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STRUCTURAL ANALYSIS OF MARITIME FENDERS

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Abstract. *Fender systems are essential structural elements responsible for protecting the berth during docking maneuvers for vessels, with the main objective of absorbing impact energy during berthing, during mooring and in possible maneuvers for repositioning ships at the pier. In this sense, maritime fender has proven to be an important tool to protect structures and prevent material and human damage during the mooring of ships. These structural elements are designed to dissipate the kinetic energy of vessels, minimizing damage caused by collisions and helping to maintain the integrity of ships and port structures. The structural design of fenders and their subsequent analysis consider a series of factors, part of them related to maritime dynamics and the location of the berth, such as winds, currents, waves, tidal variations, and others variables related to port operations, such as size of vessels, speed, and types of ship approach. In this work the main goal is to study the fender system used in one of the berths of Itaqui Port, with the purpose of establishing an analysis of applied loads and strength of these important structural elements. In order to that, some local conditions of the port were taken into consideration, such as: tidal variation, types of vessels, their arrival frequencies and port berthing practices. All of those data was used do compute the kinetic energy of the ship that the fender needs to dissipate which allows to select a specific fender model. To generate the computational model, information gathered from data made available by engineering and maintenance areas of the Itaqui Port were used. The rubber element in the fender is responsible for dissipating the kinetic energy so will be the focus of this structural analysis. Its non linear hyper elastic behavior is described using the two parameter Mooney-Rivlin model. An structural analysis of displacements and stresses using the finite element method of a cylindrical fender considering a pure compressive state was performed and results discussed.*

Keywords: *fender; ship; pier; mooring; energy.*

1. INTRODUCTION

In recent decades, the demand for general cargo transport has grown significantly through port operations around the world. Itaqui Port stands out in this scenario due to its natural characteristics that classify it as a deep water port, with strategic and privileged geographic positioning (EMAP, 2021). This Port presents itself as a major economic hub for the State of Maranhão, which has been undergoing transformations regarding its industrialization and technological development, ceasing to be considered a predominantly livestock/agricultural State to stand out as a point of convergence in the *Arco Norte* region of Brazil (EMAP, 2021).

When dealing with cargo handling, transport costs can be reduced by using larger ships, consequently requesting a larger draft (Sakakibara and Kubo, 2008; Comin and Souza, 2017; Mostofi and Bargi, 2012). Therefore, adaptations and expansions in the ports are imposed, providing constructions in more challenging conditions, so that the loads and requests in maritime constructions and moored vessels will be greater and more complex. Most of these actions happen when a vessel approaches the pier, at that moment, it is important to dock the vessel as smoothly as possible at low velocities and angles (Mostofi and Bargi, 2007; Grm, 2021; Schellin and Ostergaard, 1995). Even in those conditions, great forces are exerted on the fenders and mooring lines that are usually fixed on the wharf. After berthing and when all the mooring lines are secured, other conditions act at the vessels, such as: wind gusts, tidal movement and level variation, loading and unloading of materials and supplies, these conditions also produce kinetic energy that must be dissipated by the fenders and secured by mooring lines (Versteegt, 2013; Gaythwaite, 2004). According to the ABNT (1990) Standard, the fender is an indispensable structural element for the protection of the mooring of vessels, having as main objective the absorption of impact energy in the berthing and constant performance in the protection while they are berthed.

In order to obtain a safe and secure anchorage for the ship, there are limits to the acceptable movement and required strength for fenders, especially during the transfer of liquid bulk. For design purposes, it is important to predict all these loads and the required fender strength as accurately as possible. Several international and national standards are available and can be referred to in such a design (ABNT, 1987; BSI, 2014; ROM, 1990; EUA, 2012). In the elaboration of a project for fender systems, it is essential to know the vessels characteristics and their arrival frequency, in addition, knowledge of local conditions such as tidal variation, incidence of waves, wind currents and other meteorological factors are also important. Another criteria for selection of fenders are the environmental conditions and how aggressive are the local sea behavior.

The present work proposes a static structural analysis of a fender used in one of the berths of Itaqui port, with the purpose of understanding the relation between displacement and stresses for a typical berthing maneuver for a fender made of natural rubber reinforced with carbon black. To solve this problem a non linear finite element analysis was performed, which considers two kinds of non linearity, large deformations and hyper elastic material behavior of the rubber.

2. METHODOLOGY

2.1 Standards

Fenders selected for a given pier must comply with a sequence of criteria. For this, norms are established that relate to inherent characteristics of ships, ports, climatic/environmental factors, such as: depth; tide; marine current; waves; winds, etc., and the location where fenders will be installed. These standards establish that the energy absorption capacity of a fender is a very important factor to guarantee the safety of ships and the docking quay. Another factor of paramount importance is the maximum and minimum deadweight tonnage (DWT) of ships that can berth, and their frequency of docking at the pier.

Existing norms set representative values of actions that must be considered in the design of shelter or mooring structures, of a port, maritime or fluvial nature (ABNT, 1987; BSI, 2014; ROM, 1990; EUA, 2012). With regard to the mooring action, that is, actions resulting from the impacts of ships already berthed on the docking structure. These efforts stood by the pier can be categorized in types of actions. Figure 1 shows the action flowchart from the maritime side, illustrating the efforts due to mooring and specifically for vessels. Mooring forces arise due to the berthing of ships and maneuvers that are projected towards the pier and are secured by lines, guaranteeing the stability of movements for the proper moorings.

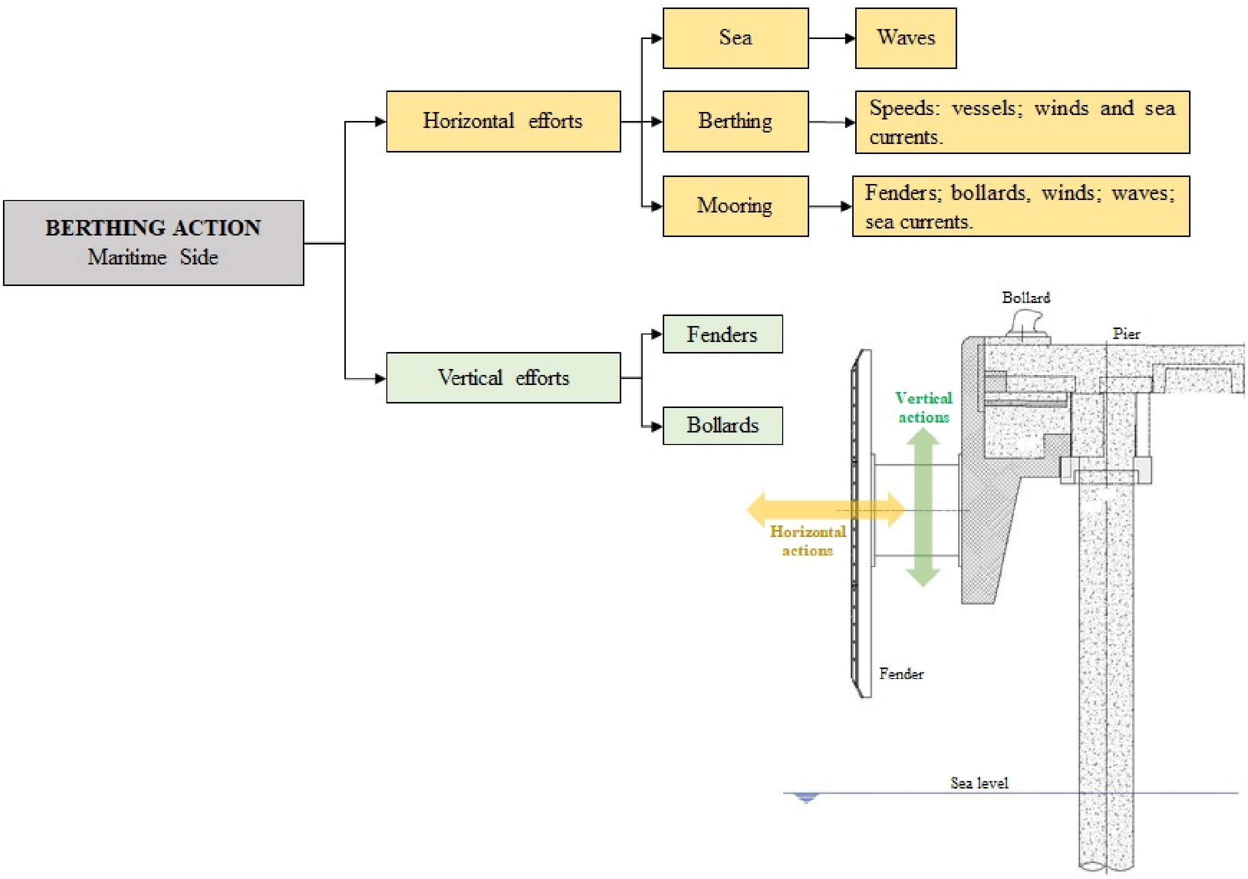


Figure 1. Berthing actions observed from the maritime side.

It is not an easy task to accurately quantify these efforts, since they depend on a complex combination of factors, such as: size of vessels, approach speeds, execution of maneuvers, action of winds, waves and sea currents, among others.

2.2 Mooring energy

The principles which fenders are based on is the law of conservation of energy, that is, the kinetic energy of the vessel during approach actions is transferred to the pier, part of this energy being absorbed by the ship's hull and another portion by the deformation of fenders, mostly its rubber core. A panel is usually present, with the purpose of distributing the pressures exerted on the hull of the ships. These panels must be sized to ensure good durability. UHMW-PE (Ultra-high molecular weight polyethylene) is commonly used to compose the construction of these panels, covering a metallic plate. This first material has great durability and some desirable mechanical properties, such as: great resistance to wear by abrasion, high resistance to impact and low coefficient of friction, allowing ships to slide over the panel when impact occurs. In this way, minimizing the loads acting on the fenders which would otherwise be subjected to great shear forces (ABNT, 1987).

There are several methods for designing and dimensioning fenders, one of them is the Classic Kinetic Method (CKM), considered in this work, being the oldest and widely used by Standardization Institutes and fender manufacturers (ABNT, 1987; BSI, 2014; ROM, 1990; EUA, 2012). This method establishes that the energy to be absorbed by the fender must be equal to that transmitted by the vessel to the pier. For safety reasons, situations must be taken into account where, for unforeseen reasons, unplanned approach maneuvers are performed. According to some fender manufacturers, the berthing energy is determined by calculating the kinetic energy of the ship berthing towards the pier. The ship's impact will generally be on a single or a pair of fenders (BSI, 2014).

Due to the existence of external parameters present in the docking process, the amount of energy is constantly affected by some coefficients related to the vessel, such as: mass of water entrained, eccentricity of the impact with the fender, rigidity of the pier and ship and safety factor for unplanned maneuvers. In this way, it can be defined that the docking energy of a ship is given by (BSI, 2014),

$$E_A = \frac{1}{2} M \, {V_A}^2 \, C_m \, C_E \, C_c \, C_a \, F_s, \tag{1}$$

where, M represents the ship's mass, V_A ship's approach velocity, C_m is the virtual mass coefficient, C_E the eccentricity coefficient, C_c dock configuration coefficient, C_a damping coefficient, and F_s safety factor. Determination of these all these factors can be made using equations present in standards like BSI (2014) and ABNT (1987).

Maritime fender systems must be designed to absorb the impact energy of vessels, at the time of berthing, in order to avoid damage to ships or to the pier structure. When it comes to the fender system selection process for a given pier, it is observed that there is no single solution. Although there are norms that establish criteria for selecting them, there are specific conditions that make the design more complex, such as: geographic and climatic zone, influence of wind action, tidal variation, characteristics of the maneuvering basins, depth of the channels of navigation, nature of the berthing structures and the variation of ships that will berth.

2.3 Mechanical behavior of fenders

After kinetic energy is computed, one is able to select an appropriate fender model, which vary in shape, size and material. Various manufacturers display in catalogs a variety of fenders which can be used to select a specific model according to its capacity to dissipate energy. After this process the geometry, material, maximum displacement, energy and reaction forces are established. A following structural analysis can then be performed.

The main energy dissipating element of a fender is its rubber core, which stands between a metallic panel and the concrete structure of the dock. This panel has the function of receiving the ship impact, with low friction coefficient and to transfer it to the rubber core. The whole fender is fixed with bolts at the docks side.

Rubber is a nearly incompressible hyperlastic material capable of withstand large amounts of deformation and return to its original shape once loads are removed. Its non linear mechanical behavior can be described by its density energy strain function W and several phenomenological material models such as Neo-Hookean and Mooney-Rivlin. Besides the rubber behavior, large displacements requires a non linear finite element method approach. This is true because the geometry can have significant distortion from its original shape which can cause stiffening or softening and phenomenons like buckling (Tan and Chang, 2018).

In this work, the material behavior is described using the Mooney-Rivlin model with two parameters. The strain-energy potential for this model is presented in Equation (2)

$$W = C_{10}\left(\overline{I}_1 - 3\right) + C_{01}\left(\overline{I}_2 - 3\right) + \frac{1}{D_1}\left(J - 1\right)^2 \tag{2}$$

where C_{10}, C_{01} e D_1 are empirically determined material constants. $\overline{I}_1$ and $\overline{I}_2$ are invariants of the left Cauchy-Green deformation tensor $\mathbf{B}$. J is the determinant of the deformation gradient and equals one for incompressible materials.

The material used for the fender system installed at Itaqui port is a mixture of natural and synthetic rubber, reinforced with carbon black and calcium carbonate. However, due to unavailability of experimental data for this particular material, the authors opted for using a natural rubber reinforced with carbon black which has similar properties. The material constants are given in Table 1:

Table 1. Elastic constants of Mooney-Rivlin model with two parameters.

Parameter	Value
C_{10}, MPa	0.3339
C_{01}, MPa	-3.37e^{-4}
D_1, MPa^{-1}	1.5828e^{-3}

2.4 Structural analysis by finite element method

For this analysis software Ansys Mechanical was used. Geometry was modeled at Ansys SpaceClaim and has dimensions depicted in Figure 2. This geometry was obtained from technical drawings provided by EMAP, which manages the Itaqui Port. It represents the rubber core and its dimensions. This geometry is imported to Ansys Mechanical and the usual steps for a simulation are taken: mesh generation, imposing of boundary conditions, material and constitutive model definition.

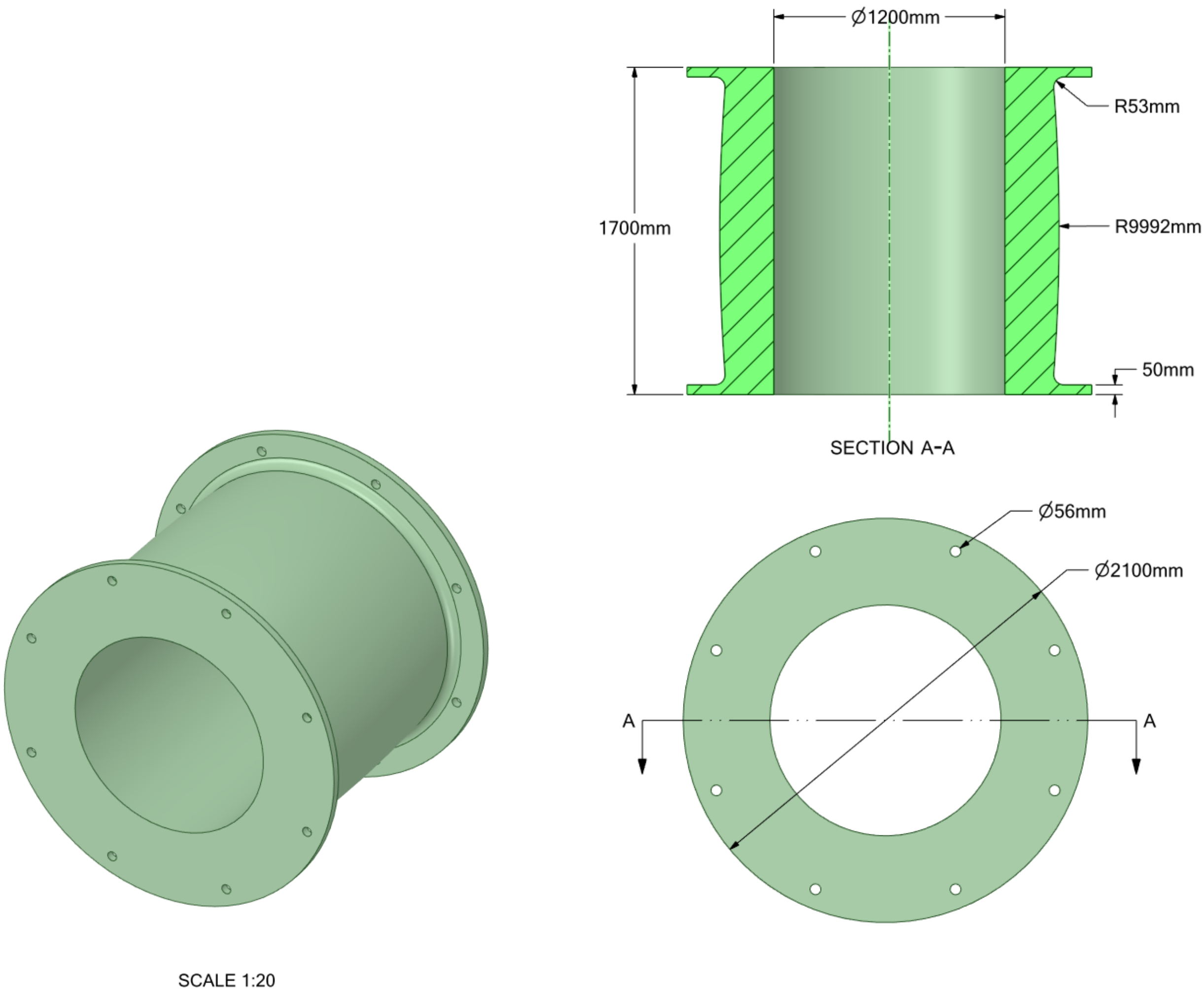


Figure 2. Geometry and dimensions of the rubber fender.

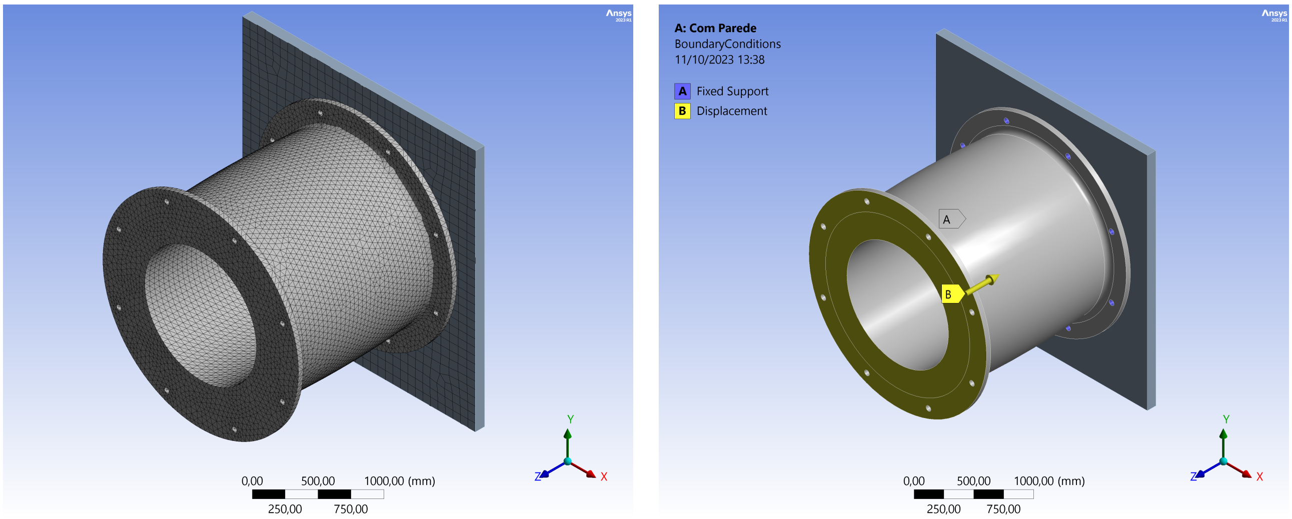
A comprehensive simulation for this application would involve a dynamic analysis of the ship impact on the complete structure of the defense and its connection with the dock. However for this preliminary work the author chose a static analysis considering the rubber part of the fender and a rigid fixed wall made of concrete. A simple uni-axial compressive case was used considering a prescribed displacement at the other end. Those conditions will be illustrated and better defined at the next section.

3. NUMERICAL RESULTS

Some of the usual conditions of a structural analysis must be changed if one is to capture the non linearity for this type of simulation. Firstly, the material behavior of rubber was included via Mooney-Rivlin model and the use of parameters in Table 1. Secondly, geometric non linearity can be treated by setting Ansys Mechanical to consider the possibility of large deformations.

The mesh uses a 4-noded tetrahedral linear element, with a maximum edge size of 0.05 m and is presented in Figure 3a. The total number of elements is 109463 and 24554 nodes.

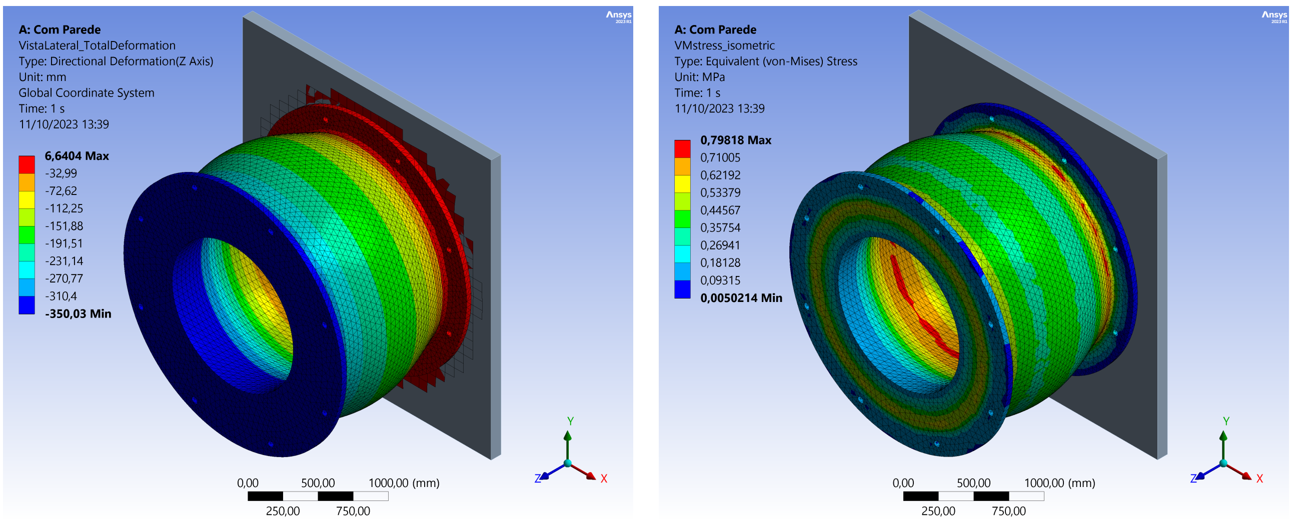
This model consists of a concrete wall (which is set to have a rigid behavior) that holds the rubber essentially acting as a fixed support. Also, holes where bolts are positioned were indicated as fixed supports. The surface at opposite end has a prescribed displacement in z-direction set to $u_z = -0.35$ m. This specific value is in the range of displacement this structure has to endure according with its manufacturers. This boundary conditions are displayed in Figure 3b.



(a) (b)

Figure 3. Mesh (3a) and boundary conditions (3b) used in this simulation.

As this is a non linear analysis the solver uses iterative methods to force equilibrium until convergence is reached. Results for total displacement ($u = \sqrt{u_x^2 + u_z^2 + u_z^2}$) and equivalent von Mises stresses are presented in Figure 4.



(a) (b)

Figure 4. Results for total displacements (4a) and equivalent von Mises stresses (4b) obtained with this simulation.

Analyzing Figure 4, it is possible to observe the large deformation in the middle section of the fender, which resembles a buckling behavior. Stresses also reaches a maximum value in this region, 0,798 MPa. The concrete wall acts only as a fixing point or a barrier to the movement, considering its elastic behavior was defined as rigid, it will not be considered in this analysis.

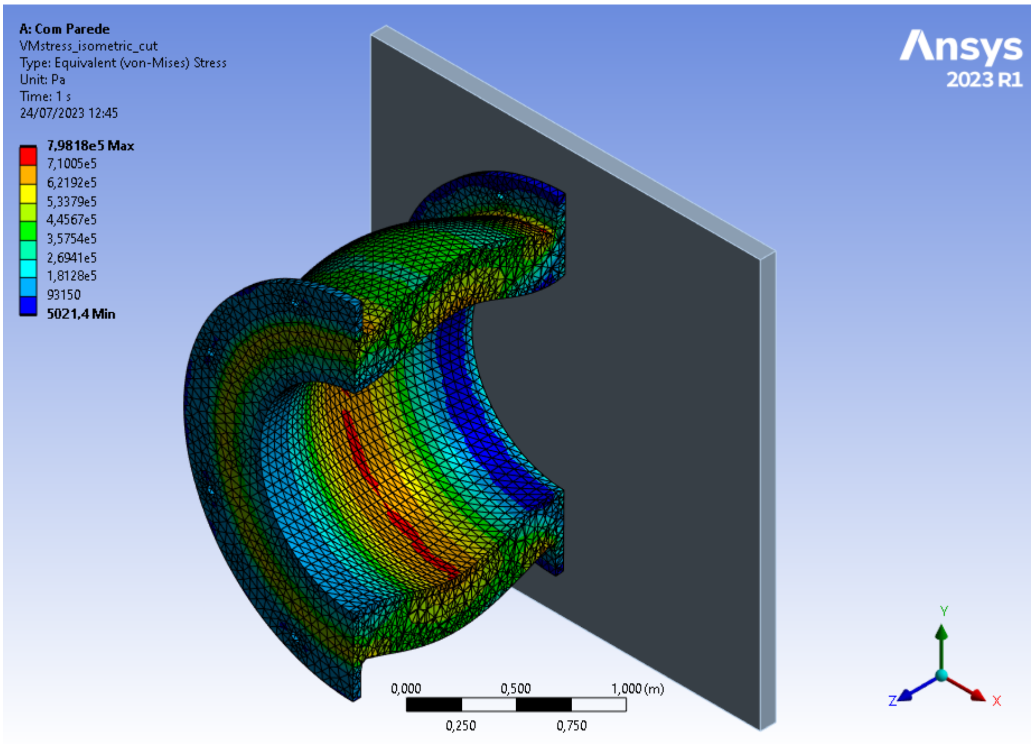


Figure 5. View of a section plane of the fender rubber core.

Finally, Figure 5 presents a section view of the fender which shows the position of maximum von Mises equivalent stress and details regarding the deformed shape in true scale.

4. CONCLUSION

This work presented a structural analysis of a cylindrical fender made of natural rubber reinforced with carbon black. Hyper elastic effect was included with Mooney-Rivlin model. Preliminary results were presented as a part of an ongoing project which aims to perform a complete dynamic analysis of this model. It was possible to evaluate both displacements and stresses that permitted a better understanding of this model mechanical behavior.

5. ACKNOWLEDGMENTS

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