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A HYBRID MODEL OF STRESS-LIFE AND STRAIN-LIFE FATIGUE USED TO PREDICT HIGH POWER ELECTRICAL ROTATING MACHINES FAN FATIGUE DAMAGE.

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Abstract. High power electrical rotating machines are generally designed with one or more fans assembled directly on its shaft to force air to cool down its core. It is common the usage of fans with elevated peripheral speed due to large dimensions of the machines or to high angular speed of the electrical motor or generator, this generates high stress on the weld notch and tip of the blade. Because of that, fatigue damage on high power electrical rotating machines fan blade is crucial to perform their design to ensure reliability to operate on a predetermined number of cycles. However, due to its complex geometry multiple zones are subjected to critical loads, these loads generate notch stresses where there are welds and high strains in the tip of the blades and the weld root. Therefore, a hybrid model is proposed to evaluate the damage of a stress-life fatigue method coupled with a strain-life fatigue method. In order to validate the method under study, rolled carbon steel AISI 1020 mechanical properties were obtained using the software Granta®. A prototype was used in test conditions to predict the failure mechanics of the tip of the blade, and a comparison to the separated methods was used to validate the technical feasibility. The stress life fatigue used in the weld gives a conservative view of the component life and the strain-life method alone is feasible if the weld has a high safety factor. The coupled method provides a bolder predication on high stress and strain near the weld notch where high stress and strains are present.

Keywords: Fatigue, Failure analysis, Electrical rotating machines

1. INTRODUCTION

Electrical rotating machines generate a considerable amount of heat in their core due to electrical losses in the copper winding or squirrel cage and mechanical losses, such as vibrations and bearing friction. Because of this, a fan is usually needed to cool down the core. High-power machines are larger in dimensions compared to lower-powered ones. They have more heat to dissipate; for this reason, the fan becomes larger, the peripheral speed of the blades becomes a critical factor in the design, and usually, the geometry of the fan is complex and has many notches to evaluate (Tong, 2014). There are multiple design choices for the rotating machine's fan, from injected polymer or cast aluminum to welded steel sheet. But when it comes to a custom ordered machine, making an aluminum casting mold or an injection mold becomes economically unattractive, so the preferred choice is a steel welded sheet. Because of that, some problems must be solved. The slenderness of the blades must be well-designed for their mechanical integrity, the backplate must also resist the load generated by the blades, and the fan must have a fatigue life above of what the machine is designed to operate. So, the fan must resist the fatigue damage at the tip, because of the high peripheral speed, and at the weld, because of the notch stress and weld defects.

Numerous fatigue assessment methods have been developed to evaluate the lifespan of structures and components under loading. Today, most fatigue assessments are made using finite element analysis (Pountiainen and Marquis, 2006). "The most common method is the stress-life (S-N), which was the first method used to predict the life of metals and is still used for components where stress is applied within the elastic range (Bannantine, 1989). However, when there is a significant plastic strain, the S-N method is not very applicable, and a strain-life (e-N) approach is recommended (Mitchell, 1987). There are others fatigue assessment methods, but they are for already initiated cracks for short or long cracks (Fricker, 2002). Figure 1 shows the different parameters (loads) to the method of fatigue life assessment.

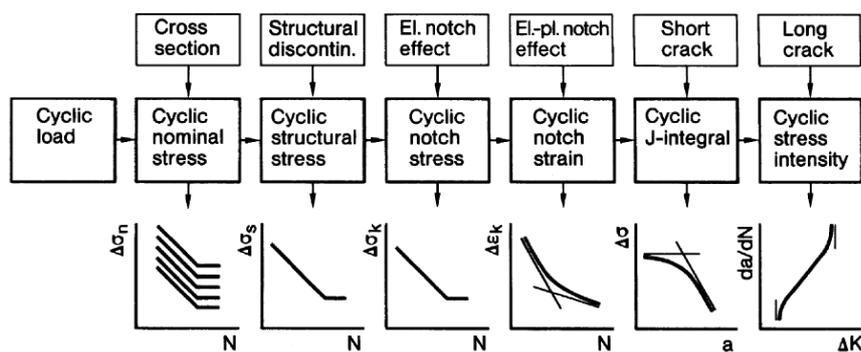


Figure 1 - Approaches for description of the fatigue strength and life (Fricker, 2002).

The strain-life method is based on the observation that, in many components, the material's response at a critical location (notches) depends on strain or deformation. Because the stress-strain response to strain at low loads is linear, as a consequence, in this range, load-controlled and strain-controlled tests are equivalent. So, at high load levels, or, better called, low cycle fatigue, the cyclic stress-strain response is best modeled under strain-controlled conditions. Therefore, at high load levels, often referred to as low-cycle fatigue, the cyclic stress-strain response is best modeled under strain-controlled conditions. Another observation is that the strain at a notch behaves similarly to a polished sample in a uniaxial stress test, as shown in Figure 2 (Bannantine, 1989).

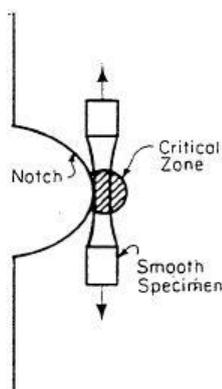


Figure 2: Notch effect (Bannantine, 1989).

Weld fatigue has become very important in the industry, especially in the automotive, which there are methods for estimating the weld fatigue at these industries (Rupp, Störzel and Grubisic, 1995). Normally, the fatigue method for welds is based on crack initiation and crack propagation and this method depends on a lot of factors such as material properties, weld geometry, and welding defects, and in thin sheet structures the fatigue life is mainly given by the strength of the joint (Nykänen, 2016, Fermér, Andréasson and Frodin, 1998). Other factor is that welded structures have steeper S-N curves than a flexible joint (Fermér, Andréasson and Frodin, 1998).

One simple way to calculate weld fatigue is through nominal stress, which involves calculating the stress in the sectional area while disregarding the local stress-raising effects and comparing it directly to stress-life curves created under the same circumstances. However, when there is no clearly defined nominal stress due to complicated geometric effects, another method must be employed.

Figure 3 (Hobbacher, 2016) shows the difference between the nominal, hot spot structural stress and the notch stress.

A problem with weld fatigue is due to the difficulties in representing the singularities of the weld. Finite element modeling cannot directly provide the actual peak stress at the weld toe (Myung et al., 2010). Some standards offer fatigue curves and methodologies for assessing weld fatigue using finite element analysis. The most commonly used standards include the recommendations for the fatigue design of welded joints and components from the International Institute of Welding (IIW) (Hobbacher, 2016), the British Standard BS7608 guide for fatigue design and assessment of steel products (BS7608, 2015), Eurocode 9 (Eurocode, 1998), and DNVGL-RP-C203 for the fatigue design of offshore steel structures (DNV, 2016).

These methods are divided into four categories. The first method is nominal stress, which represents the stress from the FEM analysis excluding the geometric effect of the notch. The second is the hot spot stress, which is the maximum stress obtained by linear extrapolation to the weld toe. This approach is typically used for fatigue-resistant welds (Myung et al., 2010). The third is the notch stress, in which the weld is modeled with a radius at the weld to eliminate singularities.

The last method is a crack initiation method, where it is assumed that a crack already exists due to the welding processes. There is a tradeoff when analyzing the weld with each method. In general, the more mesh-insensitive the method is, the harder it becomes to model. As the hot spot structural stress method uses a less refined geometry and compensates for it analytically, the mentioned standards may offer ways to determine the hot spot stress, but they can differ in various aspects.

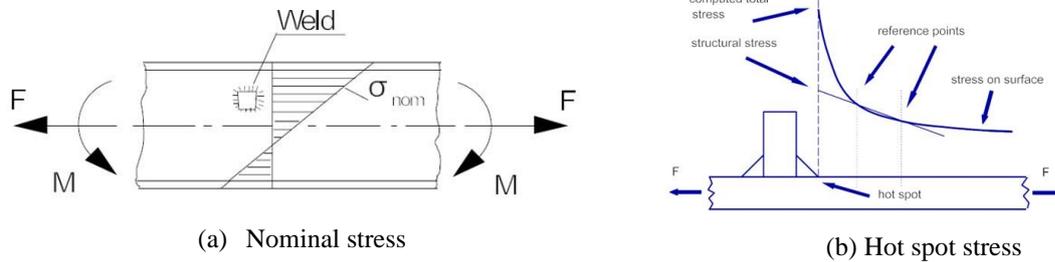


Figure 3: Nominal and hot spot structural stress on a welded component (BS 7608, 2015).

Regarding mesh requirements, the DNV standard is very strict, requiring 8-node elements of a cube with half-thickness (t) of the welded plate on each side of the cube. This method can be challenging to implement in FEM because it is not always possible to create such elements. The BS 7608 (2015) and the IIW standards (Hobbacher, 2016) are similar in terms of meshing. They offer two extrapolation approaches: linear and quadratic. In both, there is a fine mesh method and a coarse mesh method, making it easier and more flexible to use these approaches (Figure 4). A compilation of standards used on industry is shown on Table 1.

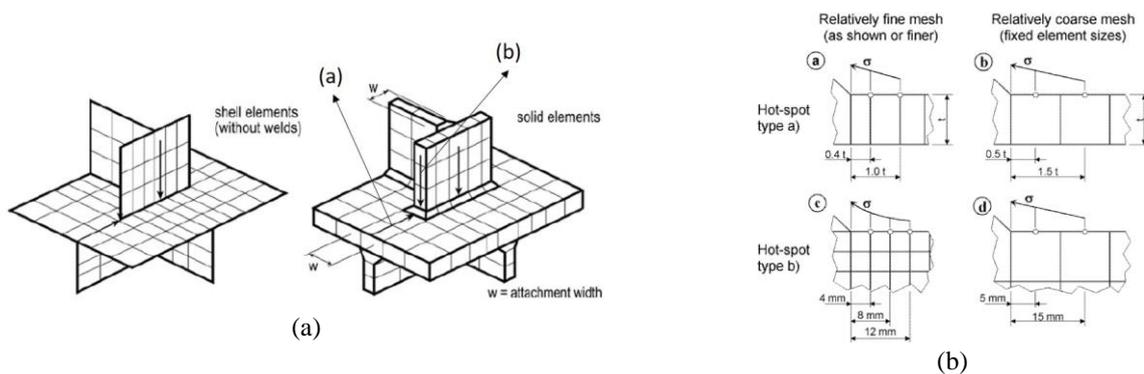


Figure 4: Structure hot spot method (a) Typical mesh for weld analysis, (b) extrapolation method for hot spot stress (Hobbacher, 2016).

Other papers propose different methods for fatigue analysis in weld. Dong (2001) rightly points out that the readily available and widely used methods in the industry, such as hot spot stress and nominal stress, cannot accurately calculate nominal stresses and stress concentration factors because they strongly depend on element size. Dong (2001) proposes a method to calculate structural stress using equilibrium equations through the thickness near the weld notch, creating a mesh-insensitive approach for analyzing weld behavior.

Ratiainen et al. (2021) proposes a traction fatigue assessment for complex structures with the motivation that shell methods proposed by standards overestimate the weld life. He propose a method that calculates the fatigue life based on traction stress at the weld root. Vantadori et al. (2020) use the hot spot method combined with a critical plane approach to estimate the weld life on a random vibrational context, Its novelty lies in the use of the hot spot method for non-proportional loading. The so-called Volvo method (Fermér, Andréasson, and Frodin, 1998) is very popular in the industry, especially in the automotive sector. Its motivation is to provide a method that is not very sensitive to mesh and can be used with a coarse mesh. The method assumes that most cracks initiate at the weld toes. Therefore, by using the normal stress perpendicular to the weld line, it calculates the total stress by summing the normal and bending stresses along the line. Its popularity is due to the application on the nCode software.

When considering these criteria and S-N curves for low alloy steels, such as cold-rolled AISI 1020, the fatigue properties of the weld perform better in low-cycle fatigue, but as the number of cycles increases, the base material exhibits better behavior. Because of this, a hybrid method that can be reused for various designs is proposed to meet these criteria.

Table 1: Comparison of weld fatigue analysis on most common standard.

Weld method	Observation	Mesh sensitive
IIW (International Institute of Welding)	To evaluate the weld fatigue resistance, two methods are presented, the nominal stress and hot spot stress. The nominal stress uses empirically teste data to directly correlate the stress to life. The hot spot stress uses an extrapolation method to use FEA data to correlate the damage to the empirically data.	The nominal stress method is not mesh sensitive, but it is empirically tested for conditions that are not always met in real models. For the hot spot stress method, it can be more or less mesh sensitive, having some flexibility regarding the mesh, but still making a reliable extrapolation. A mesh criterion must be met to use the coarse or fine mesh method.
BS7608	Similar to the IIW standard, the BS7608 uses the two methods to evaluate the weld fatigue resistance of nominal and hot spot structural stress. But it gives a more detailed way of calculating stress through thickness of thick plates.	For the mesh sensitivity, it is the same as the IIW. But, when calculating the stress through thickness, brick elements must be made (hexa).
Eurocode 9	It does not have a FEA specific method to calculate fatigue life, it uses nominal stresses and empirical data.	It is not applicable, since it has no hot spot method, so no direct FEA method is used in this standard.
DNVGL-RP-0005	Specific for offshore structures. It has corrosion correction, and air and salt water s-N curves. For finite element analysis it has a same approach as IIW and BS7608.	It has no mesh flexibility; the standard recommends only one type of modelling. And no 3D method is proposed.

Table 2: Comparison of weld fatigue analysis on recent papers.

Weld method	Observation	Mesh sensitive
Dong (2001)	Equilibrium near the weld using through thickness stress distribution.	It is somehow mesh sensitive near the notch, the equilibrium should minimize or eliminate the mesh size sensitivity.
Rautainen (2021)	Uses equilibrium on the welded component to retrieve nodal forces and momentum. With this force a nominal weld stress is calculated.	Since it uses nodal forces and momentum, it needs a continuum mesh on the weld toe line and weld root line.
Vantadori et. Al (2020)	Uses the hot spot structural stress method on a random vibrational loading of a real component under complex environment. Because of that it needs a critical plane approach to estimate the life of the component.	It has the same mesh size sensitive of the BS7608 and IIW standards, since it uses the same extrapolation method.
Fermér, Andréasson and Frodin, (1998)	Uses also nodal force to calculate the balance of the weld and decomposes the stress (on membrane and bending stress) and calculates the normal equivalent to the weld toe, since, according to the author, it is the most common crack initiation location on the weld components.	Not so much mesh size sensitive, it accepts coarse mesh.

There are papers that use low cycle fatigue for rotating machinery, including turbines subjected to high temperatures. Zhu et al. (2017) tested combined cycle fatigue under four load-controlled parameters, including high-cycle stress amplitude and frequency, as well as low-cycle stress amplitude and frequency. Zhu et al. (2017) explained that the amplitude coming from vibrational loads is relatively small (falling below the endurance limit), and it does not accumulate

damage on the turbine blades. So, the damage accumulated on these turbines in the high-cycle fatigue (HCF) is caused by in-flight vibrations. Azeez et.al (2019) used the strain-life method to predict the life of a steel turbine operating at high temperature to evaluate the low cycle fatigue combined with creep mechanism, Yue et. Al (2021) used a threshold damage method under combined high and low cycle fatigue to predict the life of turbine blades. for high cycle fatigue, the aerodynamic induced vibrations and the low cycle fatigue was due to centrifugal forces generated at certain rotations. Most of papers uses the Miner's rule (Eq. 1) to count the cycles.

$$D = N \left(\frac{n_{HCF}}{N_{HCF}} + \frac{1}{N_{LCF}} \right) \quad (1)$$

Even though there are methods in the literature for predicting the life of a weld using stress-life fatigue, no generalized method exists for welds and components that are subjected to different stress states throughout the component. Furthermore, to allow for a more flexible design, more sophisticated methods of fatigue must be employed. This paper presents a hybrid method to predict the damage of a component using the strain-life method in areas where the strains are higher and the stress-life method in areas where there is a weld notch.

2. METHODOLOGY

In order to validate the hybrid method, four fans (Fig. 5) were first analyzed numerically, and then prototypes were field-tested. The numerical test was conducted using 50,000 rotations at nominal velocity and 1,000 rotations with a 20% increase above nominal velocity. The field test involved using a fan on a machine operating at 20% above the nominal velocity of the fan.

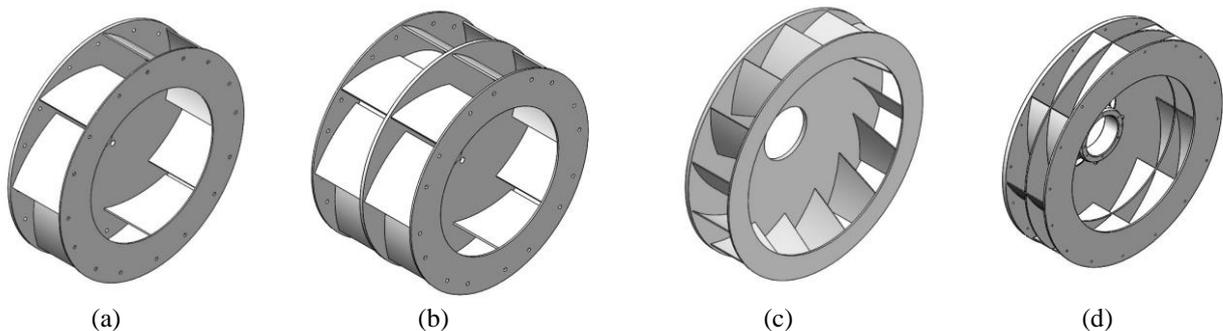


Figure 5: Fans studied.

To evaluate the models numerically using finite element analysis with Ansys® (Ansys® 2022:R1), two things were done. First, biaxiality was evaluated to determine whether a critical plane approach is necessary for using the strain-life method. Second, the appropriate curve for evaluating the weld according to the BS7608 standard for the hot spot method of extrapolation on surface meshes was checked. The BS7608 standard recommends that, if the weld experiences normal forces that deviate more than 45 degrees from the normal to the weld, a correction factor must be applied to account for biaxiality.

Two considerations were taken into account for this study. The first consideration is that the aerodynamic loads' vibrations are low enough to be less than the endurance limit of the materials, so they are not considered in the analysis. The second consideration is that a damage threshold was established to determine whether local damage was higher in the weld or in the base metal. In other words, since the damage threshold varies from component to component, it is necessary to confirm which component part is the limiting factor (either the weld or the base metal) to determine which fatigue curve (stress-life or strain-life) will be used. The logical flow of the damage is shown in Figure 6, and the results for both methods are displayed in Figure 7.

Next, the cumulative damage (D) done on each cycle was calculated using Miner's rule. According to this rule, the strain-life curve of the base metal is used for low-cycle fatigue, and for high-cycle fatigue, the s-N curve of the weld is employed, as shown in Equation 2. Here, n_{HCF} represents the number of high-cycle fatigue cycles to which the component is subjected, N_{s-N} is the life of the weld at the stress level of the high-cycle fatigue, N_{e-N} is the strain life of the base metal at that strain level, and n_{LCF} is the number of low-cycle fatigue cycles.

$$D = N \left(\frac{n_{HCF}}{N_{s-N}} + \frac{n_{LCF}}{N_{e-N}} \right) \quad (2)$$

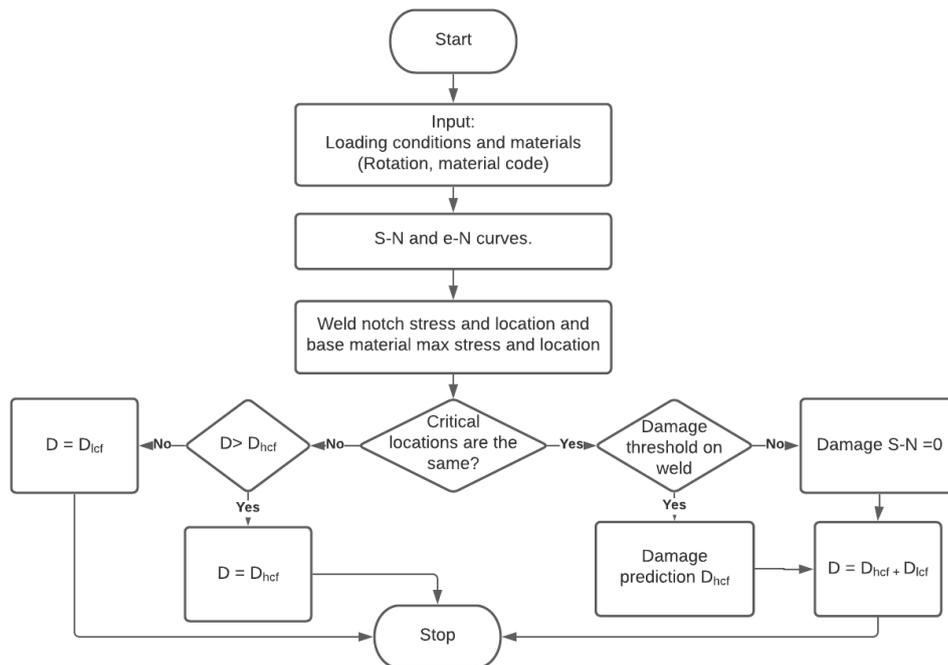
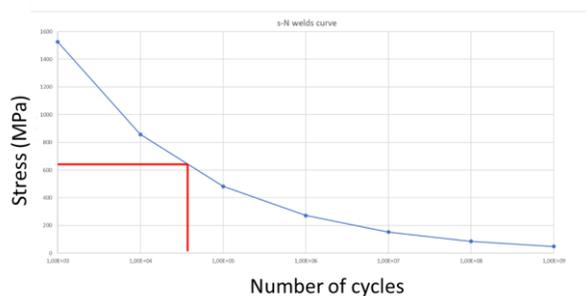


Figure 6: Flowchart for the combined model.



(a) Life on a stress-life curve



(b) Life on a strain-life curve

Figure 7: Life on stress-life on weld and strain life on base metal.

Even though there is a proportional loading, due to the complex notch in the weld, an evaluation of biaxiality was conducted to assess the necessity of a critical plane analysis. At the hot spots, the value was considered low enough to employ a uniaxial approach, with biaxiality not exceeding 0.5 near the weld on the first fan, for example. Figure 8 displays the biaxiality factor at the critical spot of the first fan.

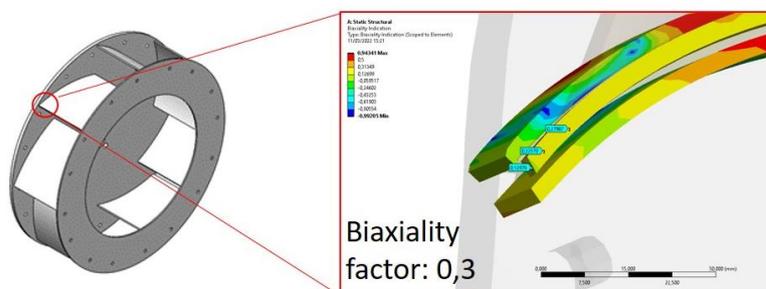


Figure 8: Biaxiality factor of the first fan.

The base material used was carbon steel AISI 1020. Table 3 presents the chemical composition and the minimum values of mechanical properties for carbon steel AISI 1020, as rolled, obtained from Granta® software (Granta Selector 2022 R1 Version: 22.1.1). The area reduction and fatigue properties from Table 4 were extracted from the ASM Handbook (ASM International, 1993).

Table 3: Chemical composition and mechanical properties retrieved from Granta®.

AISI 1020					
	C (%)	Fe (%)	Mn (%)	P (%)	S (%)
	0.17 – 0.23	99.1 – 99.5	0.3 – 0.6	0 – 0.04	0 – 0.05
Young's Modulus	Yield Strength	Tensile Strength	Strain	Poisson's Ratio	Area Reduction
205 GPa	295 MPa	395 MPa	28%	0.285 – 0.295	64%

Table 4 - Fatigue properties

Fatigue properties (strain life parameters)					
Strength Coefficient	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient	Cyclic Hardening exponent
834 MPa	-0.114	0.169	-0.453	1482 MPa	0.29

(Ansys Granta® Selector, 2022; ASM International, 1993).

The IIW hot spot method was used to evaluate stress on the four fans (as shown in Figure 5), at both the edge and the surface plate. For the stress-life curve used in the hot spot structural stress, a weld classification of F2 from the BS7608 standard was employed. Additionally, stress analysis was conducted on the weld toe using the extrapolated results. Table 5 presents the parameters used during the numerical analysis of these four fans.

Table 5: Parameters for simulations

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Element size (mm)	1.675	2.125	2.125	2.125
Plate thickness (mm)	3.35	4.25	4.25	4.25
Machine nominal rotation (rpm)	3600	1800	1800	1800
Weld dimensions (mm)	4	4	4	4

3. STRESS AND FATIGUE DAMAGE ACQUISITION

The points used for extrapolating the structural hot spot stress are shown in Table 6. This extrapolation estimated the damage due to weld fatigue for 50,000 cycles at nominal speed and for 1,000 cycles at 20% over nominal speed. The corresponding damage, as calculated in Table 7, was determined using the weld classification of F2 and Miner's rule for damage accumulation.

Table 6: Von misses stresses at the weld.

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Nominal speed (50,000 cycles)				
Node 1 (edge, MPa)	309*	130	666*	172
Node 2 (edge, MPa)	317*	131	687*	174
Extrapolation (edge, MPa)	325*	132	688*	176
Node 1 (plate, MPa)	340*	105	585*	127
Node 2 (plate, MPa)	341*	106	587*	129
Extrapolation (plate, MPa)	342*	107	589*	131
1.2 x Nominal speed (1,000 cycles)				
Node 1 (edge, MPa)	421*	206	1037*	269
Node 2 (edge, MPa)	431*	208	1063*	272
Extrapolation (edge, MPa)	441*	210	1089*	275
Node 1 (plate, MPa)	481	187	809	199

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Node 2 (plate, MPa)	483	189	810	201
Extrapolation (plate, MPa)	484	191	812	203

*These values were obtained under a linear elastic finite element. It was used a Neuber correction to calculate an equivalent stress and strain to estimate the fatigue damage. And the plasticity model for an isotropic hardening was the Ramberg Osgood for cyclic stress the material parameters for that correction are listed on the Table 4. That means that the true stress and strain, when considering the plastic strain, are far below this value.

Table 7: Damage at the weld.

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Nominal speed (50,000 cycles)				
Damage (edge)	1,2	0,03	2	0,6
Damage (plate)	1,5	0,02	1,93	0,33
1.2 x Nominal speed (1,000 cycles)				
Damage (edge)	0,1	$1,5 \cdot 10^{-3}$	0,2	0,01
Damage (plate)	0,12	$1,3 \cdot 10^{-3}$	0,17	0,007

The strain-life method was used for the steel sheet to estimate damage at the weld toe and blade tip, utilizing the fatigue properties from Table 4. The chosen damage combination method was the maximum principal stress since a critical plane approach was not considered necessary due to the low biaxiality at the notch, as demonstrated in the example shown in Figure 8. Additionally, a Morrow mean stress correction was applied for the strain-life approach, while a Goodman mean stress correction was used for the hot spot structural stress.

Table 8: Damage on the weld toe and blade tip.

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Nominal speed (50,000 cycles)				
Stress weld toe (MPa)	362	130	873	174
Stress blade tip (MPa)	723	180	160	116
Damage on the weld toe	0,75	$3,9 \cdot 10^{-4}$	1,75	0,013
Damage on the blade tip	2,53	$5 \cdot 10^{-5}$	0,5	0,0005
1.2 x Nominal speed (1,000 cycles)				
Stress weld toe (MPa)	493	206	1364	272
Stress blade tip (MPa)	984	280	280	183
Damage on the weld toe	0,15	$2,6 \cdot 10^{-2}$	0,25	0,002
Damage on the blade tip	0,22	$3,5 \cdot 10^{-6}$	0,02	0,0005

Then, the combined method proposed in 'Eq. 2' and Figure 6 was employed to predict the damage of the fan. This combined method shares similarities with the approaches put forth by Zhu (2017) and Azees et al. (2019). However, the key distinction lies in the fact that they deal with aerodynamic vibration, which introduces a low load that justifies their proposed methods. In contrast, Azees (2019) employs a non-linear damage count method distinct from Zhu (2017). The method presented in this paper is justified by the challenge of measuring the e-N curve on weld toes accurately. Instead, empirical curves are used on the toes and subsequently combined through a threshold method.

4. APPLIED METHOD

The tests were conducted to verify the failure modes of the fan, as depicted in Figure 9, where point A represents the weld notch, and point B is the blade tip. Among the four fans tested, the first and third fans exhibited high strain at the blade tip (point B) and the initiation of cracks at the weld notch (point A). However, only fan number three was deemed to have failed during the field test.

The constitutive model used was the isotropic elastic model and the number of elements the four fans as shown on the Figure 5 were:

- Fan a: 24132 Elements
- Fan b: 32135 Elements
- Fan c: 25412 Elements
- Fan d: 34405 Elements

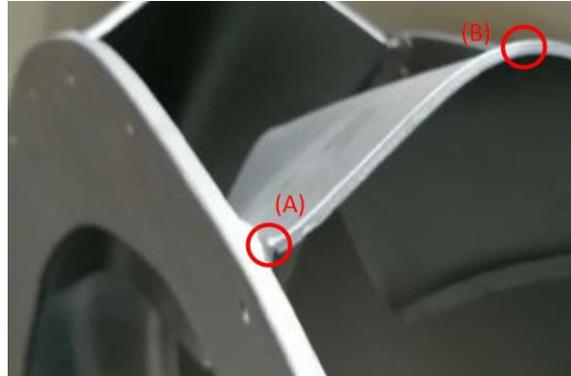


Figure 9: Field test of fan number three.

So, by employing the proposed method to determine the optimal way of evaluating the fan's lifespan, the data from Tables 5 and 6 were combined, as illustrated in Table 7.

Table 9: Structural hot spot and strain life damage.

	Fan (1)	Fan (2)	Fan (3)	Fan (4)
Nominal speed (50.000 cycles)				
Extrapolation method (Weld)	1.2	0.03	2	0.6
Extrapolation (plate)	1.5	0.02	1.93	0.33
Damage weld toe (strain-life)	0.75	$3.9 \cdot 10^{-4}$	1.75	0.013
Damage fan tip (strain-life)	2.53	$5.00 \cdot 10^{-5}$	0.5	$5 \cdot 10^{-4}$
Highest damage	2.53	0.03	1.93	0.6
1.2 x Nominal speed (1,000 cycles)				
Extrapolation method (Weld)	0.1	$1.5 \cdot 10^{-3}$	0.2	0.01
Extrapolation (plate)	0.12	$1.3 \cdot 10^{-3}$	0.17	$7 \cdot 10^{-4}$
Damage weld toe (strain-life)	0.1	$2.6 \cdot 10^{-3}$	0.2	0.002
Damage fan tip (strain-life)	0.22	$3.5 \cdot 10^{-6}$	0.02	$5 \cdot 10^{-4}$
Highest damage	0.22	$2.6 \cdot 10^{-3}$	0.2	0.002

The results from the finite element analysis predicts the behavior of the field tested fans. The fans one and two had very high damage, representing failure if they were subjected to the condition of 50,000 cycles at nominal speed. However, the weld actually didn't interfere on the damage accumulation, when the fan is subjected to static load or even very low fatigue. As it happens at the field tests with velocity 20% above the nominal. Thus, the geometric effect of the notch was the only responsible for the stress raising near the weld, but the limit is usually reached at the base metal. The steep s-N curve for weld is the responsible for this behavior, at low cycles, it behaves similar to the base metal but, at high cycles, it severely drops the fatigue resistance of the component.

Another important result is the damage at the fan tip. For fans with long blades, this presented a more significant issue because the strain experienced at that location was of a high magnitude, and low-cycle fatigue failure was anticipated. For instance, in the case of fan number one, the damage was more pronounced at the blade tip, and consequently, high damage was expected.

5. CONCLUSION

A well-designed fan for electric machines can achieve reduced noise, lower temperatures at the core, and lighter machines. That's why lighter fans are crucial for machine designs. In this regard, the hybrid method proposed for fan designs to make more accurate damage predictions has been successful in predicting the damage of fans that operate under extreme load conditions.

During numerical analysis, only the fan number three was considered to fail under the field test. So, some conclusions could be made. First, even though the fan tip works on a high damage on a strain-life method, meaning that there is high probability of a crack nucleation but the lack of a notch effect doesn't potentialize the crack propagation, and thus it is safer to work on the fan tip with higher damages for very low cycles, but attention must be made for higher cycle even though the fan number one didn't fail under field test, it operates on a high stress enough to fail under fatigue.

For future work, more powerful fans can be analyzed. Higher flow rates and pressures can generate significant aerodynamic vibrations that may have a considerable impact on the fan's lifespan. In the case of the four fans analyzed in this study, this factor had less significance because peripheral speed was the primary source of the load.

6. ACKNOWLEDGEMENTS

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