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Agustín de Betancourt's plunger lock: Analysis of its construction through computer-aided engineering

La esclusa de émbolo buzo de Agustín de Betancourt: Análisis de su construcción mediante ingeniería asistida por ordenador

J.I. Rojas-Sola (*), E. de la Morena-de la Fuente (**)

ABSTRACT

The objective of this research is to analyze the construction of the plunger lock designed by Agustin de Betancourt in 1807. For this, a computer-aided engineering (CAE) study has been conducted, namely a static analysis by finite-elements method from the three-dimensional model built with computer-aided design (CAD) techniques using Autodesk Inventor Professional parametric software. The results show that the most unfavorable position occurs when the plunger is lifted, as in this position the elastic limits of the materials are exceeded. Therefore, the main conclusion is that the plunger lock is poorly dimensioned, although this is because the specifications sheets had only a functional or descriptive value, since the plunger lock was never put into practice. In any case, the Spanish engineer designed a novel diver-plunger lock-balance system.

Keywords: Agustín de Betancourt, plunger lock, computer-aided design, computer-aided engineering, static analysis, finite-element analysis, Autodesk Inventor Professional, cultural heritage.

RESUMEN

El objetivo de esta investigación ha sido analizar la esclusa de émbolo buzo diseñada por Agustín de Betancourt y Molina en 1807. Para ello, se ha realizado un estudio de ingeniería asistida por ordenador, concretamente un análisis estático por elementos finitos basado en el modelo tridimensional obtenido con técnicas de diseño asistido por ordenador mediante el software paramétrico Autodesk Inventor Professional, a partir de la planimetría original del expediente. Los resultados muestran que la posición más desfavorable ocurre cuando el émbolo buzo está completamente levantado, sobrepasándose los límites de elasticidad de los materiales. Por tanto, la conclusión principal es que la esclusa está mal dimensionada, aunque esto se debe a que las láminas sólo tenían un valor funcional o descriptivo, no habiendo sido llevada nunca a la práctica dicha esclusa. Sin embargo, el ingeniero español diseña un novedoso sistema de equilibrio émbolo buzo-contrapeso.

Palabras clave: *Agustín de Betancourt, esclusa de émbolo buzo, diseño asistido por ordenador, ingeniería asistida por ordenador, análisis estático, análisis por elementos finitos, Autodesk Inventor Professional, patrimonio cultural.*

(*) Escuela Politécnica Superior de Jaén, Universidad de Jaén (España).
(**) Programa de Doctorado, Universidad de Córdoba (España).
Persona de contacto/*Corresponding author*: jirojas@ujaen.es (J.I. Rojas-Sola).
ORCID: https://orcid.org/0000-0001-9001-1050 (J. I. Rojas-Sola); https://orcid.org/0000-0003-1407-5903 (E. de la Morena-de la Fuente).

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1. INTRODUCTION

The works and academic activity of Agustín de Betancourt y Molina, a pre-eminent Spanish engineer of the 19th century, served in training many engineers in Europe and helped to modernize his times. The present study, from the standpoint of engineering, analyses one of the designs to which he devoted the most time, the plunger lock, a key piece in an ambitious canal system about to be built in Europe.

The main document by Betancourt regarding canals is entitled "*Mémoire sur un nouveau système de navigation intérieure*" (Report on a new system of inland navigation) (1), its purpose being to change the transport system to canals throughout Europe. His years of work in the Inspection of the Canal of Castile (2), and the Imperial Canal of Aragon (3) constituted early experience that he would complete with his studies at the School of Bridges and Roads of Paris and with his trips throughout Europe. This gave him a full perspective of the European situation in this respect. His project was a possible economic alternative to the canals that were being designed in that period and for which he needed a new type of lock of specific characteristics: the plunger lock.

The novelty of this proposed system stemmed from the design of shallow canals for vessels of between 8 and 11 tonnes (T). This invention offered clear advantages: on the one hand, canals were simpler to construct; on the other, less water was needed to maintain the flow; and finally the pull of an 11-T barge was easy and thus the transport speed was greater. In that period, ships were pulled by teams of horses helped by small sails. However, disadvantages arose in the locks. Their maneuvering required water resources on opening and closing lock sluice gates, and furthermore it was quite slow and therefore a big barge would be preferable over several small ones. To resolve this, Betancourt designed the plunger lock, which did not consume water during the raising and lowering of the barges and required simple maneuvering manageable by a single person. This device, a key element in the new inland navigation system, is analyzed in detail below.

Finally, the French government, which thoroughly knew the navigation system proposed by the Spanish engineer, concluded that an intermediate solution could be reached between the canals existing in France and the one designed by Betancourt and thus never executed his lock (4). No studies are available on the impact of the work of the Spanish engineer on the building of canals in France (5), nor any technical study on the plunger. He is mentioned often and a different type appears within the catalogue of locks (6, 7). Although the advantages of this type of lock continues to be valid for building canals in regions with more irregular water resources, this device was never used, since it functioned only in shallow canals. The present study continues a line of research opened by authors on the works of the renowned Spanish engineer from the viewpoint of CAD & CAE techniques (8, 9, 10).

2. MATERIAL AND METHODS

The starting material was only the information available in the webpage of the Proyecto Agustín de Betancourt de la Fundación Canaria Orotava de Historia de la Ciencia (11). This webpage shows information related to this record entitled *Mémoire sur un nouveau système de navigation intérieure*, dated August 1807, presented in the Science Academy of Paris and published in 1808. It consists of a 31-page report explaining the problem as well as a favorable 11-page report from the National Institute signed by Bossut, Monge, and Prony showing 4 sheets with theory, plans, and applications. Figure 1 presents the multiview projection (elevation, top, and profile views) as well as a transverse section of the plunger lock.

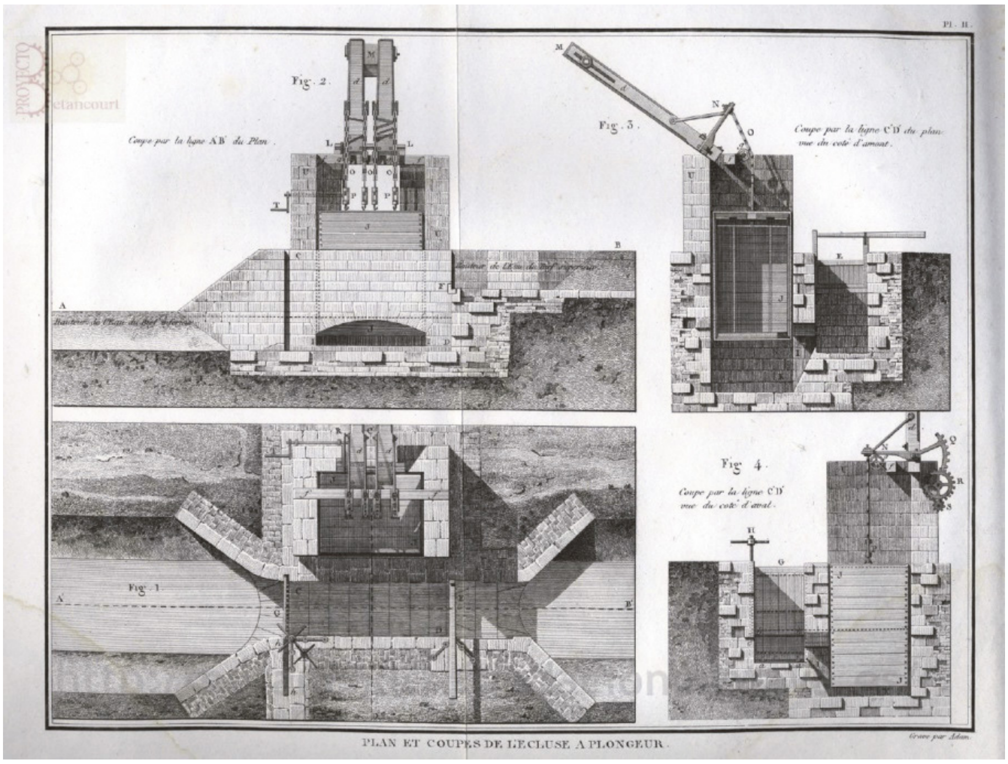


Figure 1. Multiview projection and transverse section. Image from the *Fundación Canaria Orotava de Historia de la Ciencia*.

2.1. Computer-Aided Design

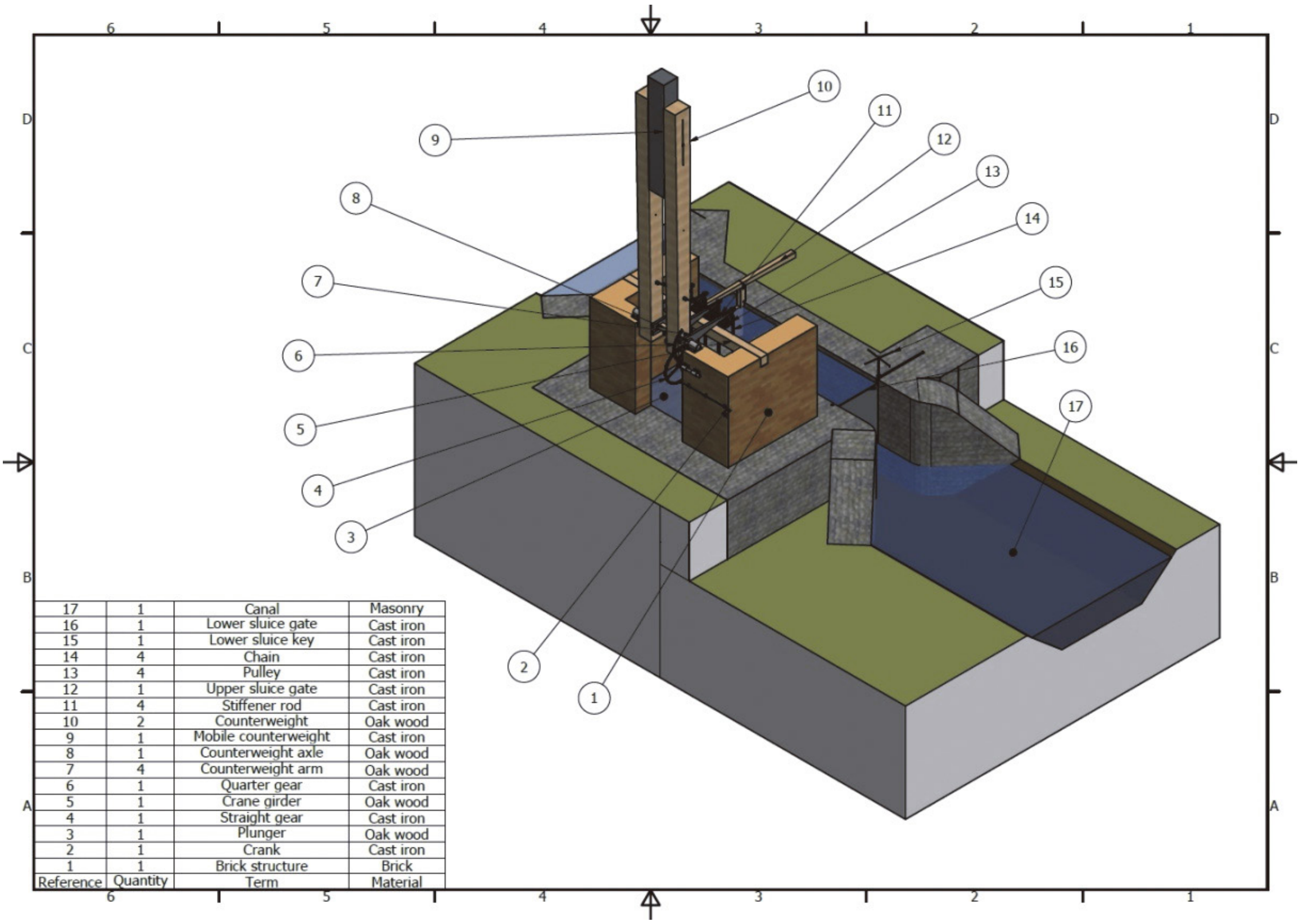
Despite the dearth of information available, descriptive or graphical, reliable results are feasible in the CAE stage, based on 3D modeling in prior studies (12), enabling an accurate static analysis. The means used for the 3D modeling was Autodesk Inventor Professional 2016 (13), parametric design software that provided digital restitutions from the information available, both graphic and descriptive, although the absence of detail has made it necessary to make a series of dimensional and geometric assumptions for the correct functioning of the invention.

As indicated in Figure 2, the plunger lock consists fundamentally of four parts: a brick structure for a number of structures over the canal itself, the sluice gates (upstream and downstream of the lock), the counterweight system that raises and lowers the plunger, and the plunger system with the elements that facilitate its movement.

The lock is situated over the canal [17], which is trapezoidal in section and has a change in level of 2.6 m. In the front of the drop a material resistant to drag is needed, since as the canal section diminishes and loses height, the kinetic energy of the water increases. The walls of the canal in the lock are of made of reinforced stone. Parallel to the narrow portion, where the drop is situated, stands the brick structure [1] inside of which a shaft is dug to a depth sufficient to house the plunger [3]. This shaft meets the central part of the canal through an opening in the form of a low arch to permit the passage of water through the canal to the shaft and vice versa. The sluice gate [12] situated upstream of the lock is the gate type, blocks the entire section of the canal, and rotates over its axle to permit the water of the upper zone to pass to the lower one. The sluice gate opens in the opposite direction of the water course so that the very current helps seal off its passage.

Downstream, the mechanism is more complex. The sluice gate [16] is metal and moves on wheels through the groove transversely crossing the bottom of the canal. The sluice is opened and closed by a key [15] on both ends. This key is simply a vertical axle with a straight gear on the end with the cogs on the lower part of the sluice gate in such a way that, when the axle turns, the sluice gate moves across the canal, closing off the passage of the water.

The counterweight system is articulated. The counterweights [10] are supported by a mobile axle [8] that allows the rotating of the counterweight on one end. This pair of counterweights holds another [9] between them, this third one being made of iron and having the freedom to be adjusted higher or lower in order to provide the position of equilibrium with the plunger. Furthermore, the system is quite heavy and therefore this axle has special iron attachments. The arms [7] joined to the counterweight axle serve to pull the plunger at four locations, and, so that they function correctly, the rod [11] connected to each of them provides rigidity and reinforces the structure.



Reference	Quantity	Term	Material
17	1	Canal	Masonry
16	1	Lower sluice gate	Cast iron
15	1	Lower sluice key	Cast iron
14	4	Chain	Cast iron
13	4	Pulley	Cast iron
12	1	Upper sluice gate	Cast iron
11	4	Stiffener rod	Cast iron
10	2	Counterweight	Oak wood
9	1	Mobile counterweight	Cast iron
8	1	Counterweight axle	Oak wood
7	4	Counterweight arm	Oak wood
6	1	Quarter gear	Cast iron
5	1	Crane girder	Oak wood
4	1	Straight gear	Cast iron
3	1	Plunger	Oak wood
2	1	Crank	Cast iron
1	1	Brick structure	Brick

Figure 2. Overall plan of this lock, indicating all its components.

Also, the movement system has a set of gears moved by a crank [2], and so that such a heavy mechanism could be lifted, Betancourt projected a gear ratio of 1/64, using two large gears. The crank has a straight gear on one end with 6 cogs, which meshes with another straight gear of 144 cogs [4] the latter being joined solidly on its end to a small one of 6 cogs. This meshes with a quarter gear [6] joined solidly to the counterweight axle, which has 16 cogs so that, to change from one extreme position to the other requires 16 turns of the crank.

Finally, the plunger system is joined to the counterweight by chains [14] and for it to move vertically a system of pulleys was designed [13] in such a way that the chain always pulls the plunger vertically. Also, over the shaft inside the brick structure, lies a crane girder [5] with 4 built-in pulleys guiding the chains, lowering vertically until reaching the plunger. The chain and the plunger are joined by rings placed on the plunger itself and, so that the four chains have the same stress, the end of the chains is connected to a double-hook turnbuckle.

The novelty of Betancourt's lock, as will be discussed below, was the lock system designed to raise and lower the water level without using significant amounts of water. For this, the engineer designed a submergible structure (plunger) that displaced the water from the shaft to flood the canal of the lock where the barge was located. As shown in Figure 3, when the counterweight is vertical, the plunger is submerged, displacing the water from the shaft to flood the navigation canal. On the contrary, when the counterweight is horizontal, the plunger rises and the water returns to the shaft, emptying the navigation canal. These are the two extreme positions of the device on which the CAE study is made.

2.2. Computer-Aided Engineering

2.2.1. Preprocessing

For the simulation by CAE, the first stage consists of preparing and simplifying the model in order to facilitate the analysis. The objective of this first step is to establish calculation conditions that can be assumed by the computer without compromising the analytical results. On the other hand, of the multitude of positions that could be analyzed, the 2 extreme ones are chosen, and thus the invention is analyzed under its most unfavorable conditions.

- First of all, the terrain was eliminated, as were the upper and lower sluice gates, the brick base, and the water of the canal.
- For the calculation of the structures, water has physical properties that escape analysis. Thus the plunger is a wooden structure containing several cubic meters of water. This element, which escapes structural analysis, has to be replaced by a load on the bottom of the box that simulates its weight.
- On eliminating the retainer wall on which the structure is situated, it is vital for the elements that are bolted to and supported by the wall continue as such. Therefore, the surfaces in contact with the wall must be defined as fixed or built-in supports, depending on the relation that they have with the wall.
- Finally, when the plunger is submerged in the shaft, it exerts no load on the chains. Thus, it was eliminated from the analysis so as not to distract attention from the structure that truly undergoes stresses without influencing the results.

Lastly, it bears indicating that no load was added by the operator of the machine exerting force on the crank to raise and lower the counterweights. The system is in a position of constant equilibrium, as Betancourt mentioned in his report, and therefore the maneuverability of the mechanism requires only minor forces, negligible in comparison to the dozens of tonnes that the counterweights and the plunger weight. Therefore, to include moments of inertia in the crank, what will affect the axles does not translate into appreciable stresses compared to those caused by the loads of the system, but it does complicate the analysis.

2.2.2. Assignment of materials

The next stage consists of assigning a material to each component of the ensemble. However, in the original documents

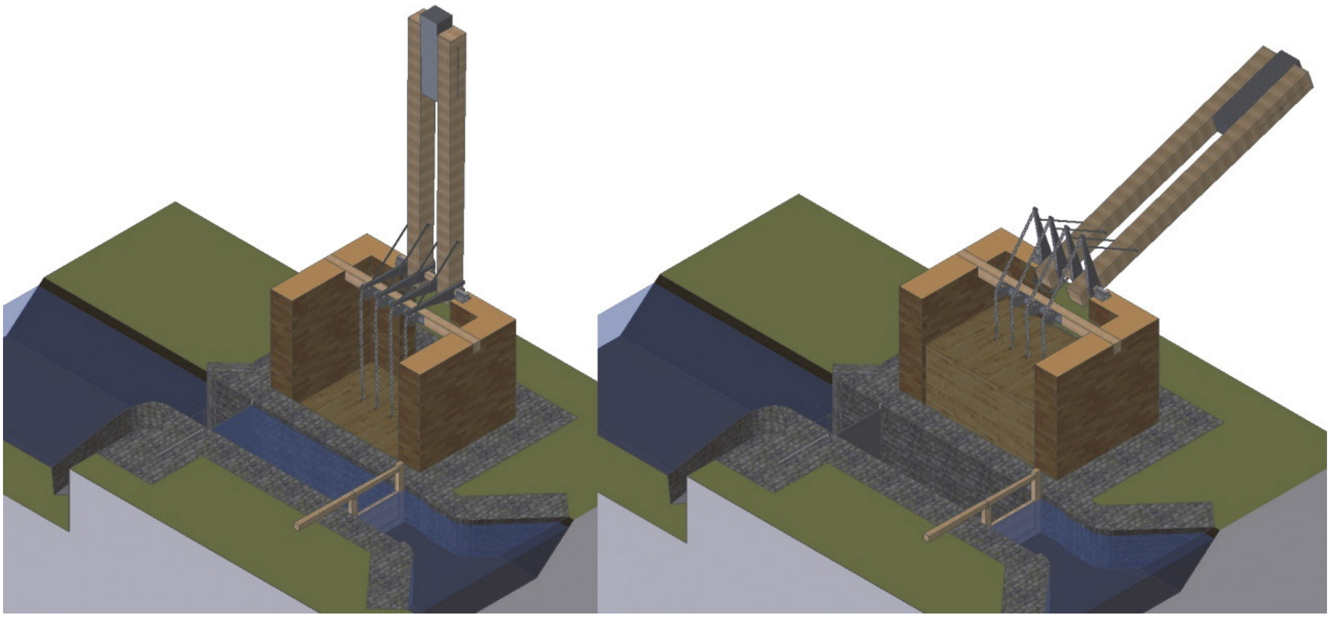


Figure 3. Extreme positions: plunger in its lowest position (left) and in its highest position (right).

on the lock the materials are not specified. The specification sheets show that the device has wooden and metal parts, but the exact materials are not specified. Furthermore, it is known that the lock was never built and therefore there are no later documents to elucidate this matter. For all these reasons, simple materials were assigned as those that Betancourt would have had access to in that period. The materials chosen appear in the material library provided by the software itself, and they are the ones that appear to best fit the requirements of each element: cast iron for the metal pieces, and oak for the wooden parts.

The software used (Autodesk Inventor Professional) provides the physical properties of each material: thermal, mechanical, and elasticity limits. The cast iron is isotropic and its physical properties are: Young modulus (210,000 MPa), Poisson coefficient (0.30), density (7,150 kg/m^3), and breaking stress (758 MPa). Oak wood has physical properties that depend on the direction in which the study is made as it is an orthotropic material. The most favorable conditions arise when the material works in the direction of the grain, as in the other two orthogonal directions the physical properties are more limited. Therefore, it is important in the wooden parts the main axes are always in the direction of the grain: Young modulus (210,000 MPa), Poisson coefficient (0.30), density (760 kg/m^3) and breaking stress (41 MPa).

2.2.3. Boundary conditions

After the assignment of the materials and the removal from the simulation of any elements that could not be submitted to static analysis, the following step was to define the boundary conditions of the elements that have a support function. Each support can function in a certain manner based on the degrees of freedom that define their mobility in such a way that the definition of this mobility affects the static analysis of the ensemble. The supports can be built-in, articulated, mobile, or rollers. Thus, the software determines the boundary conditions according to the freedom of movement in each component of the support.

First, the elements that have no freedom of movement are defined, i.e. the surfaces that are built into the brickwork, such as the supports of the different axles (Figure 4, upper left), as well as those that are bolted to the brick wall (Figure 4, upper right). Second, the articulations or elements that have freedom to rotate were defined. These components cannot be moved longitudinally but can rotate, and therefore they have a lower degree of freedom (rolling restriction). These include the hinges of the counterweights, the pulleys, and the supports fixing the axle (Figure 4, lower left). Finally, the support surfaces having freedom of movement in only one direction were defined, but there were none in the lock.

The boundary conditions did not depend on the two extreme positions proposed for the static analysis, but the contact points between the parts did change depending on the position studied. Autodesk Inventor Professional automatically detects the contact between the contiguous surfaces provided the surface is not excessively complex. When the plunger is completely out of the water, the chain rests in its middle on the pulley. However, the contact between the chains and the pulleys deserves careful attention. Despite that in the model several links were defined as being tangent to the pulley, in

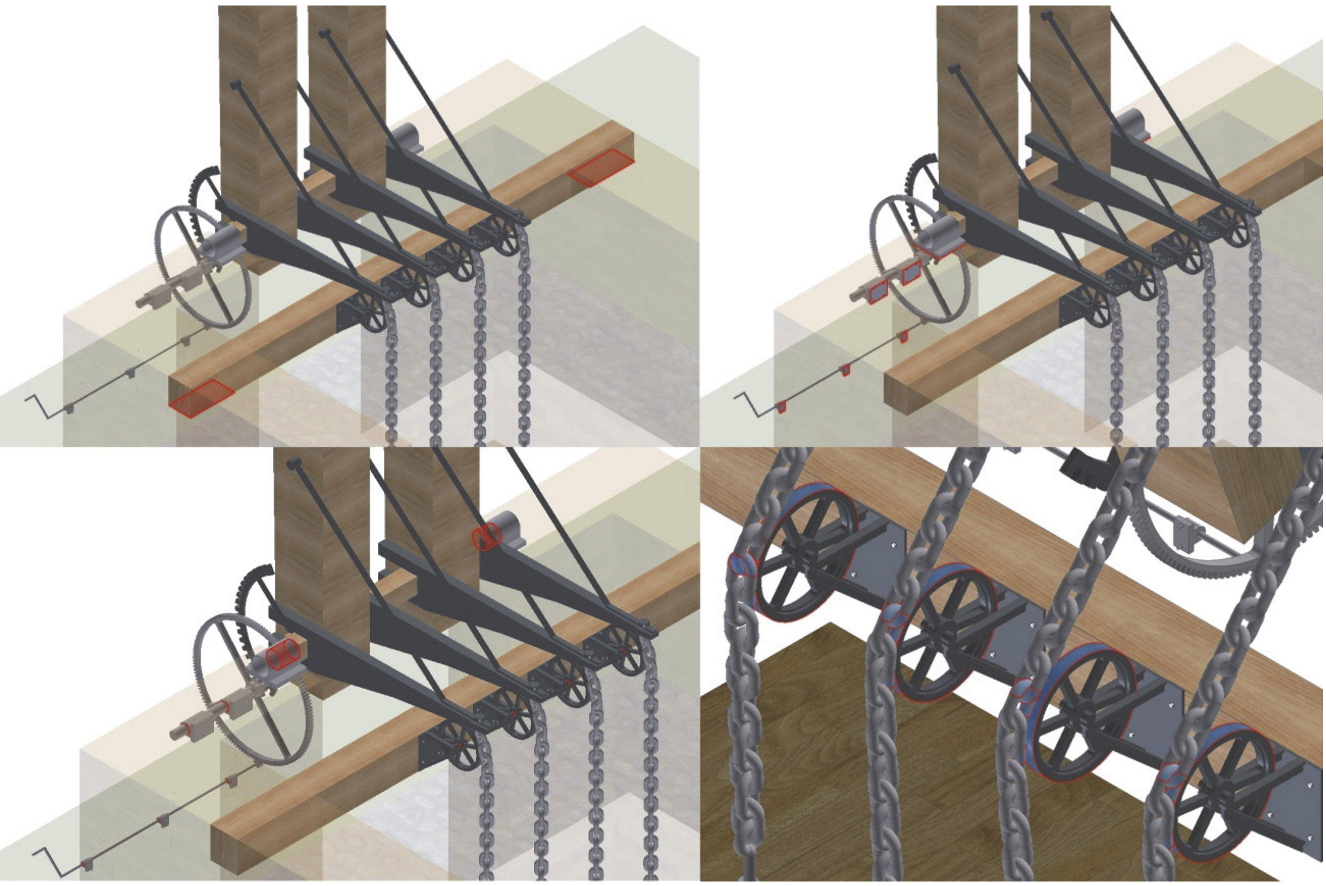


Figure 4. Types of restrictions: built-in (upper left), bolted (upper right), rolling (lower left), and manual activation of contacts (lower right).

fact, because of the geometry of the two elements, their positioning is not correct and therefore it is necessary to define them manually. This must be done for each of the four chains (Figure 4, lower right).

2.2.4. Forces applied

The next-to-the-last stage before simulation consists of defining the forces that will act on the ensemble. The stress that the lock will undergo is fundamentally gravity, but, as explained in the pre-processing section, as water could not be included in the stress analysis, the water remaining inside the plunger must be replaced by an equivalent force that will act as uniform pressure on the lower surface of the plunger. Also, when the plunger is submerged, it does not act and therefore it can be considered only when the plunger is raised.

The software used allows gravity and its direction to be defined with precision. If the direction of the axes in the CAD model is used, the gravity vector is defined as an intensity of ($9.81\ m/s^2$) in the direction of the Z axis and in the negative sense. If it is defined in this way, without being determined at a specific point, the software itself represents the gravity applied in the center of the masses of the ensemble despite affecting all the elements (Figure 5, left).

On the other hand, the pressure on the bottom of the plunger (Figure 5, right), modeled with an empty box, corresponds to the pressure exerted by a volume of water equivalent to the inside volume of the box. The dimensions of the interior of this plunger are 4.713 x 3.413 x 4.730 m, and therefore its volume is 76.0842 m^3. The fact that the water density is 0.998 g/cm^3 gives a water mass of 75,954.925 kg.

Thus, the force that this mass of water exerts on the bottom of the plunger proves to be:

$$F = m \cdot g = 75{,}954.925\ \text{kg} \cdot 9.81 \frac{m}{s^2} = 745{,}117.81 N \qquad [1]$$

Therefore, the pressure derived from this force F applied on the surface S is:

$$\sigma = \frac{F}{S} = \frac{745{,}117.81\ N}{16.085\ m^2} = 46{,}323.76\ Pa \qquad [2]$$

2.2.5. Meshing

The last step before the simulation consists of discretizing the model by preparing a geometric mesh that is adjusted realistically to the geometry of the mechanism. At first, the smaller the size of the mesh the better the fit to the reality represented. In principle, the smallest elements need a mesh size far narrower than they do the large elements, but, as demonstrated, exceptions must be made in this general rule. On the other hand, a smaller mesh size is advisable for the places where the forces are applied directly, since the distortion of the geometry of these places has great repercussion in the overall piece, since it distorts the stress from its origin.

Autodesk Inventor Professional automatically discretizes the model, although the variables for the building of the mesh can be modified. The default values used are of medium size for the mesh of 10% of the length of the element to be discretized, a minimum size of the element of 20% the medium size, a modification factor with a value of 1.5, and a maximum turn angle of 60º. For the present simulation, these values are completely assumable although afterwards it will be confirmed that for certain elements this mesh is excessive (Figure 6).

In addition, the software enables a mesh to be made manually in order to establish a given mesh on specific surfaces. It is not necessary to refine the mesh in the areas in which the forces are applied because the only one that is applied to a specific body, the pressure at the bottom of the plunger, is applied to a large surface area of simple geometry.

On the other hand, in the present study, there is an almost insurmountable problem with the chains that raise the plung-

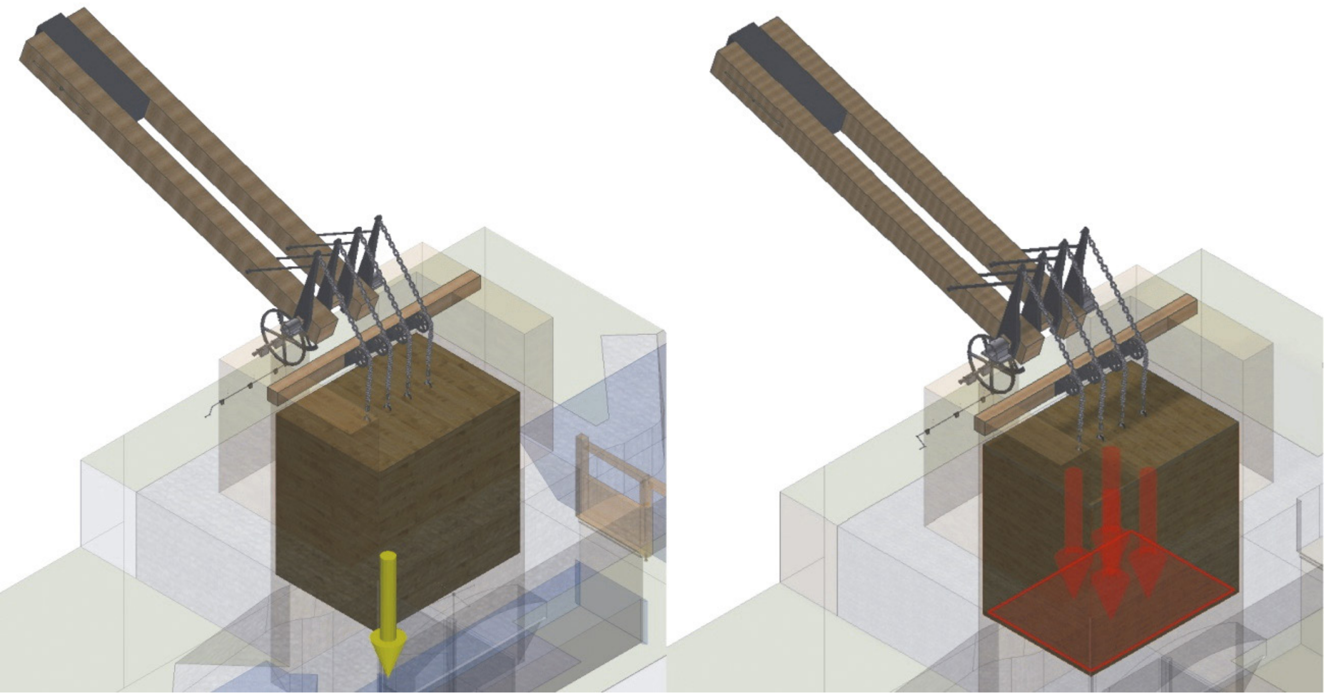


Figure 5. Force of gravity applied in the center of the masses (left) and the uniform pressure in the bottom of the plunger (right).

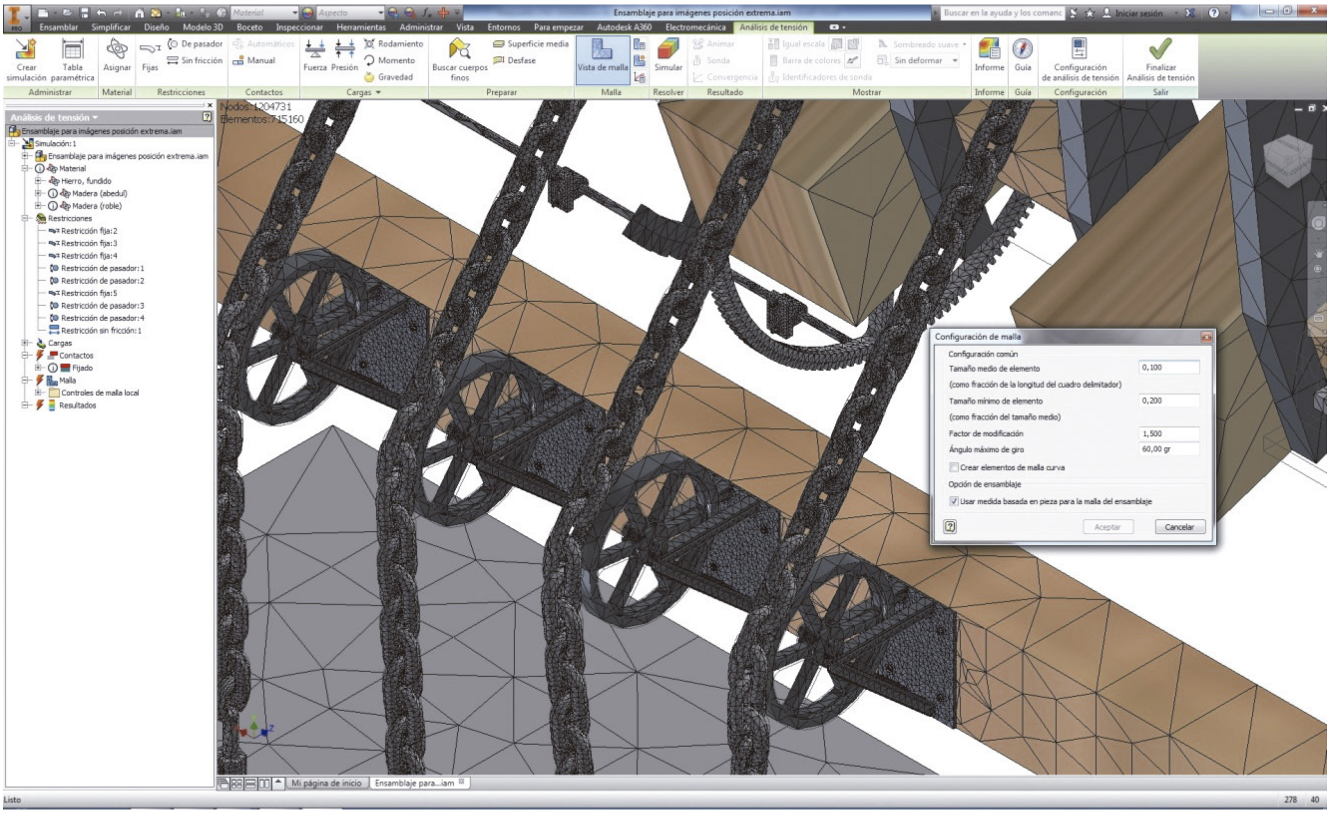


Figure 6. Meshing process.

er. The links of these chains were defined individually by the sweep in the circular section over a tracing of a tight curve, this toric geometry being in itself complex for the computational analysis. For the assembly of the links, one to another, it was firstly necessary to define a pair of points on the surface of the link, one in the inside-upper zone, and another in the inside-lower zone of the other, and then, by opposition, restricting the upper point of the link with the lower one of the other. Each link is relatively small and its mean mesh is some 10% of its length. Furthermore, since it is a curved element, the density of the mesh is still greater in the inside zone of the link, precisely in the inner curve where the point of contact between links was defined, so that for the computational analysis the contact between links continues to be situated at a point and therefore the results of the stresses are not real, with values far greater than real ones.

Therefore, the control of the local mesh in this case permits a greater mesh size so that the point of contact presents a greater surface area and diminishes the stresses. This action softens the problem presented although it does not resolve it, adopting a mean mesh size of 20 mm on the upper and lower surface of the link. Figure 7 shows the mesh on the links after changing its size. It can be appreciated that, despite the in-

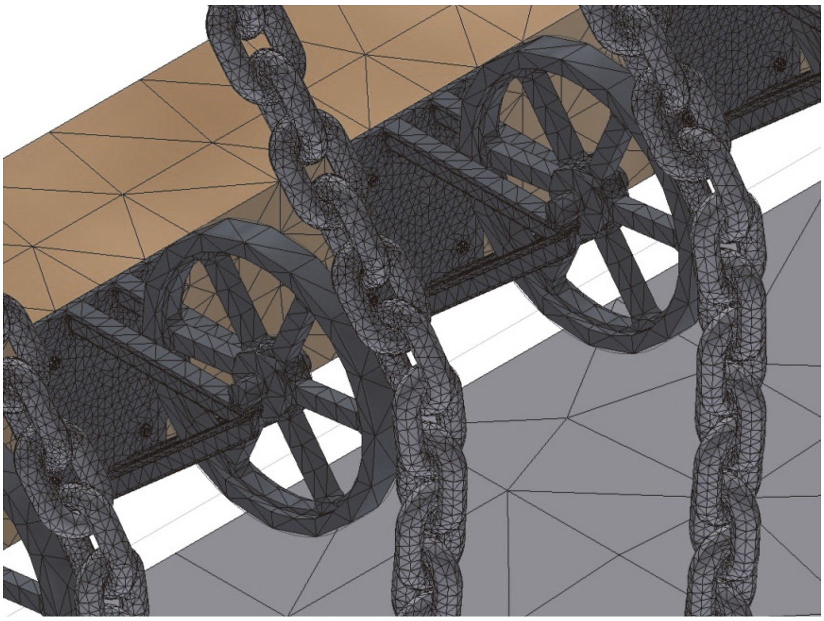


Figure 7. Discretization found after refining the chain links.

creased mesh size, on the inside of the link the mesh is denser than on the outside because of the curved geometry.

3. RESULTS AND DISCUSSION

The results of the simulation are presented in the form of von Mises stresses, safety coefficient, deformation, and displacement (Figure 8). The static analysis was made based on the extreme positions of the lock; that is, when the plunger is completely lowered and when it is at its highest position.

With respect to the von Mises stresses, it can be seen that when the plunger is lowered, in general, there is no part submitted to great stress (Figure 9, left). Thus, the contact between the pulley on the right and the chain is the point of greatest stress, with a value of 219.3 MPa. On the contrary, when the plunger is raised, it can be appreciated that many elements work at very high stresses (Figure 9, right). The part subjected to greater stress also proves to be the contact point between the pulley and the chain, but just the opposite, i.e. the pulley on the left. The link that is in contact is submitted to a stress of 2,643 MPa, far higher than the breaking stress (Figure 9, right).

A detailed observation of other places also shows that several points are subjected to excessive stresses with values of nearly 2,000 MPa; particularly the link at the end of the counterweight arm (1,859 MPa), and the turnbuckle that connects the plunger to the chain (1,843 MPa).

These elements are excessively stressed because of the density of the mesh, since currently a chain of cast-iron links of 25 mm in diameter lifts, with sufficient safety, a mass of 200 T, while in the present static analysis, the links of almost 2 inches break on supporting a stress exerted by a similar mass. This helps explain that it is not a dimensional problem but one derived from the analysis itself. Furthermore, it is known that the breaking stress for compression in a direction parallel to the grain of the oak wood is some 41 MPa, and that of cast iron 758 MPa. Thus, the results show that several elements of the ensemble work above these limits and thus would break.

A second factor that indicates to what point the lock is working above its possibilities is the safety coefficient. This coefficient is calculated as the division between the von Mises stress for each element and the elastic limit of that element. To work with a coefficient of a unit would mean that the element is working at the elastic limit of the material and therefore runs the risk of breakage. The scale of the safety coefficient goes from 0 a 15, estimating that an element is correctly sized when working in a range of 2 to 4.

Figure 10 shows the safety coefficient when the plunger is in the two extreme positions. When it is at the lowest point, almost the entire ensemble has a very high safety coefficient. The point presented by a lower safety coefficient (Figure 10 left) is the axle of the counterweight, with a value of 2.91. Therefore, the whole of the mechanism works far from its breaking point, and in fact it could be considered oversized.

However, when the highest position of the plunger is analyzed, the result changes notably. According to Figure 10 (right), some of the elements work under the optimum for the design, and even below unity. The element that is worst dimensioned, according to this analysis, is the arm of the wooden counterweight situated on the left end. The point at which this makes contact with the first link of the chain is the least safe, with a value of 0.18. However, this element is not the only one that calls attention to itself for it low safety

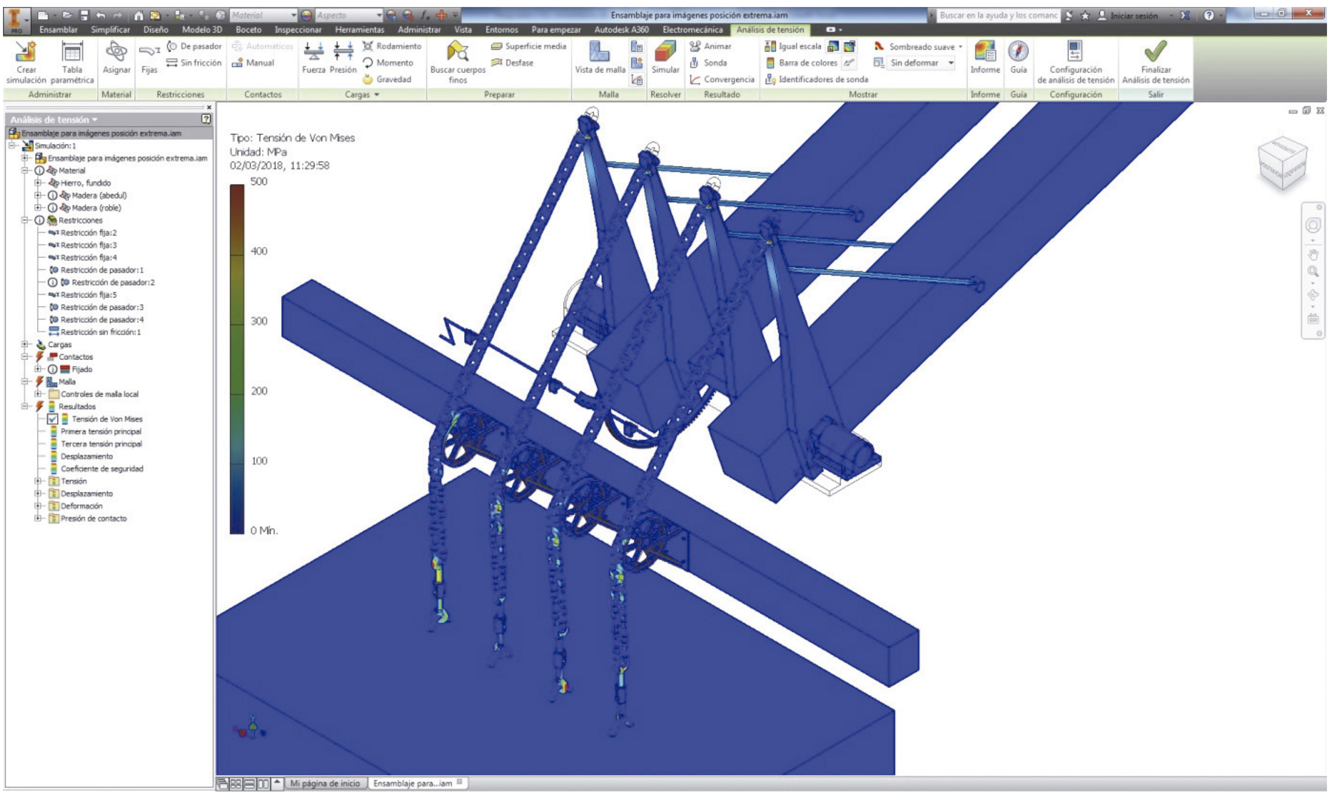


Figure 8. Stress analysis process.

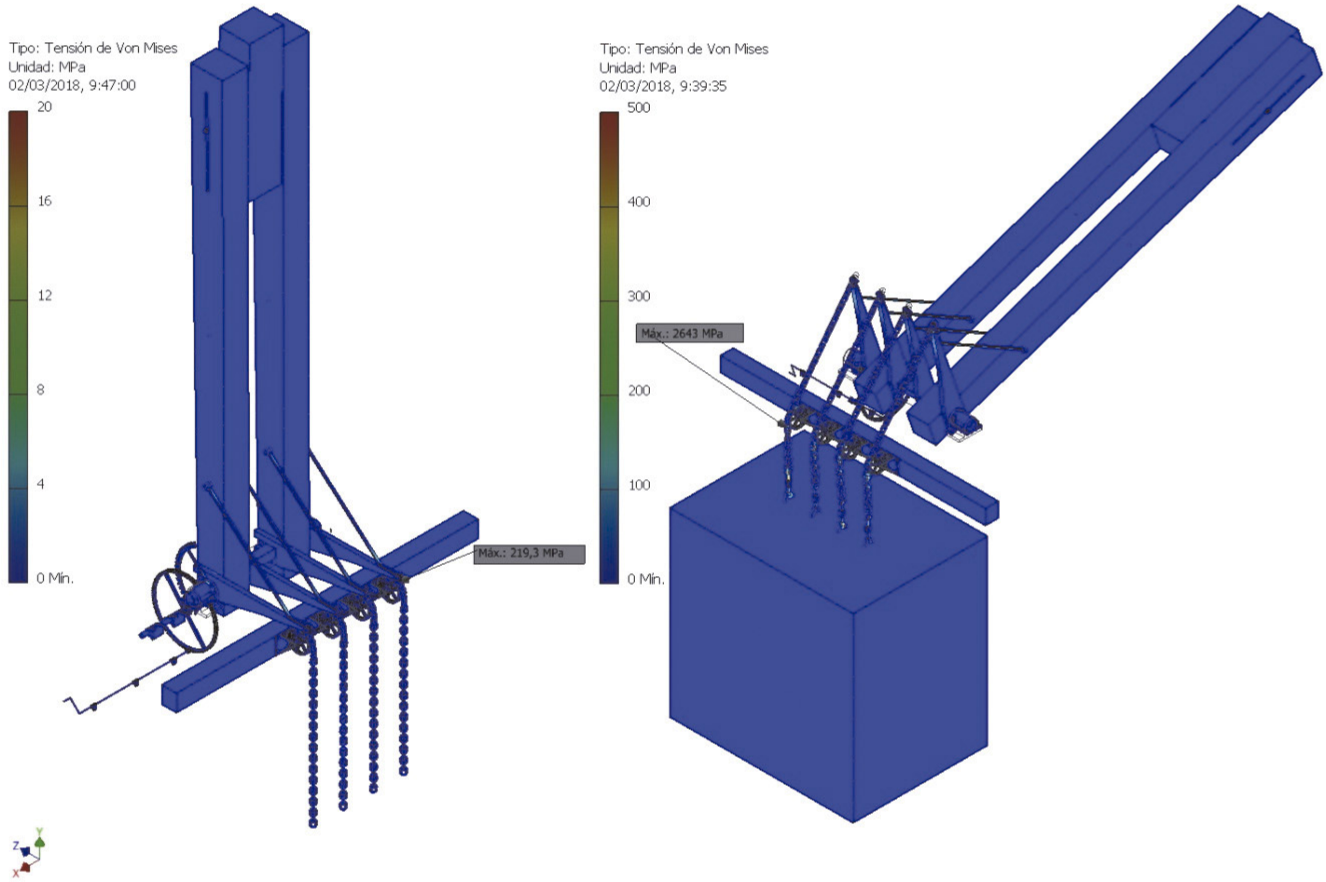


Figure 9. Von Mises stresses with the plunger in the lowest position (left) and in the highest position (right).

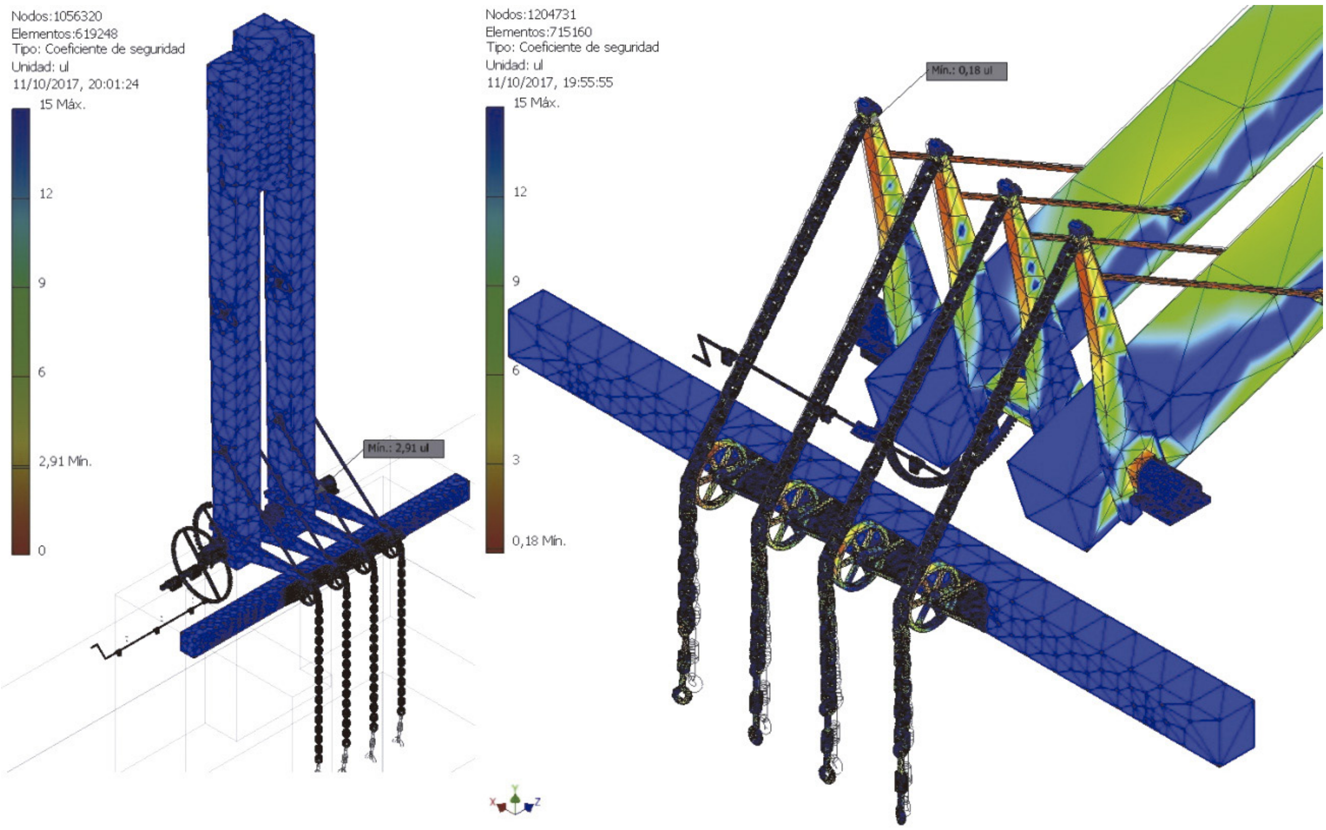


Figure 10. Safety coefficient with the plunger in the lowest position (left) and in the highest position (right).

coefficient, but the rest of the arms, the metal bracing, the chains, the pulleys, and their supports all work with values of between 0.5 and 2. In this case, it is not only a question of software problems on analyzing the chain but rather that the invention is badly dimensioned in terms of the plans used to build the 3D model of the ensemble.

Another striking point is the bolt of the mobile counterweight. This bolt would also be badly dimensioned to meet the force caused on fixing the counterweight of almost 10 T situated between the two wooden counterweights. Its safety coefficient is also 0.18. Probably, by re-dimensioning both the axle as well as the bolt to make them stronger, the problem could be solved.

On the other hand, in the case of the equivalent deformations (division between the size of the deformation and the length of the element), similar results are not found in the two previous cases. On the one hand, when the plunger is in the lowest position, the ensemble does not present great deformations, resulting in a higher deformation in the support of the chain with the pulley on the right with a value of 0.00159, this proving almost imperceptible. On the contrary, when the plunger is in the highest position, substantial deformations results with a maximum value of 0.1349, representing a deformation of 13.49% of the size of the element. This deformation is located in the hook of the turnbuckle and the hook of the plunger.

Finally, the greatest displacements, when the plunger is in the lowest position, occur in the upper part of the counterweight, where they hardly reach 4 mm, while when the plunger is in the highest position, the greatest displacements are located in the plunger itself, reaching a displacement of 750 mm, an excessive displacement that never would occur, since the walls of the shaft would impede it, but this brings out the problem in this extreme position (Figure 11).

4. CONCLUSIONS

This study presents the results of the static analysis by CAE techniques applied to a 3D model of a plunger lock designed by Agustín de Betancourt y Molina in 1807, and undertaken with Autodesk Inventor Professional.

The high number of components, their complexity, and the materials used in some parts, justified a pre-processing to simplify the ensemble before the simulation, without affecting the results found but significantly diminishing the computational requirements and the simulation time. However, based on the results, the simulation of some elements (fundamentally the chains) is a pending challenge for the software used, this being a common problem in most cases.

With respect to the results found, it bears noting that the highest stresses borne by the ensemble occurred when the plunger is raised, and therefore the entire structure should support the weights of this plunger and the counterweight (a value close to 200 T). Also, it was corroborated that some of the elements undergo excessive stresses, although the study of the safety coefficient of the ensemble is striking in indicating that it is not a problem exclusively due to the limits of the software itself but that Betancourt's design, according to the dimensions and proportions of the existing plans, is poorly made, and the deformations and displacements only confirm this conclusion.

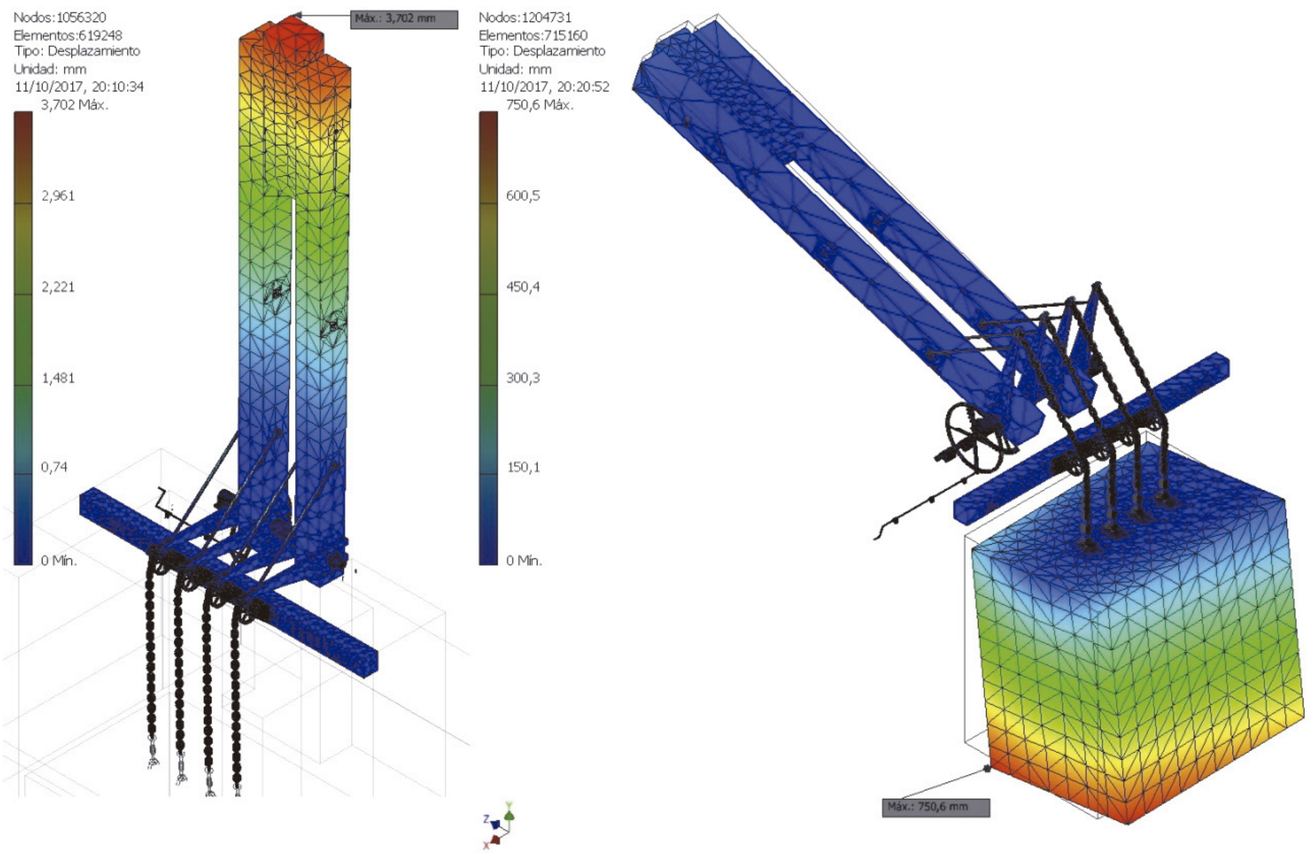


Figure 11. Displacement with the plunger in the lowest position (left) and in the highest position (right).

The historical analysis of this invention has shown that the plunger lock was never put into practice. The drawings used by Betancourt were not meant to be a scale model with which to put the invention into practice, but rather to serve a double purpose: on the one hand, to act as a letter of presentation of the project in the case of possible sponsors and, on the other, to reaffirm the theoretic solution that the engineer had presented in his report, and thus the material was more conceptual than technical. A careful reading of the report and knowledge provided by the present study could give rise to a study to explain why Agustín de Betancourt designed his lock with erroneous dimensions.

The findings presented here do not at all diminish the ingenuity of the invention nor the existence of a theoretic solution that could materialize the idea of the Spanish engineer: an easily managed lock, without energy consumption, which would take maximum advantage of water resources of the canal from a system in equilibrium.

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