NUMERICAL FATIGUE EVALUATION IN AGRICULTURAL EQUIPMENT WELDED UNIONS

Rafael Kappaun
Róbinson J. Jabuonski Jr.
Stara S/A Indústria de Implementos

Rafael Vetturazzi
ESSS - Engineering Simulation and Scientific Software

Agenor Dias de Meira Jr.
UPF - Universidade de Passo Fundo

ABSTRACT

Grain transportation is critical for agricultural production since harvesting demands reliable equipment for the efficient execution. Although the robustness of the implement is fundamental, over-dimensioning may results in waste of inputs and fuels, increasing costs and may causing loss of commercial competitiveness. Agricultural chaser bins are the connecting elements during the harvest process. It is common practice to align the chaser bin with the harvester for storage and later transfer the grains to the truck that drains production to silos, ports, railway points and industries. To meet this activity, the development of the equipment requires a high level of reliability. Therefore, this work presents a durability evaluation of the chaser bin header. Through finite element analysis and field stress measurements, the level of stresses acting on the component is calculated. Subsequently, the component's fatigue life is evaluated with a focus on welded joints using dedicated software, based on the Volvo-Chalmers method. The calculation of damage and fatigue life is performed according to membrane and bending stresses criteria of the elements connected to the weld profile. The chaser bin header indicates a fatigue life of 687 hours for the test track signal and 27,444 hours for the signal measured on field. For 10,000 hours minimum service life it is recommended to physically test the component in 250.2 hours on the test track.

INTRODUCTION

The self-unloading chaser bin is a machine specialized in bulk grain transportation, from the harvester to intermediate storage facilities or to another transport vehicle, usually with greater capacity, such as a truck. [1]

For better use of the available harvest time, it is desirable not to stop the harvester to transfer the grains into a truck.

To accomplish that a chaser bin is used to follow the harvester and the grain transfer between the machines is carried out in motion. Subsequently the bin is moved to a truck where the grains are transferred again. Figure 1 shows these two stages of grain transportation. Although it is possible to monitor the harvester directly by a truck, this is not practiced due to occasional soil compaction and less maneuverability beside the harvester.

Figure 1 - Stages of grain transfer;
a) Harvester transferring grains to the chaser bin;
b) Chaser bin transferring grains to the ruck.
Source: Authors, 2020.

The self-unloading chaser bin, Figure 2, is basically constituted by header, reservoir, chassis, axles, high flotation tires and discharge duct system. It can have one or two axles and a load capacity of 40 cubic meters.

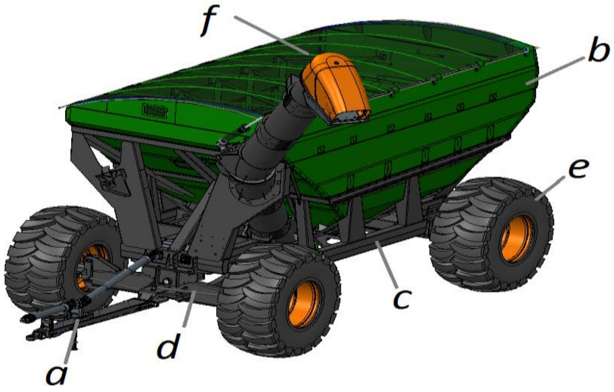

Figure 2 - Self-unloading chaser bin;
a) Header; b) reservoir; c) Chassis; d) Axis;
e) High flotation tires; f) Discharge duct system.
Source: Authors, 2020.

With a reservoir tapered shape, the equipment allows the self-discharge through the discharge ducts. These ducts have helicoids that, driven by the tractor's power take-off, drain the product out of the reservoir. These components are developed to achieve high work performance. With a discharge tube diameter of 500 millimeters the discharge capacity can reach up to 10,000 kilograms by minute.

The header is the connecting component between the tractor and the chaser bin chassis. Figure 3 highlights the evaluated component and shows how the header is mounted to the tractor's drawbar. The implement has a mass of 8,520 kilograms, and a load capacity of 33 cubic meters. Considering a seed density of 850 kilograms per cubic meters, it results in a total mass of 36,570 kilograms. This component is constantly under the effect of random loads of traction when the tractor pulls it, and of compression, due to the terrain irregularities transmitted in the bin/tractor coupling. In addition, there are forces resulting from accelerations in pull-out and braking. The focus of this work is to evaluate the durability of the header chaser bin with a load capacity of 33 cubic meters.

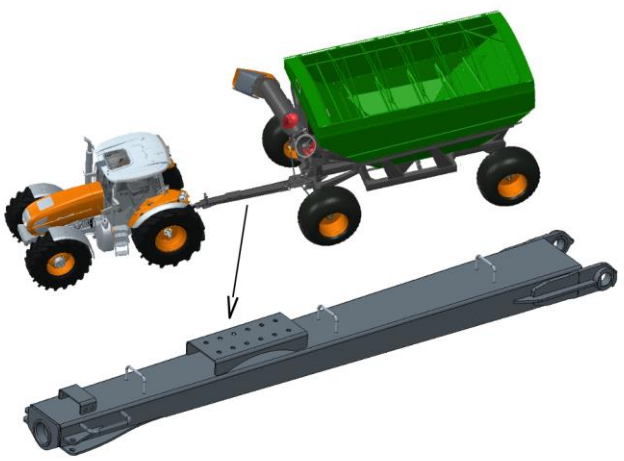

Figure 3 – Header chaser bin.
Source: Authors, 2020.

The vast majority of material properties tests are related to the stress-strain diagram (Figure 4), where the load is applied gradually, with enough time for the deformation to fully develop. In addition, the specimen is tested until rupture, so the stresses are produced only once. Tests of this kind are known as static conditions. Such conditions approximate the real conditions to which many machine components are subjected [2].

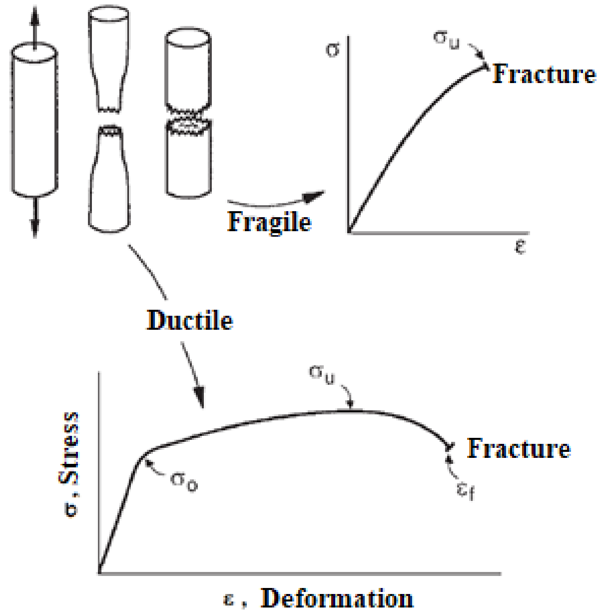

Figure 4 - stress-strain diagram.
Source: Adapted from Downling, 2013 [2].

However, situations often occur where the loads and, consequently, the tensions, vary or fluctuate between levels. For example, a certain fiber on the rotating axis surface, which is subject to the action of bending loads, undergoes traction and compression for each revolution of the axis. If this axis is part of an electric motor, the fiber is stressed in tension and compression with the same frequency of the motor rotation. If this axis is also loaded axially, an axial stress component is superimposed on the bending component. Thus, there will always be some tension in any fiber of the axis, which will make the tension level fluctuating. These types of loading on machine components produce stresses called variable, repeated, alternating, floating, etc. [3].

Also according to Budynas and Nisbett [3], it is common to verify that machine members have failed under the action of repeated or fluctuating tensions. However, in a more accurate analysis, it appears that the maximum real stresses were well below the ultimate strength of the material and, very often, below the yield strength. The most distinguishable feature of these failures is that the stresses have been repeated many times and, therefore, this failure is called fatigue failure.

Dowling [2] exposes that mechanical components are frequently subjected to repeated loads. Cyclic stresses resulting from these loads can lead to microscopic physical damage to the materials involved. Even with stresses well below the material's strength limit, microscopic damages can accumulate continuously with the loading cycle until they crack or result in other macroscopic damage that leads to component failure. Therefore, this process of damage and failure due to cyclic loading is called fatigue.

The American Society for Testing and Materials – ASTM [4] defines fatigue as:

> *The process of permanent, localized, progressive structural change in a material subject to conditions that produce stresses and fluctuating deformations at some point or points and which can culminate in cracks or complete fracture after a sufficient number of fluctuations or cycles.*

Welding process is used in many industries as an effective and economical method for making structural joints between metal parts. However, the nature of the welding process causes a fatigue resistance of the joint that is generally lower than the parts to be joined. At the same time, welds are often made with geometric features or with changes in the structure section. As result of these facts, even in a well-designed structure, typically welded joints are more susceptible to fatigue failure. Any assessment of durability in a welded structure must therefore give priority to the assessment of fatigue in welded joints [5].

There are numerous reasons why the fatigue strength in welded joints is, in general, significantly less than the parts welded together or the parent material, such as:

- The weld geometry typically generates stress concentrations. The tension will typically be higher at the root or at the bottom of the weld toe, and the shape in these areas may not be well controlled;

- The process will often generate defects that can act as crack initiation spots, such as slag inclusions, incomplete melting, porosities, etc.;

- The heat-affected zone (HAZ) occurs, where the base material has been heated to a high temperature and cooled quickly. This can cause major changes in the microstructure and mechanical properties;

- The welding process will generate residual stresses, which can reach the same amount of resistance to the material flow.

All of these factors indicate the welded joint fatigue strength as very different from the parts involved. As result, it is unreasonable to expect to be able to make good fatigue predictions for a joint based on the properties of the plates or other parts being joined. Because of that, most historical methods and standards are based on a characterization of the fatigue behavior of entire joints, usually in the form of S-N curves. These curves effectively incorporate all the effects of defects, unknown residual stresses, notches and changes in material properties that are introduced when welding is done.

This standard procedure, however, results in evaluation limitations of the welded structure, mainly because that it does not consider the residual stresses due to the welding process (heating and cooling of the heat-affected zone), in addition to disregarding the effect of geometric dimensional variation, since there is a tendency for thin profiles to show less fatigue resistance compared to thicker profiles. An additional aspect that must be considered in this type of numerical assessment is related to the challenge of extracting a coherent stress field. This difficulty occurs mainly due to the occurrence of stress concentration in welded regions where there are geometric transitions and, consequently, numerical singularities.

In 1998, however, a partnership between Volvo Car Corporation and Chalmers University of Technology presented a numerical methodology that seeks to circumvent the limitations described above, aiming at an effective fatigue assessment model in welded structures for thin sheets. This approach, called Volvo-Chalmers, was implemented in the Ansys nCode software to assess welded structures subjected to different conditions of static and dynamic stress [6].

The aforementioned methodology demands the use of a previous structural model of finite elements with components and weld profile represented by shell elements. The verification of the weld profile as top or fillet is carried out according to the normal orientation of the weld in comparison to the other components. The stress evaluation acting in the region is a combination of the membrane and bending stresses calculated in the previous structural model. The procedure is facilitated by the design of the shell elements, since this evaluation is carried out directly through the evaluation of stresses along its thickness.

Different tests indicate that the fatigue strength is higher in structures predominantly subjected to flexural stress when compared to rigid models with a greater contribution of membrane stresses [6]. Thus, the Volvo-Chalmers method determines the contribution of bending to the verified total stress, and thereby establishes whether the weld is essentially rigid or flexible.

This stress conversion is added to a pair of S-N curves representing the fatigue life of a joint subjected to membrane stress and pure bending. The curve is interpolated according to the effort ratio verified in the previous finite element model, as can be seen in figure 5. These same curves are optimized to meet loads of variable amplitude.

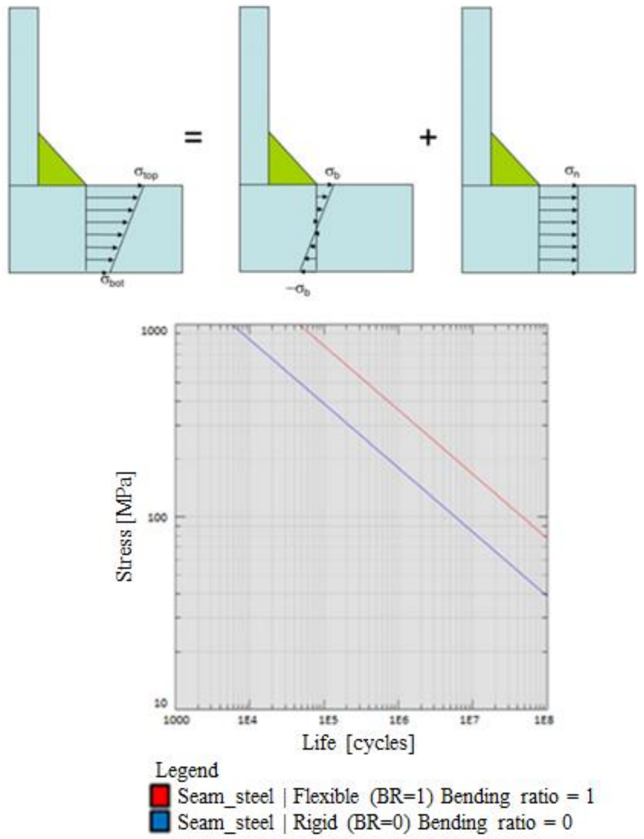

Figure 5 – Combination stress response and S-N curve representation for welding.
Source: nCode, 2018 [6].

With the focus of developing products with quality, reliability and durability, it is necessary to use advanced engineering tools. Although the robustness of the chaser bin is fundamental, over-dimensioning, on the other hand, results in waste of inputs and fuels, increasing costs and may cause loss of commercial competitiveness. Ensuring the minimum fatigue life in the components of a project is a major challenge.

METHODS AND PROCEDURES

By finite element method, where the continuous profile is discretized into a finite number of elements, it is possible to determine the structural behavior of components with complex shapes, using computational resources. From the development of geometry with the aid of CAD resources, it is possible to perform the mesh generation and knowing the active loading, it is also possible to determine the most requested regions of the component, establishing predictions regarding its structural behavior [7].

The finite element analysis performed in the present study was developed with the aid of the Ansys Workbench Mechanical software, while the fatigue assessment model is calculated using the Ansys nCode DesignLife software. The source geometry presents a plate profile with constant thickness, which allows the conversion into SHELL181 shell elements. In addition to the geometric profile, the weld bead is also represented as shell elements, with the definition of the geometry as a constant profile and thickness linked to the distance from the root to the top of the respective bead.

Figure 6 shows the geometry already prepared with the average surfaces of the components and highlighting the region considered critical with the plot of the finite element mesh. It is important to looks for high quality elements in the representative regions of the weld bead and adjacent areas, since the fatigue assessment focuses on these points. Good mesh quality in this geometric portion means the correct representation of stresses verified in the virtual model.

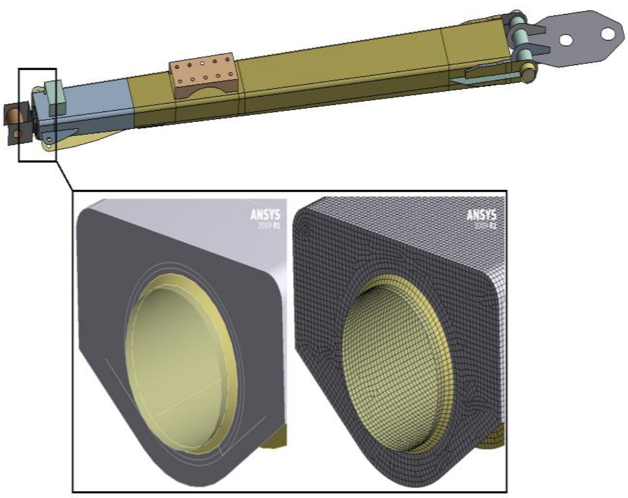

Figure 6 – Geometry and mesh.
Source: Authors, 2020.

To determine the displacements, stresses and reactions from the header, a static analysis is configured. Figure 7 shows the model used in the simulation, which shows that, in addition to the header, the tractor coupling components and the connection base are included. These two components are necessary for a correct representation of the stiffness surrounding the object of study. A fixed support constraint is applied to the connection base, which restricts all degrees of freedom at the selected edges, highlighted by blue. A force of 1 N is applied to the coupling with its loading direction indicated by the red arrow. After executing the solution, it is possible to extract the desired results.

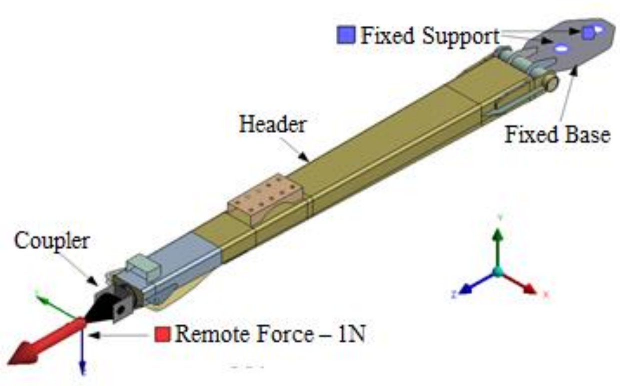

Figure 7 – Static structural analysis.
Source: Authors, 2020.

For experimental measurement of cyclic loading, HBM's MGC Plus data acquisition unit was used with a self-made pin type load transducer, mounted at the articulation point between the header and tractor drawbar coupling. Figure 8 indicates the location of the load transducer assembly and the transducer itself.

Figure 8 - Load transducer mounting location.
Source: Authors, 2020.

Data acquisition was performed in the field under normal operating conditions, and a second signal was collected on the test track of Stara, the component manufacturer.

Figure 9 shows the both collected traction strength signs. In both cases, the machine had a maximum load and travel speed of approximately 15 kilometers per hour, with the signal being collected for 400 seconds at an acquisition rate of 50 Hertz.

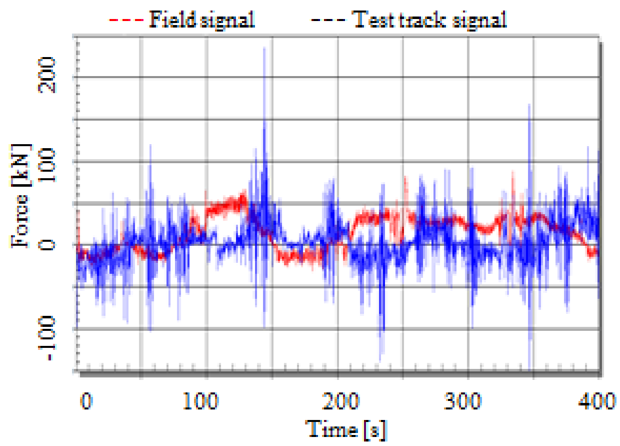

Figure 9 - Signals acquired in field and test track.
Source: Authors, 2020.

With a model available to representing the level of stresses acting on the header and having field and test track loading, it is possible, with the aid of fatigue calculation software, to determine the representative damage of each signal and the respective component life.

The structural analysis result file evaluated with a unit loading is combined to data collected from the load multiplying factors in the time domain (field signal and test track signal), and the calculation of fatigue damage and life is performed in different application scenarios. This assessment allows the engineer to evaluate the durability of the structure facing different operating conditions.

RESULTS AND DISCUSSION

Figure 10 shows the distribution of maximum principal stress in the model with the unit load. This result is given as input for the calculation of fatigue life and damage.

The frontal region of chaser bin is, by prior knowledge, the region that presents the greatest concentration of loads and where occurs the tendency to fail due to fatigue. The prior evaluation through the finite element model presents the same results direction. Thus, the evaluation of welding fatigue is focused in this geometric portion, specifically in the two beads that connect the transmission axis in the tip of the header.

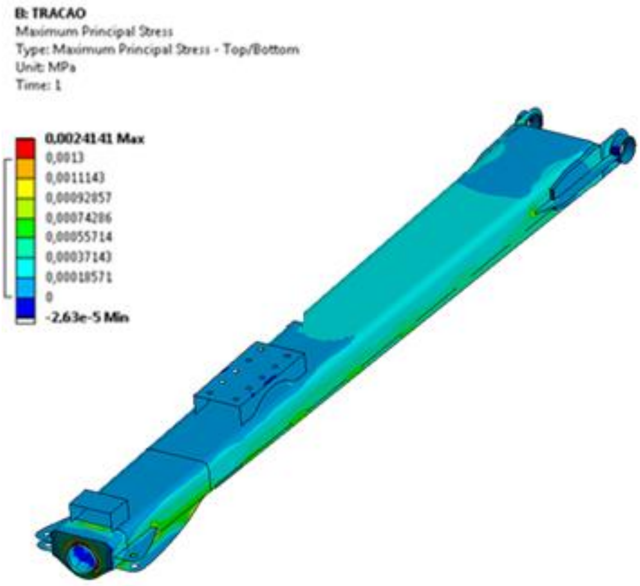

Figure 10 – Maximum principal stress.
Source: Authors, 2020.

The fatigue analysis procedure includes the recognition of the results file from Ansys Workbench Mechanical, by importing the rst file to the interface in Ansys nCode. Also as input data, the collected signals are imported and converted to an s3t format (Figure 11). The data combination is performed directly by the solver that uses the Volvo-Chalmers criteria as correlation to calculate the accumulated damage. The user must also inform the representative geometries of the weld beads to evaluate the regions adjacent to them.

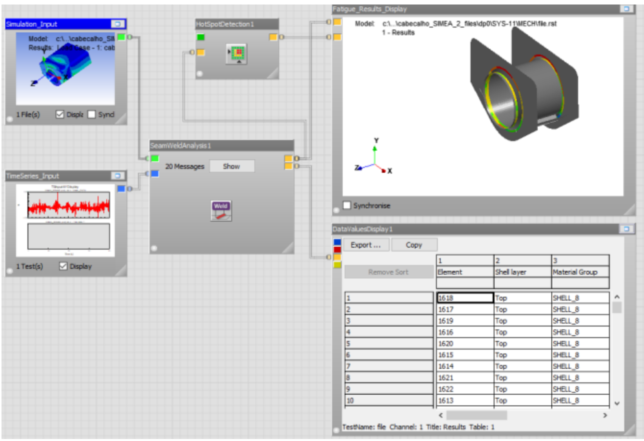

Figure 11 - Graphical interface for processing fatigue analysis.
Source: Authors, 2020.

Figures 12 and 13, presented next, graphically demonstrate the fatigue life of the header welded region when submitted to the test track signal and the field signal. The red region shows the minimum fatigue life response verified. The structure submitted to the test track signal indicates a minimum life of 6,180 cycles, while for the field signal the minimum life is 247,100 cycles.

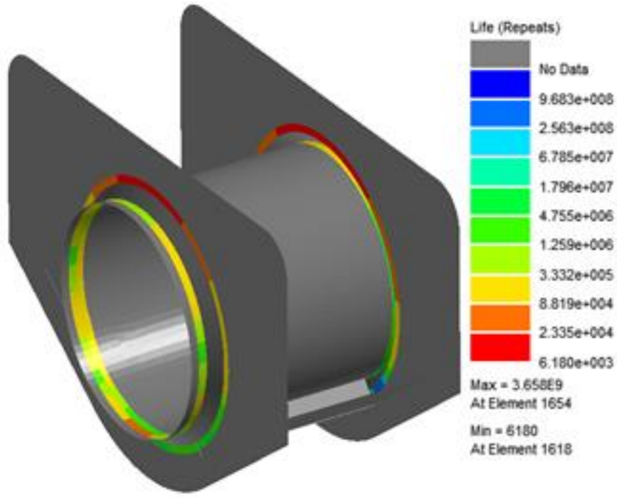

Figure 12 - Fatigue life of structure subjected to the test track signal.
Source: Authors, 2020.

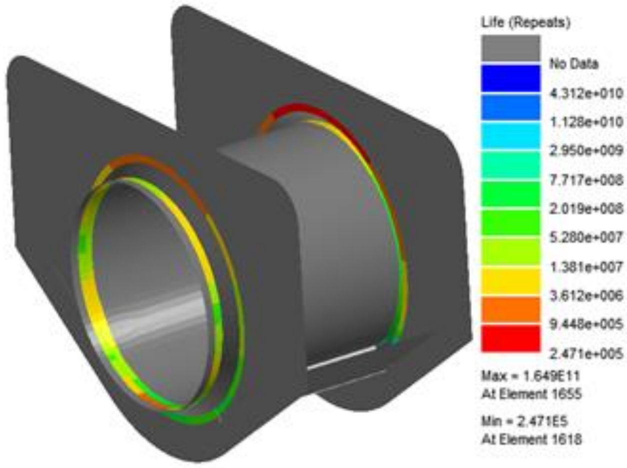

Figure 13 - Fatigue life of structure subjected to the field signal.
Source: Authors, 2020.

It is important to note that, since the signal lasts 400 seconds, the life calculated in both scenarios is a multiplicative representation of the number of cycles to which the component is subjected. For an assessment of life as a temporal condition, the number of cycles must be multiplied by the signal acquisition interval, in this case, 400 seconds. Thus, it is possible to estimate the header fatigue life on the test track at 687 hours, while for the signal in the field, it is 27,444 hours.

The fatigue analysis also allows the assessment of the accumulated damage in the two applied signal scenarios. For the test track a damage of 4.04e-6 is calculated, while the field signal shows an accumulated damage of 1.62e-4. This evaluation indicates that the test track is 40 times more severe than the field, thus allowing an accelerated physical test of the header.

Following the minimum fatigue life demand in 10,000 hours of service for the header, it is possible to dimension the test time on the test track in order to speed up the physical evaluation of the equipment. Figure 14 shows the correlation between the results.

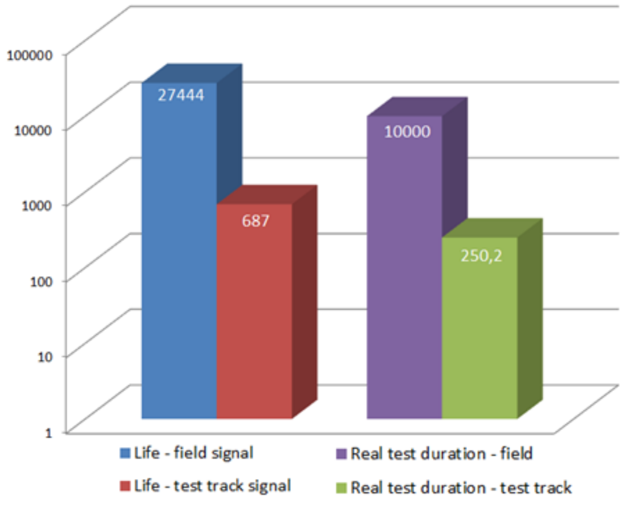

Figure 14 - Fatigue life and real test duration.
Source: Authors, 2020.

The damage correlation of the test track and field signals allows us to establish a test demand of 250.2 hours on the Stara test track to represent the damage related to the life of 10,000 hours of field work in the respective header. This evaluation corresponds to 2,252 test cycles within 400 seconds of the evaluated signal.

CONCLUSION

The Volvo-Chalmers methodology for assessing weld fatigue is efficient in approaching agricultural equipment, since it encompasses the vast majority of components produced basically by medium and low thickness plates. In addition, the use of specific S-N curves makes the evaluation process simpler and faster, reducing the demand for specific fatigue tests for each material tested.

The critical points of life in fatigue verified in the virtual model are aligned with the verified in the physical model, which represents an excellent numerical correlation of the proposed problem. This approach also encourages the evaluation of different welded structures that are not part of what was initially proposed in this scope.

The damage correlation of the test track and field signals gives an indication of the demand required for the physical test in number of cycles. These data are important for the correct representation of the damage verified in operation to the test run of Stara. For the analyzed component, this correlation is an order of 250.2 hours of track test for a life of 10,000 hours of field work.

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