Design and Optimization of Cages for the Transport of Hydrogen Cylinders

R. Miralbes, D. Valladares, L. Castejon

Abstract— **The aim of this article is the establishment of a design methodology for cages used for the transport of hydrogen in cylinders, using a structural design methodology based on the finite elements.**

So, in the article the regulation, the load cases, the loads, the boundary conditions and the simulation method adapted for the simulation of the welds and the bolts will be analyzed.

In addition, the whole process of the design carried out will be explained and how a final optimized design has been obtained, bearing in mind the weight, the regulation and the stocks politics.

Index Terms—**Cage, FEM, design, stress, hydrogen,**

I. INTRODUCTION

Nowadays the use of hydrogen has gained great importance, mainly due to hydrogen cell vehicles, its use in hospitals and business and due to its use in isolated areas such as an absorption and storage energy source. Regarding this last use, it is noteworthy that alternative energy, especially wind energy, is generated in delocalized points and is fed into the grid at the time of production, which may be during peak or off-peak hours, with different economic benefits.

In order to maximize the profit made from energy sources, hydrogen can be generated through wind turbines by water hydrolysis during off-peak hours, and can be poured while the power into the grid during peak hours and use the hydrogen obtained for local supply. It is also possible to continuously generate hydrogen (in both peak hours and off peak hours in off-grid installations, for subsequent sale or use.

Therefore, a secure storage system and appropriate for the amount of hydrogen to be stored is needed. So the most feasible alternative to other storage and transport systems are the cages for hydrogen bottles.

This method has the advantage of being a modular system composed of several cages that can be loaded onto a vehicle for transport to the location of its use. In addition a moderate amount of gas is stored, less than a tank and more than a single cylinder, making it suitable for use in small and medium-sized industries.

However, there is no clear methodology for the design and analysis of these structures since it is relatively modern and so it has therefore been necessary to define a design methodology using the finite elements and the regulation UNE-EN 13769.

II. REGULATION UNE-EN 13769

Hydrogen bottle cages come under the UNE-EN 13.769 regulation: *“Botellas para el transporte de gas. Baterías de botellas. Diseño, fabricación, identificación y ensayo”*, because their behaviour seems to have a bottle battery behaviour.

This regulation establishes that:

- The base must provide for drainage.
- It must be stable in normal conditions of use (it must be verified with a test or with a calculus)
- It can not have prominent elements
- The valve access must be secured.
- The removable coverts must be secured to avoid opening with impact loads.
- The lifting lugs must be designed to support two times the own structure weight with the loads and, in that case where there are four lugs this condition must be fulfilled in two of them.

Moreover it establishes three load cases that must be met by testing:

- Vertical elevation test
- Vertical falling test
- Rotational falling test.

III. INITIAL CAGE DESIGN

To perform the initial design of the cage standard criteria and specifications established by the regulation have been considered. Thus a cage for 16 standard hydrogen bottles has been designed, which weighs 247 kg. the weight of the stored gas and the cylinders themselves is 1010 kg., so the total weight will be 1257 kg.

The cylinders will be usually transported on a trailer (with a MAW of 35,0000 kg.), and discounting the weight of the vehicle, it can carry 21,000 kg, or a 16 cylinder cage that will have the appropriate dimensions to be able to enter) trailer in two longitudinal rows, with eight cages per row.

With regard to its base, a perforated plate to facilitate drainage (see figure 1) has been opted for.

With that in mind, analyzing the stocks polity, the existing profiles, weldings and joints, the design presented in Figures 1 and 2 has been obtained.

Manuscript received March 4, 2010. for the WCE 2010

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One of the main problems of the model developed has been the design of the upper anchorages for the cylinders to the cage. In order to solve it, an iterative process of design has been carried out, from an initial geometry in "T" profile with screwed unions, because they are not a frequently removed element (see figure 15.), as are frontal anchors, and these frontal elements have fewer structural problems.

At the bottom, rectangular closed profiles have been used as parts, "lift truck sections", to be used by a forklift, because they provide a high security against falling.

In addition, a single central hook for vertical lift has been used, which allows for the use of the cage without slings: the hook must be structurally analyzed in depth too.

IV. USE OF FEM FOR THE STRUCTURAL DESIGN

After the first pre-design of the resistant structure, the use of numerical simulation tools via the FEM[1 is considered to analyze and optimize the cage structurally. This method allows for numerical simulation but it is also satisfies the validation with an experimental test. Furthermore it even gives the gravity centre to carry out the stability analysis that the regulation specifies.

To make the numerical simulation, the non-structural parts of the model have been deleted: valves, fittings, etc., and shell elements have been used to simulate the main parts (see figure 3) except for the bolts, top closures and the central bridge that have been modelled with volumetric elements[2]

Elastic-plastic curves have been used to simulate the material, thus simulating the properties of the material by two curves (one in the plastic zone and another in the elastic). (see figure 4).

As has been mentioned in section 2, there are three load cases:

A. *Case 1: vertical elevation load case*

To make the calculation the weight of the cylinders and the gas has been simulated, magnified by a 2 factor scale, using a uniformly distributed load on the bearing area of the bottles. (see figure 5) and a clamp has been imposed on the central bridge in the hook support area (see figure 6).

In this case, the gravity acceleration has been imposed and the parts are analyzed in terms of stress and strains, using a safety coefficient of 1.11 and a maximum deformation of the base of 5 mm.

In this case, the parts subject to higher stresses are the top hook and the base, although the vertical profiles have very high stresses. Because the hook is a critical element, it has been analyzed including its welding as shown in Chapter V.

This simulation is performed statistically.

B. *Case 2: vertical falling load case*

To ensure the safety of the cylinders, the regulation requires simulating a 0.1 m height fall to the floor, with a minimum angle of 5º with the floor.

To overcome this test, they be moved using a forklift or sling. In addition, the bottles must remain attached to the cage.

It is important to say that the norm for this and the following cases, nothing is mentioned about working in elastic regime; this means that after the fall, in terms of structural strength, the only condition to be fulfilled is that the material reaches its tensile strength during the impact creating a risk in breakage of the bottles. This condition makes sense because if there is any problem, the first and most important aspect is the safety of the bottles because, after the fall, the cage would be replaced.

In addition, the pipes must not be damaged. To simulate these elements, beam elements have been used with their rigidity and the interference of them with other elements (see figure 7).

In this case the base is simulated like a rigid deformable element, while the structures is 5º inclined with the two axes forming the bottom of the base, so that the first impact occurs on the corner which is the worst possible load case (see figure 7). The fall is due to only the gravity effect.

To simplify the calculation, the impact is made just from the instant before the crash until a few milliseconds after the shock, introducing the initial velocity that would appear in this instant.

To simulate the load, the hydrogen cylinders are discretized individually, with a density equivalent to their own weight and the weight of the content of gas. To simulate the contact an auto contact has been imposed.

In this case, the most critical zones are the profiles where the cage hits the ground, and the horizontal anchors, which should be able to hold the bottles in the cage.

C. *Case 3: rotational falling load case*

Again, in order to ensure the safety of the cylinders, the regulation imposes the following test, with a turnover and a fall to the ground from a 1.2 m height.

In the regulation, the requirements specified to overcome this test are similar to those in the preceding paragraph. The ground is simulated by a rigid deformable element. As for the structure, it is situated at a height of 1,200 mm. It has also been supported (UF = 0, rotation free) by nodes belonging to one of the edges of the base frame on which the cage will turn (see Figure 8). Again the fall is only due to gravity.

This load case is very similar to the above in terms of calculation, simplification, simulation of the load, auto contact, and areas to be analyzed.

V. CENTRAL BRIGE SIMULATION

The central bridge is one of the most critical areas, especially during the vertical elevation test with twice the weight, so it should be studied in depth.

This part has some elements: a solid tube bending and reinforcing brackets attached to the cage by welding. Therefore, in these areas high stresses may appear due to the problems arising in the welding.

To analyze it, a sub model of the area in which the welds are included has been used.

To do the simulation the displacements in the boundary nodes of the global model have been imposed on the nodes of the boundary nodes of the sub model, and interpolating the displacement for the intermediate nodes.

These displacements are introduced to the sub-model as boundary conditions[3].

By carrying out the calculation, what the levels of stress are like in a critical area can be checked more precisely.

The sub model has been achieved by reducing the size of the elements and increasing the number of nodes to 65,000 elements and 64,000 nodes[4] (see Figure 14).

VI. TOP BOLTS SIMULATION

The top bolts simulation has been achieved using volumetric elements that simulate the screw, coupled between the areas in which the screw is. So, what is sought is that their behaviour is very similar to reality (see fig 10)

VII. INITAIL RESULTS AND REDESIGN

Once the model of the structure is made and after the placement of the charges and the establishment of boundary conditions, the FEM calculation is started for each of the three load cases dictated by the regulation.

Subsequently the stresses and strains will be analyzed according to the criteria established by the regulation. Thus, for case 1 it is observed that the safety factor must be greater than 1.11 the yield stress, while for cases 2 and 3 it is observed not to reach the ultimate tensile in the area, therefore the valves and pipes will not be damaged, and fittings and the cage can retain the cylinders.

Due to client confidentiality, stress – strain tables tension-deflection for each part is not included.

After the obtained results with the initial model the initial conclusions are drawn. Both in the case of vertical lift and vertical falling there are not any problems, only a slight over sizing is appreciated. The most critical zone is the central bridge (see figure 11) for the case of vertical elevation and for the vertical falling for the forklift profile (see figure 12)

However, in the rotational falling load case problems do appear, owing to the high deformation of the upper carriages and an excessive movement of the cylinders. So some bottles are not held and come free in the test. This is why the structure behaviour is incompatible with the regulation requirements so the carriages must be redesigned (see figure 13).

It has also been observed that breaks appear in the valves and in the pipes. This is because the carriages are unable to hold the bottles, so they damage the pipes.

Therefore some design modifications have been proposed, aimed on the one hand to reduce the weight of the hook and, on the other hand, to make some modifications of the upper carriages.

About the hook, the results show very similar tensions to the yield limit, so the new model is more optimized (see figure 14). Despite the increased tension, the results remain valid as the regulation stipulates. Furthermore the new model now just concentrates stresses on a small attachment area, while the rest of the elements have lower stress levels than the limit imposed

With regard to the redesign of the carriages, an iterative process was followed (see figure 15).

The re design process was this: in the first iteration two carriages were modelled like shell elements, with a thickness of 5 mm. The section measures 50 × 24. In the 2nd iteration, two carriages were modelled with solid elements, reinforced by an upper plate (8 mm.) and by reinforcement for the angular profile (3 mm.); now the section increases to 70 mm x 48 mm. In the 3rd iteration the 2nd carriage model has been used but it has been used three times instead of two. Finally in the 4th iteration reinforcement plates are removed for the angular profile.

Finally, the containing problems of the cylinders are solved with the modification of the carriages. Again the case of vertical elevation and vertical falling are overcome (very similar results). Nevertheless the appearance of an area in the upper rungs that exceeds the tensile stress in the rotational falling load case is noted. With regard to the area where the bolts connect to the upper carriages, this area suffers a lot because now the bottles are well contained and that weight effort falls directly on the bolts (see figure 16).

In this situation a bolt redesign is proposed; instead of the base of the bolts being welded to the top of the profiles (see Figure 17), the bolts are going to across through the whole profile, so the stress is spread over more material and so stress concentration does not appear (see figure 17).

Finally an optimization of the mass of the structure has been proposed because all the previous modifications have increased the mass. With the advantage already mentioned (that can exceed the yield strength of the material in case of falling) the study of the parts where it is feasible to make a thickness reduction has been carried out.

After the thickness reduction, the critical load case is the vertical elevation one, since as already noted, if it is needed to work with a safety factor, the stress level will not be able to exceed 90% of yield strength. After checking this loading case and seeing that the thickness reduction proposals were valid, the rest of calculations were carried out, with satisfactory results (see figure 18).

A 28.6 Kg. mass reduction has been obtained; this represents a 10.3% material savings from 277 kg. to 249 kg.

VIII. CONCLUSIONS

Once all the calculations of both the full model and the sub model have been done, conclusions are drawn. In the light of the results, we can see that the newly designed structure passes the regulation requirements. On the one hand, stress levels do not reach the established maximum limits and on the other hand, the deformations do not prevent the subsequent rise of the cage and they secure the position of the cylinders.

What must be highlighted in the evolution of the design is where the most important changes lie: in redesigning higher carriages, bolt modifications, and mass reduction of 10.3% on the final prototype.

Moreover, the finite element method presents considerable advantages to the design of such structures. Thus, it allows making a simple and cheap structural design of the cage, both for static and dynamic load cases without the need to make a prototype. It also allows for making some modifications and optimizations of the structure suppleness.

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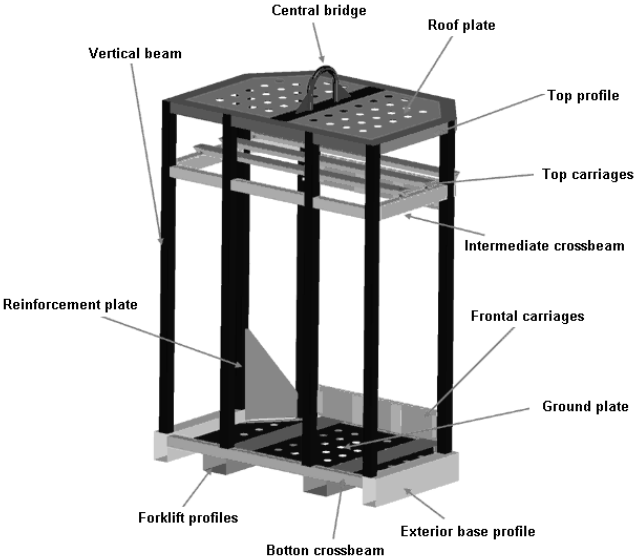

Figure 1: parts of the designed cage for hydrogen bottles.

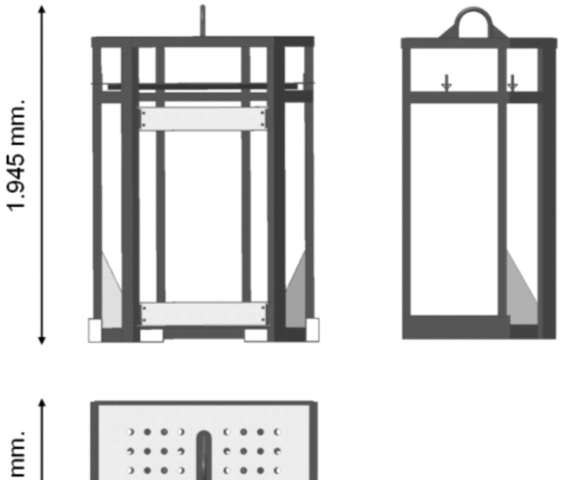

Figure 2: principal dimensions of the cage design.

Figure 3: FEM model of the cage.

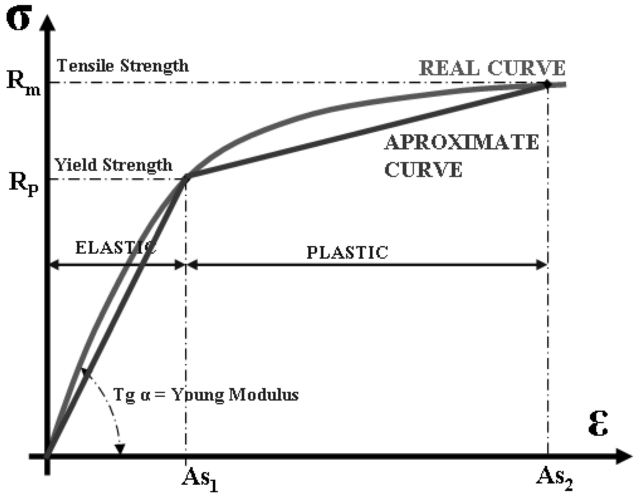

Figure 4: Material simulation model

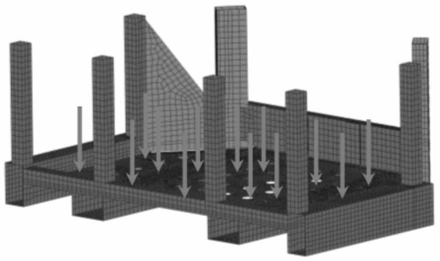

Figure 5: loads for the vertical elevation load case

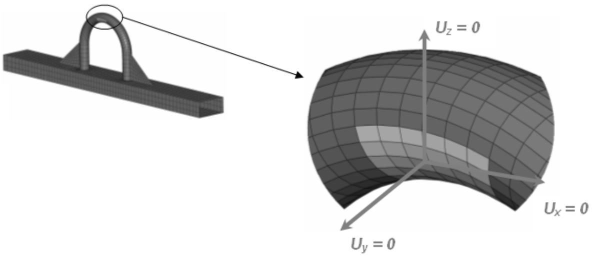

Figure 6: boundaries in the hook for the vertical elevation load case.

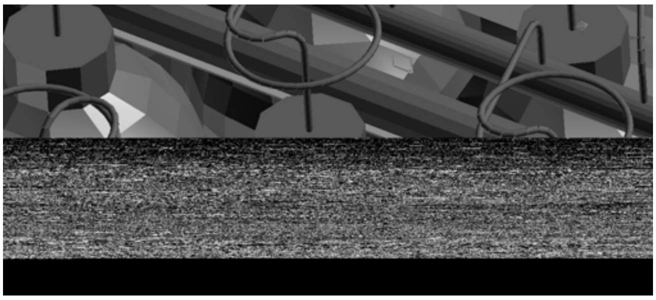

Figure 7: simulation with the FEM of the bottles and the piping.

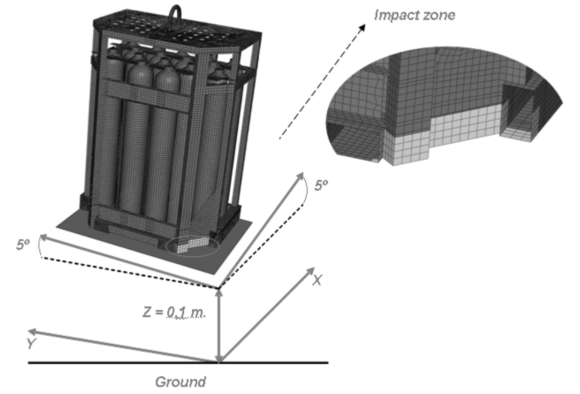

Figure 8: vertical falling load case

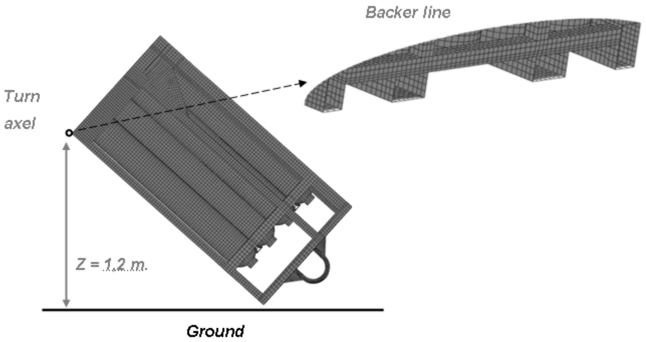

Figure 9: rotational falling load case

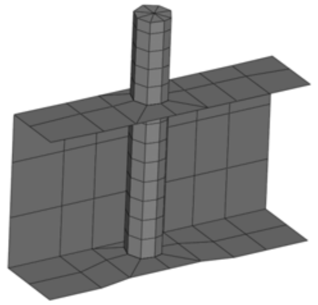

Figure 10: bolt simulation

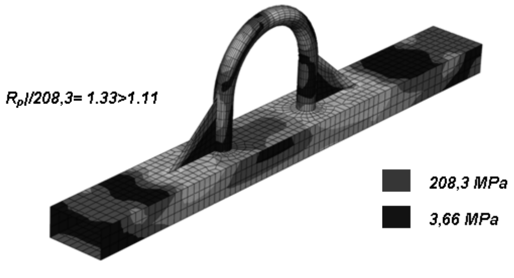

Figure 11: results in term of Von Misses stress in the central bridge and the hook.

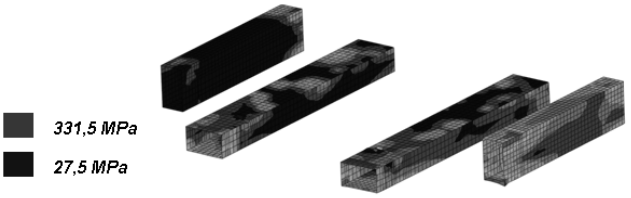

Figure 12: results in term of Von Misses stress in the vertical falling load case for the rectangular section for the forklift truck

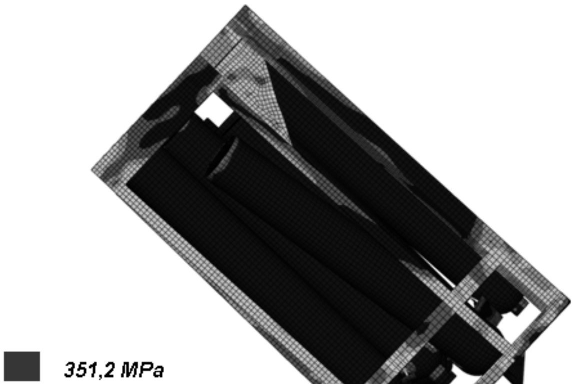

Figure 13: results in terms of Von Misses stress in the rotational falling load case.

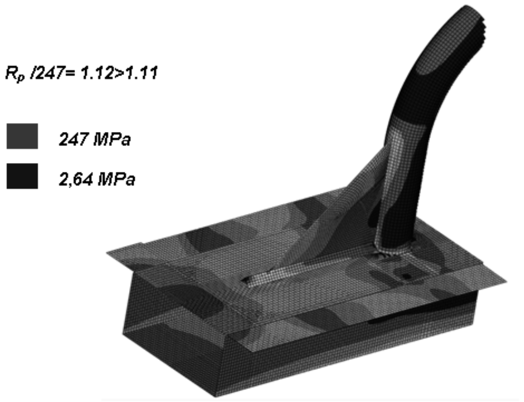

Figure 14: sub model results in terms of Von Misses stress in the vertical elevation load case.

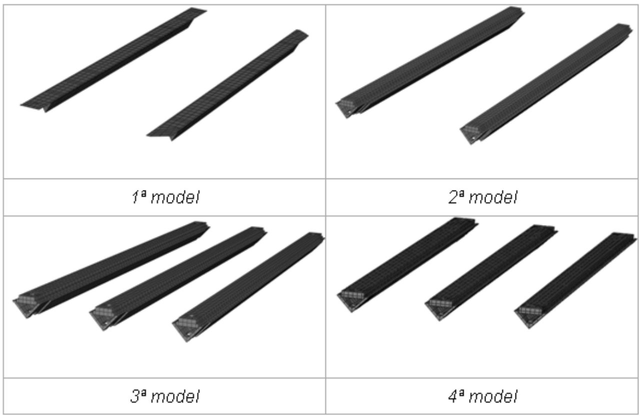

Figure 15: design model evolution of the top fastener.

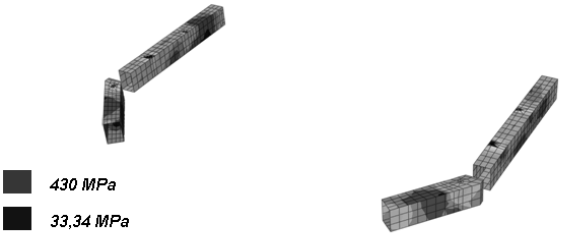

Figure 16: results in term of Von Misses stress in the rotational falling load case for the rectangular section where the bolts are connected

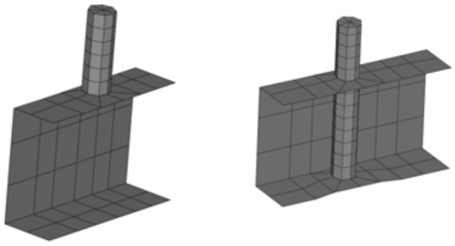

Figure 17: design model evolution of the bolt union.

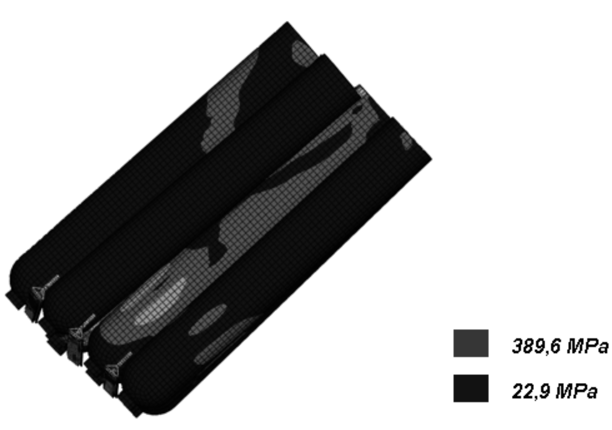

Figure 18: final position of the bottles for the rotational load case