Structural Analysis of La Giralda's 16th-century Sculpture/Weather Vane

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Abstract

This paper presents an analysis of the mechanical behaviour of a historical sculpture known as *El Giraldillo*, which, in addition to its ornamental qualities, also functions as a weather vane. The 4-metre-tall bronze sculpture has crowned *La Giralda*, the bell tower of the cathedral of Seville, since 1568. The mechanical behaviour of the sculpture/structure must clearly be analysed before undertaking its restoration to guarantee that it is capable of withstanding the mechanical actions to which it will be subjected, including self-weight, wind action, thermal effects and seismic agitation. The analysis was conducted by studying the object's current state of preservation with the aid of a finite element numerical model. The most significant results of this analysis are presented in this paper.

Key words: bronze sculpture – weather vane – restoration – finite elements – structural analysis

1. Introduction

The Giraldillo, a bronze sculpture of extraordinary dimensions and great historic, artistic and symbolic value, was manufactured in 1568 (Fig. 1). The sculpture is unique in that, in addition to its aesthetic value as a sculpture, it also serves as a weather vane perched atop the Giralda Tower of the cathedral of Seville (Fig. 2).

The Giraldillo ensemble is comprised of a sheet of cast bronze attached at various points to an internal structure of bars that rests on the axis about which it rotates (mounted at the top of the tower). The sculpture represents the figure of a woman holding a flag or standard in her right hand and a palm frond in her left hand. It is 4 m tall, about 4 m wide, and weighs approximately 1,500 kg excluding the weight of the axis.

The structure could be described as a sort of rack to which the bronze sculpture is attached, which basically consists of three horizontal members braced by two vertical members, besides the flag mast and the palm frond bar (Fig. 3).

The axis is inserted into the sculpture; its pointed tip fits into a central casting near the upper brace (at breast height in the sculpture) in such a way that it is the only point of contact for support and rotation. This is a pinned interaction point, so only horizontal and vertical interaction forces (and a small torsional friction moment around the axis) can be induced at this point. In the lower part, the axis passes through collars in the middle and lower horizontal members. Because of the imbalance of the Giraldillo or horizontal forces (induced by the wind, for instance), there is a contact zone with the axis at the lower horizontal member, so horizontal interaction forces are also induced between the internal structure and the axis.

The 5.4 m-long axis is anchored to the top of the Giralda Tower. It has a square solid section below the feet of the sculpture (132 mm in side length) and a cylindrical section inside the sculpture (110 mm in diameter).

The sculpture also has six internal iron strips that serve as stiffeners and reinforcements. These stiffeners follow the internal geometry of the sculpture and are riveted at certain points along their trajectory. Four of them are located from the waist of the sculpture to its neck (two at the front and two at the back of the sculpture), whereas two more are located along the right arm. The cross section of these stiffeners is 40 mm wide and 5 mm thick approximately.

The damage suffered by the Giraldillo over more than 400 years of history led to undertaking an ambitious project to restore this work of art. As expected for this type of project [2], an inter-disciplinary working group was set up including historians, restoration experts and chemical, mechanical and materials engineers.

The creation of such a working group made it possible to conduct a comprehensive study of the Giraldillo's historical, physicochemical and mechanical properties to ensure the selection and application of the necessary criteria and restoration techniques.

One of the project's first steps was to conduct a mechanical behaviour study of the Giraldillo, which is essential for proper restoration from a structural point of view.

A finite-element model was developed to study the Giraldillo's response to different mechanical stresses to which it is subjected. This numerical tool has been successfully used in the structural behaviour analysis of various historical buildings, mainly of masonry construction (see [2], [3], [4], [5], for example). However, the application of this method to bronze sculptures is not very common (the authors are only aware of the case referred to in [6]), and there are no known cases of this method being applied to a mechanism of his sort.

The analysis of the finite element model has provided clues as to the main causes of the Giraldillo's deterioration, and conclusions drawn from the analysis have made it possible to design a new internal structure to replace the original one and several internal elements to reinforce the sculpture.

2. Historical context

The city of Seville was the capital of Al-Andalus from the mid-12th century until the mid-13th century. A great mosque was built for the city during that period; the minaret of the mosque was the lower portion of the present-day Giralda Tower (from ground level to a height of 55 m).

Seville was re-conquered by the kingdom of Castile in 1248 and would later become one of the world's most important cities in the 16th century with a central role in Spain's relations with the recently discovered American continent.

It was at that time that the decision was made to transform the ornamental structure adorning the top of the former minaret into a Renaissance-style bell tower. The project, designed and directed by architect Hernán Ruiz, sought to extol the power and triumph of the Catholic faith. The project was completed in 1568 and extended the tower's total height to 96 m with the new Renaissance-style bell tower. The rotating decorative weather vane placed atop the new tower, named the 'Colossus of the Victorious Faith,' would lead to the tower becoming popularly known as the 'Giralda' (from the Spanish verb for rotate: *girar*). With the tower itself adopting the popular name of 'Giralda,'the weather vane subsequently assumed the diminutive moniker 'Giraldillo.'

The Giraldillo is a unique work of art, not only in artistic terms but also from a technical point of view, considering the complexity of design implied by a weather vane with such particular features. The manufacturing procedure must have been no less complicated, employing a single-pour, lost wax casting technique with the mould in a vertical position and the original internal structure inside it.

The design of the sculpture seems to have been based on a classical Minerva, or perhaps even more likely, on Marco Antonio Raimondi's *Palas Atenea* (Fig. 4), therefore making it a unique combination of pagan elements to symbolise the triumph of the Catholic faith. Several contributors were involved in its design and construction (though the degree of each contributor's involvement is unknown) including the architect Hernán Ruiz, the painter Luis de Vargas, the sculptor Juan Bautista Vázquez "the Elder" and the founder Bartolomé Morel. Throughout its more than 400 years of history, the Giraldillo has directly witnessed every type of inclement weather condition, from gale-force winds to earthquakes that have befallen the city and left their mark on the sculpture. This has made it necessary to undertake inspections, repairs and renovations of varying degrees, which have all been quite complex due to the Giraldillo's sheer size and weight as well as its difficult access, which requires complex scaffolding systems.

The most significant of such actions took place in 1770, fifteen years after the Lisbon earthquake of 1755. It required a complete disassembly of the Giraldillo, replacement of its internal bar structure and the addition of iron reinforcements inside the sculpture (Fig. 5). The current restoration project will have a similar scope.

The first scientific studies of the Giraldillo were conducted in 1980 and 1981. Several restoration actions were performed on the bronze surfaces of the sculpture and some of the internal structural elements. It was determined that the Giraldillo was in a very poor condition, leading to the recommendation that it should be dismounted, temporarily replaced with a replica and completely restored. The process began in 1999, when the original Giraldillo was dismounted and taken to the restoration laboratory of the Andalusian Historical Heritage Institute (*Instituto Andaluz de Patrimonio Histórico)*. The work described in this paper forms part of the first phase of the restoration project and consisted of a study of the Giraldillo prior to being restored. Mechanical behaviour and structural integrity analyses are considered essential to draw up project plans for modern restoration.

A more comprehensive history and description of the Giralda and the Giraldillo can be found in references [1] and [7].

3. Cumulative effect of damages inflicted on the Giraldillo throughout its history

The Giraldillo's state of preservation was studied at the beginning of the restoration project. For the first time, it was possible to examine its parts in a restoration laboratory and thus perform a thorough analysis of the marks left by time (Fig. 6).

From a structural point of view, different types of damage and imperfections were observed in the structure and internal iron reinforcements as well as in the bronze sculpture itself.

As for the iron structure, significant levels of corrosion were observed in various areas, with some areas showing complete disintegration, such as the lower section of the left vertical member. The structure itself was given a somewhat three-dimensional character by a transversal member that formed part of the upper horizontal structure and connected the sculpture's chest and back with the contact point where the sculpture rests on the bearing and the rotation axis. The connections between the transversal member and the sculpture were so damaged that a portion of the bronze sculpture on the chest had to be completely removed (during the restoration in the 1980s) and replaced with a provisional bolted cover that allowed partial observation of the inside of the sculpture.

Widespread corrosion was also observed in the sculpture's internal reinforcements, which consist of six iron strips joined with bronze-plated rivets. As in the case of the internal structure's left vertical member, they also showed signs of galvanic corrosion as a result of the bronze-iron interfaces. Numerous patched-over areas and cracks were observed in the sculpture itself (Fig. 7). The patches, which had been applied to cover holes and cracks, had to be removed to allow a proper study of the holes and cracks themselves. Most of the cracks that had not been covered with patches were covered with soft-weld beads applied during the repair work done in the 1980s (Fig. 8).

There are many possible reasons for the damages and imperfections observed in the Giraldillo: original manufacturing defects, damage resulting from the various attempts at repair work carried out over the centuries (mainly that of 1770) corrosion and ill-conceived structural design.

However, a detailed study of the sculpture, including metallographic, chemical and radiographic analyses, among others, seems to indicate that most of the defects observed in the bronze are most probably a result of the original manufacturing process. One can easily imagine how difficult the lost-wax fabrication procedure must have been for a piece of such size and complex shape specifications.

Some of the damages observed may also have occurred during the repair work carried out in 1770, when the original members of the internal structure were removed and replaced with a new structure, which certainly must have had an impact on the bronze itself.

Lastly, the corrosion observed in the iron elements is the result of inappropriate material selection, while the damages at the chest and back connections are the result of faulty structural design. The calculation model presented below is the basis for a mathematical analysis that might explain how these effects occurred and to what extent they may affect the mechanical behaviour of the Giraldillo, which would be necessary to guarantee its preservation before it is returned to its position atop the Giralda Tower.

4. Finite element model

A finite element model [8] was developed and analysed using commercially available ANSYS software.

4.1 Geometric representation

Due to the complexity of the sculpture’s shape, the most complicated part of developing the finite element model was the geometric representation.

Various techniques have been used to effectively generate digitised geometric representations of works of art [9]. The case of the Giraldillo is very complex due to its sheer size and the fact that it is an anthropomorphic sculpture with numerous details. However, obtaining precise information about every detail in the sculpture was not deemed necessary, given that the objective was to build a finite element model that could be used to analyse the sculpture's mechanical response. The finite element model would be used to represent the sculpture's shape with enough detail to make reasonably accurate predictions of the mechanical stress levels that would occur in various zones in a number of different load bearing situations. An excessively detailed representation of the sculpture's shape would complicate the construction of the calculation model and its analytical application, and would be unnecessary considering the degree of detail needed for the purposes of the present study. The sculpture's hands are an example of simplification of finite element model representation. First, their shape is extremely complex, and second, a close inspection revealed that they are among the most rigid areas of the sculpture and in perfect condition. They were therefore replaced with bar-type members of similar stiffness that would adequately represent the transmission of force between the sculpture and the internal structure at these points, thereby providing the information needed for this study. Knowing the stress levels in the sculpture's hands, for example, would not make any significant contribution to the analysis.

Two representations of the Giraldillo were combined to obtain a simplified geometric model that would later serve as a basis for building the finite element model. One was generated using digitised photogrammetry (Fig. 9) whereas the other one was produced using a theodolite laser and applying topographical techniques (Fig. 10).

This was accomplished by cutting the representation into slices perpendicular to the Giraldillo's axis and generating a contour image for each slice (Fig. 11). The interval between adjacent contour sections was 100 mm approximately. Subsequently, each pair of adjacent contour sections was joined using a series of triangular surface elements. These triangular surface elements would later serve as the sheet-type finite elements used to represent the bronze sculpture (Fig. 12).

The arrangement of the bar-type members (internal structure and internal reinforcements attached to the sculpture) was based on the sculpture representation described above, direct observations and measurements taken on the entire assembly.

Data on the thickness of the sheet-type elements used to model the sculpture were applied in accordance to with the measurements taken with ultrasound equipment. The thickness measurements were taken by the Material Science Group of the School of Engineering (University of Seville), part of the interdisciplinary working group responsible for the Giraldillo's restoration. The thicknesses measured ranged from a few millimetres to several centimetres, showing clear evidence that the bronze was improperly poured in certain areas.

The various defects or damages observed in the sculpture and its structural elements (e.g., patches applied to the outer surface, cracks and material wear) were also taken into account in the model. For the cracks, a non-linear type element was used to model the free opening and its resistance to the compression stress created upon sealing the other side, while the patches, riveted to the sculpture at other positions on the surface, were considered as thin shells and the only element of resistance in the areas where they were applied.

Only when the internal structure, reinforcements and patches were disassembled during a subsequent intervention was it possible to accurately predict the magnitude of many of these defects and irregularities, which explains why the first-phase analysis of these defects in the model was conducted conservatively, thereby ensuring results that would always err on the side of caution.

A total number of 1,700 nodes, 2,712 shell elements, 2,713 bar elements and 1,616 link elements were used in the model. In spite of the complexity of the Giradillo's geometry, it is not necessary to consider a larger amount of nodes and degrees of freedom to obtain accurate enough results. A more complex model would lead to a greater effort in building the model and obtaining and processing results, and would not provide much more useful results.

4.2 Material properties

It is difficult to establish the mechanical properties of materials used in historical elements with any level of precision because they have been hand made following procedures for which there is little documentation available today. The matter is further complicated by the fact that regulations governing preservation often prohibit taking samples that could be used to determine material properties.

To include the mechanical properties of the Giraldillo's materials (bronze and steel) in the calculation model, values based on information found in the literature were combined with data collected from the results of several tests conducted on the original material. This provided information on its composition, metallographic structure, surface hardness, etc.

Metallographic studies indicated that the cast bronze is an alloy made of copper, tin (1%) and lead (12%). Tensile tests were also conducted on cast bronze test pieces with properties similar to those of the original sculpture. As for the iron, it can be considered to have similar properties to steel, except for the tensile strength and elasticity limit, which may lie between 130 and 260 MPa. The iron of the internal structure and reinforcements of the Giraldillo exhibited a 35 Rockwell B hardness level.

With this information available, values for the following properties were inferred: Young's modulus (E), Poisson's ratio (ν), elastic limit (σ_E), strength limit (σ_R), density and expansion coefficient (α). The values used in the calculation model shown in Table 1 below were selected conservatively so as to err on the side of caution. A linear elastic behaviour has been assumed for the numerical analysis. The elastic limit has been considered as the maximum acceptable stress level in the analysis..

4.3 Mechanical loads

The model was analysed by considering the various loads the Giraldillo has been subjected to throughout its history. These loads were considered on the basis of standard codes, historical data, material properties, geometric and weight measurements of the Giraldillo ensemble at the restoration laboratory, and experimental measurements that were collected during a one-year period, when the Giraldillo was atop the Giralda Tower, before the start of the restoration project. This experimental work was carried out by two external companies [10]. Such companies installed temperature sensors inside and outside the Giraldillo, a vane, an anemometer, and strain gauges on the supporting structure to estimate environmental conditions on the Giraldillo and its correlation with mechanical forces at certain points. Therefore, taking into account all this information, loads were eventually considered as follows:

- Weight of the Giraldillo ensemble. It was determined on the basis of the density of the materials and experimental measurement at the restoration laboratory by using load cells under the support structure used during the restoration process (Fig. 14). The measured weight of the sculpture with its internal bar structure was 1,384 kg, the weight of the palm frond was 95 kg, and the weight of the standard was 185 kg.
- Thermal loads. Three different temperature distribution profiles representing extreme situations were considered: uniform heating, uniform cooling and variable distribution as a representation of solar radiation. In all cases, temperature levels were based on the experimental measurements from the previously mentioned campaign, on Spanish codes NBE AE88, NBE CT79, UNE 1000001:1985 and UNE 1000014, and on a few simple heat-transfer analysis models. According to the codes recommendations, uniform heating or cooling of 30ºC from the reference temperature should be considered. Experimental measurements indicated that such extreme situations are far enough from those actually observed and are not likely to occur.

These measurements also showed a maximum temperature difference of 20ºC between the side of the Giraldillo receiving sun radiation directly and the opposite side.

For the heat-transfer analyses models, a balance was established between solar radiation and convection outside and inside the sculpture. The parameters needed for this analysis can be found in the standard codes cited above. At the latitude of Seville, intense solar radiation can be estimated as 1,000W/m^2. The heat transfer convection coefficients considered were 17W/m^2/ºC and 9W/m^2/ºC outside and inside the sculpture respectively.

From all these data, the most severe scenarios were considered for the structural finite element model analysis.

Therefore, uniform heating and uniform cooling were considered as an increase or decrease of 30ºC with respect to the reference temperature, which had been set at 25ºC. The non-uniform temperature distribution profile was based on the extreme weather conditions of a cold winter day with intense solar radiation striking the front of the sculpture, producing temperature differences of 25 ºC at different points on the Giraldillo. The temperature at any given point was determined by the amount of solar radiation received.

- Wind action. To consider wind-produced effects, observations of the Giraldillo's behaviour made prior to its restoration had to be taken into account. Due to the poor condition of the rotating mechanism, a wind speed ranging from 3 to 11 m/s (depending on the Giraldillo's position and the wind direction) was required to make it rotate. Two different wind-load scenarios were thus considered: wind speed of 11 m/s hitting the Giraldillo frontally and wind speed of 45 m/s hitting the weather vane laterally. These scenarios were selected according to historically recorded wind-speed data for the city of Seville and standards set forth in code NBE AE88. In the latter scenario (45 m/s), the wind would be hitting the Giraldillo laterally because, in conditions of such extremely high wind speeds, it would be pointed in the direction of the wind. The 45 m/s wind speed scenario was considered as it is set forth in

Spanish standard code NBE AE88 for a 100 m-high building in the city of Seville. Wind action load is considered through static pressures applied over the surface of the sculpture, taking into account wind direction and surface orientation, as it is also set forth in NBE AE88. The analysis of wind action is therefore static.

- Seismic Action. Seismic load was considered according to standards set forth in codes NCSE 94 and NCSE02, applying a modal superposition based on an elastic response spectrum, similarly to other standard codes for seismic analysis (e.g., the European guide Eurocode 8). The elastic response spectrum is defined according to geographic location (city of Seville), soil type (cohesive [11]) and return period (500 years). The values that define the elastic response spectrum are shown in table 2. A linear interpolation between these values was made when necessary.

A simple model of the Giralda Tower composed of bar-type finite elements was also included in the analysis (Fig. 13) to appropriately consider seismic excitation. According to the geometry and material properties of the Giralda Tower, which is basically a masonry building, its weight can be estimated at 14,336 tons [1], and the mechanical properties of the masonry can be estimated as E=6GPa for the elastic Young's and ν=0.2 for the Poisson's ratio [1]. Moreover, its first natural frequency is 0.645Hz [11].

The simplified bar-type finite element model should be capable of reproducing the first mode shape and frequency of the tower. Therefore, the finite element model should include a cantilever beam with an equivalent mass (m_{eq}) and equivalent stiffness. The first natural frequency can be written as

$$\omega_n = \sqrt{\frac{k_{eq}}{m_{eq}}}$$

where, for a cantilever beam model,

$$m_{eq} = m_{tower} \cdot 33/140$$

$$k_{eq} = \frac{3 \cdot E \cdot I_{eq}}{L^3}$$

E is the elastic modulus, *Ieq* is the equivalent inertia of the beam model and *L* is the height of the Giralda Tower (L=90 m).

From all these data, an equivalent inertia of 2,601m^4 is obtained.

Given that the mass of the tower was assessed in the finite element model from the expression

$$m_{eq} = \rho \cdot A \cdot L$$

an area of *A*= 114.49 m^2 (square section of 10.7 m edge length, equivalent to the mean edge length of the tower) and an apparent density of ρ=327.9 kg/m^3 was introduced.

Therefore, a beam-type finite element with these properties was introduced in the numerical model, so the first natural frequencies and modes were properly simulated and the ground motion transfer from the foundation of the Tower to the Giraldillo was taken into account.

5. Analysis of results obtained from the model

Stress levels and displacements produced by the actions described above (or any combinations of such actions) and their impact on both the sculpture itself and its internal structure were analysed.

The study of the effect of each action separately was useful to assess their impact on the Giraldillo and try to mitigate their damaging effects in the subsequent restoration process.

In addition to the independent analysis, various combinations of actions also had to be considered to assess the different possible load situations. These combinations were useful to determine maximum mechanical stress levels that may occur in different areas of the Giraldillo and prospects for conservation of the weather vane. Mechanical stress levels were compared to the elastic limit assumed for the material. A set of coefficients was also used to analyse the effect of the combined actions, which were established in accordance with Spanish NBE-EA95 standards.

When combining the effects of different actions, results are strictly non-superimposable, as non-linear type elements are used for the cracks in the static analyses. It was considered that modelling a step-by-step load history for each load combination to prevent a non-realistic behaviour of the cracks was too complex and unnecessary to obtain realistic enough results.

5.1 Self-weight

It was necessary to know the weight of the Giraldillo to ensure that the model would appropriately represent the weight distribution of the various components, obtained through experimental measurements, as mentioned above. It is important to bear in mind that the Giraldillo's centre of gravity is slightly off-centre with respect to the axis and lies just 12 cm towards the standard, on the right side of the sculpture. Thus, a very precise equilibrium (with respect to the axis) was achieved in the manufacturing process by taking the dimensions and weight of the sculpture into account. The displacements (Fig. 15) produced by this imbalance are minimal and clearly fall within the acceptable range (maximum relative displacements of about 1 cm), especially considering that the Giraldillo is nearly 4 m tall and that the plinth where the rotating axis is anchored lies approximately 2.5 m below the sculpture's feet.

The gravity-induced mechanical stress levels observed in the Giraldillo are minimal (Fig. 16). Maximum stress values up to 35 MPa can be observed on the central part of the upper horizontal bar because of bending moments induced by the weight of the various components of the Giraldillo ensemble. For the rest of the internal bar structure, typical values are around 10 MPa. Values in the sculpture were lower than 6 MPa.

The left arm was the area most weakened by the effects of previous repair work, mainly the replacement of the original internal structure in 1770. The numerical results showed the overload caused by its being partially filled with lead to improve equilibrium. This effect would be avoided by a new internal structure and reinforcements designed during restoration, as will be explained in a forthcoming paper.

5.2 Thermally-induced effects

As for thermally-induced effects, the stress levels reached in the different temperature distributions are very similar in all cases. Mechanical stress results from the different expansion coefficients of the bronze and the iron structure and internal reinforcements of the sculpture, with higher stress levels occurring at the connection points between the two different materials (Fig. 17).

Therefore, the areas where the thermal effects are most significant are those where the thermal deformations of the sculpture and internal iron elements are restricted. Higher stress levels are observed along trajectories extending from the internal iron strips that serve as reinforcements of the cast bronze sheet of the sculpture, with even higher concentrations at connection points. Similar effects are also observed at connection points with the internal structure. It is important to highlight the chest and back connections, which may be part of the reason for the deterioration observed in these areas, combined with the damage caused by the 1770 addition of the upper horizontal member in the internal structure. However, the maximum Von Mises equivalent stress levels found in the sculpture are around 24 MPa on the left shoulder and the right arm, where, conservatively, the thin external patches attached to the structure were considered as the only resistant elements for these areas in the finite element model. Von Mises equivalent stress levels of around 10 MPa were observed at other connection points.

Regarding the internal reinforcements, it is important to mention that due to the restriction of free thermal deformation imposed by the sculpture, stress levels observed ranged between 80 MPa on the strips along the right arm and 30 to 50 MPa on the rest of them.

These stress levels, however, are by no means high and did not explain the appearance of fatigue-related fissures. Although thermal oscillations can produce significant stress level variation in a fatigue analysis, it should be noted that the number of cycles they cause (daily at their most frequent, in this case) is much lower than that required to produce fatigue cracking.

5.3 Wind effects

Since the Giraldillo works as a weather vane and is continuously subjected to wind action, wind could be suspected to be the cause of most of the sculpture's damages and defects. However, wind-generated forces proved to be insignificant. Therefore, the idea that cracks in the sculpture are a consequence of wind load induced fatigue has been discarded, since Von Mises equivalent stress levels produced by wind action are negligible (maximum values are around 0.3 MPa at certain connection points of the sculpture and 18 MPa at the horizontal middle and upper members of the internal bar structure). These values are much lower than those expected for a fatigue limit, according to the elastic and strength limit of the materials (Table 1). Nevertheless, a new section for these elements of the internal structure should be proposed during the restoration process, so that they could more easily bear the induced horizontal bending moments caused by wind pressure on the standard and palm frond, as they are the only significant forces induced by the wind. By doing so, any fatigue effect will be completely avoided.

It was also determined that a high-speed wind (45 m/s) hitting the Giraldillo laterally causes lower mechanical stress than a lighter wind (11 m/s) striking it frontally (Fig. 18). Therefore, beyond the issue of preserving the Giraldillo's function as a weather vane, the conservation effort also proves to be important to minimise wind-generated stress. The bending and torsion moments predicted in the axis with the numerical model (579 Nm and 2,581 Nm respectively) matched the experimental results (600 Nm and 2,747 Nm, respectively) obtained before the restoration process began with strain gages attached to the axis and wind-speed readings taken simultaneously [10].

The mechanical response of the Giraldillo under wind action has also proved that it shows a good aerodynamic behaviour when it is correctly positioned according to wind direction, so little force is induced because of wind pressure in that situation.

5.4 Seismic load

The seismic response was obtained through a dynamic modal analysis and linear superposition according to the elastic response spectrum that defines the seismic load, as explained above. It should be noted that this is a linear dynamic analysis, so the non-linear elements that were used to consider the cracks cannot be used for this kind of analysis. Therefore, cracks are always considered to be open under seismic action, with no stiffness if they close. Although this is not the real situation, the results will err on the side of caution.

The modal analysis showed that local modes of the Giralda Tower and the Giraldillo were uncoupled and the first mode of each was the most relevant. The presence of the Giralda Tower does not affect the qualitative response of the Giraldillo in terms of deformed shape, but it significantly increases the displacements and accelerations of the Giraldillo, and therefore the inertia forces and stresses in it.

The deformed shape of the Giraldillo under lateral and frontal seismic excitation are shown in Fig. 19 and Fig. 20, respectively. These deformed shapes are almost identical to the first two vibration modes of the Giraldillo alone from a qualitative point of view. The contribution of higher modes to the seismic spectral response analysis is almost negligible.

Another significant result was the numerical model's ability to accurately predict the Giraldillo's first two vibration modes and natural frequencies: a lateral vibration with a frequency of 1.14 Hz and a back-front vibration with a frequency of 1.09 Hz. These results closely match the experimental data taken on the replica (manufactured to temporarily replace the Giraldillo during its restoration). This dynamic response was analysed before the replica of the Giraldillo was mounted atop the Giralda Tower. This was done by measuring the acceleration induced on its supporting axis, below the feet of the sculpture, when it was pushed away horizontally from its equilibrium position and then left to oscillate. The first natural frequency was obtained from this free vibration experiment.

The seismic load cause the highest mechanical stress levels in the sculpture and internal structure of the Giraldillo. The only significantly high stress levels, however, occurred in the areas of force transmission around the sculpture/internal structure connection points (Fig. 21 and Fig. 22).

In a frontal seismic movement, high stress levels are obtained around damaged areas of the right arm (almost 95 MPa). This level cannot be accepted, according to the material properties (Table 1) and hypothesis of elastic behaviour. In spite of the fact that the finite element model is too conservative to consider patches and cracks in this area, it is clear that this effect will clearly require some improvements when the Giraldillo is restored. Thus, it would be necessary to uncouple the right hand from the stick of the standard to prevent the inertia forces of the standard from being transmitted to the right arm. Moreover, the internal reinforcements of this arm should be replaced by more resistant ones.

In the rest of the sculpture, equivalent Von Mises stress levels are less than 30 MPa, with the highest values located around damaged areas, where external patches and cracks are located.

Regarding the internal bar structure, the most significant stress levels are reached by the upper horizontal bar because of the horizontal bending movements induced by the movement of the standard. This effect is similar to that observed for the frontal wind action. However, the stress level is acceptable again (80 MPa), although the flexural behaviour of this bar should be enhanced during restoration.

As regards lateral seismic excitation, the inertia effects of the standard and palm frond movement are much lower. Generally speaking, the stress levels of the sculpture, internal bar structure and reinforcements are lower than in frontal seismic movement. Nevertheless, high stress levels can be observed in the sculpture at connection points with the internal structure located at both legs. This is due to the fact that the inertia forces of the standard and palm frond act perpendicular to the bronze shell of the sculpture, instead of tangent to its surface, as happens when frontal vibration takes place. The equivalent Von Mises stress levels observed at these connection points are higher than 100 MPa, which is not acceptable. Nevertheless, these values are not so high in the real situation, since they turn to acceptable values at a short distance from the connection point (around 5 cm). That means that a more detailed model for these areas would be needed for the restoration of the Giraldillo and these connection points should be adequately designed to reduce the transmission of these inertia forces perpendicular to the bronze sheet.

5.5 Load combination

Combining the effects of different actions proved that the stress levels undergone by the Giraldillo are by no means cause for alarm, since they are far enough from the elastic limit of the materials (Table 1). High stress levels result in certain areas only in combinations involving seismic action. In these cases, high stress levels affect points where the sculpture is connected to the internal structure or where patches have been applied to the bronze sculpture. This is the case in the damaged areas of the sculpture's left armpit and right arm, as a result of poorly conceived structural design or inadequate attention to construction detail. Stress produced by the weight of the palm frond and the standard or by oscillations caused by wind or seismic activity is transferred to these areas, leading to unacceptable stress levels, as mentioned above for seismic action.

However, the model is too conservative in these areas. In fact, the sculpture/structure joints and overall functional adequacy of the structure could be improved through an appropriate restoration process, which would require a more realistic and less conservative model.

Maximum values between 20 and 40 MPa were observed in damaged and cracked areas, whereas stress levels below 8 MPa were obtained for the rest of the sculpture.

As for the internal bar structure and reinforcements, the highest stress levels are due to bending forces on the horizontal members of the structure, induced by horizontal loads (seismic and wind action) and vertical loads (self-weight and thermal loads). However, maximum stress levels (90 MPa) are well enough below the elastic limit of the material of the structure.

During this analysis of the mechanical behaviour of the Giraldillo prior to the restoration process, no special attention was paid to its supporting axis. This will be considered in detail when the Giraldillo is replaced atop the Giralda Tower again. To do so, a new supporting axis will have to be placed on the Giralda once the replica of the Giraldillo and its axis are dismounted, since the original one was unfortunately cut into pieces when dismounted. However, the results obtained from this preliminary analysis showed that a new axis with similar dimensions to the original one would ensure the stability of the Giraldillo.

6. Conclusions

The finite element model discussed in the present paper has proven to be useful for the accurate analysis of the Giraldillo's mechanical response to the different actions to which it is subjected.

In conclusion, the Giraldillo can easily withstand the different mechanical loads to which it is subjected. This supports the hypothesis that the defects are mainly a product of the original casting and assembly process and renovation/repair work carried out over the centuries, and not the result of the mechanical actions to which it has been subjected. Observations made while studying the Giraldillo (clearing, removal of patches, historical studies, etc.) also support this hypothesis.

The study confirms that the structure placed inside the Giraldillo in 1770 was designed effectively. Forces induced by self-weight, thermal loads, wind and earthquakes on the sculpture, the standard and the palm frond can be adequately transmitted to the supporting axis, which is the crucial element to ensure the stability of the Giraldillo.

However, the corrosion that has occurred over the years has had a serious impact on the condition of certain iron elements of the internal bar structure and reinforcements. For this reason, corroded elements will have to be replaced with stainless steel elements that are more compatible with bronze in terms of resistance to corrosion and thermal expansion. The design of the new internal structure should be very similar to the original one, with only few changes that would improve its response to external conditions. Basically, corrosion should be avoided and with a proper selection of its material the flexural behaviour of the horizontal members should be enhanced. The internal iron reinforcements and external copper reinforcements should be replaced with an internal reinforcement system that is more complete and more compatible with the bronze sculpture.

Certain elements should be designed at the connection points between the sculpture and the internal structure to ensure the effective and safe transmission of forces. The weight and oscillations induced by the wind and earthquakes over the standard and the palm frond should not be transmitted to the sculpture but directly to the internal bar structure.

The conclusions reached here lay the foundations for undertaking a restoration project that would guarantee the Giraldillo's preservation before returning it to its position atop the Giralda Tower. The design, manufacturing, assembly and installation phases of the new structure, internal reinforcements and supporting axis will be presented in a forthcoming paper.

Acknowledgements

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Figure captions

Fig. 1 The Giraldillo as seen atop the Giralda Tower before undergoing restoration [1].

Fig. 2 Dimensions of the Giralda Tower

Fig. 3 Schematic diagram and dimensions of the Giraldillo and its internal structure.

Fig. 4 Palas Atenea (16th century engraving by Marco Antonio Raimondi)

Fig. 5 Image of the document prepared in 1782 describing the work done in 1770

Fig. 6 The Giraldillo at the beginning of the restoration process.

Fig. 7 An example of patches applied to the sculpture (left hip).

Fig. 8 Cracks in the areas of the abdomen and chest covered with welds applied in the 1980s.

Fig. 9 Photogrammetry of the Giraldillo (A. Almagro, School of Arab Studies, Granada).

Fig. 10 Three-dimensional image of the Giraldillo figure (Dept. of Graphic Engineering, University of Seville).

Fig. 11 Section-by-section representation of the Giraldillo's shape.

Fig. 12 . Finite Element Model.

Fig. 13 Giralda-Giraldillo Model.

Fig. 14 Measuring the weight of the Giraldillo in the restoration laboratory

Fig. 15 Representation of the total displacement (in metres) from the effects of its own weight (the image after deformation is superimposed on the contour image of the figure before it was deformed). The imbalance towards the standard (right side) can be clearly observed.

Fig. 16 Von Mises equivalent stress map (0-50 MPa), representing the effects of its own weight.

Fig. 17 Von Mises equivalent stress map (0-50 MPa), under uniform heating conditions.

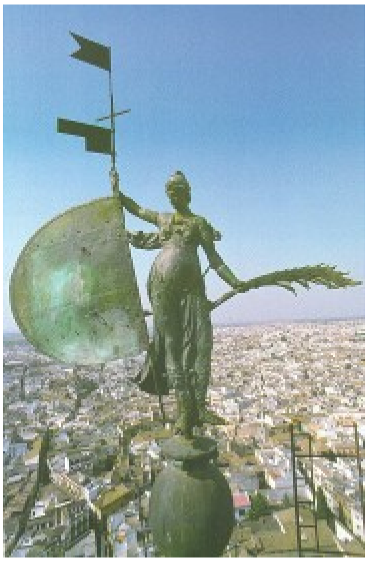
Fig. 18 Von Mises equivalent stress map (0-50 MPa) observed under the conditions of an 11m/s headwind.

Fig. 19 . Deformed shape under lateral seismic action

Fig. 20 . Deformed shape under frontal seismic action

Fig. 21 Von Mises equivalent stress map (0-50 MPa) produced by frontal seismic action.

Fig. 22 Von Mises equivalent stress map (0-50 MPa) produced by lateral seismic action.



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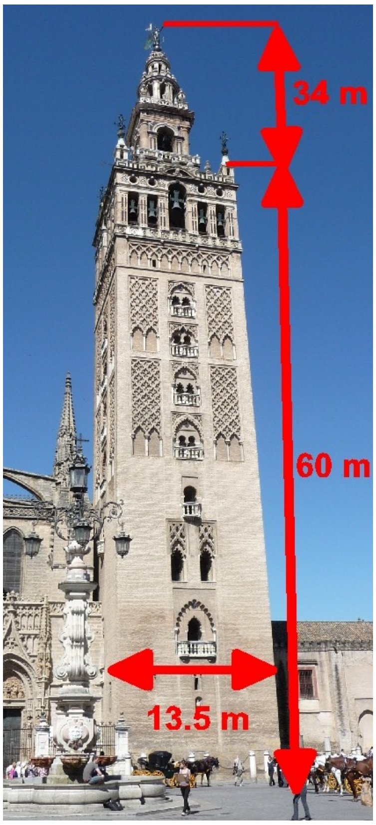

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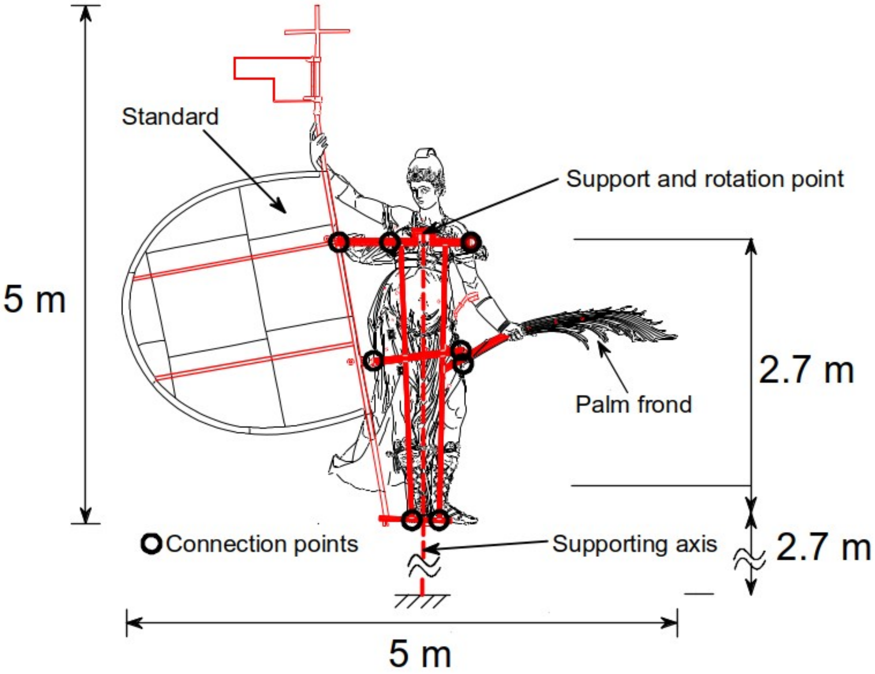

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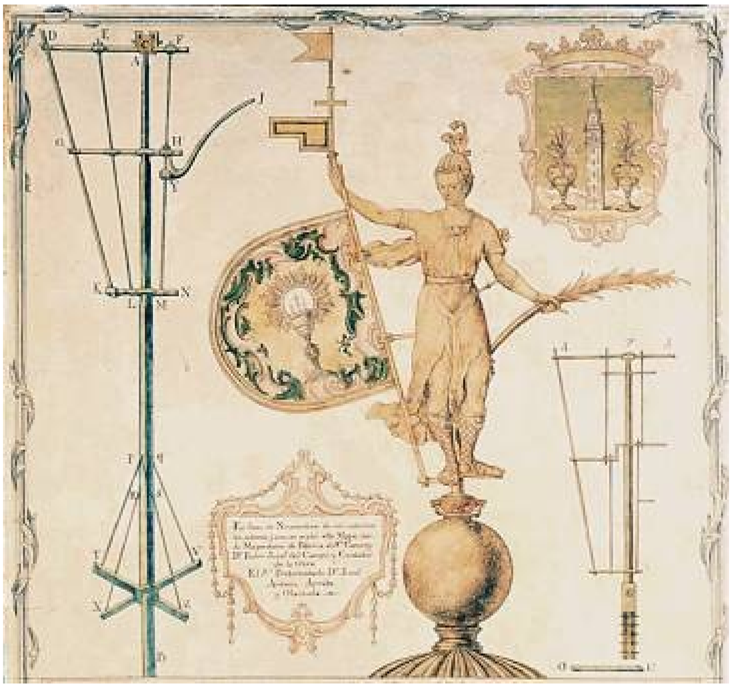

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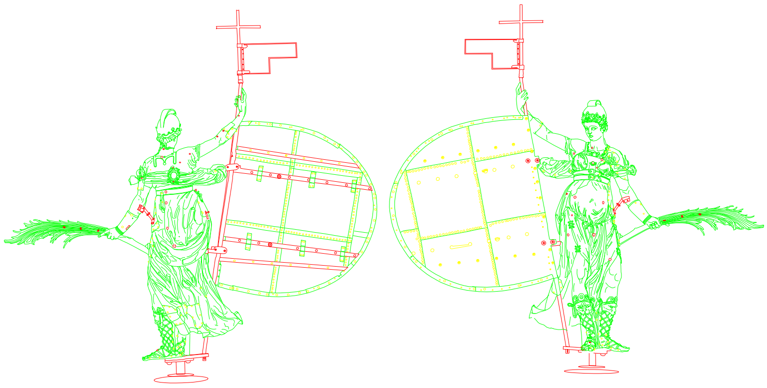

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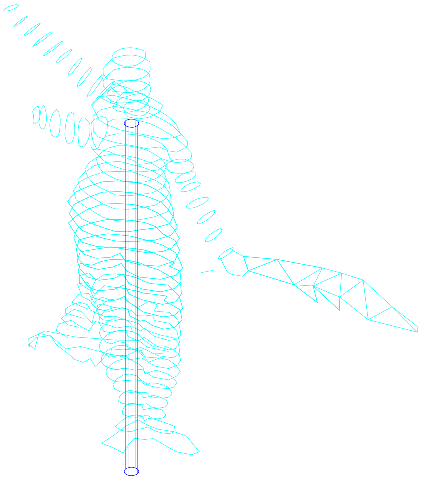

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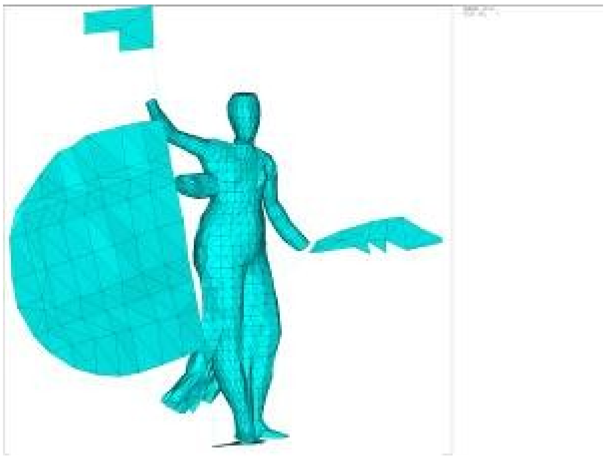

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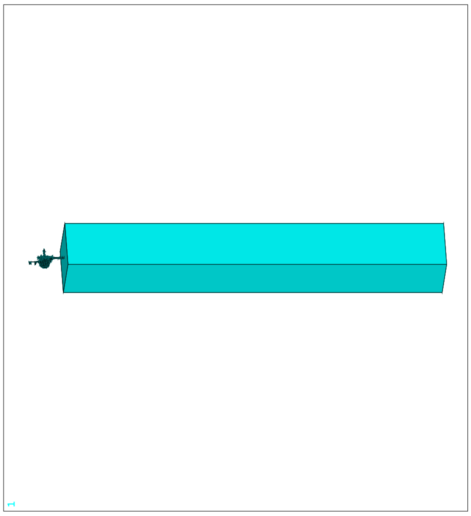

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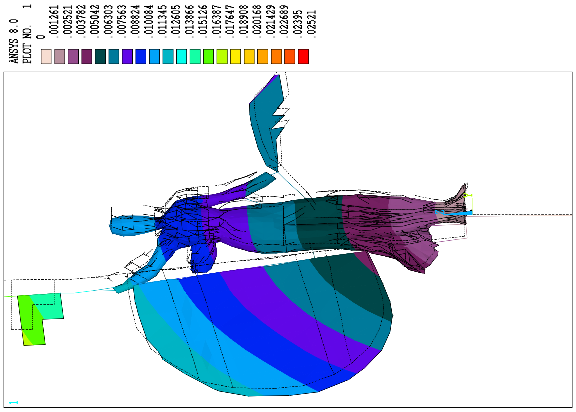

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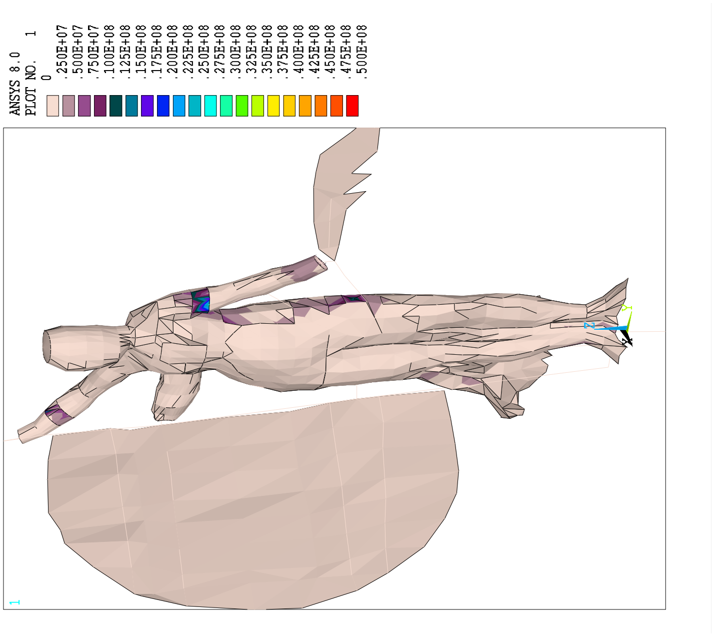


Fig. 16 Von Mises equivalent stress map (0-50 MPa), representing the effects of its own weight.

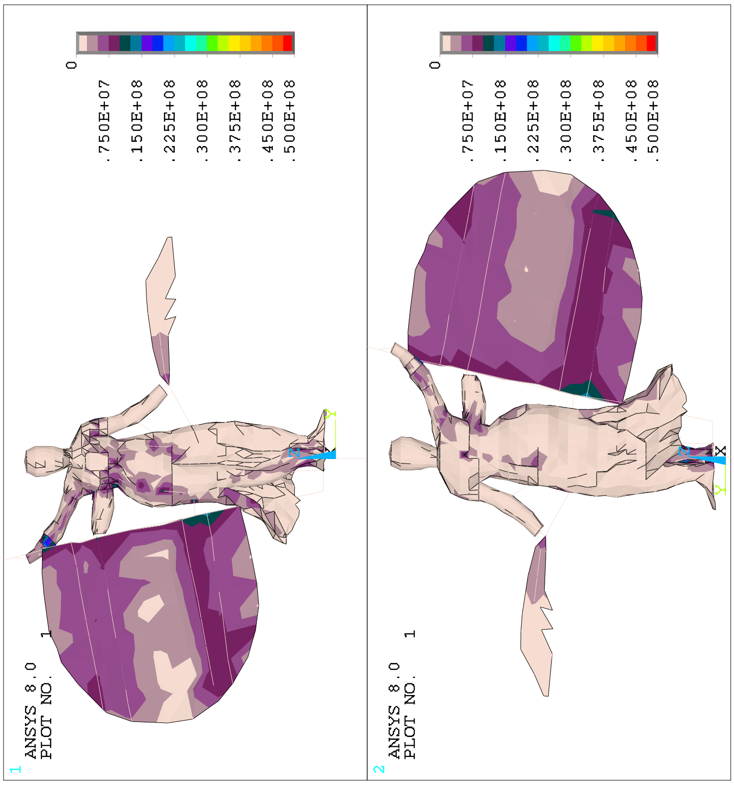
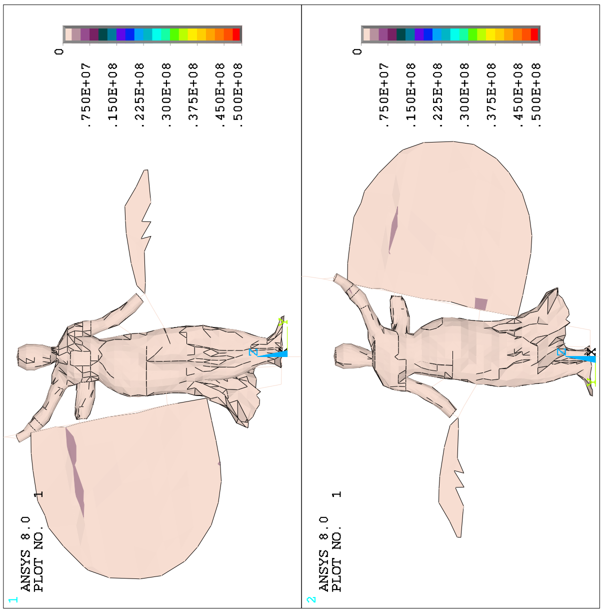


Fig. 17 Von Mises equivalent stress map (0-50 MPa), under uniform heating conditions.



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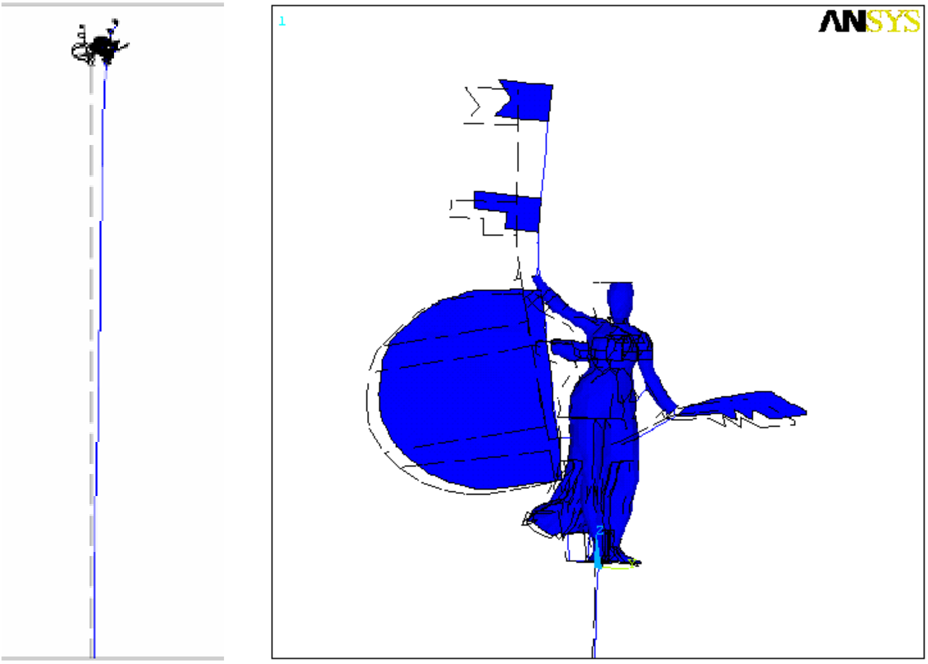

Fig. 19 . Deformed shape under lateral seismic action

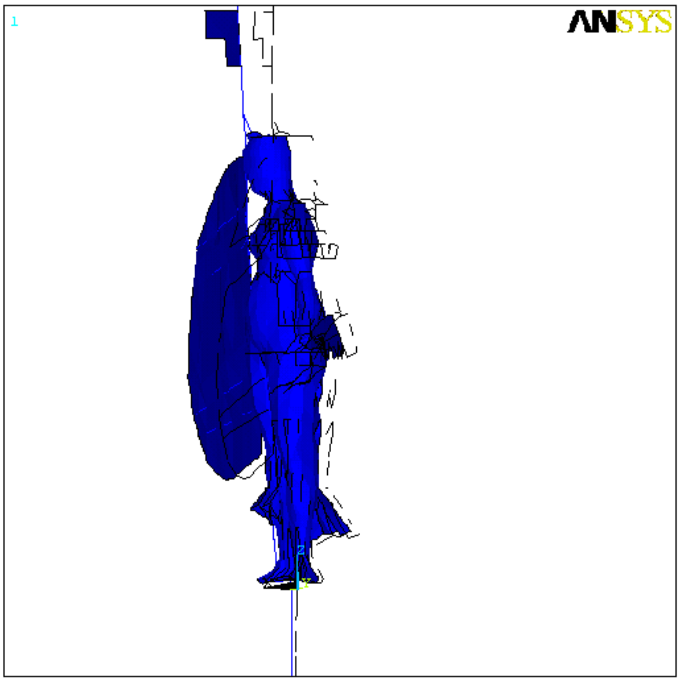

Fig. 20 . Deformed shape under frontal seismic action

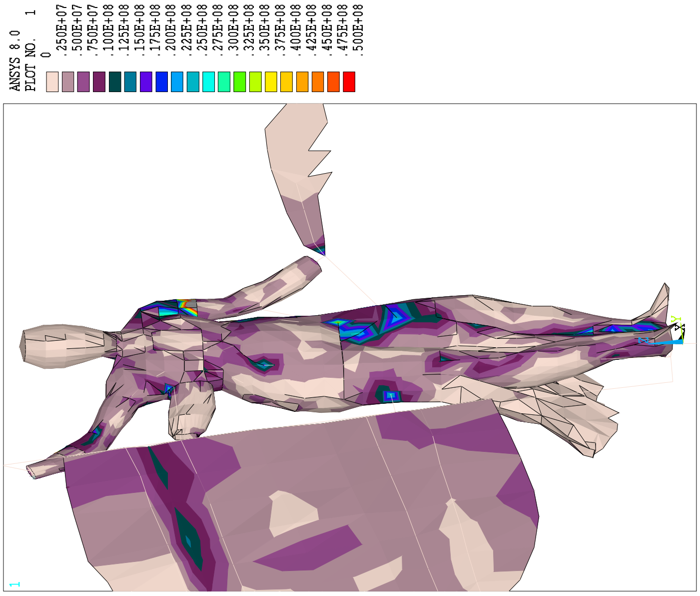

Fig. 21 Von Mises equivalent stress map (0-50 MPa) produced by frontal seismic action.

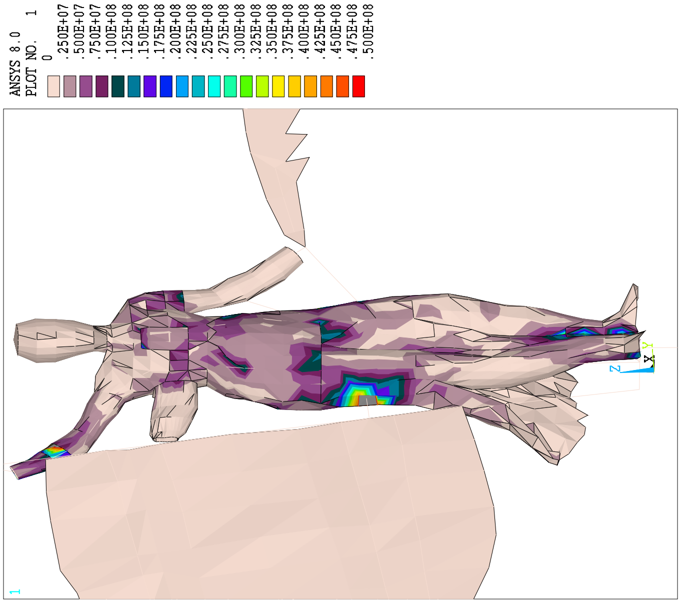

Fig. 22 Von Mises equivalent stress map (0-50 MPa) produced by lateral seismic action.

Tables

Table 1. Mechanical properties of materials

	E (GPa)	ν	G (GPa)	σ_E (MPa)	σ_R (MPa)	Dens. (kg/m$^{3)}$	α (ºC^{-1})
Bronze	70	0.35	26	50	80	9000	18 10^{-6}
Iron	*210*	*0.3*	*81*	*130*	*260*	*7870*	*12* 10^{-6}

Table 2. Values of the elastic response spectrum for the seismic load

Frequency (Hz)	Acceleration (m/s^2)
0.67	*2.36*
1.08	*3.8*
3.45	*3.8*
4.60	*3.08*
6.90	*2.35*
13.79	*1.63*
27.6	*1.26*