THE SCULPTURE OF THE CHRIST OF THE BLOOD: STRUCTURAL MECHANICAL ANALYSIS BASED ON 3D MODELS AND VIDEO TECHNIQUES FOR THE STUDY OF RECURRENT PATHOLOGIES

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ABSTRACT

The Christ of the Blood is an emblematic work of Spanish baroque sculpture. A sculptural heritage from the 17th century, unique for its symbolism and turbulent history. It was badly damaged during the Spanish Civil War and was divided into thirty fragments, which were recomposed by important local sculptors of the time through complex interventions. As is tradition, after the war, the sculpture has continued to be paraded in a procession every year on the occasion of Holy Week. The movements derived from this parade affect the integrity of the sculpture, although in a particular and critical way on the right foot, which requires recurrent interventions from the 1940s to the present day. There is a dilemma between tradition and preservation, between devotion and integrity. The studies and tests carried out so far are limited to the evaluation of the state of the structure, the materials and the application of new conservation treatments, but they do not contribute decisively to the prevention of its degradation. The research presented here aims to develop a dynamic structural study of the forces and stresses to which the sculpture is subjected during its annual parade. To do this, computer simulation by finite elements is chosen, which requires a three-dimensional model which is available as a result of previous research. At the same time, advanced video measurement techniques are used to obtain initial data for the simulation process, such as maximum acceleration. Finally, possible solutions are provided that allow the repair, prevention and conservation of this invaluable heritage asset, as well as a technical assessment and economic investment of the application of each of them.

KEYWORDS

3D digitizing; Video measurement technique; Computerized simulation; Structural mechanical analysis; Religious heritage.

1. Introduction

The Christ of the Blood is an emblematic work of Spanish baroque sculpture. It belongs to the Archconfraternity of the Precious Blood of Murcia and was made by the sculptor from Strasbourg Nicolás de Bussy (h. 1640-1706) in 1693. It is taken out in procession every Easter Wednesday afternoon, being a Passion work of great devotion and esteem in the Murcian Holy Week. It is an unicum, especially in its iconography, showing Christ carrying the cross while he steps on the mystical winepress, formed by the blood that flows from his wound and that collects a depressed little angel, a medieval representation carried to the sculpture in three dimensions, in polychrome cypress wood. In it he combines the exaltation of the Passion of Christ as well as the Eucharistic sacrament, counter-reformist values in which the sculptor delves with deep dramatism into the theatrical aesthetics of the Baroque. The Christ, when he parades in the procession, gives the impression that he is walking while carrying on his shoulders the cross, which symbolizes the burden of the sins of the world [1].

Unfortunately, it was a work that was quite badly treated during the Spanish Civil War, practically destroyed, but reconstructed thanks to two sculptors, Juan González Moreno (1908-1996) and José Sánchez Lozano (1904-1995). It has subsequently undergone two important restorations, one in 1991, in the workshops of the Museum of Fine Arts of Murcia, and between 2003 and 2004 in the Restoration Centre of the Region of Murcia.

The sculpture has a deep structural problem, especially in its right leg, where it receives loads that make it an area of special fragility. In addition, it was one of the most fractured areas in the destruction it suffered during the Civil War. The interventions carried out there have taken special care in this sector. Its deterioration always causes great concern to stewards, brothers and faithful men, hence the need to study possible solutions to stop the constant wear that can lead to a situation of irreversibility and loss.

The destruction of works of art during the Spanish Civil War (1936-1939) took place in a climate of iconoclastic and anticlerical exaltation. Much of the historical-artistic heritage disappeared forever, although after the war restitution and recovery work was carried out, as occurred with the Christ of the Blood. The sculpture, mutilated, was scattered in thirty parts, collected by the sculptor Clemente Cantos. His head had been torn off and burned, he suffered multiple fractures and large cracks opened up, especially in his chest and the one that tore part of the twin and ankle from his right leg, his feet were burned and there was a great loss of support [2]. Juan González Moreno assembled the sculpture at the Museo Provincial de Murcia in September 1936 (Fig. 1.b). Inside the box-shaped cavity in the area of the back, (Fig. 1.a) where the cross was to be anchored, the sculptor found the famous handwritten card written by Bussy, where he expressed his deep religious beliefs and mystical feelings when making his work. This box also has its importance from the structural point of view. At the time, this emptying of the sculptures was a common procedure to reduce weight and improve stability by allowing the vertical axis of the center of masses to be adjusted to the exact center of the base. The burnt head of Christ was recovered years later, in 1940, as a woman bought it from some children who played football with it, and with the help of a friend they hid it during the contest. At Christmas 1940, the sculptor Sánchez Lozano restored the entire sculpture, giving it back its original appearance.

The foot area was always problematic. González Moreno recomposed it and stuccoed it, prior to Sánchez Lozano's intervention, but it is known that in 1946 the latter was consulted about placing a supplement for the foot, which must have given stability problems. Years later, around 1958 and 1959, Juan González Moreno would intervene in this area, as María Dolores Piñera has shown [3]. In the files of the brotherhood there is no allusion to such an action, but a photograph of this date, in which the Virgin Mary of the Marraja Brotherhood of Cartagena appears in the foreground, can be seen in the background of the workshop, the Christ of the Blood with his head covered and some intervention on his right leg. Therefore, although not documented in the files, the sculptor from Aljucer must have restored the piece.

Already in the intervention of 1991 in the workshops of the Museum of Fine Arts of Murcia, the crack of the leg had to be fixed, which was still giving problems, and work was done to give stability to the image. To do this, a stainless-steel rod was included to serve as a counterpoint and absorb the vibrations and movements of the wood in the procession (Fig. 1.c) [4].

In the 2003-2004 restoration, it was well documented how the sculpture had been made by Nicolas de Bussy and what the restorers' interventions had been. Juan González Moreno limited himself to assembling the fragments and stuccoing the joints and cracks, as can be seen in the 1936 photo (Fig. 1.a). Sánchez Lozano restored the entire work, intervening especially in the burnt head and in the anchoring system of the cross on the back, after closing the box. At this time, it was noted that the metal rod was in good condition and had not caused any deterioration in the wood.

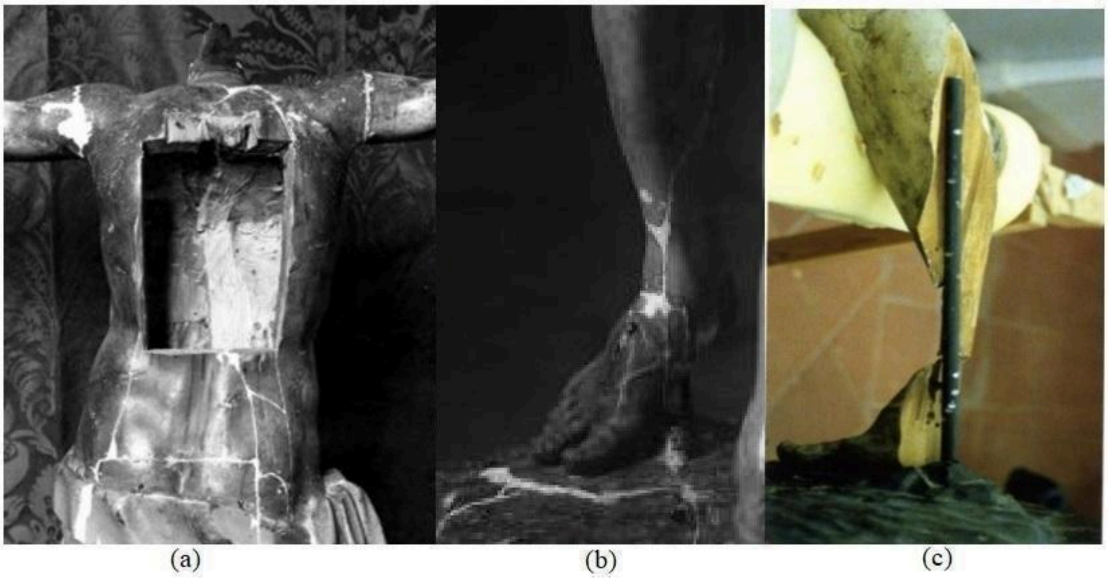

Fig. 1. (a) Box-shaped cavity in the area of the back. Source: J. Bernal, F. López Soldevila et al., Cristo de la Sangre Nicolás de Bussy. La imagen restaurada, Ayuntamiento de Murcia, Centro de Restauración de la Región de Murcia, Murcia, 2004, p. 11. (b) Bottom rear image of the 1991 restoration. Source: Archivo Regional Región de Murcia-ES.30030.AGRM/341-FOT_NEG,046/02. https://archivogeneral.carm.es/archivoGeneral/arg.muestra_detalle?idses=0&pref_id=463777. (c) Placement of a rod in the right leg in 1991. Source: J. Bernal, F. López Soldevila et al., Cristo de la Sangre Nicolás de Bussy. La imagen restaurada, Ayuntamiento de Murcia, Centro de Restauración de la Región de Murcia, Murcia, 2004, p. 13.

2. Research aim

The main object of the research that concerns us is the analysis of the degree of affectation of the sculpture of the Christ of the Blood while it is carried by men on his throne during the procession. Recent research has proven the suitability, especially in sculptures with complex fracture plans and localized cracks, of methodologies based on mechanical diagnosis from 3D models [5]. In our particular case, In order to carry out this work, computer simulation is used to show graphically and numerically by means of a dynamic-structural analysis, the areas of greatest tension and deformation of the sculpture, seeking to explain the origin of the cracks that usually appear in the foot and to propose solutions that allow the conservation of this heritage.

3. Materials and methods: 3d digitizing and video analysis techniques

In addition to a detailed preliminary theoretical study, for the application of this complex technique as input data, a three-dimensional digital model of the sculpture is required, as well as the physical parameters that describe the forces to which the sculpture is subjected as a result of the movement. Below, the digitizing processes carried out to obtain the 3D model are described, as well as the characterization of the movement from the video measurement technique.

3.1. 3D Digitizing

In recent years, 3D scanning techniques have become an indispensable tool for the analysis, documentation, conservation and prevention of heritage. These models have become the "archive" most demanded today by historians, conservators, restorers, mathematicians, etc., since they allow the possibility of carrying out numerous studies, analyses and research with them, which by other means would be very costly and laborious to carry out.

The 3D digitization of this sculpture by means of the main techniques of digitalization of the heritage, such as photogrammetry, terrestrial laser scanner and structured light scanner, were essential for the total understanding of this heritage property and, above all, for the realization of the present analysis, creating the possibility of improving the prevention and conservation of the studied sculpture.

The first studies carried out on this sculpture began by using the 3D digital photogrammetry scanning technique. The workflow of the use of this technique and the conclusions obtained have been published in the Spanish journal E-rph [6]. As can be seen in the aforementioned article, a model of great geometric quality and real texture was obtained, which was the basis for establishing a line of research on the main 3D scanning techniques for heritage.

Continuing with this line of research, this sculpture was subjected to the study of the 3D scanning techniques of the terrestrial laser scanner and the structured light scanner. This second part of the research is pending publication [7], where the workflows of the use of these techniques and some recommendations about their use can be found.

The performance and study of these three 3D scanning techniques (Fig. 2) made it possible to carry out a comparative analysis, both graphically and numerically, of all of them, obtaining relevant results. These investigations concluded that the technique of structured light scanning is the technique that provides the best geometric and resolution details in the smallest details of the sculpture such as eyes, eyebrows, mouth, hands, etc., which digital photogrammetry does not manage to obtain. However, digital photogrammetry was also considered a valid technique for the digitisation of heritage, as a 3D model of fairly good resolution and proportions was obtained which is very similar to that obtained with the structured light technique, although the use of photogrammetry was recommended, provided that the object to be digitised does not present too many small details or the 3D model obtained is going to be decimated or reduced in polygons later, to be used in 3D printing, digital web platforms, virtual reality applications, calculation software, etc.

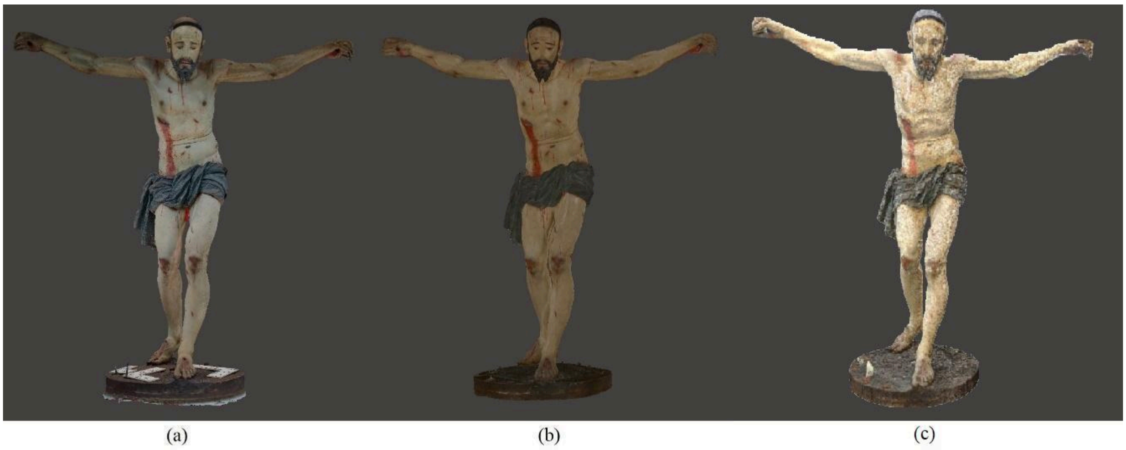

Fig. 2. 3D models obtained from the sculpture using three different scanning techniques. (a) Photogrammetry. (b) Light structured scanning. (c) Laser scanning. Source: own elaboration

3.2. Video measurement technique

3.2.1. Preliminary Analysis

A starting point is that we don't have objective data on the magnitude of the forces acting over the sculpture of the Christ, as a consequence of its movement along the procession. This issue is usually solved through physical measurement devices on the object, such as encoders, sensors, etc. A pretty alternative solution is the use of video measurement techniques [8]. We will use it to obtain an approximation of these parameters as input information for the process of computerized mechanical simulation.

The interest of our measurement is focused exclusively on the video sequences where the maximum accelerations to which the sculpture is subjected are recorded along the almost three kilometres of distance and five hours of duration of the procession.

A first analysis shows that these do not appear while the throne is advancing or standing, but in the transitory states of its ascent to the shoulder and standing on the wooden stick, because the difference in height between the two must be bridged at each stop and start. To this must be added the practical impossibility of the manoeuvre being carried out in a synchronised manner, to which the accumulated fatigue contributes, which, in addition to diminishing reflexes, causes the average height of the throne to drop during the advance. As a result of this dynamic difference, non-zero resultant forces appear and, therefore, accelerations that affect the whole. The conclusion is that the most abrupt accelerations take place in the final phase of the procession and in the transitory state of stopping the throne on the rack.

Among the multiple video fragments available, one is chosen corresponding to the beginning of the last quarter of the procession, in a critical situation as it is the exit of a 90º curve, and that can be visualized in the following link https://youtu.be/wXr132woGVQ (last access date: 16/04/2020). The file is in .mpeg4 format, with a resolution of 640x304 pixels and a frame rate of 30,079.

3.2.2. Technique used

Based on the chosen sequence, the procedure to follow consists of detecting the interval of frames in which the maximum angular displacement of the sculpture is registered after the throne is resting on the shelves when stopping. This operation is carried out visually frame by frame using QuickTime®. The interval finally chosen for the measurement is composed of 5 frames with a total duration of 132,983 ms and includes full lateral displacement from the equilibrium position. The decomposition of the video sequence to .jpeg format frames is carried out using Adobe Premiere®.

Due to the reduced quality of the video and its tripodless capture, the measurement of the angular displacement of the sculpture has to be done through a combined system. First, for each of the images in the interval frames, the pixel that contains the nail of the left hand of the Christ is accurately located using Adobe Photoshop ®. Next, a line is drawn between this pixel and a second reference pixel located on the base of the sculpture itself, which is in turn anchored to the throne (Fig. 3.a). For the exact measurement of the angle of each line, the Hough transform is used (Figs. 3 c, d). The angle increments measured in each frame in relation to the time elapsed since the beginning of the interval allow the calculation of the average angular velocity function in each instant of time of the interval, being its graphic representation the one shown in Fig. 3 b.

The maximum acceleration is obtained at the starting instant of the movement and for its calculation it is necessary to evaluate the function derived from the angular velocity. For this reason, it is necessary to perform the polynomial regression on the angular velocity nodes to obtain their polynomial with maximum precision (Determination factor, R^2=1,0) which results in Eq. (1).

$$f(t) = -12.682{,}964t^4 + 3.918{,}912t^3 - 470{,}848t^2 + 27{,}579t \quad Eq.\ (1)$$

Its first derivative in t=0 gives us the maximum slope in the maximum turning interval, i.e. the maximum angular acceleration whose value is 27,579 rad/s^2. Excel ® and Matlab ® are used for these calculations, the latter also for calculating the Hough transform. This maximum angular acceleration will be used to calculate the maximum inertia force in subsequent mechanical analysis.

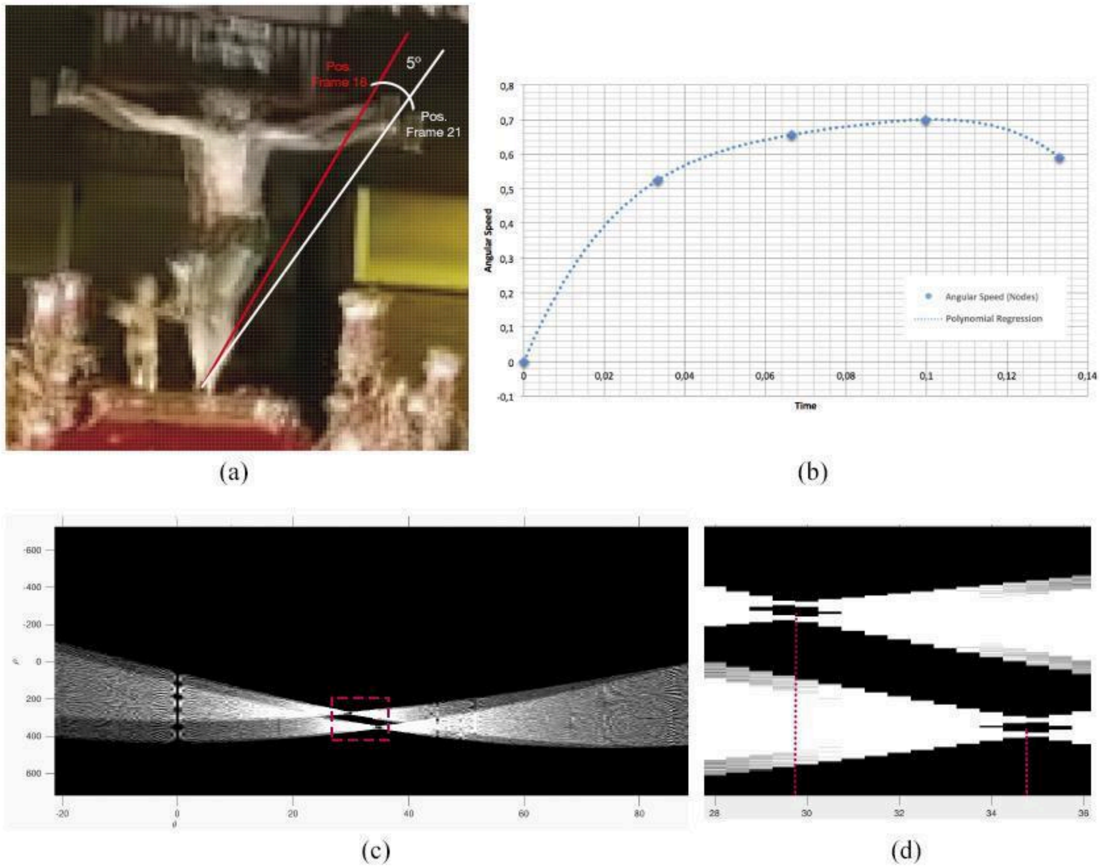

Fig. 3. Video measurement technique. (a) Superimposed captures showing the maximum angle of deviation of the sculpture (b) Graphic of the polynomial regression of the mean angular velocity (c) Hough transform applied to lines in figure a (d) Detailed measurement of the angles through Hough transform. Source: own elaboration.

4. Calculation: dynamic-structural analysis.

Engineering strength analysis is performed on elements with regular geometry, which allows the use of certain mathematical or graphical procedures, in the worst case. The sculpture of the Christ of the Blood is a solid with very irregular shapes and sections, the same as in the forms of human beings. Therefore, although a rigorous scientific basis is always maintained, the conclusions will be of a qualitative nature and within a practical environment.

4.1. Previous considerations.

In order to carry out this analysis, the following simplifications are considered in the study:

- Each stop and restart process has different and unpredictable conditions, so the most general dynamic case is analysed.
- Due to the impossibility of characterising the inertial force as a cyclical fatigue force, a static structural simulation is carried out. The graphic information of stress state and

unitary deformations obtained allows to locate the critical points of the structure, being representative of the dynamic or fatigue loading state.

4.2. Analytical basis

The difference in time of forces made by the Nazarenes at the moment of stopping the throne or resuming the march, cause a torque on the throne and the sculpture as a whole. This torque causes, according to the law of dynamics that defines the turning movement Eq. (2), an angular acceleration on the solid.

$$M_R = I_G \alpha \quad \textit{Eq. (2)}$$

Where M_R represents the moment of force on the centre of masses G of the assembly, α represents the angular or rotational acceleration and I_G is the moment of inertia, which accounts for the mass distribution of the solid with respect to the axis passing through G. It can be seen that the higher the moment of inertia, the lower the angular acceleration of the assembly.

Fig. 4.a schematically shows the rigid solid formed by the throne and the sculpture of Christ. The centres of mass of the whole and of the sculpture are shown, as well as the forces, moments and accelerations that act on them. The assembly rotates on the longitudinal axis of the throne, since the moment of inertia is less than that of the transversal axis.

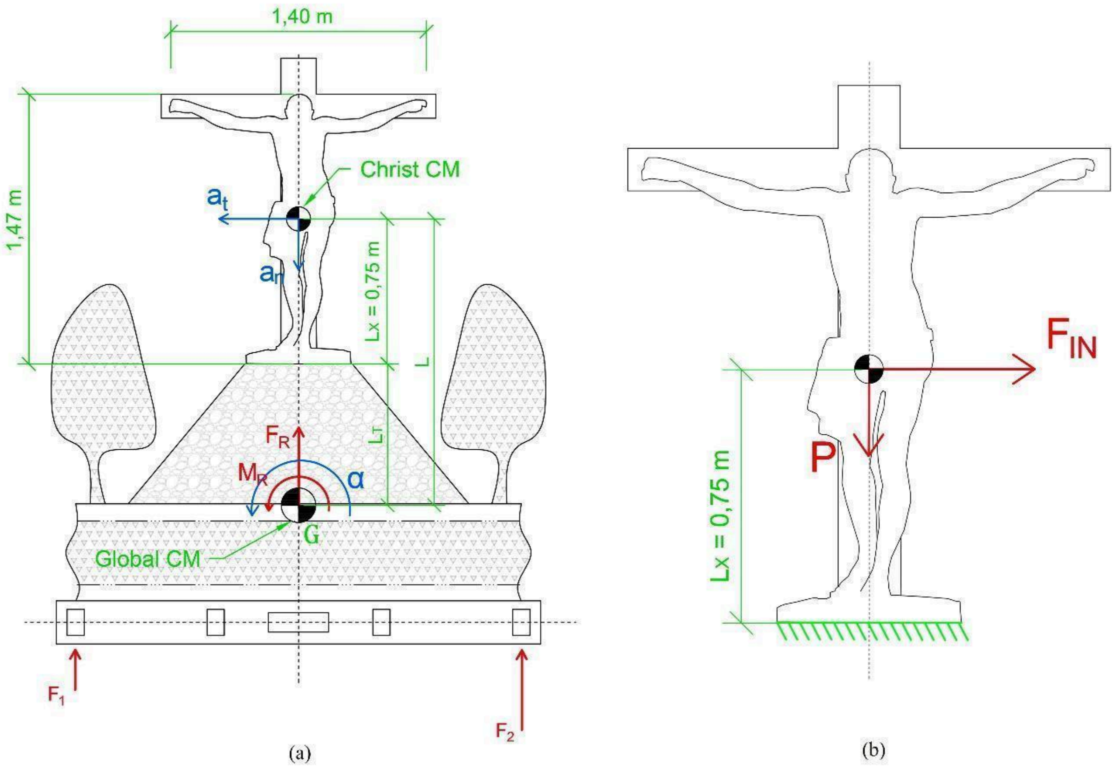

Fig. 4. Technical diagrams. (a) Overall set under study and (b) Scheme of forces on the sculpture. Source: own elaboration.

The center of masses of the Christ, since it is separated from the point of rotation, suffers tangential and normal accelerations to the trajectory Eqs. (3) and (4) [9]. Both components of the acceleration are directly proportional to the distance L.

$$a_t = \alpha L \quad \textit{Eq. (3)}$$

$$a_n = \omega^2 L \quad Eq.\ (4)$$

By Newton's law of dynamics, sculpture suffers inertial and centrifugal forces. Both forces are applied on the centre of masses of the sculpture and have the opposite sense to the accelerations that cause them [10]. Their modulus are expressed according to the Eqs. (5) and (6). The load state of the sculpture is shown in Fig.6, where the weight force (P) is included and the centrifugal force is obviated. According to Fig. 3.b, the maximum angular acceleration is given at the initial instant, the angular velocity being zero. Therefore, normal acceleration and centrifugal force are also nullified Eq. (6).

$$F_{in} = ma_t \quad Eq.\ (5)$$

$$F_c = ma_n \quad Eq.\ (6)$$

In the video analysis, it is observed that the sculpture violates the rigid solid hypothesis when it begins to have relative displacement with respect to the throne. For this reason, once what has happened in the complete system has been explained, the sculpture is studied individually (Fig. 4.b). As can be seen in the video used in the section 3.2. Video Measurement Technique, the throne induces angular acceleration instantly and remains fixed from that moment on. The angular acceleration with respect to the base of the sculpture, obtained in this section, is used to estimate the forces suffered by the sculpture. This load state could be studied as seismic ones [11][12]. A similar remarkable study is the analysis of the cracks in the ankles of Michelangelo's David [13]. In that case, cracks are due to the excessive mass of the sculpture and the eccentricity of its centre of mass.

As a conclusion to this analytical section, it is worth noting the following: the inertial force is directly proportional to the mass of the Christ, to its lever length (which in turn depends on the height of the base and the height of its centre of mass) and to the torque generated by people, and inversely proportional to the moment of inertia of the whole.

4.3. Computerized mechanical analysis.

4.3.1. Type of load: fatigue.

The design of mechanical elements in engineering considers, mainly, two types of failure: by resistance or by fatigue. In the failure by resistance, the breakage is given when in a point the maximum stress of the material is exceeded. In our case study, we have a fatigue load. The inertia force is not static but cyclical, and it acts on a slightly damped system. Fig. 5 shows in qualitatively way the representation of the deviation that the Christ of the Blood suffers in each process of stopping or starting, as a function of time. At the beginning of the function it is the maximum peak, which corresponds to the maximum deviation in the process, and then the curve is attenuated until it reaches rest again.

In a situation of mechanical fatigue, the alternation of tensile and compressive stresses begins by causing a microcrack in the material, which with the repetition of numerous cycles propagates and extends. In fatigue, therefore, it is possible to reach structural collapse without reaching the maximum stress of the material [14].

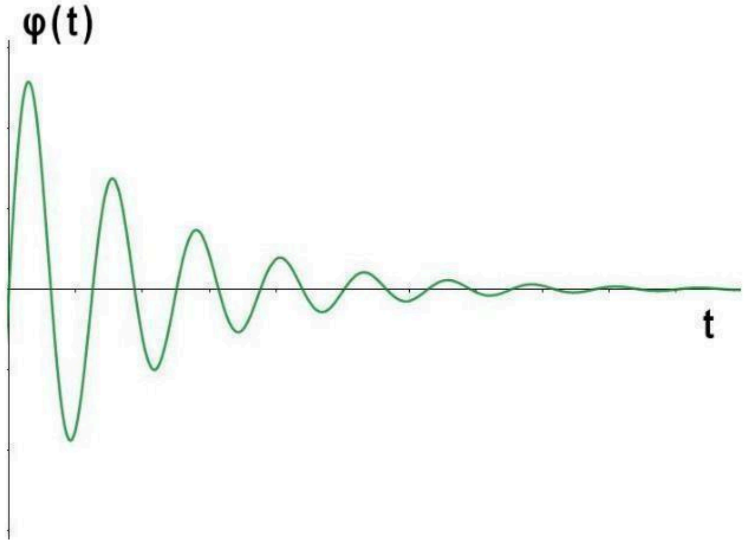

Fig. 5. Displacement of sculpture as a function of time

4.3.2. Mechanical characteristics of the Christ of the Blood.

Using the digital 3D model of the sculpture, the position of the centre of masses is obtained, as well as other relevant properties. In order to obtain the mechanical properties, the cross and the hollow in the ribcage are taken into account (Fig. 1 a). In Figs. 6 a and b, the position of the centre of mass is shown, both in plan and side view.

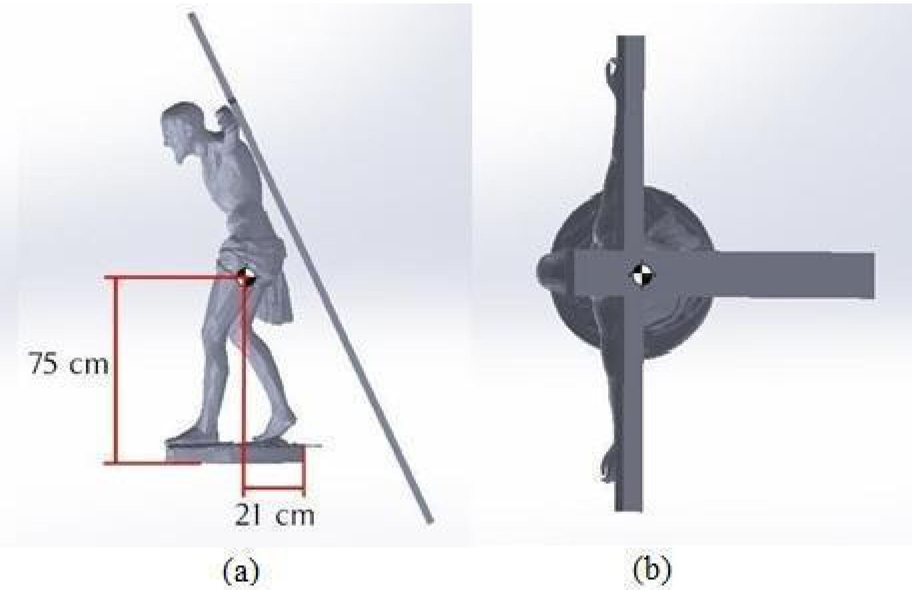

Fig. 6. Centre of masses. (a) Side view of the model, (b) Plan view of the model. Source: own elaboration.

In accordance with the type of wood used by the sculptor Nicolas de Bussy, the mechanical properties of the wood of Cupressus Sempervirens L. (Mediterranean Cypress) are chosen [15]. Wood is an anisotropic and heterogeneous material, so its properties may vary depending on the arrangement of the fibres and on each particular variety. The age of the sculpture and its interventions make the mechanical characterisation of the wood practically impossible. In the mechanical software some generic properties are introduced according to bibliography [16][17]. In Table 1 the dimensional and wood properties of the sculpture are summarized.

Table 1
Mechanical properties of the sculpture and Cupressus Sempervirens L.

Height foot-head	1.40 m
Height base-foot	0.07 m
Wingspan	1.40 m
Total volume (with cross)	79,499.48 cm^3
Total mass (with cross)	43.72 kg
Density	550 kg/m^3
Young modulus	8,050 MPa
Poisson's ratio	0.4
Elastic limit	101 MPa
Tensile strength	63 MPa

4.3.3. Preparation of the model.

Once the load state has been characterized, the simulation of the model is carried out using 3D CAD mechanical software. The SolidWorks® package, together with the Simulation complement, allows us, given a solid, to establish some boundary conditions and apply forces on it. The software creates a mesh and calculates by finite methods the unit stresses and deformations suffered by the fibres.

Due to the computational load, the mechanical simulation software only supports low resolution 3D models, so the differences between the geometry of the 3D models obtained by photogrammetry or scanning are irrelevant. The model obtained by photogrammetry is used, whose resolution is drastically reduced to 4 thousand vertices, compared to its original resolution of 10 million vertices. Once the solid is imported into the software, the following structural adaptations are made:

- The lower surface of the base is flattened, in order to facilitate the introduction of the clamping edge condition.
- According to the force scheme in Fig. 4 b, this is a structure model with cantilever load. Therefore, there will only be mechanical stress from the point of force application to the clamping, i.e. from the centre of mass to the base. The rest can therefore be eliminated.
- A rectangular prism is added to the height of the centre of masses by joining the two legs. With this it is possible to add a condition of equal displacement in the head of both legs, which happens in the real model with the waist of the Christ. In addition, in order to achieve an effective application of the two forces, two cylindrical extrusions are added at the exact location of the centre of masses, according to Fig. 7.

4.3.4. Structural simulation.

The material features defined in Table 1 are applied to the solid. A clamping condition is established on the lower face of the model base, completely limiting the 6 degrees of freedom of the solid: the displacements and the turns in the three axes of the space. Finally, the weight and inertia forces are added at the respective points of application. The weight force is applied in a downward vertical direction, while the inertia force is applied in a horizontal direction, considering the most unfavourable case. As for the amount of them, the weight force is calculated with the mass and acceleration of gravity, and the inertia force is calculated with the angular acceleration with respect to the base (obtained in the Video Measurement Technique section), the height of the centre of mass and the mass of the stature. In Table 2 the conditions of the simulation are summarized while in Fig. 7 the simulation model is shown with the conditions applied.

Table 2
Simulation conditions.

Element	Point of application	Value
Fixed mounting	Bottom side of the base	Total limitation
Weight force	Upper cylinder	429 N
Inertia force	Side cylinder	868 N
Total mesh nodes	-	160,621
Total mesh elements	-	107,149

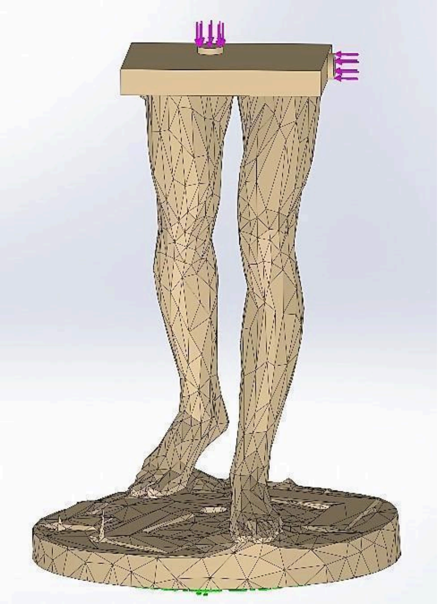

Fig. 7. Simulation model with load conditions. Source: own elaboration.

5. Results

Below are the graphic solutions regarding the equivalent unit deformation of the material. The blue colour reveals zero deformation, while the warmer zones indicate those of maximum deformation.

In the left foot the critical zone is in the ankle joint, on both the external and internal side (Fig. 8, zones 1 and 2). Maximum stress in zone 2 is 11 MPa (safety factor = 9.2). On the right foot there is a critical zone under the sole (Fig. 10, zone 3): this point coincides with a concentration of stress due to the introduction of the metal rod in the base (see Fig. 1, c), so the deformation does not occur directly in the sculpture material. With the exception of the latter, two critical areas are observed: at the back of the foot on the Achilles tendon (Fig. 8, zone 4), and another on the previous side of the talus (Figure 8, zone 5).

Excluding the area located on the sole of the right foot, the greatest mechanical stress is found on the front of the right support. Maximum stress in this zone is 14 MPa (safety factor = 7.2). In addition, the right foot will always be in a more unfavourable situation due to the construction characteristics set out in section 1. Introduction. The left foot is made up of a single piece, while the right foot is a joint of several pieces. This union of pieces facilitates the appearance of the crack.

This area of the talus coincides exactly with the opening point of the crack in the right foot of the Cristo de la Sangre (Fig. 9, a). At this point the initial crack opens and advances following the trajectory of the separation of the internal pieces of the foot (Fig. 1, a and 9, b).

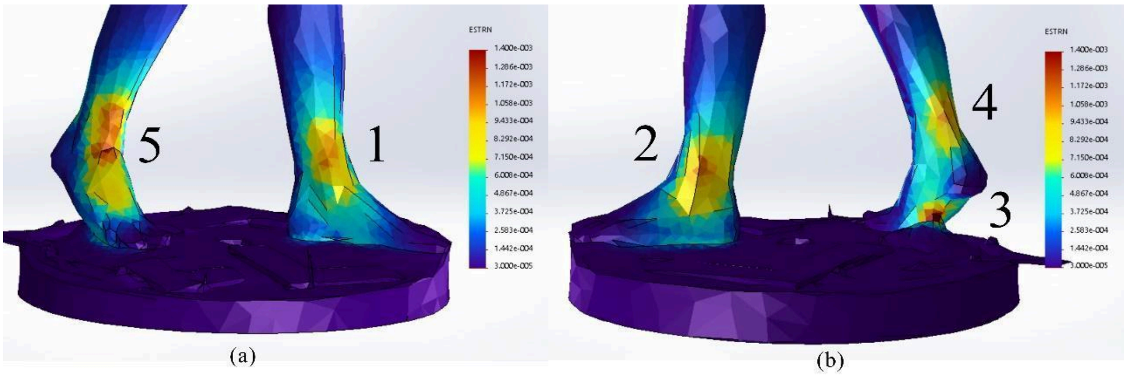

Fig. 8. Graphical results of equivalent unit deformations in side views. (a) Left side, (b) Right side. Source: own elaboration.

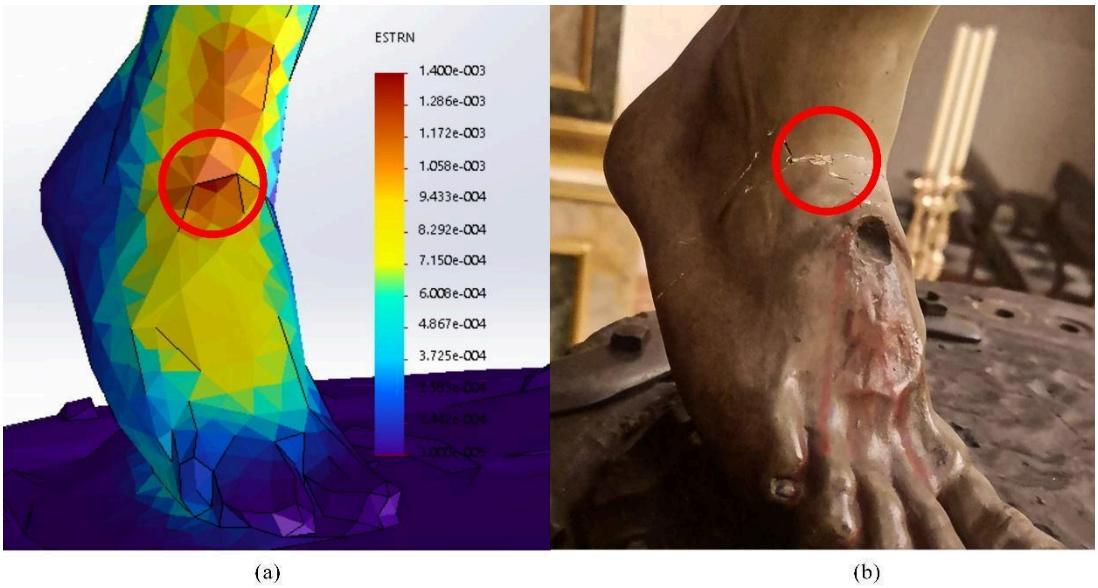

Fig. 9. Detailed comparison. (a) Computerized Simulation, (b) Real photograph (February 2020). Source: own elaboration.

6. Discussion: proposed solutions.

Finally, once the initial problems, the analytical approach and the result of the simulation have been explained, certain solutions are proposed that will contribute to maintaining the integrity of the Christ of the Blood. It is technically explained that these proposals reduce inertial force and the probability of cracking, but they do not guarantee the total disappearance of it. All of them are perfectly compatible.

6.1. General awareness.

In a general way, the whole group of people who surround the Christ of the Blood (from the president of the Archconfraternity to any of the faithful) must be aware of the structural fragility of the sculpture. Every action on sculpture must be done with the conservation of its integrity as the only priority.

As explained in the section Dynamic-structural analysis, the origin of the force of inertia is in the people who carry it in procession. One of the most effective measures for reducing structural stress in sculpture is to minimize this difference in forces at the moment of stopping. People, as far as their physical conditions allow it and always maintaining the traditional style of loading, must soften this gesture by trying to lift in unison and avoid any unnecessary abrupt manoeuvres. By minimizing the torque, the angular acceleration of the assembly is also minimized Eq. (2).

6.2. Modifications to the throne.

One of the basic modifications on the processional throne would be the reduction of its mass. With this, the fatigue of the people who carry it would be reduced, the throne would go down less along the procession, so the torque made would be reduced and also the acceleration that is induced.

According to Eq. (2), an increase in the moment of inertia of the whole would reduce the acceleration caused by the same torque. Therefore, another proposal would be to modify the mass distribution of the throne. In order to increase its moment of inertia and stability, it is necessary to move mass away from the axis of rotation under consideration. One option would be to place a mass belt along the entire perimeter of the platform. In conclusion, adding the above, the throne should be in a situation of maximum moment of inertia with the minimum possible mass.

On the other hand, according to Eq. (3), both the height of the base and the height of the centre of masses contribute to the increase of the inertia force. Lowering the center of masses from the sculpture of Christ is complicated, since it would involve adding mass at the base. Reducing the height of the base of the throne could be easier.

6.3. Modifications in the sculpture.

Perhaps one of the simplest measures would be to add elastic elements in the union of the sculpture and the throne. This would increase the damping of the system, as explained in the section Type of load, softening the acceleration peaks.

On the other hand, uncoupling the cross from the sculpture would be structurally beneficial: the sculpture would bear less weight from the cross. Currently, the cross has two joints: at the base by means of a metal piece and at the back of the Christ sculpture. Due to the high inclination of the cross and the strong union at the back, the sculpture receives the greater part of the weight of the cross. It is proposed to incorporate a third support of the cross, clamping it rigidly to the structure of the throne. This union would be the main one, being able to reduce the tightness in the union of the cross with the back of Christ. In Fig. 10 the proposal is schematically represented in side section view.

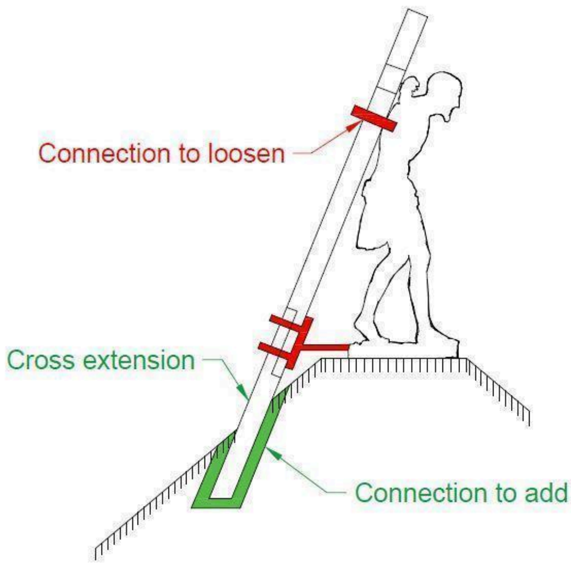

Fig. 10. Proposal for the support of the cross in the throne. Source: own elaboration.

6.3.1. Total or partial reproduction of the sculpture.

Using the impression of the digitized model is the most interventionist proposal. First of all, it is possible to reproduce the set formed by the base and the two feet. In this way, a continuous piece is obtained in the whole critical area of tension, being able to move the joint between the reproduced part and the original sculpture to a section with less mechanical stress, reducing the probability of cracking. As a last option, the proposal of manufacturing a full replica of the sculpture is considered, starting from the high-resolution digitalized model. These solutions highly depend on manufacturing methods technical viability.

6.4. Summary and technical assessment.

The following table summarizes all the proposals, which are evaluated with respect to several technical criteria.

Table 3
Summary of proposed solutions vs issues in its development

Proposed solutions	*Technical complexity*	*Economic investment*	*Intervention in sculpture*
Reduction of throne mass	Medium	Very low	Null
Redistribution of mass on the throne	Low	Low	Null
Stand height reduction	Medium	Medium	Null
Inclusion of elastic elements in the joints of Christ	Low	Very low	Very low
Incorporation of the third support of the cross	Medium	Medium	Very low
Partial sculpture reproduction	High	High	High
Total reproduction of the sculpture	Very high	Very high	Very high

7. Conclusions

The main conclusions that we have obtained from this investigation lead us to confirm the suspicions that the area of the feet of the Christ of the Blood is subjected to a state of tension and forces that are too high and that cause, to a great extent, recurrent and constant damage to the sculpture.

It has been demonstrated that, specially, the right foot is subjected to a situation of mechanical fatigue that, together with the alternation of numerous cycles of traction and compression efforts, to which it is subjected during the parades of the Spanish religious festivities, originates the micro cracks in the material and compromises the integrity of the internal piece. To make this statement, after deducing the mathematical equations that govern it, it has been analysed by means of a study of forces, its centre of masses, axis of rotation and moments of inertia. The main technique has been finite element computerized simulation.

Likewise, the results of the unitary deformations produced by the sculpture have been shown graphically and numerically, with the maximum deformation being found in the area of the right ankle, coinciding exactly with the opening of the recurrent crack and following the trajectory of separation of the different internal pieces that make up this foot.

Likewise, it is clear the importance of the use of new technologies, 3D digitization and techniques such as video measurement to carry out studies and analyses that allow to solve problems of integrity, prevention and conservation of heritage from parading, because without these tools, the study carried out would not have been possible. On the other hand, sensing is an emerging and necessary technology to increase the accuracy of these simulations.

Finally, on the basis of results and the quality of the available 3D models, a set of possible solutions to resolve the structural problems detected, to allow the tradition goes on affecting the integrity of the heritage as little as possible, have been proposed. In spite of the fact that each one should be studied in depth, a quick and concise preliminary analysis of their development has been carried out according to their technical complexity, economic investment and degree of intervention in the sculpture. The incorporation of a third support of the cross, the redistribution of mass on the throne and the inclusion of elastic elements in the joints of the basement, have been found in this order as the most feasible solutions to be carried out without modifying the sculpture as a whole.

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