MODELLING THE BEHAVIOUR OF A LARGE SPAN GLULAM ARCH OF ATLÂNTICO PAVILLION

Maria João HENRIQUES[1], Pedro Belé MATEUS[2], Pedro PALMA[3] and Helena CRUZ[3]

[1]*Applied Geodetic Division, National Laboratory for Civil Engineering, Portugal*
[2]*Faculty of Sciences, Lisbon University, Portugal*
[3]*Timber Structures Division, National Laboratory for Civil Engineering, Portugal*

Abstract: Atlântico Pavilion, designed for the world fair Expo'98 in Lisbon, is a multi-purpose hall created to receive an audience up to 16,500 people. It is a remarkable structure. From the outside it resembles a futuristic spaceship. But it is the inner timber roof structure which turns it in one of the most emblematic buildings of its kind. The Pavilion has one of the largest glued laminated timber (glulam) structures in the world, with a maximum of 114 m span. This structure supports the arched roof and it is fixed to the concrete foundations by means of pinned joints.

Since 2000 the National Laboratory for Civil Engineering is responsible for following up the glulam structure. The monitoring includes: periodic visual inspections and measurements of wood moisture content, continuous measurements of standard environmental conditions relevant to the structure, and the determination of horizontal and vertical displacements by geodetic surveying methods. Vertical displacements of one of the arches, function of the influence of several parameters, are modelled. The model is calibrated using data from previous measurement campaigns.

The paper describes the Pavilion glulam structure and the monitoring system and presents the results, as well as the numerical models for describing environmental conditions and vertical displacements. These models fit well the historical behaviour of the studied arch. Measured displacements closely follow a pattern that can be described as a function of environmental conditions (temperature and relative humidity) and age of the structure, thus suggesting the strong influence of these variables and the absence of materials degradation or structural instability phenomena so far.

1. INTRODUCTION

The Atlântico Pavilion was built to fill the need of a multipurpose arena for large scale shows, sport events, conferences and concerts in Lisbon area. It was erected to accommodate several cultural and leisure attractions created for Expo'98, the world fair held in Lisbon in 1998. As many of the buildings constructed for this event, it was meant to remain after the closure of Expo'98.

The Atlântico Pavilion encloses one large volume defined by being, at its construction, the largest laminated timber structure in Europe. The innovative design of this structure created the need to closely follow its behaviour, reason for the setting of a monitoring system. This paper describes the studies undergone to establish a simple mathematical model that describes the historic behaviour of this structure. This model doesn't intend, by no means, to replace a structural model of the arch. It only intends to check if the displacements follow a pattern that can be related to a response to atmospheric conditions and age.

2. THE ATLANTICO PAVILION GLULAM STRUCTURE

From the exterior, the Atlântico Pavilion resembles a futuristic spaceship. Some people see the shell of a horseshoe crab. The inside of the roof structure of Atlântico Hall, the main hall of this building, looks like an upturned hull of a wooden 1500's ship, not only for its form but also for the materials used: glued laminated timber elements and wood planks in the inner layer of the roof. On the outside, the dome is covered with zinc sheets, with several insulating layers.

The glued laminated timber, or glulam, is a structural timber product in which individual wood planks are end and face bonded together to make a straight or a curved member, where the grain of every plank runs parallel to the main direction of the structural element. This engineered wood has very interesting mechanical properties in comparison with an equal size element of solid wood, it has a good weight/resistance relation, as well as a good fire resistance due to the low surface / cross section ratios normally corresponding to large timber members. This glulam structure is composed by 15 truss arches, spaced 9 m, of variable geometry because of the building's irregular form. The span of these arches varies from 52 to 114 m. Each arch is fixed to the concrete foundations by means of pined joints placed in the deambulatory, the area that surrounds the Atlântico Hall. The glulam is made of Norway spruce (*Picea abies*) and type I adhesive (glue suitable for indoor and outdoor environments), and it was surface treated with a preservative product to provide a suitable fungicide and insecticide protection.

This structure, one of the biggest timber structures in Europe – it was awarded the first prize by a jury voting on four criteria: fire resistance, ecological features, acoustics, and length of span - was one of the first designed in accordance with the ENV 1995:1995 *Eurocode 5: Design of timber structures*, which sets the requirements for mechanical resistance, serviceability, durability and fire resistance of timber structures.

Fig. 1 – The Atlântico Pavilion

Fig. 2 – The roof structure of Atlântico Hall

Fig. 3 – The feet of the arches as seen in the deambulatory.

Fig. 4 – The erection of the glulam structure

3. MONITORING ATLANTICO PAVILION

The National Laboratory for Civil Engineering (LNEC) was consulter of the Pavilion owner, during the phases of design, construction and setting of the glulam structure; later it was also contracted to follow up this structure for safety evaluation purposes (Cruz, 2007). The structure monitoring includes: periodic visual inspections and moisture content of the timber, continuous measurements of environment variables relevant to the structure and the determination of horizontal and vertical displacements by geodetic surveying methods.

3.1. The environment inside de Pavilion

The atmospheric conditions inside the Pavilion depend on several factors: i) the outside atmospheric conditions; ii) the inside activities (events); iii) the blackout blinds (*up* or *down*) on the roof windows; iv) the air-conditioning system (*on* or *off*). Inside the Pavilion, the temperature and relative humidity of the air are recorded every 30 minutes, in eight points of the structure, using long term relative humidity and temperature data loggers (Fig. 7). The location of these points is presented in Figure 12.

About one kilometre distance, in Cabeço das Rolas garden, there is an automatic meteorological station that records temperature, air humidity, wind velocity, wind direction and precipitation. Although not being so near the river Tagus (the Pavilion is 150m away; Cabeço das Rolas is 500m) the meteorological conditions are not much different from one another. The data is recorded every hour.

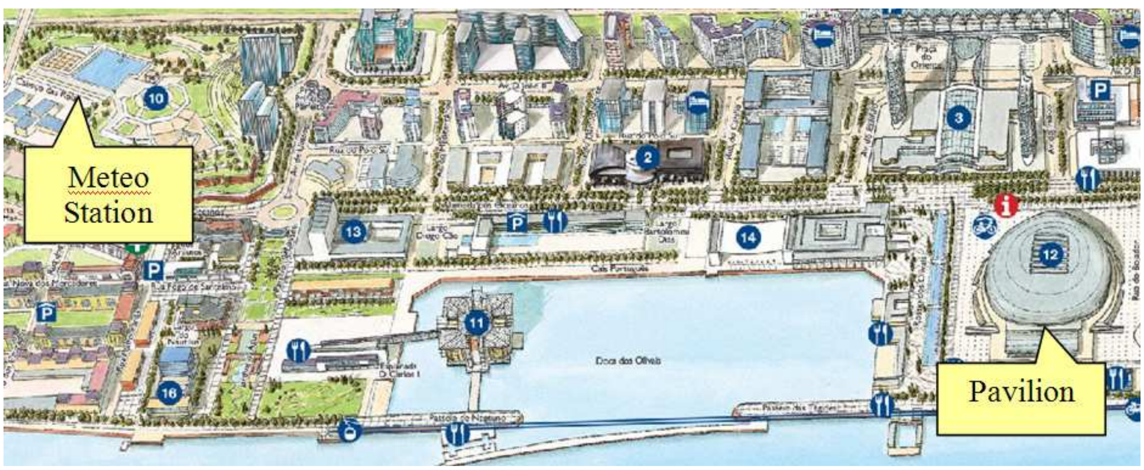

Figure 6 – Schematic view of the south area of *Parque das Nações*

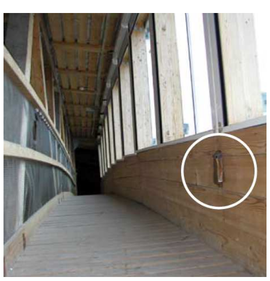

Fig. 7 - Data Logger

Fig. 8 - *Cabeço das Rolas* meteorological station

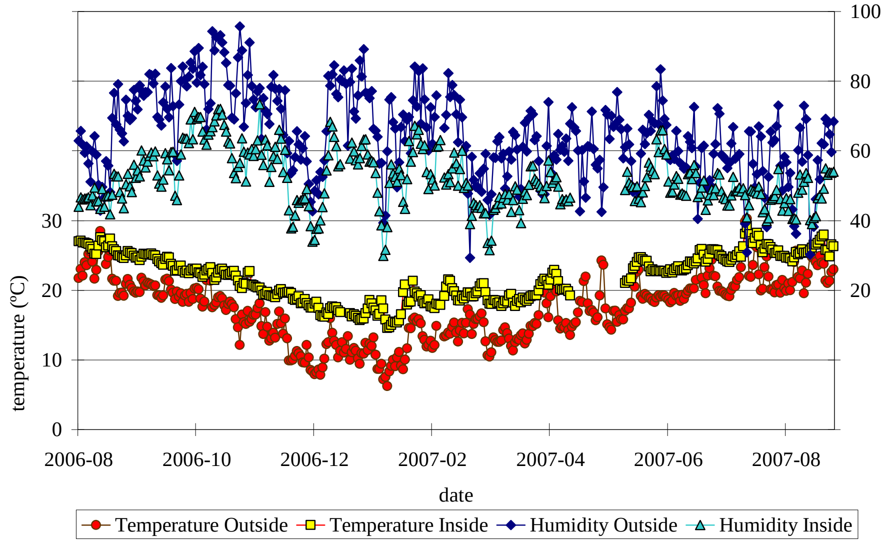

Fig. 9 – Average temperature and humidity inside and outside the Pavilion

Usually, inside temperatures and humidity have less extreme values that the outside values (see Fig. 9 concerning the period from August 2006 to September 2007). It is important to stress that the inside values presented is this paper are measured near the roof, not at the arena level. In average, during the winter the inside temperature is 6ºC higher than the outside temperature; on the other hand, during summer, differences are smaller: around 4ºC higher. During this season, the hottest periods of the warmest days are always cooler inside the Pavilion, up to 9ºC. Concerning the relative humidity, the air inside the Pavilion is usually dryer than the outside air.

Analysing the daily variations (Fig. 10), we can see that there is a shift between the inside and outside conditions. See for example four days in August 2006, a period with no events inside the Pavilion. Concerning the daily highest and lowest temperature, they are reached inside the Pavilion two to four hours later; concerning the humidity this shift is a little bigger: four to six hours later. During the winter this time span is shorter.

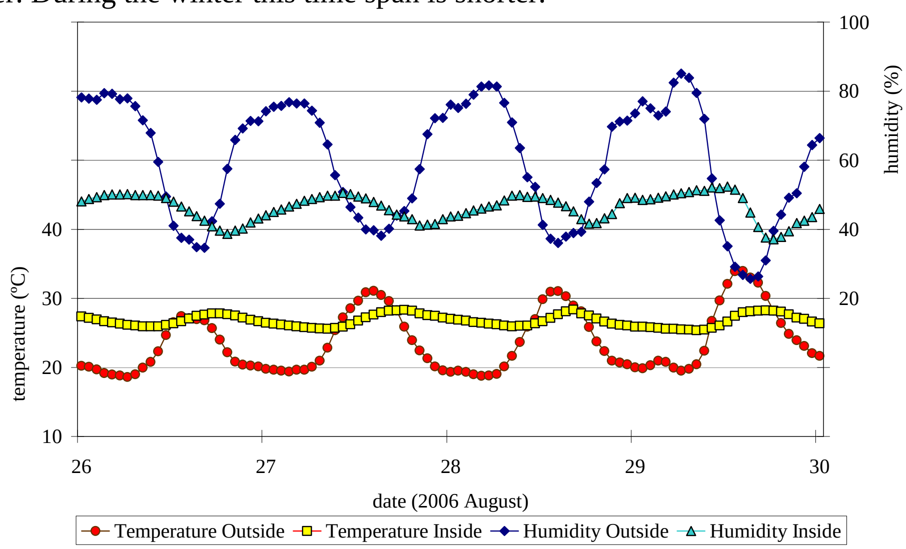

Fig. 10 – Temperature and humidity inside and outside the Pavilion (no events)

During events, the atmospheric conditions inside the Pavilion change for a few hours. The temperature always rises, but the attendance is a key factor. Usually the temperature raises 0.5ºC to 1ºC, a few times 2ºC, except for the mainstream music events, with large attendances and where the arena is also occupied by the audience: here the temperature raises 2ºC to 3ºC. As an example it was chosen a twelve days period in 2007: from March 26th to April 06th. Table 1 shows the name of the event and the time when the show started; Figure 11 presents the corresponding graphic of the temperature and humidity.

Day	Name	Hour (begining)
March 28, 29, 30	Disney on Ice	20:00
March 31		11:00; 16:00
April 01		11:00; 15:00; 19:00
April 04	Shakira	20:00

Table 1 – Events in the Pavilion

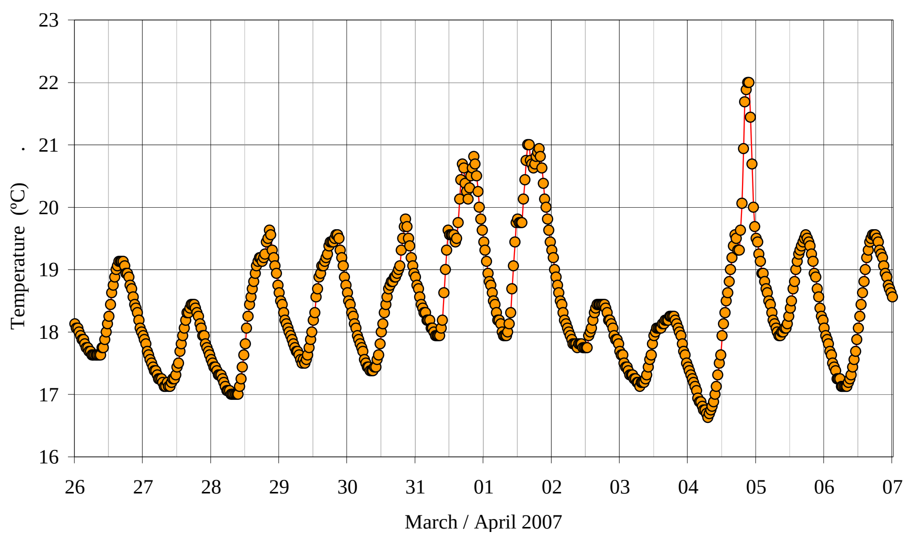

Figure 11 – Temperature inside the Pavilion. Events influence

3.2. The Geodetic Monitoring System

The displacements of the structure are monitored in 28 points (Fig. 12) on the arches: 21 of these points were placed in 2001, just before the first observation campaign (2001 February); the last seven points three years latter. These points are materialized by medium and large size Leica reflector tapes (Fig. 13), glued on wood supports; these are fixed to the east side of the selected arches. The reference frame has four points, all on the technical towers, which are reinforced concrete structures, on the east side of the hall, and are independent from the glulam structure: two pillars (Fig. 14) with Kern centering devices (PN, PS) and two targets for visual pointing (RN, RS).

The observables consist of horizontal angles (origin at the target reference points), zenith directions, distances and meteorological data, this one near the pillars. The measurement equipment includes a Leica theodolite T2002 (directions measurements), a Leica tacheometer TCA2003 (distance measurements) and a Commeter D4130 (a handheld unit that combines a thermometer, a hygrometer, and a barometer).

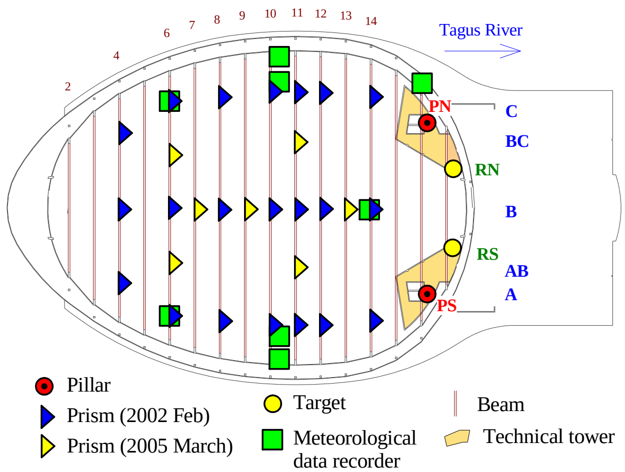

Fig 12 – Observation scheme

Fig. 13 – Reflector tapes

Fig. 14 – Theodolite and pillar

Since February 2001, a total of 14 campaigns were made, usually twice a year, one in winter, the other in summer (see Fig. 16). The displacements (i.e. variations of coordinates) were computed from the observables (variations of the horizontal angles, zenith directions and spatial distances, these ones correct from the effect of the local meteorological conditions) using the method of the variation of coordinates. The software used, developed in LNEC, also performs quality control of the observables.

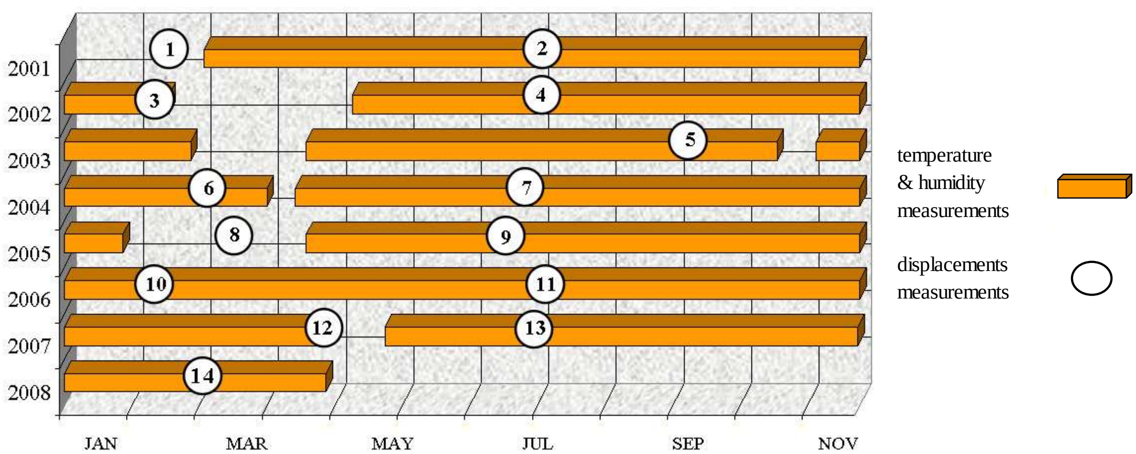

Fig. 16 – Campaigns and periods with atmospheric data

The study presented in this paper concerns the displacements of a single point - the central point of arch n.º 14, point B14. In Fig. 17 is presented a graph of the daily average of the relative humidity and temperature, recorded by the data logger placed near point B14, as well as the vertical displacements measured since February 2001.

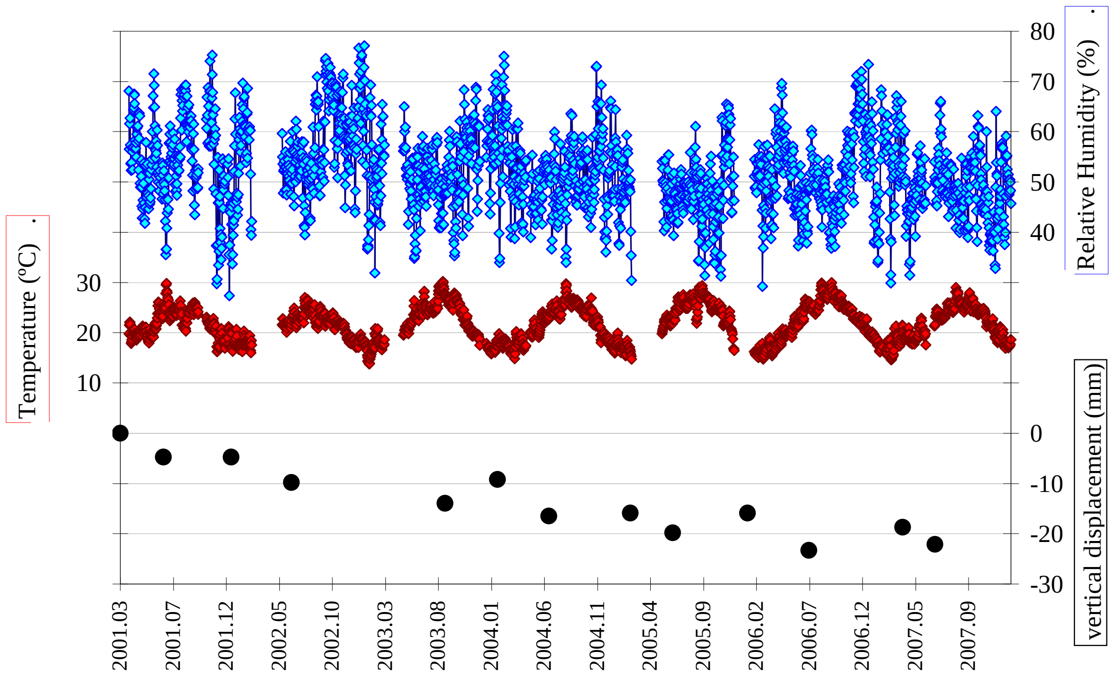

Fig. 17 – Temperature and relative humidity of the air and vertical displacements of B14

3.3. Modelling the Temperature, the Humidity and the Vertical Displacements

Applying Fourier analysis to the only complete year (2006) of meteorological data, led to the conclusion that the temperature can be well modelled by the conjunction of two basic functions (one with an annual period, another with a daily period); the humidity needs several functions to be modelled (a total of 23, clearly a sign that the humidity is far more complex).

The lower chord of the arches has a big cross-section (40.5x109.0 cm^2). Therefore, diurnal variations of the atmosphere inside the Pavilion, namely as a consequence of events, have little effect in these elements. For this reason the functions used to model the temperature and the humidity didn't take into account daily variations.

From the analysis made to the year 2006, one could take coefficients from the analysis of Fourier to build two functions that would relate the day of the year with: a) the temperature; b) the humidity. But as there are records from 2001 to 2008, it was decided to calculate new functions that would take into account all the data registered: in 2095 days (not 2493 days because of de lack of data in some periods). For instance, the temperature inside the Pavilion can be described using the function

$$T = (-2.421\cos(d \times 2\pi / 365) - 3.810\sin(d \times 2\pi / 365) + 21.343)^{\circ}\mathrm{C} \qquad (1)$$

where the variable d stands for the day: the first of January of 1900 is day 1.

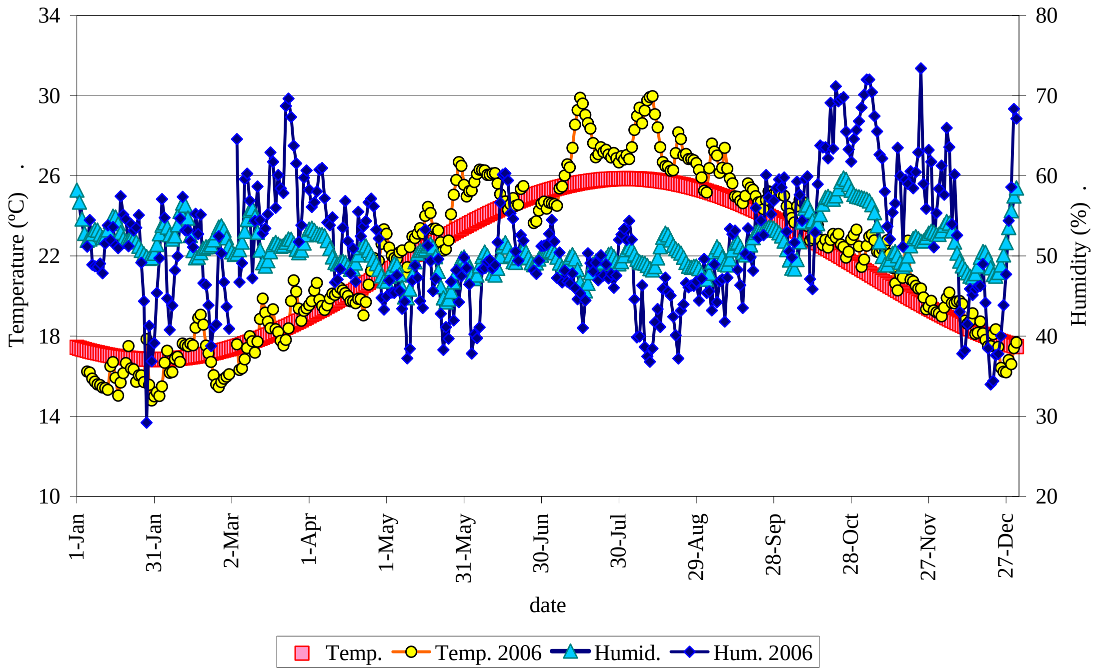

Fig. 18 - Temperature and relative humidity estimated and measured in the year 2006

In Figure 18 shows the annual variation of temperature and humidity using the derived functions ((1) in the case of temperature). The same graphic shows the daily mean values of 2006.

From the many functions that is possible to build to establish a relation between the variables temperature (*T*), humidity (*H*), age (*A*) and the displacements (*D*) it was decided to study three functions (here called D_1, D_2 and D_3). Due to the fact that the arches respond slowly to the atmospheric variations, the values of T and H here used are the average of six days. The use of functions like (1) makes it possible to establish results for any day, starting in the 1st of August 1997 (the day the roof was completed), even in those periods where there is no atmospheric data (for instance, epochs 1, 8 as seen in figure 16).

$$D_1 = a_{11}\,T + a_{12}\,H + a_{13}\,ln(1/A) + a_{14} \qquad (2)$$

$$D_2 = a_{21}\,T^2 + a_{22}\,T + a_{23}\,H^2 + a_{24}\,H + a_{25}\,ln(1/A) + a_{26} \qquad (3)$$

$$D_3 = a_{31}\,T\,H + a_{32}\,T + a_{33}\,H + a_{34}\,ln(1/A) + a_{35} \qquad (4)$$

A stands for the "age" of the structure. A=1 on the 1st of August 1997, the day the roof was erected.

There were established three systems of 13 equations with 4, 6 and 5 unknowns, for functions 1, 2 and 3, respectively. The three systems were solved using Matlab. After estimating the values of the unknowns (a_{11},..,a_{14}; a_{21},..,a_{26}; a_{31},..,a_{35}) it is possible to estimate the displacements given any date after 1 of August 1997 (the day the roof was completed). Figure 19 shows the displacements measured and the displacements computed using function D1, being the temperature and the humidity computed from the functions mentioned above (equation (1), in the case of the temperature). The displacement of epoch 2001-Feb was set to zero. To better see the adjustment of this model to reality (i.e. displacements measured), the display of the computed displacement in the campaign days is highlighted using a different sign (a dot). The campaign 14, made in

February2008, will be used (see below) to test if the difference between the predicted and the measured values is significant.

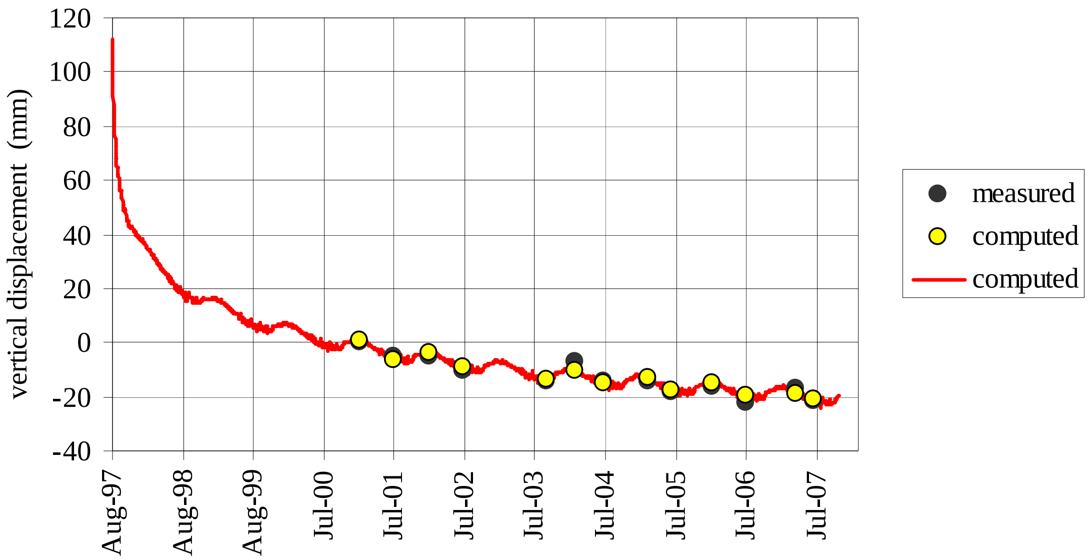

Fig. 19 – Measured and computed displacements

Table 2 shows the values of the displacements - the measured (*m*) and the computed - as well as the corresponding deviations. In the bottom line of the table are presented the estimates of the standard deviation (SD) of the displacements. Function D_2 is, as expected, because is the one with more coefficients, the equation that better fits the data. But, as function D_1 has similar results and is simpler, since it is a linear equation, it has been chosen to perform the next analysis. The third function, usually used when there is correlation between the variables, has showed worse results, fact that is not strange as there is a weak correlation between temperature and humidity.

	Displacements (mm)						
Date	*m*	D1	dev.	D2	dev.	D3	dev.
2001-02-07	0.0	0.2	-0.2	0.1	-0.1	1.0	-1.0
2001-07-25	-4.8	-5.4	0.6	-5.1	0.3	-5.2	0.4
2002-02-01	-4.8	-2.9	-1.9	-2.7	-2.1	-4.1	-0.7
2002-07-22	-10.1	-8.9	-1.2	-8.2	-1.9	-8.3	-1.8
2003-09-29	-14.3	-13.3	-1.0	-12.7	-1.6	-13.7	-0.6
2004-02-25	-7.2	-10.1	2.9	-10.2	3.0	-10.6	3.4
2004-07-19	-14.2	-14.9	0.7	-14.3	0.1	-14.2	0.0
2005-03-07	-14.1	-12.8	-1.3	-12.6	-1.5	-13.4	-0.7
2005-07-05	-18.6	-17.7	-0.9	-17.7	-0.9	-17.7	-0.9
2006-02-01	-16.3	-14.2	-2.1	-14.4	-1.9	-15.1	-1.2
2006-07-25	-22.1	-20.0	-2.1	-20.1	-2.0	-19.5	-2.6
2007-04-16	-17.0	-18.0	1.0	-16.6	-0.4	-18.7	1.7
2007-07-17	-21.8	-21.3	-0.5	-21.0	-0.8	-20.6	-1.2
SD			1.45		1.39		1.54

Table 2 – Displacements measured and computed

The function D_1 has the following expression:

$$D_1 = -0.56mm\ {}^oC^{-1}\ T\ -0.25mm\ H + 17.77mm\ ln(1/A) + 150.72mm\ . \qquad (5)$$

In Table 2 one can see that in the campaign of 2004-Feb there is a large deviation of the computed value in relation to the measured one (-2.7mm). Performing an analysis, on that epoch, of the adjustment involving the 21 object points it was seen that the "uplift" affected all the points and that there weren't outliers (analysis made possible because the network is highly redundant). So it was decided to fit a new function, D4 as seen in equation (6). The new displacements are presented in Table 3.

$$D_1 = -0.48mm\ {}^oC^{-1}\ T\ -0.34mm\ H + 18.05mm\ ln(1/A) + 155.41mm\ . \qquad (6)$$

It is interesting to analyze the displacements computed to the last epoch (2008-Feb). One can see that the deviation of the displacement calculated is large. But should be paid attention to the values of temperature and relative humidity recorded: the atmosphere was hotter and dryer than usual. These abnormal atmospheric conditions may be in the origin of an unusual behavior of the arch.

	Displacements (mm)			Temperature (ºC)			Humidity (%)		
Date	*m*	D4	dev.	*m*	*c*	dev.	*m*	*c*	dev.
2001-02-07	0.0	-0.6	0.6		16.9			55.1	
2001-07-25	-4.8	-5.0	-0.6	24.5	25.8		51.9	48.9	
2002-02-01	-4.8	-3.3	1.2	18.4	16.8		59.6	50.1	
2002-07-22	-10.1	-8.5	0.7	25.6	25.8		46.7	47.3	
2003-09-29	-14.3	-13.6	-0.5	25.7	23.8		49.5	53.4	
2004-02-25		-10.8		16.1	16.9		50.3	51.6	
2004-07-19	-14.2	-14.6	-1.4	25.8	17.2		48.8	47.3	
2005-03-07	-14.1	-13.4	1.0		17.6			51.1	
2005-07-05	-18.6	-17.7	0.4	25.1	25.3		47.6	50.5	
2006-02-01	-16.3	-14.9	1.4	16.3	16.8		47.4	50.2	
2006-07-25	-22.1	-19.8	1.8	28.4	25.8		47.0	49.2	
2007-04-16	-17.0	-18.3	-1.0	18.3	20.1		45.2	49.1	
2007-07-17	-21.8	-21.1	-0.6	25.6	25.7		50.5	47.7	
SD		rr	1.04						
2008-02-25 (D4)	-18.3	-19.5	1.2	18.8	17.2	1.6	63.0	52.0	11.0

Table 3 – Displacements, temperature and humidity measured and computed

Adjusting the computed displacements to the measured ones has however a limited significance, since these functions only account for environmental conditions and do not include the effects of any variable loads, like the wind and cable suspended equipment, which also affect the measured displacements. In spite of the variable loads, which may explain the deviations found, it can be seen that the environmental conditions play the major role, having a distinct influence in the cyclic component of the measured vertical displacements. In addition to this seasonal component, there is also a long term trend which account for the creep effects in the structure mainly due to long-term loading.

The functions used also allowed the estimation of the displacements before the first campaign (see Fig. 19). Between the 1st of August of 1997 and the first campaign the model has estimated a displacement of 45mm. Although there is no way of validating the data, this value seems realistic.

4. CONCLUSIONS

The observed seasonal displacement variation may be described by a sinusoidal cyclic function and the long term behaviour by a logarithmic type function.

The response of timber structures to the seasonal environmental changes of the Portuguese climate is in counter-phase with the behaviour of steel and concrete structural elements: during the hot and dry summers the structural members shrink (downwards vertical displacements of the arches) and during the cold and wet winters they swell (upward vertical displacements of the arches).

The established model is able to describe with reasonable accuracy the vertical movement of the arch. This indicates that the environmental conditions (temperature and relative humidity of the air surrounding the timber structure) and the age of the structure (that indirectly accounts for creep effects) are the most significant factors to determine the global displacement of the arches. Other factors like wind loads and transient loads such as cable suspended equipment in the arches at particular occasions, that were not taken into account, may well explain the deviations found between modelled and real displacements. It is however remarkable the good adjustment found.

This model allows an estimation of the total displacement of the structure since its conclusion, although this should be regarded carefully. The slope of the curve and the good agreement with reality so far suggests that no materials or structural deterioration took place. At last it should be said that a finite element model of the structure will be developed, accounting for the structural members and joint's constitutive relations. This structural model will allow determining the component of the vertical displacements that are due to permanent and variable loads and to compare this with the results of the present descriptive "environmental" model.

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Corresponding author contacts

Maria João HENRIQUES
mjoao@lnec.pt
Applied Geodetic Division, National Laboratory for Civil Engineering
Portugal