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NUMERICAL ANALYSIS OF DIFFERENT BOSS GEOMETRIES FOR A COMPOSITE OVERWRAPPED PRESSURE VESSEL

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Abstract. *Composite overwrapped pressure vessels (COPV) have been adopted to meet the growing need for lightweight pressurized gas storage systems. For safety reasons, international standards require the COPV dome region to be reliable in a way that burst failure must occur at the cylindrical section. This way, boss-liner attachment is important to meet the needed strength parameters for torque and pressure loads. This work has the goal of studying the effect of different boss geometries on critical boss-applied torque for a Type IV pressure vessel. These geometries vary on groove and indentation shapes, proving distinct mechanical joints. Finite element analysis software Abaqus/Standard is used for the numerical modeling. A refined local COPV model in the boss region is used for computational cost reduction purposes. Two contact types are studied, one considering cohesive behavior at the boss-liner interface, and the other taking into account friction at that interface, disregarding adhesion between the parts. High-density polyethylene is selected as the liner material, and CF8 stainless steel is used for the metallic boss. The load at the boss is determined according to NBR NM-ISO 11439, which sets the test torque as two-fold the torque specified by the valve manufacturer. A reference point is used for applying the load at the boss thread region, and fixed boundary condition is set at the dome section equator. Due to the complex geometry of the parts, multiple partitions and mesh techniques are adopted to discretize the model. Post-processing is done by analyzing the boss region structure torsional stiffness and maximum equivalent stress at the liner body. Multiple boss models that fulfill the standard requirements were found, and the ideal boss was selected based on the geometry manufacturability for the microfusion process, considering future application.*

Keywords: *Composite overwrapped pressure vessels, boss geometry, torque load, pressure load, finite element method.*

1. INTRODUCTION

Composite overwrapped pressure vessels (COPV's) have been adopted to satisfy the growing demand for gas and pressurized air storage systems, specially regarding compressed natural gas (CNG). Pressure vessels are divided into classes I to V, depending on their construction characteristics and materials, where class IV COPV's are given by a polymeric liner surrounded by a wound laminate composite. Type IV pressure vessels stand out from traditional metallic containers by its low mass and lack of corrosion related issues, which reduces carrier vehicles' fuel consumption and maintenance costs (Farhood *et al.*, 2017).

The structure of a COPV class IV is given in Figure 1. The cylinder section, as the name suggests, has the shape of a cylinder, and it is limited by the start of the dome sections at COPV both ends. In a closer look, it can be observed the main components of the pressure vessel: boss, liner and composite. The boss is usually metallic, and it is responsible for providing a reliable connection with the filling/discharge valve. The liner is made of a polymeric material, generaly by rotary molding, and must have sufficient thickness to avoid leakage through the vessel walls. Finally, the overwrapped composite develops the main structural role for the application, withstanding the high internal pressure loads required for CNG storage.

The dome section geometry presents great influence on the COPV performance, and many studies are focused on finding optimal shapes for such region. Sharma *et al.* (2022) analyzed the influence of 6 distinct dome shapes on burst pressure and weight performance of class III pressure vessels, which are formed by metallic liners instead of polymeric liners. A mathematical approach is adopted to determine the liner thickness, based on the loads observed in the filament winding process, and dome shapes evaluation is conducted through FE analyzes, which are validated with experimental tests.

Similar studies concerning the effects of the composite laminate winding pattern on COPV's burst pressure have gained popularity in the last decade, for example Regassa *et al.* (2022) and Nebe *et al.* (2022). Although, boss design influence on pressure vessels performance remains unexplored, and boss region failure modes are poorly covered in conventional FE models.

For safety reasons, international standards require the dome region of the COPV to be reliable, so that the burst pressure is limited by the cylindrical section (central region). Therefore, the geometry of the dome and the coupling between the boss and the liner are essential to ensure the resistance parameters for standard established torque and internal pressure loads.

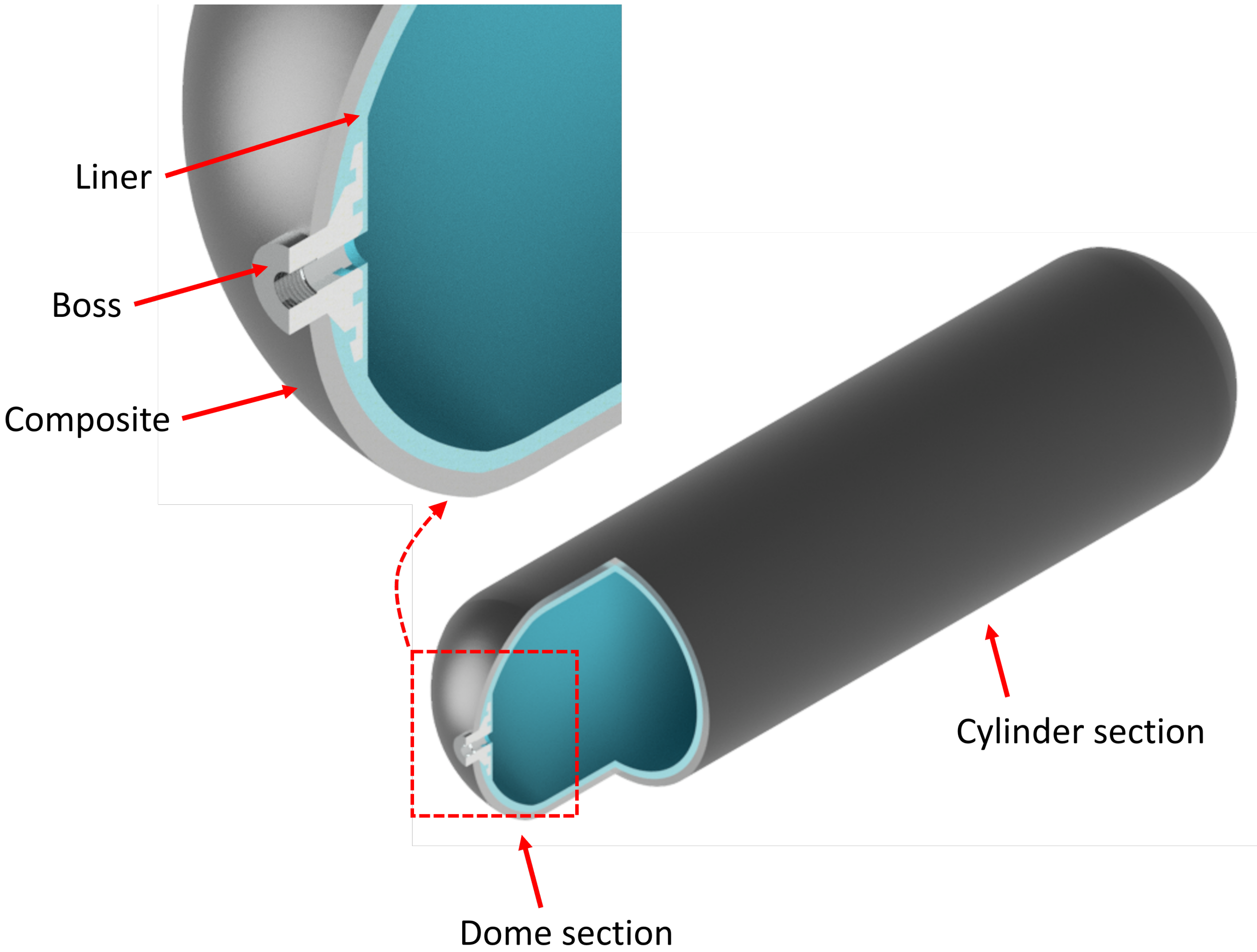

Figure 1. Class IV COPV structure.

Thus, this research seeks to obtain a boss geometry for a class IV COPV, which must withstand the torque and internal pressure loads defined by the NBR NM-ISO 11439 standard. At first, the study focuses on the survey of standards, articles and patents on COPVs, exploring mainly their design requirements and constructive aspects. The acquired information is then applied to the development and validation of a specific metallic component for the project, which is conducted through computational techniques and tools. The geometry selected from the study is a potential innovation for the area of pressure vessels, since it presents an original and advanced solution to meet the established requirements. It is expected that its optimization will contribute to the advancement and improvement in the area of development of class IV COPV's.

2. METHODOLOGY

In a first step, a literature review on pressure vessels was conducted, with emphasis on the collection of information on dome and boss geometries in patents and scientific articles. After that, the activities performed by the fellow involved the determination of the dome geometry for the COPV liner. For this, studies that analyzed the influence of the type of dome on the burst pressure and volumetric capacity of pressure vessels were adopted. The work of Sharma *et al.* (2022) was selected as the main bibliography for the design stage, which examined the performance of a COPV with metallic liner for 6 different dome geometries. Thus, based on the results of the article, the ellipsoid dome geometry III was selected, and the obtaining of its cartesian points was performed with the implementation of the equation given in the article in a Python algorithm. The calculation of the liner thickness was conducted according to Sharma *et al.* (2021), which takes into account the fiber tension in the composite winding and the yield strength of the liner material.

Then, the study was started to define the geometry of the boss based on the torque and internal pressure loads. The proposed boss concepts are given in Figure 3, which vary in groove/channel shapes and cutouts, providing different mechanical joints. The FE analysis software Abaqus/Standard is used for the numerical modeling, and the computational models are limited to the dome region because of the lower computational cost involved and because it is the area of interest. Liner-boss assembly region main dimensions are given in Figure 2. The materials considered for the boss, liner and composite were, respectively, CF8 stainless steel, high density polyethylene (HDPE) and glass fiber reinforced epoxy (GFRE), whose mechanical properties are given in Table 1. Since the objective of the analysis does not cover the verification of composite integrity, the material was considered isotropic and homogeneous. Also, in order to explore the effects of the degree of adhesion on the composite-liner and boss-liner interfaces, they were simulated for bonded contact (without sliding) and friction contact (with sliding) models.

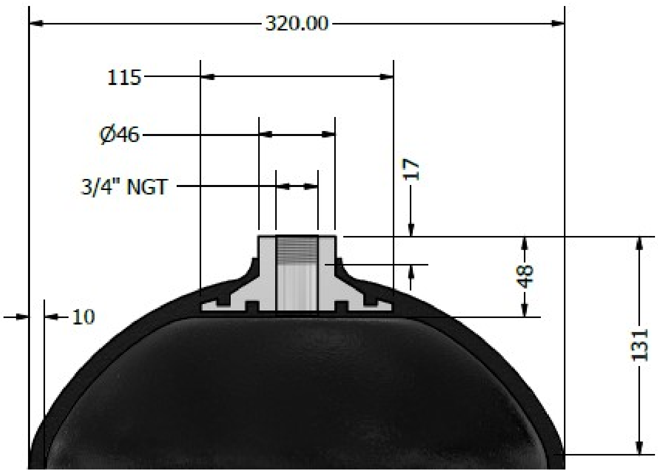

Figure 2. Region of study main dimensions.

Table 1. Components' mechanical properties

Property	**CF8 stainless steel** (ASME, 2011)	**HDPE**	**GFRE** (MECH-Gcomp, 2023)
Young's modulus, $\mathbf{E}$	203 GPa	0,9 MPa	44,8 MPa
Poisson's ratio, ν	0,29	0,45	0,2
Yield strength, $\mathbf{S_{ut}}$	385 MPa	26 MPa	N/A

For torque loading, the load on the boss is determined in accordance with NBR NM-ISO 11439/19, which establishes the critical torque as twice the torque specified by the valve manufacturer. A reference point is used to apply the load in the thread region of the boss, and a fixed boundary condition is defined at the transition from the dome to the cylinder section. Due to the complex geometry of the parts, multiple partitions and meshing techniques are adopted to discretize the model. The analysis for internal pressure is conducted with the same models adopted for torque loading. The breaking load of the COPV is established by NBR NM-ISO 11439/19 as 3.65 times the value of its working pressure. Thus, considering a valve tightening torque of 180 N.m and a work internal pressure of 20 MPa, the loads applied to the models are described in Table 2.

Table 2. Loads applied to the models

Load	**Value**
Thread torque	360 N.m
Internal pressure	73 MPa

The post-processing is performed by calculating the safety coefficients of the models for their maximum equivalent

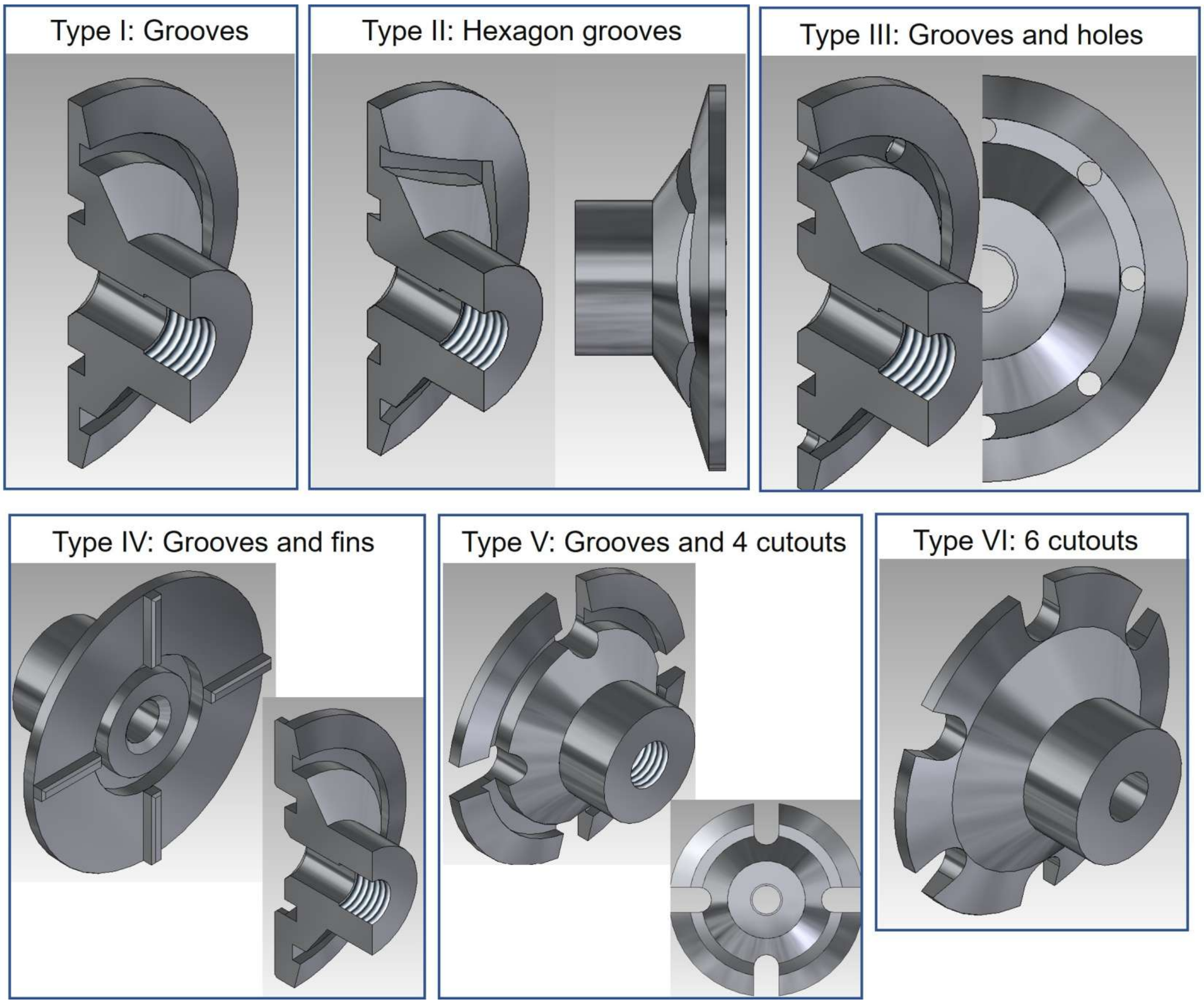

Figure 3. Proposed boss concepts.

stresses, taking into account their yiels strenghts (Table 1). Figure 4 shows the image of the boundary conditions and loads and Figure 5 shows the image of the mesh used for the COPV model. General purpose linear brick elements C3D8R are used to mesh the models.

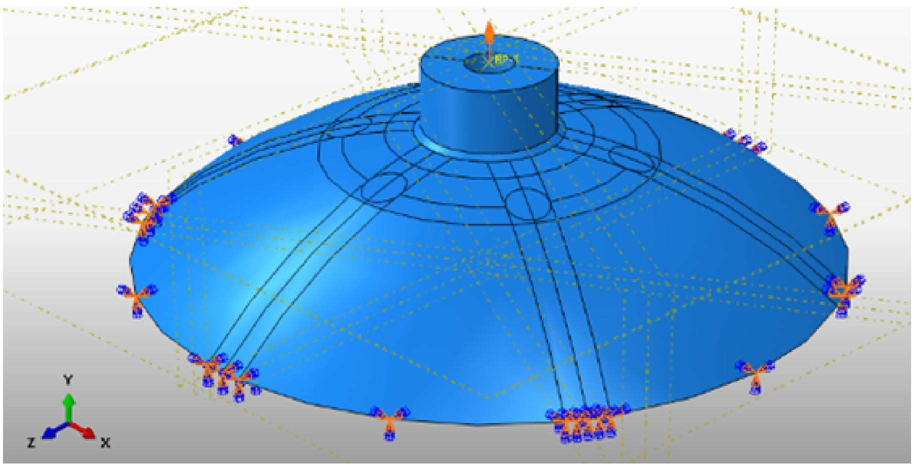

Figure 4. FE model boundary conditions.

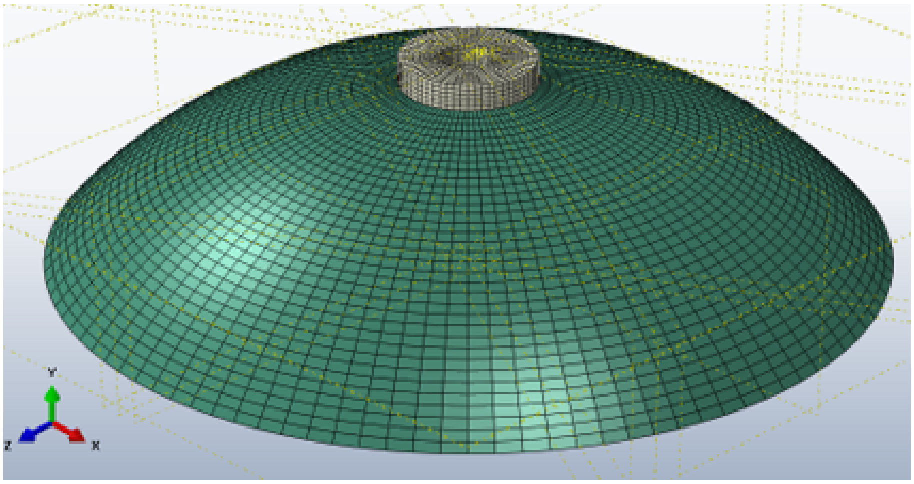

Figure 5. FE model mesh.

3. RESULTS AND DISCUSSIONS

The results presented in this section focus on the analysis of the integrity of the boss and liner for the designs proposed in Figure 1. It is important to emphasize that only the models without adhesion at the boss-liner and composite-liner interfaces are discussed, since the models with bonded contact are not very conservative with respect to the safety factors found. This is due to the greater distribution of loads along the structure, and low stress levels in the notch and channel regions. The failure is considered to occur when the maximum equivalent stress (σ_{max}) based safety factor (SF) is less than 1, meaning that the stress observed in the body is greater than its yield strength.

From Figures 6 and 7, it is possible to observe that Type I presented a null maximum equivalent stress for the liner and the boss. This is due to the total slip at the boss-liner interface, making the application of the model unfeasible due to torque loading. Investigating the other designs, it can be seen from the curves in Figure 7 that all bosses present satisfactory results. For the liner, on the other hand, only Types V and VI promote stress levels below the yield strength of HDPE, with safety factors of 1.91 and 1.26, respectively. This factor can be explained by a more uniform stress distribution in the liner, which is induced by the presence of the cutouts in the boss base.

For the internal pressure loading, it is possible to analyze in Figure 8 that all models present liner failure for the rupture pressure of 73 MPa. For the 6 models, the location that presents stresses above the HDPE yield limit is near the boss throat, and this behavior is due to its crushing between the boss and the composite, which have higher stiffness than the liner. However, analyzing Figure 9, it is noted that only Types V and VI meet the design requirement for internal pressure loading, unlike the other designs. The main advantage of these models is the lower bending stiffness at the base of the boss, which allows lower stress gradients at this location for the load analyzed, which tends to expel the graft.

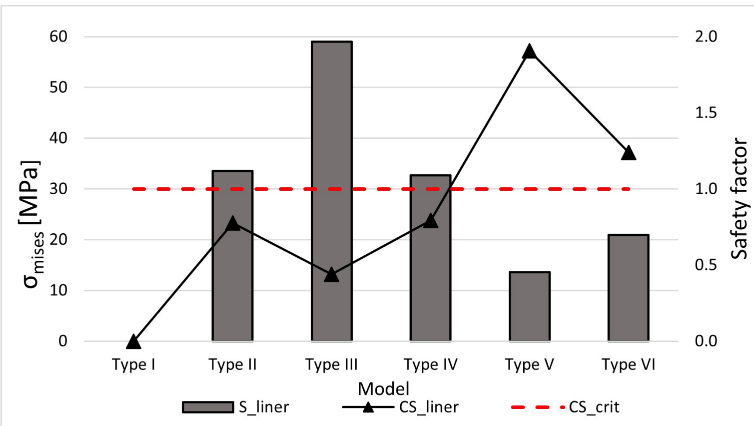

Figure 6. Liner models' mechanical integrity for torque load.

Considering the results presented, it is noted that Type V is the most suitable for the application, followed by Type VI. However, considering its production process through microfusion, it is necessary to optimize its geometry in order to promote the proper flow of material in the mold, since sharp corners and cutouts make this impossible. In addition, the optimization should be focused on reducing the mass of the boss and reducing the crushing of the liner between the boss

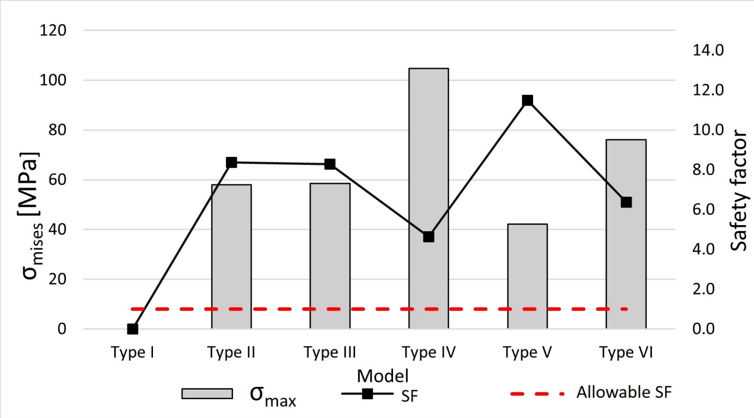

Figure 7. Boss models' mechanical integrity for torque load.

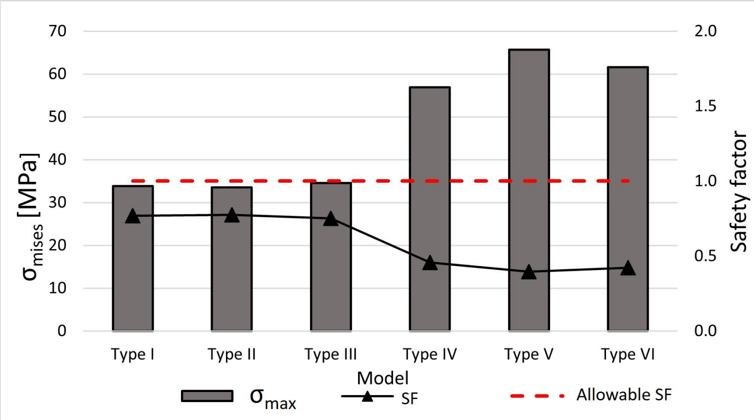

Figure 8. Liner models' mechanical integrity for internal pressure load.

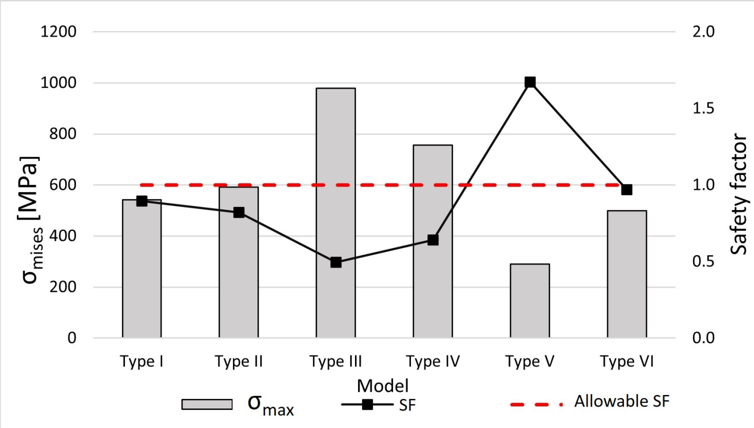

Figure 9. Boss models' mechanical integrity for internal pressure load.

and the composite for internal pressure, which will make all the design requirements fulfilled for Type V. The optimization variables adopted for the future study are the thickness of the base, the number of cutouts and the inclination of the boss cone.

4. FINAL CONSIDERATIONS

The present work was developed for investigating the effects of different boss geometries on maximum torque and burst pressure withstood regarding a COPV class IV boss region. It was considered 6 boss concepts, and the numerical analysis was performed at the FE software Abaqus/Standard. The results showed that the Type V boss model presented optimal results, when compared to the other 5 geometries. Therefore, because of microcast flow issues associated with the fabrication of the Type V boss complex geometry, it is proposed a parametric optimization of such concept.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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