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Finite Element Method Analysis of a Mechanical Part

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Abstract

The development of projects through the use of computers for drawings, as well as the simulation of mechanical parts and components through the use of professional software, is today a fundamental premise in the mechanical industries, which increasingly value the potential of these programs both in terms of design and

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manufacturing. In this article, a CAD project was developed and the simulation of the part designed by the finite element method used the Siemens NX software, for this 3D sketches and 2D drawings were generated, the structural analysis was also carried out through the finite element method (FEM). During the entire process, certain logical sequences were followed for these types of applications, which made it possible to identify the most vulnerable points of the part and thus verify the limit of its robustness.

Keywords: Siemens NX; CAD; FEM.

1. INTRODUCTION

With all the advances in CAD techniques, software packages for computational mechanics have become frequent, enabling the user to perform not only the design (graphical representation of the project), but also simulations from generated models. When not, specific software that uses the finite element numerical method and/or the finite volume numerical method has as input models built with the aid of CAD software.

The general objective of this work is to develop the CAD design and perform the behavioral analysis in a virtual 3D environment of a mechanical part that is used in safety mechanisms through the use of Siemens NX software to understand the physical structural behavior of the same part under extreme loads. The procedures followed were documented in the methodology and the results obtained allowed us to affirm the advantages of using this software in CAD/CAD simulation in terms of time, human resources and costs savings.

2. THEORETICAL FOUNDATION

Mechanisms

According to (CHANG, 2020), a mechanism is a mechanical device that transfers motion and/or effort from a source to an output.

For (NORTON, 2010), a mechanism is a device that transforms any movement into a desired pattern and generally develops forces of low intensity imparts little power.

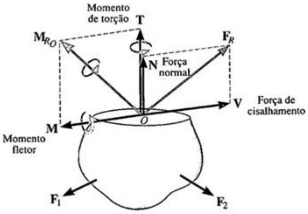
According to (FLORES; PIMENTA CLARO, 2005) the mechanical systems are the result of the combination of mechanical subsystems responsible for transmitting effort and motion from a source to an output. They are composed of rigid and/or flexible bodies connected by joints and requested by efforts or moments that can come from the action of springs, dampers or external forces to the system. The study of mechanisms is governed by the laws of classical (or Newtonian) mechanics, which deal with translation and rotation movements, and can be divided into three distinct and complementary areas. These are: statics, kinematics, and dynamics.

Resistance of materials

According to (HIBBELER, 2010) the strength of materials is a discipline of mechanics that studies the relations of external loads applied to bodies subject to deformation and the internal reactions caused. The studies involve the application of statics principles to determine the internal loads from external loads to the system. In order to determine the dimensions of the elements, their deflection, and their stability, it is necessary to understand the material's behavior and thus develop the equations used in strength of materials.

HIBBELER himself, (2010) exposes that the effects of efforts applied to a body generate 4 resulting forces and moments. They are: The normal force, which arises perpendicular to the section area and occurs when two parts of the body are compressed or tensioned in opposite directions; The shear force, which occurs in the plane of the section when two parts of the body slide against each other; The torsional moment, caused when external forces tend to twist the body; and the bending moment, caused when external forces tend to bend the body. The action of the resulting internal efforts on a certain point of the section area causes internal stresses that, in turn, cause the deformation of the body, as shown in Figure 1.

Figure 1 - Internal forces in a body.



Fonte: Hibbeler, 2005.

Source: Hibbeler, 2005

Tension

For (GRECO; MACIEL; DA SILVA ALMEIDA, 2019) stress is a quantity that represents relationships between internal stresses and surface dimensions in the particles of a deformable solid. The stress components are constructed by plots associated with the direction normal to a given plane and by plots associated with the directions in the very plane of the surface considered. To determine the concept of stress, one must consider the body as continuous, that is, it has a uniform distribution of matter, so one can see that a force acting on an area of the section varies proportionally to the variation of the area of the section. Thus, being **F** a resultant internal force acting on the area of the section as shown in **Erro! Fonte de referência não encontrada.**, when studying a fraction tending to zero of the cross-sectional area **(ΔA)** there is, acting on it, a fraction of **F (ΔF)** that also tends to zero, as well as its components in the x, y and z axes. The component **ΔFz** consists of the normal force that, when acting on **ΔA**, results in the normal stress (σ), as shown in the formula *(1)*.

$$\sigma_z = \lim_{\Delta A \to 0} \frac{\Delta F_z}{\Delta A} \qquad (1)$$

This stress σ_{zz} can be either compressive or tensile depending on the direction of the normal force.

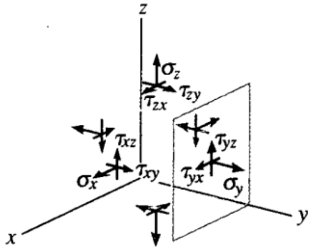
The shear stress, on the other hand, occurs when the components **ΔFx** and **ΔFy** act tangentially to the area fraction **ΔA**, as occurs in the formulas *(2)* e *(3)*.

$$\tau_{zx} = \lim_{\Delta A \to 0} \frac{\Delta F_x}{\Delta A} \tag{2}$$

$$\tau_{zy} = \lim_{\Delta A \to 0} \frac{\Delta F_y}{\Delta A} \tag{3}$$

If, besides the sections parallel to x-y, planes parallel to x-z and y-z are sectioned, a cubic element can be extracted that represents the state of stress acting around a chosen point of the studied body. Thus, one has, for each plane of the cube generated, the normal and shear stresses acting on the point studied. See figure 2.

Figure 2 - Stress state.



Source: Hibbeler, 2005.

Deformation

According to (SILVA; PANNONI, 2020), deformation is the change in shape of the structural element when subjected to a set of forces. The elements of substructures are differentiated as to the type of deformation suffered.

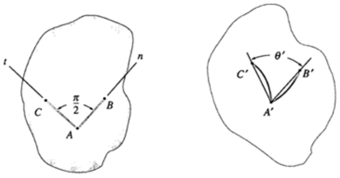
According to the author (HIBBELER, 2010), whenever a force is applied to a body there is a tendency of deformation that can be more or less visible to the naked eye, and in many cases only a measuring tool would be able to measure it. In practice, the measurement of deformation is done by means of experiments, from which it can be related to the applied loads or the internal stresses of the body.

Then, considering the Greek letter $\varepsilon_{méd}$ (epsilon) as the symbol of the average normal strain and that the length of the straight-line AB tends to zero, we have the formula *(4)*.

$$\varepsilon_{méd} = \lim_{B \to A \text{ eixo n}} \frac{\Delta s' - \Delta s}{\Delta s} \tag{4}$$

Conceptually, when the deformation acts by changing the angle formed by two straight lines (AB and AC), directed in the n and t axes, perpendicular to each other, it is called shear deformation. As shown in Figure 3.

Figure 3 - Shear deformation. In (a), undeformed body and in (b), deformed body.



(a) (b)

Source: Hibbeler, 2005.

The Greek letter designated to represent the angle is γ (gamma). After deformation the straight-line segments turn into curves, forming the angle θ'. Therefore, the equation that characterizes the shear deformation is given by the formula (5).

$$\gamma_{nt} = \frac{\pi}{2} - \lim_{\substack{B \to A \text{ eixo n} \\ C \to A \text{ eixo t}}} \theta' \tag{5}$$

Stress-Strain Diagram

The concepts that define normal and shear stresses and strains are widely applied in the development of mechanical system designs, both to define the design and arrangement of components in a mechanism, and to analyze the behavior of the complete system and/or of its individual parts.

According to (DE ALMEIDA, 2021) the properties of materials are obtained from mechanical tests, among which stands out the uniaxial tensile test. The tensile test is probably the most widely used in general terms, given its simplicity in relation to other tests available, as well as the amount of information provided about the mechanical behavior of a given material. This type of test uses standardized specimens, usually of circular cross section, in a testing machine that applies a progressive unidirectional load. As the load value increases, the specimen elongates until rupture.

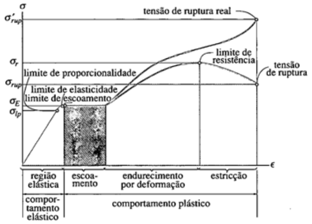
In these tests we obtain data regarding stress σ, found from the formula (6) (where P is the applied load and A_0 is the initial section area), and strain ϵ, found from the formula *(7)* (where δ is the length change and L_0 is the initial length).

$$\sigma = \frac{P}{A_0} \tag{6}$$

$$\epsilon = \frac{\delta}{L_0} \tag{7}$$

Relating stress and strain gives the stress-strain graph, shown in Figure 4. In the elastic zone, the material undergoes reversible deformations, i.e., it can still return to its initial state**,** and is limited by the **yield strength, σ_E**. In the yield zone, the material undergoes irreversible deformations, known as plastic deformations. By applying more load, the specimen moves from the yield zone to the strain hardening zone, where the length of the specimen increases while the cross-sectional area decreases. This phenomenon occurs uniformly until the yield **strength stress, σ_r,** is reached. From this point on, it goes to the yield strength zone, where the cross- sectional area decreases considerably in a specific point of the specimen, the phenomenon occurs until the yield **stress,** σ**rup** is reached.

Figure 4 - Stress-Strain Diagram for Steel



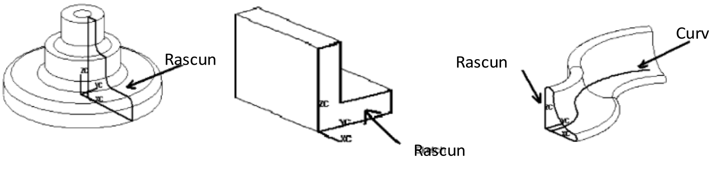
Source: Hibbeler, 2005.

CAD/CAM/CAE

According to (LEE, 1999) to maintain competitiveness today, industries must introduce new products with better quality, lower cost, and shorter delivery time. At the same time, the memory capacity of computers, processing speed, and user-friendly interfaces are evolving, integrating engineering and production activities, reducing product development and production time and costs.

There is a huge range of computer-aided engineering software. In mechanical engineering, specifically, there are three main ones: CAD; CAM; and CAE, the respective translations being: Computer Aided Design, Computer Aided Manufacturing, and Computer Aided Engineering. The diagram shown figure 5 shows the product development process.

Figure 5 - General shaping features. In (a), revolution feature, in (b), extrusion feature and in (c) scanning feature



Source: Ming C. Leu, 2019.

Computer Aided Design (CAD)

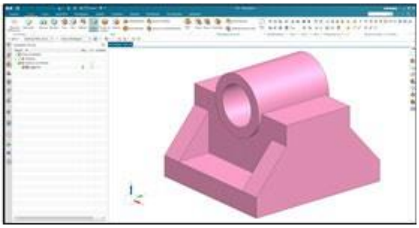
CAD is the abbreviation for computer-aided design, that is, any software that uses the graphic potential of the computer and presents functions that facilitate the design process. This software has geometric tools for manipulating shapes, as well as analysis and optimization programs. The most basic activity of CAD is to define the geometry of the design (both structural and parts), positioning of components (mechanical and electronic), and producing a 3D drawing in a virtual environment and the technical drawing for manufacturing by machining. The geometries created in CAD systems serve as a basis for further analysis using CAE and CAM functions. The greatest benefit of CAD is the ease in modifying the produced drawings (3D and 2D), allowing quick adjustments and improvements, reducing rework, resulting in the consequent reduction of time and costs related to project development.

The process for developing a new part in the 3D virtual environment of most CAD's begins with the sketch drawing, which consists of drawing straight lines and curves in an origin plane. At first without defined dimensions, but which can be added and modified at any stage of the project, facilitating adjustments and corrections. The drawing made will define the external limit of the object, forming the silhouette of the piece. From this point on, the shape can be extruded, revolutionized, or even "swept" along a curve, as shown in Figure 6. After the part gets its general shape, details are added through removal features, such as: drilling, tapping and cutting, and operation features, such as: chamfers, threads, mirroring, etc.

Once the 3D model of the part is ready, as shown in 6 , the technical detailing of the part begins, shown in

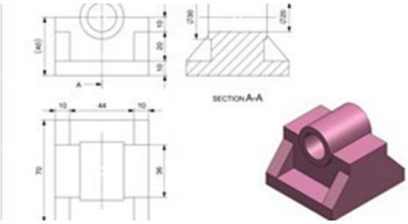
Figure 7, which is fundamental if the manufacturing process is machining. The technical detailing in CAD software always follows the standard of some international standard, and usually has templates for each type of sheet, but can be modified according to the user's preference. The technical detailing environment allows you to create dimensions, cuts, and highlight details, as well as specify surface finishes, detail assembly orders, and make tables such as the bill of materials (BOM).

Figure 6 - Example of a 3D part.



Source: Own authorship

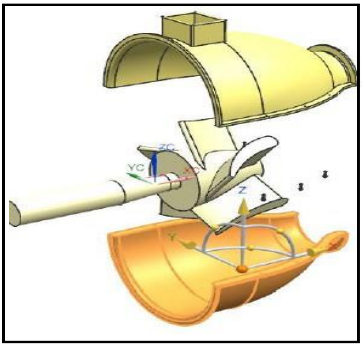
Figure 7 -Technical detailing of the part.



Source: Own authorship.

When all the parts of a mechanism or structure have been designed in the 3D virtual environment of the software, it is time to perform the assembly, shown in Figure 8, which occurs through constraints and movement relationships such as: coincidence of faces or concentricity between axes. This step allows the designer to identify and correct possible conflicts in the movement of the parts, in addition to determining the actual assembly process and the list of all materials needed for the project development.

Figure 8 - Exploded view of mounting on the NX.



Source: Ming C. Leu, 2019

F INITE ELEMENT METHOD (FME).

The first applications of FEM were in structural engineering problems, more specifically, stress analysis. In this type of problem, the goal is to determine stresses, strains and displacements in a solid body subjected to certain actions such as loads (applied forces) and settlements (imposed displacements). Examples of such applications include the study of the behavior of civil structures such as buildings, bridges, dams, and tunnels, where finite elements are used in the discretization of beams, slabs, trusses, walls, foundations, etc.

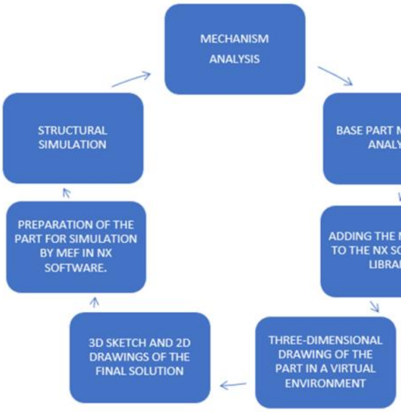
The study of stress analysis is also important in other areas of engineering, such as mechanical engineering, electrical engineering, naval engineering, etc. where analysis of the structures and mechanical parts of machines and equipment such as lathes, presses, automotive media like cars, trucks and others are required. Within the area of solid mechanics, static analysis and dynamic analysis can fundamentally be performed.

According to Alves (2013), FEM subdivides the continuous body into a finite number of parts (elements), connected to each other through discrete points, which are called nodes. That is, a discretized computational domain is created over the geometry to be analyzed.

3. MATERIALS AND METHODS

The mechanical component studied in this work is a tongue, a part that is projected out of its case and locked by an internal mechanism. First the kinematic and dynamic analysis of the mechanism's functioning was done, then the material it is made of was identified, then a 3D virtual environment replica was designed using the Siemens NX software, and finally, using the data found, the analysis was done using the finite element method in the same software. The steps for the analysis of the tongue are shown in the flowchart of Figure 9.

Figure 9 - Flowchart of the steps followed in this work



Source: Authors, 2022.

The process of adding a new material to the Siemens NX software library according to its functionality.

To perform the behavioral analysis of the tongue, it will be necessary to replicate the part in the virtual environment of the Siemens NX software. The process will be done by photo insertion of the part's image using the raster resource as shown in figure 10.

Figure10. Using the Raster Feature

Source: Siemens NX Software.

Finite element analysis in CAE software

Once you have the 3D drawing of the part in the Siemens NX virtual environment and the found material has been assigned to it, the finite element method will then be applied to the part.

4. RESULTS AND DISCUSSION

Study of the mechanism

The mechanism consists of a normally open micro solenoid actuator, a spring-loaded pawl locking piece, a spring-loaded cotter pin, a pawl, a spring-loaded pawl shaft, and a pawl return spring. The electronic lock has 2 working states: "Open" and "Locked". Each state results in different configurations of its components.

Analyze the base part material

Through the analysis performed with the help of the spectrophotometer machine, the chemical composition of the tongue alloy could be ascertained. The alloy has a metallographic conformation based on **Fe** with **73.93%**, **Cr** with **17.44%**, **Ni with 3.8%**, **C** with **0.02%**, **Mn with 0.22%**. According to its chemical composition it can be classified as a stainless-steel alloy of special type close to stainless steel **204** and **304**. Figure 11 shows the physical state of the tab after the tests.

In possession of the data obtained, a comparative analysis was developed between these and two materials with characteristics close to the mentioned steels.

Table 1. Comparative analysis of the materials.

Chemical composition in %	C	Cr	Fe	Mn	Ni
Value obtained by metallographic analysis	**0,02**	**17,44**	**73,93**	**0,22**	**3,8**
304 LN Austenitic Stainless Steel (UNS S30453) (%)	**0,03**	**19**	**67,97**	**2**	**10**
AISI Type 304L Stainless Steel (%)	**0,03**	**18**	**74**	**2**	**8**

Source: Own authorship.

Figure 11 - Image of the part after metallographic testing done on the spectrophotometer machine.

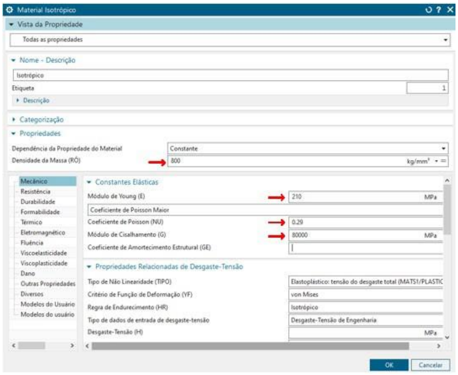
Source: Own authorship.

Adding the material to the software library

The Siemens NX software library includes some of the main materials used in the mechanical components production industry, including the 304 stainless steel that presents properties very close to the material found. However, for a more precise analysis, the new stainless steel 304L has been added to the library.

To create the new material within the software library, we followed the procedure described of this article and shown in Figure 12 e Figure 13. The following physical properties of the 304L steel taken from the MatWeb site were inserted. The density of **8000 [kg/m³]**; The Young's modulus of **210 [MPa]**; The Poisson Coefficient of **0.29** (common for steels); The shear modulus of **80 [GPa]** (common for steels); The yield strength of **210 [GPa]**; And the tensile strength of **564 [GPa]**.

Figure 12 - Insertion of the property's density, Young's modulus, Poisson's coefficient, shear modulus of the identified material.



Todas as propriedades

Isotrópico

Etiqueta 1

Dependência da Propriedade do Material Constante

Densidade da Massa (RÔ) 800 kg/mm³

Módulo de Young (E) 210 MPa

Coeficiente de Poisson Maior

Coeficiente de Poisson (NU) 0.29

Módulo de Cisalhamento (G) 80000 MPa

Coeficiente de Amortecimento Estrutural (GE)

Tipo de Não Linearidade (TIPO) Elastoplástico: tensão do desgaste total (MATS1/PLASTIC

Critério de Função de Deformação (YF) von Mises

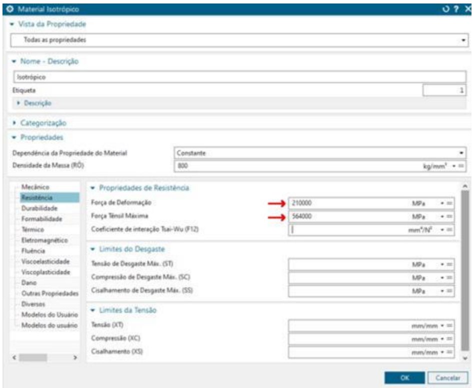
Regra de Endurecimento (HR) Isotrópico

Tipo de dados de entrada de desgaste-tensão Desgaste-Tensão de Engenharia

Desgaste-Tensão (H) MPa

Source: Own authorship.

Figure 13 - Insertion of the properties yield stress, and tensile strength of the identified material



Todas as propriedades

Isotrópico

Etiqueta 1

Dependência da Propriedade do Material Constante

Densidade da Massa (RÔ) 800 kg/mm³

Força de Deformação 210000 MPa

Força Tênsil Máxima 564000 MPa

Coeficiente de interação Tsai-Wu (F12) mm⁴/N²

Tensão de Desgaste Máx. (ST) MPa

Compressão de Desgaste Máx. (SC) MPa

Cisalhamento de Desgaste Máx. (SS) MPa

Tensão (XT) mm/mm

Compressão (XC) mm/mm

Cisalhamento (XS) mm/mm

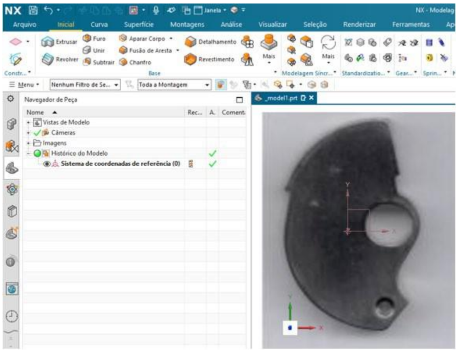
Source: Own authorship.

Three-dimensional design in a virtual CAD software environment

Knowing the behavior of the mechanism components and the tongue material, it was possible to make a 3D drawing of the tongue in order to submit it to analysis by the finite element method (FEM). The part has a complex geometry, which makes it difficult to measure its main measurements, so it was decided to import the part. See figure 14.

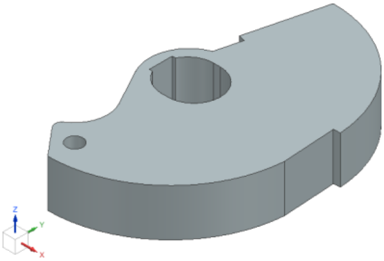
It was noted that the 3D drawing of the tongue presented a small difference from the real part, as shown in Figure 5. However, the differences did not imply any change in its functionality.

Figure 14 - Importing the tab photo into the NX 3D design environment.



Source: Own authorship.

Figure 15 - Geometric model of the tongue.

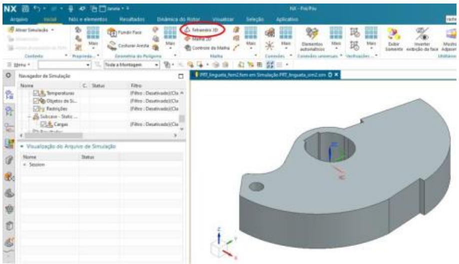


Source: Own authorship.

Preparation of the part for FEM simulation in NX software.

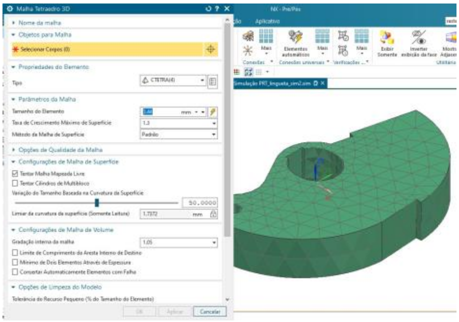
After designing the geometric model of the tongue and entering the material properties into the software library, to develop a simulation of the part regarding its structural behavior by the finite element method, using the simulation environment in the CAE part of Siemens NX. First, you must **define the type of mesh element**, shown in figure 17 shows the selected mesh in figure 16, and **the size of the mesh element, shown** in The NX already does this operation automatically. Figure 17 shows the selected mesh.

Figure 16 - Assignment of tetrahedral elements to the geometric model.



Source: Authors, 2022

Figure 17 - Selected mesh from NX software.



Malha Tetraedro 3D

Nome da malha

Objetos para Malha

Selecionar Corpos (0)

Propriedades do Elemento

Tipo: CTETRA(4)

Parâmetros da Malha

Tamanho do Elemento: [illegible] mm

Taxa de Crescimento Máximo de Superfície: 1.3

Método da Malha de Superfície: Padrão

Opções de Qualidade da Malha

Configurações de Malha de Superfície

☑ Tentar Malha Mapeada Livre

☐ Tentar Cilindros de Multibloco

Variação do Tamanho Baseada na Curvatura de Superfície: 50.0000

Limiar da curvatura da superfície (Somente Leitura): 1.7372 mm

Configurações de Malha de Volume

Gradação interna da malha: 1.05

☐ Limite de Comprimento da Aresta Interno de Destino

☐ Mínimo de Dois Elementos Através de Espessura

☐ Consertar Automaticamente Elementos com Falha

Opções de Limpeza do Modelo

Tolerância do Recurso Pequeno (% do Tamanho do Elemento)

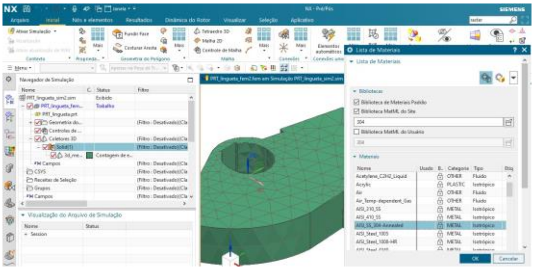
Source: Authors, 2022

Determination of the part constraints.

To obtain favorable results in this process it is important to establish the conditions or restrictions of movement of the part in such a way as to simulate the real operating and loading conditions of the part. Once this step is complete, it is necessary to start applying the loads that, like the previous one, must be as faithful as possible to the actual loading conditions of the part. In this case it is wise to load the part under the most extreme conditions (usually values above the limit load of the given operating conditions are taken).

The material, added to the library, is also assigned to the part, shown in Figure18.

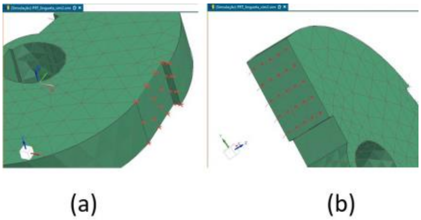
Figure 18 - Assignment of the identified material to the geometric model.



Source: Authors, 2022

Motion constraint conditions are then added, Figure 19 (a), and load application, Figure 19 (b), based on the study of the mechanism and the contact relationships of the tongue with the other components, are added.

Figure 19 - Applying constraints(a). Distribution of forces(b).

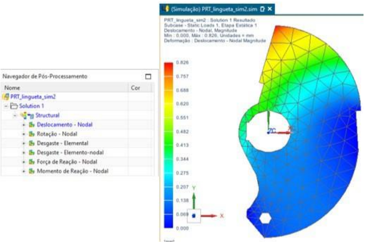


Source: Authors, 2022.

FEM Simulation

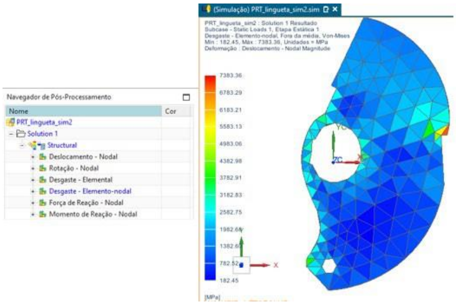
For a force of 10 tons or 100,000 N, a number much above what is traditionally used between 5 and 7 thousand Newton, according to UL standard is chosen for gauging the strength of the tongue, a maximum displacement in the order of 0.826 mm and nodal wear of 7,383.36 MPa is obtained, where the strain stress, and the maximum stress of the material, Figure 20 is 210,000 and 564,000 MPa respectively, which shows that the part can withstand much higher loads.

Figure 20 - Result of the nodal displacement simulation.


PRT_lingueta_sim2 : Solution 1 Resultado
Subcase - Static Loads 1, Etapa Estática 1
Deslocamento - Nodal, Magnitude
Min : 0.000, Máx : 0.826, Unidades = mm
Deformação : Deslocamento - Nodal Magnitude

Source: Authors, 2022

Figure 21 - Nodal wear simulation result.



PRT_lingueta_sim2 : Solution 1 Resultado
Subcase - Static Loads 1, Etapa Estática 1
Desgaste - Elemento-nodal, Fora da média, Von-Mises
Min : 182.45, Máx : 7383.36, Unidades = MPa
Deformação : Deslocamento - Nodal Magnitude

Source: Own authorship.

The analysis by the finite element method allowed us to establish the certainty that the CAD model obtained from the developed part will support the loads during the working process without difficulties. The virtual simulation developed in the model showed that under the action of the applied forces, it supports these efforts and maintains its structure without deformations that compromise its performance.

4. CONCLUSIONS

The successful culmination of the work made it possible to develop a CAD project, as well as to simulate the designed part by the finite element method using Siemens NX software.

This analysis generated the necessary data for the mechanical team of the new product creation project to innovate by modifying the geometry of the part shape, increasing its efficiency.

In the software, the fixed constraints of the tongue movement and high loads were inserted to identify the most critical points in the geometry of the tongue. As a result of applying the Siemens NX software to this analysis by the finite element method, graphical images with color gradients were generated, which show the behavior of the part both to wear and to displacement allowing the identification of the efficiency of the designed part, which due to its material, geometry and positioning within the mechanism, allows the lock to resist high loads.

The internal part of the tab geometry is directly linked to the mechanism, i.e., any modification in the mechanical system of the device would imply considerable changes in this part of the tab. In this case, the FEM analysis process can also be used, because it allows to optimize the geometry of the part before manufacturing it, reducing rework and, consequently, costs.

The studies done in this work were for forces applied in the direction of motion of this part in the mechanism. Another analysis by the finite element method can be developed by applying a normal force (perpendicular) to the plane of the movement path and, from then on, develop more efficient geometries.

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