Non-linear hygrothermal structural analysis of the elliptical dome of the church in the Universidad Laboral, Gijon, Spain.

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The Church of the Laboral University of Gijón has the world's largest elliptical masonry roof with a 40.8 m major axis. This large structure is vertically self-supported with twenty pairs of masonry ribs crossing each other, and horizontally supported by means of two elliptical ring beams at the top of the dome. In order to study this historical building, this paper presents the overall three-dimensional structural numerical analysis of the roof. It includes nonlinearities due to materials, geometry and contacts between structural elements of the building. Temperature, moisture content and dead loads are included in the hygrothermal structural analysis of the dome. In this nonlinear numerical analysis displacements, stress, cracking and crushing are evaluated. The influence of moisture content on the structure performance and other relevant conclusions are presented.

Keywords: Historical Structure, Masonry, Monitoring, Non-Destructive Inspection

Subject classification codes: include these here if the journal requires them

Introduction

The Universidad Laboral of Gijón was built between 1946 and 1956. With 270,000 m2, it was the most important architectural work in the twentieth century and is still the largest building in Spain [1]. The church building (see Figure 1) is undoubtedly the most spectacular architectural ensemble of the Universidad Laboral in Gijón. With an overall inside surface of 807 m², the church has the world's largest elliptical roof: with a major axis of 40.8 m and a minor axis of 25.2 m. The church is 25 m high from the floor to the springing line, and 33 m high to the crown. The dome has an estimated weight of 2,300 tons. For its construction, 450,000 annealed bricks from the province of León (Spain) were used. The whole structure is self-supported with twenty pairs of interlaced masonry ribs. In the crown, there is an oculus to light the interior of the Church naturally. Currently however, there is no natural lighting due to a slight sag in the dome.

The structural analysis of masonry structures, and in particular of domes, has several difficulties: nonlinearities due to the material properties, with almost no tensile strength; the lack of experimental characterisation of the mechanical properties of masonry structural elements; and in this particular case, the complexity of the geometry [2].

To solve this complex structural problem, refined mechanical models, which accurately predict the behaviour of masonry material and elements, are proposed in the literature [3-5]. These models use different strategies to take into account the highly nonlinear behaviour of the material in compression and in tension. They include cracking phenomena due to the low tensile capacity. Some of these models also provide the structural response to large displacements. It is difficult to apply current models to a 3D analysis of complex structural systems. The great number of parameters involved in the definition, and of degrees of freedom required for structural meshing, produce unmanageable data. In this work, a nonlinear structural static analysis of the elliptical dome of the church is developed, including the hygrothermal behaviour. The most relevant results: maximum displacement, stress, and cracking and crushing phenomena are presented.

Finally, valuable information from the structural response and the interaction among the elements of the structure are discussed. The most important conclusions of the hygrothermal structural analysis are drawn and a plan for the conservation of the building is proposed in order to preserve this heritage site.

Materials and methods

Analysis of the structural response of masonry structures, and in particular of domes, is complex. The nonlinear material properties of masonry, with almost no tensile strength, must be included in the numerical model. In addition, there is a lack of experimental data regarding the mechanical properties of masonry. Finally, this case is particularly complex due to the geometry of the dome which is elliptical in shape and has double curvature on three axes [6].

Previous numerical models [2, 4-5] provide a structural response to large deformations which occur under seismic actions. However, current 3D numerical models cannot analyse such complex load cases.

The numerical simulation carried out in this work uses the ANSYS Workbench 2021 R2 academic software [7]. The numerical simulation developed gives great insight into the structural response of the dome taking into account moisture and dead loads, saving costs and time in relation to experimental tests [8-9].

Material properties

In order to obtain the main masonry properties, another minor structure located near the building was tested. The brick of the minor structure is 0.24 m long, 0.11 m wide and 0.06 m thick. The mortar is 0.01 m thick [10-11]. The main material properties obtained from the experimental works are used in the FEM model, as it is presented in Table 1.

Table 1. Material properties.

Material	**E (Mpa)**	**σ_t (Mpa)**	**σ_c (Mpa)**	**μ**	**δ (kg/m^3)**	**α (°C^{-1})**	**λ (W/m°C)**
Sandstone	10,000	14.5	95	0.30	2,250	1.16E-5	1.7
Limestone	35,000	15	140	0.25	2,750	0.8E-5	1.3
Sponge (roof)	5	-	-	0.20	10	1.4e-5	2.0
Reinforced concrete	23,000	2,9	30	0.18	2,300	1.2E-5	1.63
Masonry	870	0.5	9.5	0.25	2,000	0.5E-5	0.8

Finite element model

A 3D geometrical model of the dome was done using the DesignModeller program included in the ANSYS-Workbenck as parametric CAD software [7-9]. The main components modelled are:

- Masonry ribs: elliptical arches of the dome made of masonry and concrete.

- Ring beams: there are two ring beams made of reinforced concrete to support the masonry ribs, the upper ring and the lower ring.

- Roof: the conical auxiliary structure over the ribs, including the small tower at the central skylight.

- Columns: there are twenty main building supports made of reinforced concrete

The above geometrical model is divided in mapped regions and free regions using MultiZone mesh method [7,12-13]. A pure hexahedral mesh is obtained with a sizing parameter ranging between 0.06 m for the masonry ribs and 0.2 m for the ring beams. The finite element model has more than 1,500,000 nodes and 1,200,000 elements (see Fig.4).

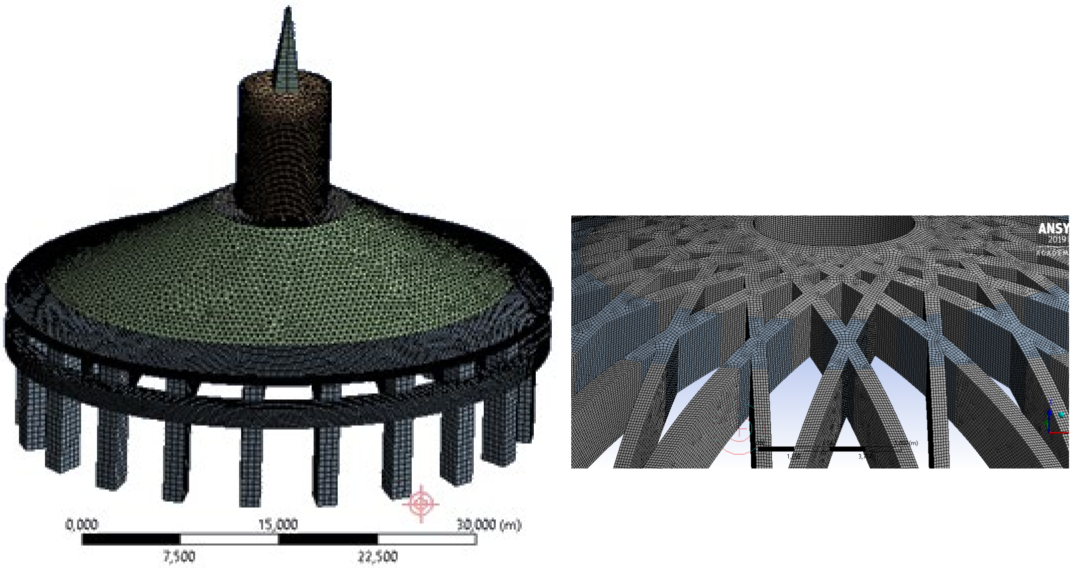


Figure 2. Numerical mesh of the church in the Universidad Laboral: overall view (left) and detail of the masonry ribs (right).

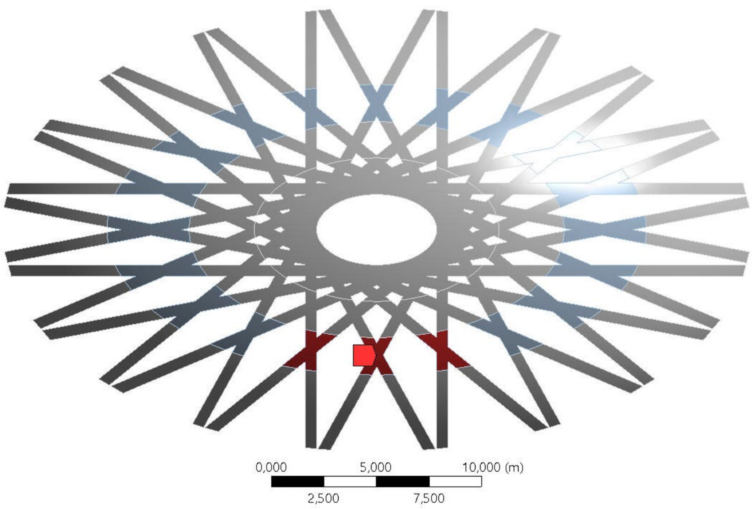
Load cases

In this work, the following load cases are studied:

1. The thermal load due to the solar radiation. A thermal flux of 200 W/m^2 was applied for the hottest weather condition in the summer [11]. Convection film coefficients were obtained from the Standard UNE-EN ISO 6946, as it is shown in Table 2 below, ranging from 25 to 5.88 W/m^{2}K [14-15].

2. The influence of moisture. The moisture located on ribs due to flaws in the waterproofing of the roof are included in the structural analysis (see Fig.3) [16-17]. Moisture content effect is analyzed using Fick’s Law [18-21].
3. The dead load. Taking into account the density of the main materials, including a study of the conical roof [22].

(a)



(b)

Figure 3. Moisture content on ribs: (a) actual view and (b) numerical model (in red).

Thermal loads and moisture content are applied to nodes and transferred to the model as temperature distribution. Analogy between moisture and temperature is possible due to Fick's Law [18-19]. After the hygrothermal analysis, the dead loads are applied and the nonlinear problem is solved using a Newton-Raphson method with adaptive descent including plasticity in the material properties. The maximum number of equilibrium iterations is 200, with an initial step of 0.01 over 1. Solution convergence is controlled using the displacement with a minimum tolerance of 0.01% and maximum load step of 0.1 [7-9].

Hygrothermal structural analysis

Thermal analysis is solved including solar radiation, conduction and convection properties [22]. Fick's Law stablish an analogy between moisture and temperature. So, a previous analysis provides a temperature distribution on the structural ribs equivalent to their moisture content [18]

Fick's Law [23-24] accepts the following assumptions:

1. Moisture expansion of saturated bricks remains constant at a value of δ=1.03×10^{-3} m/mR.
2. Specific points of the ribs show the same moisture content, R, according to visual inspections (see Fig 3).
3. Moisture effect is modelled using the thermal expansion coefficient α = 5×10^{-3} m/mK. The equivalent temperature determined using Eq.(1) provides the moisture content effect

$$\Delta T_h = \frac{\delta \cdot R}{\alpha} = \frac{1{,}03 \cdot 10^{-3} \frac{m}{mR} \cdot 1}{5 \cdot 10^{-6} \frac{m}{mK}} = 206\ K \qquad (1)$$

Resultant temperatures from thermal loads and moisture content are transferred to the structural analysis by finite element method.

Numerical results and discussion

The problem was solved on a 160-core 2.7 GHz Intel Xeon Gold 6230 dual processor, with 256 GB of RAM and 8 TB of hard drive. Total CPU time for each load case was 400 s using 20 cores and 10 interactions were needed to achieve convergence of the solution.

The main numerical results from the hygrothermal and structural analyses are presented, including cracking and crushing analyses [25-26].

Hygrothermal results

Figure 4 shows the temperature distribution obtained in the hygrothermal analysis applying summer weather and moisture conditions. Temperature ranges between 16 ºC and 222 ºC on the masonry ribs, with the maximum where the moisture is located. The variations of temperature can cause thermal stresses in the dome.

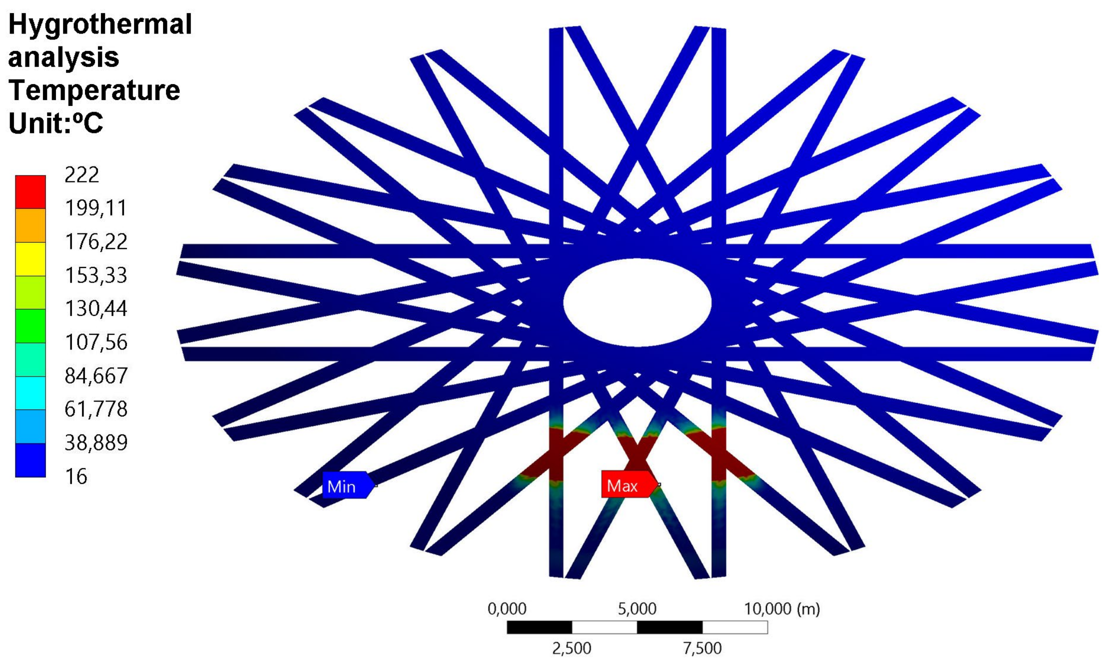
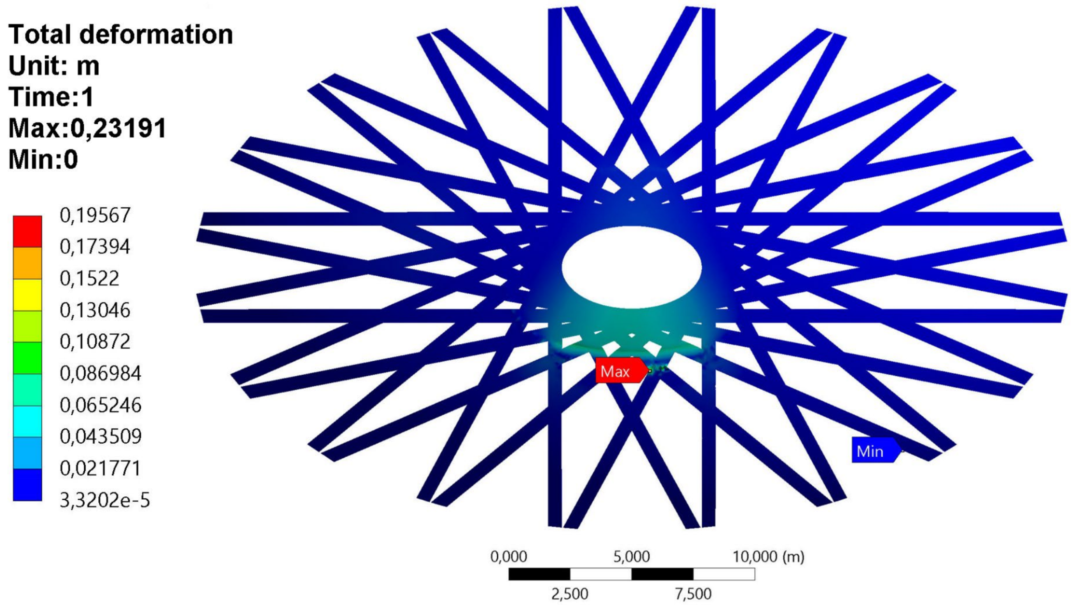


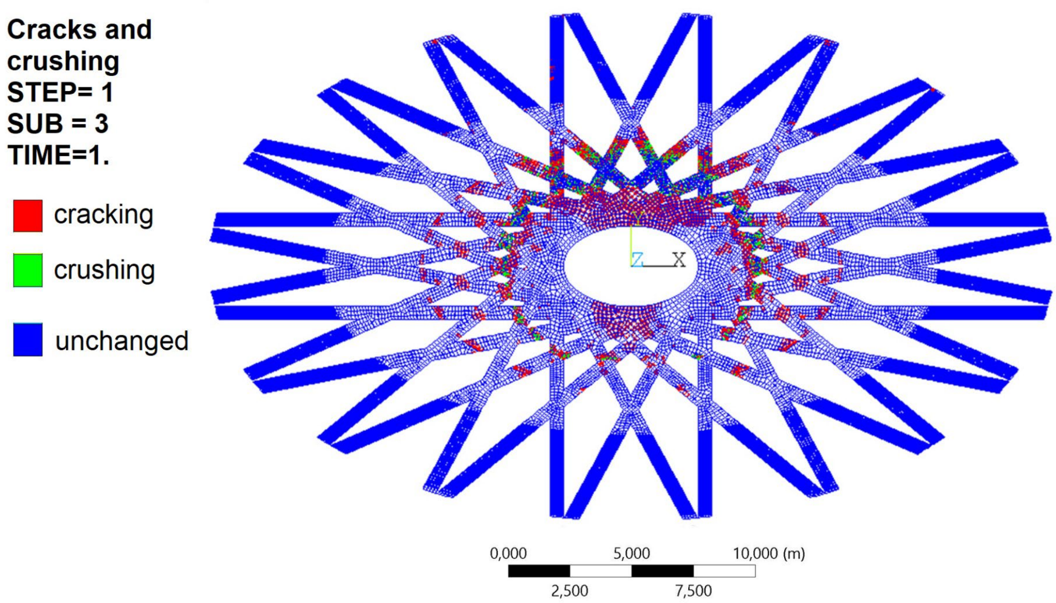
Figure 4. Temperature distribution on masonry ribs.

Structural results

Figure 5 shows the maximum displacement and cracking patterns of masonry ribs obtained from the hygrothermal structural analysis.



(a)

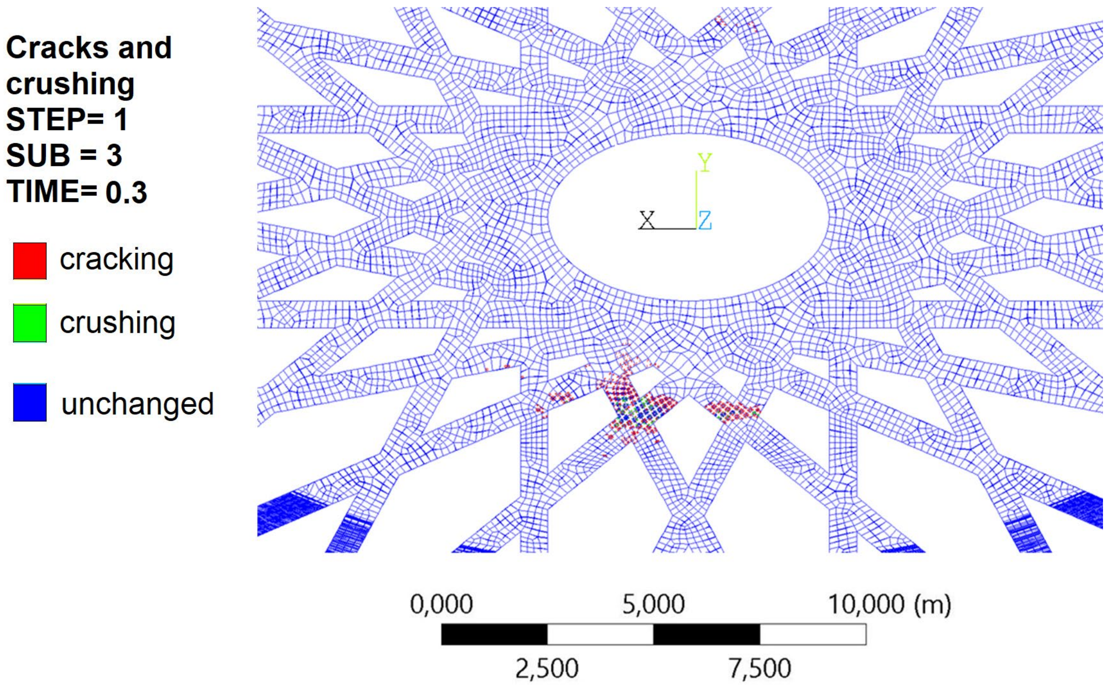


(b)

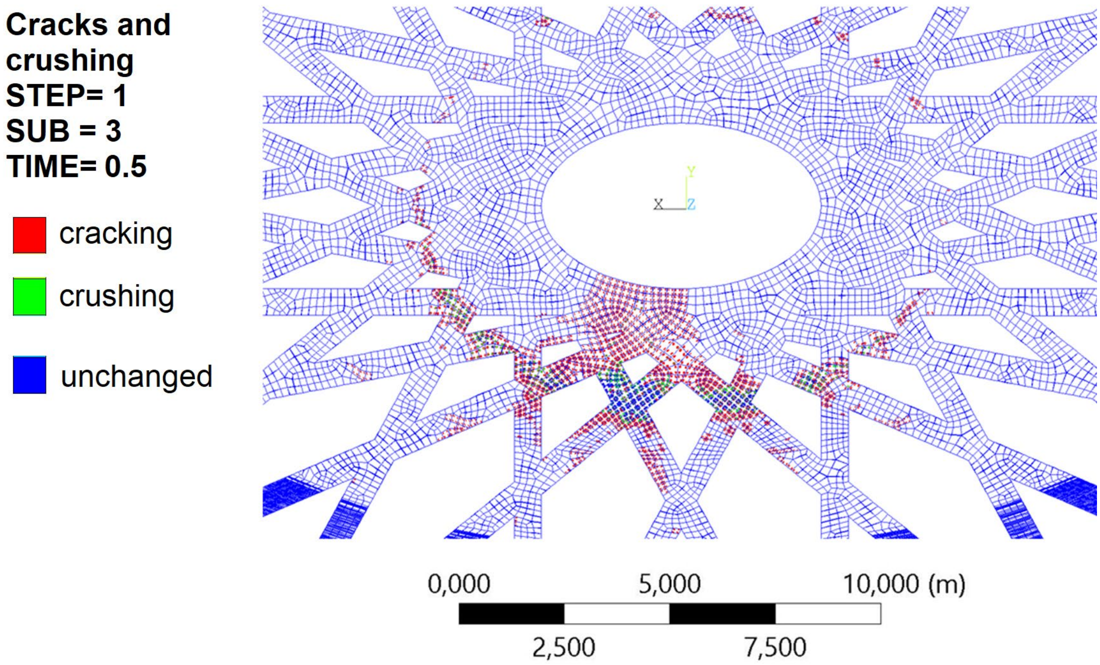
Figure 5. Main results in the masonry ribs (a) maximum displacements and (b) cracking and crushing.

The maximum displacement obtained is about 0.20 m, which lead a ratio of 126 between shorter length of the dome and the vertical displacement. The elliptical annular central beam and the short masonry ribs present cracking patterns.

The non-linear structural response shows the highest thermal and dead loads applied on the dome, the larger amount of cracking and crushing.



(a)


Cracks and crushing
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crushing
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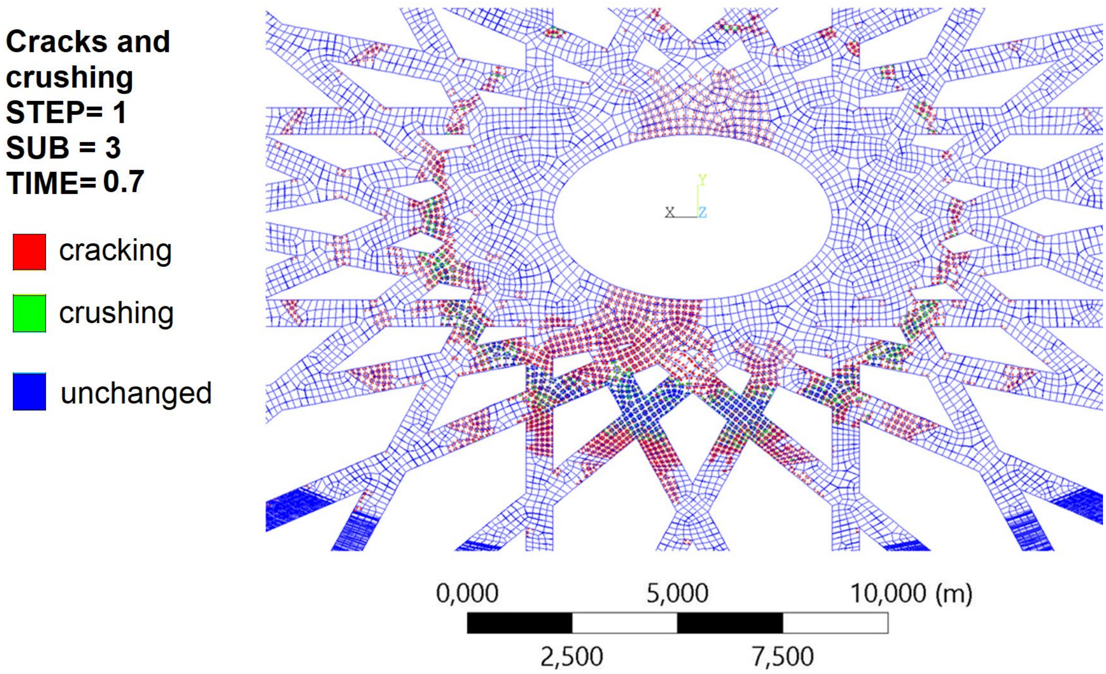
10,000 (m)
2,500
7,500

(b)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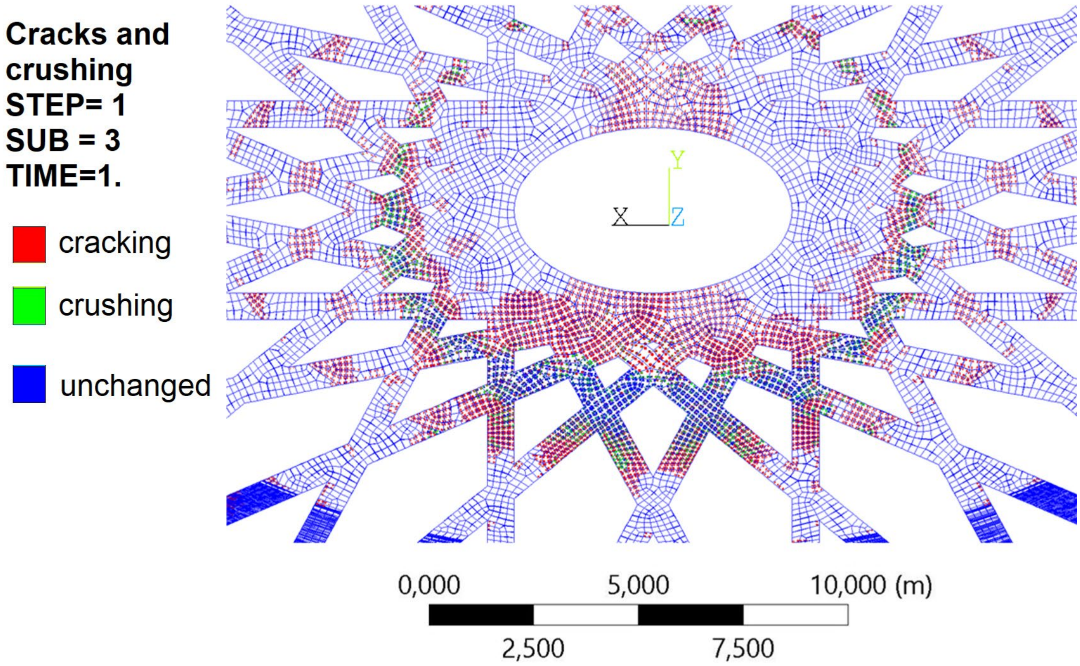

(d)

Figure 6. Crack pattern evolution at four load levels: (a) 30%, (b) 50%, (c) 70% and (d) 100%.

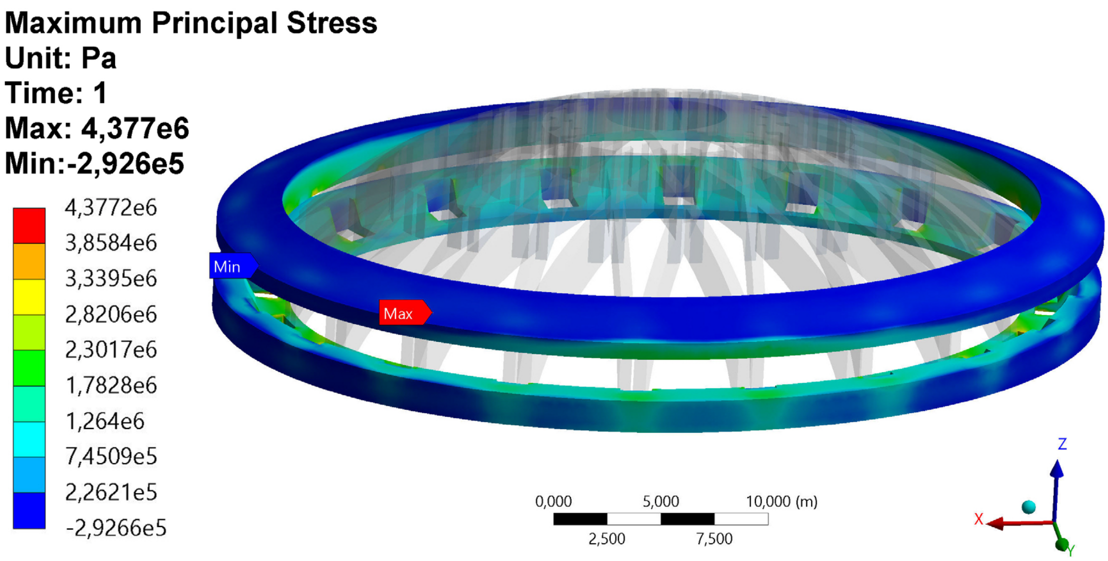

Figure 7. Maximum principal stresses on ring beams.

Conclusions

In this work, advanced numerical models determine the structural response of a masonry elliptical dome including the effect of moisture. The most important findings are the following:

- The complex geometry of the Church in the Universidad Laboral must be defined using a 3D parametric design model.
- MultiZone mesh method must be generated in the structural elements of the dome to obtain a regular tetrahedral mesh. In addition, the ribs must be divided in smaller parts to obtain a pure hexahedral mesh. The suitable element size for the geometry and dimensions of this work varies between 0.1 and 0.2.
- The temperature gradient due to thermal and moisture conditions in the masonry ribs significantly increase stresses and eventual crack defects. The stress levels are mainly due to the brick moisture expansion.
- The use of advanced numerical models including nonlinear contacts is suitable to study the hygrothermal and structural behavior of complex geometries and assembles of different structural elements, such as ribs, columns and annular rings.
- Constitutive material models are needed to efficiently model the performance of concrete and masonry bricks. In this case, William-Warnke and Drucker-Prager models were combined to obtain accurate results [25-26].
- The numerical results of the hygrothermal analysis show cracking patterns in the short masonry ribs and the elliptical central beam. These cracks can produce some deterioration in the elliptical dome.

- Tensile stress in the ring beams is close to the maximum admissible stress for reinforced concrete materials, about 4 MPa. However, the effect of moisture in the beams is remarkable being a key risk indicator of deterioration.

All in all, previous numerical simulations of these authors bring a wealth of experience to analyze the structural performance of an important cultural heritage. Visual inspections and advanced numerical models were combined to study the structural response of the elliptical dome of the Church in the Universidad Laboral. The most critical points were determined in the ribs, where the highest moisture contents were seen.

Most relevant contribution of this work is to seek advice of conservation or retrofitting of this historical building. Structural elements of the dome are at increased risk of collapse due to the moisture content and thermal loads as it was seen in this numerical study. Conclusions of this work encourage the government of the Principado de Asturias to repair the roof and avoid the current waterproofing issues as soon as possible.

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