the virtual results impacts directly in the accuracy and reliability of virtual verifications. With virtual outputs closer to the real ones, the confidence in others CAE analysis, such as a fatigue prediction, are expected to be higher.

CONCLUSIONS

Using real measurements as feedback loops in durability commercial software, a good correlation between real components and their respective finite element models was achieved. This work presented the methodology as a case study in order to facilitate the process understanding and also to evaluate its effectiveness. Nevertheless, the same methodology can be easily adapted and implemented in others analyses or future works.

Even if this method uses the force inputs to calibrate the numeric models, it was observed that the virtual strain gauges can be used to evaluate many others CAE parameters, such as: boundary conditions, mesh quality and material properties. Also, and beyond the scope of this work, it was noted that virtual strain gauges can be used to recreate force inputs from real measurements. This can desirable during design loops where a verification, and not a validation, is necessary.

Finally, the following main conclusions can be drawn from this work:

- Although additional studies are necessary to improve and automate this method, the results suggested that the proposed methodology is capable to provide good enhancements in CAE virtual analysis.
- The proposed methodology is specially recommended in analysis which the main desirable output is the strain values (e.g. damage analysis, lifetime assessment).
- Assumptions and simplifications are inherent to numeric models. Although a calibrated model is always desirable, this importance is highlighted for

final virtual verifications (such as fatigue/damage analysis), mainly due to their importance and to the errors of non-calibrated models in these analysis.

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