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Structural analysis of the roof's shell of the new terminal of the Airport of Valencia (VLC)

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1. Introduction

The social and economic current growth of the Valencian Community, and in particular of the city of Valencia, made necessary the presence of an airport adapted to the new reality of the city. A city immersed in a great number of events of world relevance; the America's Cup, the Formula 1 Grand Prix and the continuous touristic attraction of the City of the Arts and the Sciences had to be opened by a "new entrance" that would match the forthcoming events that it would host in the same manner as the three grand gates of the city wall did in the past, of which only the Quart and Serrano's Torres remain. In this way the New Terminal of the Airport of Valencia becomes a new link to the outside world with its renewed image in accordance with what is waiting behind its doors.

Keywords: Shell, concrete, prestressed, double curvature, finit elements.

2. Part I: Solution built

The project is composed of two unique buildings; the "Processor" that acts as a link between the old Terminal and the new one and the "Satellite" building that constitutes the New Departures Lounge.

The "Satellite" forms an elliptic plan open space bounded at the top by the cylindrical reinforced concrete shell and laterally by an anchored diaphragm wall and supported by steel columns. The Satellite is in itself, the new airport's Terminal enabling 5 new boarding gates.

The structure of the "Satellite" building's roof of the new Terminal of the Airport of Valencia is formed by a reinforced concrete shell structure of cylindrical cross section and elliptic plan. The shape of the roof is defined in one side by the intersection between the cylinder and an inclined plane and on the other by the intersection of the cylinder's generatrix with another perpendicular cylinder.

The approximate dimensions of the space under the roof are 50x70 meters with a maximum height of 20 meters.

Figure 1: Virtual image of the new Terminal

The roof has been designed as a reinforced concrete shell 30 cm thick that rests on an inner ring formed by a post-tensioned concrete beam, which is supported by a group of steel columns, and on very stiff reinforced concrete elements that form the shell's springing from the foundation.

2.1. Geometry of the roof

The shape of the roof is generated by a cylinder that has an oval directrix and a straight generatrix inclined an angle α= 4'2º from the horizon line.

This cylinder is limited by an inclined plane β= 35'5º from the horizon line in the rear part of the roof. The façade section is defined by the intersection of the cylinder with another cylinder of elliptic generatrix and straight directrix.

2.2. Perimeter ring

It is formed by a beam that follows the imaginary line that would link the top of the columns.

In the front area, from columns P1 to P18, the ring is embedded in the shell, forming a beam 2.10m wide and 0.35m high.

In the rear area, the ring has been designed as a beam 2.10m wide and 0.70m tall, that implies that the beam protrudes 0.40m from the shell.

The beams have been designed doubly reinforced with 20ϕ25 bars on each layer with 7ϕ12 shear links every 0.20m following the beam's directrix. The spacing of the shear links is halved around the 2.00m area situated above the columns, there are 7ϕ12 every 0.10m, to resist the punching shear stresses.

In order to improve the buildability of the reinforcement's top layer, whose direction changes in respect to the shell's bottom layer, the front beam was designed as a ring 0.35m thick, with the intention of placing the 20ϕ25 bars on the shell's top reinforcement layer.

2.3. Prestressed reinforcement

The prestressed reinforcement is a family of tendons that are placed along the center of the perimeter ring's beam in the front area while describing a parabola in the rear area of the roof.

The continuity of the prestressed effect is achieved by having 4 anchorage zones where the tendons' paths cross.

The designed tendons are formed by 12 steel Y1860 S7 cords of 0'60", placed in an of 80mm diameter duct.

In the front beam (tendon families C2 and C3) the design considers 6 tendons spaced 0.335m along their axis, placed in the center of the 0.3m thick shell. The family C2 goes from columns P18 to P5 on both sides, while the family C3 goes between columns P5 and through the centre of P1 columns.

There is only one family of tendons in the rear beam. The family C1 is formed by 9 tendons; it has a variable height layout divided in parabolic sections which have their maximum points above the concrete columns, 0.525m from the bottom of the beam, and their lowest points at midspan, 0.15m from the bottom face of the beam.

The designed prestessed force per tendon is 2333kN, this gives a total force of 14000kN for families C2, and C3 and 21000kN in the family C1 of the rear area.

The families of tendons C2 and C3 will cross in the area situated above the column P5 in order to avoid the clashing of the tendons' anchorages. For the same reason the families C1 and C2 will be crossed in area near the column P18, by extending the tendons' straight section until near the edge of the shell, where the anchoring points will be installed resulting in a 0.4m increase on the 0.30m thickness of the shell.

2.4. Reinforcement

There are two different areas in the main reinforcement of the 0.3m thick shell. The reinforcement of the beams will lap onto the shell's main reinforcement.

In area A, located in the centre of the shell, the main reinforcement is made of #ϕ16 at 0.20m in both faces, with a minimum shear reinforcement consisting in ϕ8 shear links arranged in a 0.2m x 0.2m grid. In area B, the main reinforcement is made of #ϕ25 at 0.20m in both faces, with the shear reinforcement consisting of ϕ8 shear links arranged in a 0.2m x 0.2m grid.

All of the main reinforcement is designed following the principal directions of the shell: the X direction along the longitudinal axis, in which the reinforcement bars are straight and the Y direction following the transverse axis, in which the reinforcement is composed of elliptic bars.

Areas A and B have been assigned to the reinforcement according to sections parallel to the principal directions of the shell in order to facilitate the changes in the main reinforcement.

The reinforcement in the perimeter of the shell is formed by two layers of 3ϕ25 bars and ϕ12 shear links spaced 0.2m following the perimeter guideline. This reinforcement will lap onto the main reinforcement.

Also, the reinforcement of the shell's springing is expected to consist in two beams along the perimeter of the springing and two reinforcement layers in each one of the faces.

2.5. Columns

The steel columns are spaced every 4.00m and consist in 0.4064m diameter circular hollow sections made of structural steel S355 JR. The thickness of the columns and their end fixity changes depending on its position in the building.

The rear columns, symmetrical regarding the longitudinal axis Y, are made of reinforced concrete and have a 0.90 m of diameter. The connection between the roof and the top of these columns is achieved by using neoprene bearing pad.

3. Structural Analysis

The tools used in the development of the models used to analyze the structure are described in this section.

3.1. Calculation process

The structure has been modelled using a finite element (FE) software. In the development of the model, the FE computer program becomes the centre of the process, allowing us to obtain the section properties, stiffness matrix and results of the model, starting from the geometry and some initial loads.

Given the complex geometric characteristics of the structure been analysed and the limitations in the geometric input of the program used, as is common in all commercial FE software, a so called pre-process was used in the modelling of the structure using another CAD program to define the geometry of the structure.

In the same way and with the intention of obtaining some results that were directly applicable to the required checks and that allowed a quick and intuitive interpretation a so called post-process of the results of the model was used through spreadsheets.

The model represented half of the structure along its axis of symmetry, in this way the initial drawing work was simpler and the properties derived from the structure's symmetry were used.

The equivalent prestressed forced applied to the beams was obtained from the parabolas' shape and the prestressed force.

3.2. Structural elements

The modelling of the structure has been carried out by elements type FRAME for the columns and elements type SHELL for the shell and the prestressed beams.

The geometry of the SHELL elements is mainly rectangular and occasionally triangular to increase mesh density in areas where the geometry is more complex (connection between the shell and columns, anchorage areas of prestressed, springing area).

A total of 3332 JOINTS, 3318 elements SHELL and 115 elements FRAME have been used in order to model the structure.

3.2.1. Shell Model.

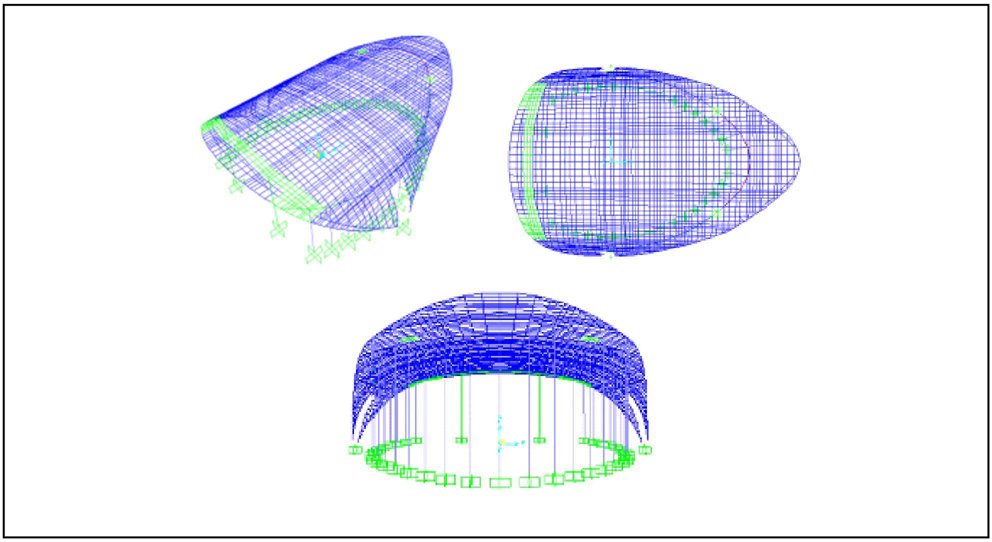

Figure 2: Finite element model

The SHELL elements have been defined with thicknesses of 0.30 m in the shell, 0.70 m in the rear beam and 1.00m in the shell's springing area.

As it has already been indicated, the section of the springing has been modelled as having a constant width of 4.00m until a height of 10.50m. It has been checked that this area is enough to provide rigid elements that would absorb the tensions of the embedment of the shell in the foundation.

3.2.2. Columns model.

The columns have been modelled with finite elements type FRAME, with the necessary boundary conditions to reflect the real behaviour of the structure.

In the latest analysed model, the steel columns have been considered as embedded in the roof, except the columns P10 to P16 in which, the rotations and the vertical loads of the top nodes have been disconnected from the shell. On the contrary there is a horizontal and vertical displacement connection between the shell and the rest of the columns.

3.2.3. Beam model.

The protruding rear beam has been included in the model by type SHELL finite elements, centred in the shell, but with an equivalent bending stiffness to represent the eccentricity between the axis of the shell and the axis of the beam. Therefore, in the model, the SHELL elements that represent the beam have been included with a thickness of 0.70 m for the membrane stresses, and with a thickness of 0.87m for the bending stresses.

3.3. Interpretation of the results

3.3.1 Shell behaviour

One of the advantages of the shell shapes is that it presents a solution to the equilibrium with stresses contained in their mid surface (membrane solution), these stresses stop to be preponderant when local or boundary actions change the deformed shape condition imposed by the membrane solution. In this case bending appears on the shell.

If something differentiates the shells to the slabs then it is their thickness. In the shells, their reduced thickness does not give any bending or torsional stiffness developing only stresses in its mid surface, on the other hand when the thickness is bigger, in the slabs, we find not only stresses in its mid surface but also bending stresses.

Looking again towards our “shell”, we realise now that its behaviour is far from the one expected to a true shell.

The important bending stresses that appear in the centre of the roof shows its behaviour like a slab, this is, it becomes necessary a high bending stiffness (thickness of 30 cm) and its corresponding reinforcement, to transmit the loads (self weight mainly) to the supports.

Why bending stresses appear considering that it is a cylindrical surface like the ones described previously and whose main characteristic was in fact the membrane behaviour? We can find the answer by looking at its geometry and the imposed boundary conditions.

When the length of a cylindrical shell is three or more times its transverse span, then it behaves like a beam of big depth, of curved section that spans along the longitudinal direction. The transverse stiffness enhancement at the ends of the cylinder, as if they were tympana, improves the structural behaviour and makes the whole surface work in compression, eliminating the bending and allowing us to reduce the thickness of it. In our case the ratio between the longitudinal and transverse spans is less than two.

The second reason can be found in the imposed boundary conditions on the structure. The transverse intersections by the elliptical cylinder and the inclined plane far from improving the stiffness of the ends; sever the surface of the cylinder stopping the natural flow of stresses from the centre to the supports. All these effects acting together make necessary, in the initial design, the creation of a new support plane inside the surface of the shell, materialized by the columns.

The interruption of this plane of support in the rear area common to the building of the "Processor" for functional reasons (it is the new access area and the natural communication corridor between the two structures) makes the presence of the concrete columns and the rear prestressed beam necessary to provide continuity, in the shells' plane, to the support area.

3.3.2 Arch behaviour

If the shell is relatively short, the arch effect will take precedence. To resist the horizontal forces of the arch it is necessary to have rigid elements in the support areas. Also the definition of the cylinder from an elliptic section reduces significantly the curvature of the cylinder in the central section.

The shell acts as frame with a slight curvature in its lintel. In the area where the shell meets thee foundation the frame it is materialized completely by concrete elements and its section is the ellipse that defines the cylinder.

When we move away from the central area we have, at the front, a series of frames materialized by sections of slightly curved lintels and steel supports. At the rear area there are a great frame with concrete columns and a lintel materialized by a post-tensioned beam.

The series of a frame adjacent to another, with the shell as a common element, allows the bidirectional flow of stresses and it collaborates in the unidirectional behaviour of the frames.

3.3.3. Slab Behaviour

The overall behaviour of the shell is finally more similar to the behaviour of a slab with a slight curvature than to the one of the much desired "shell".

The slab behaviour determines its dimensions and its reinforcement. It is difficult to believe that a slab of approximately 50 m with a thickness of 30 cm and 24.54 cm2/m reinforcement would be able to resist its own weight and that the deflections would be acceptable. There is an explanation for this, like I mentioned before, the slab has a slight curvature, sufficient so its behaviour is different from the one expected from a flat slab, enough to, because of the arch effect, develop a bigger compression area diminishing the bending stresses and transferring the loads to the supports.

If we then add the effect of the prestressed forces acting like a stiffener element on the perimeter ring where the series of arches are "supported", is understandable that the deflections are smaller than the one expected of slab of similar dimensions.

5. Part II: Alternative Solution

"The best work is the one that is sustained by its own form "

Eduardo Torroja

5.1 Object

The object of the present document is to supplement the analysis carried out of the structure of the roof of the New Terminal of the Airport of Valencia, by proposing an alternative solution to the one presented in the original project.

New solutions arise as a direct consequence of the structural analysis carried out and the study of the behaviour of the originally designed structure. This analysis had not been possible at earlier stages due to changes in the geometry of the original structure.

It is shown, in this document, the different design and modelling phases of the proposed structure and their comparison with the structure finally built.

5.2. Description

The alternative solution consists on a revolution shell generated from a hyperbolic hyperboloid, in which the general dimensions of the initial structure are maintained, as well as the overall aesthetics achieving, however, to eliminate the columns as structural elements and a structural behaviour as shell with a thickness of 0.20 m.

5.2.1. Geometry

The roof is contained in the surface of a hyperbolic hyperboloid generated from a hyperbola rotating around an axis.

The generated surface is the result of intersecting the hyperbolic hyperboloid and two inclined planes at the front and the rear of the central area.

The origin of this hyperbola is defined by the geometry of the initial design's roof so that the new proposed surface matches aesthetically the previous one, but maintaining the characteristic associated with the double curvature revolution surfaces.

Taking as a reference the starting and final points, that is the shell's springing and the line defined by a section of the generating cylinder of the original structure respectively, the generating hyperbola of the new surface is defined.

In this manner, keeping as fixed the heights of the starting and final points, the height of the central point align with the springing has been modified obtaining in this way the desired double curvature.

The second variable was the width in the springing area so that it matched the width of the generating cylinder of the initial structure.

To achieve that, as a function of the central point's height, the centre of the revolution axis and the angle covered by the hyperboloid has been calculated for their generation.

The result of rotating the hyperbola around its axis was a hyperbolic hyperboloid like the one that is shown below, origin of the proposed solution' surface.

5.4. Adopted Solution

"So that an object is highly beautiful it is necessary that its form doesn't have anything superfluous, but the conditions that make it useful, keeping in mind the material and its use. When the forms are more perfect they demand less ornamentation".

Antoni Gaudi

The geometry of the proposed final solution is described below:

5.4.1. Generating Hyperbola

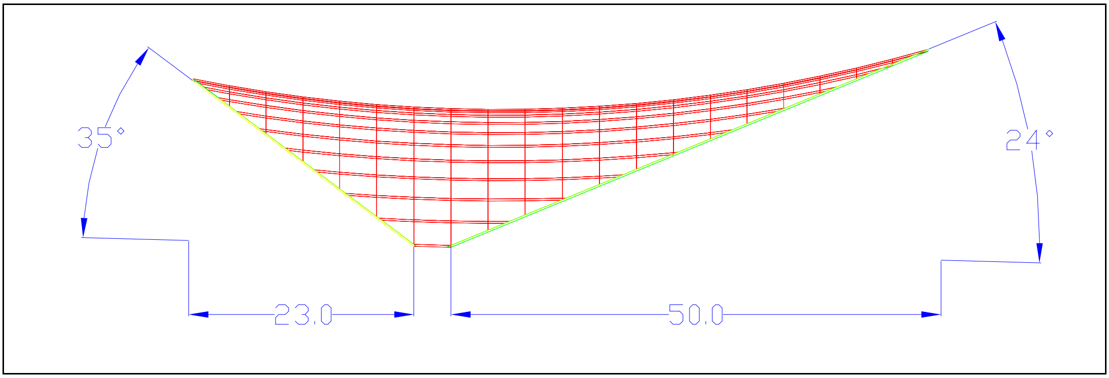

Figure 4: Generating Hyperbola

5.4.2. Intersecting rear plane

The intersecting rear plane is inclined β= 35º on the horizon line.

The height of the roof in the intersecting axis is 14.00m, and the plan projection regarding shell's springing axis is of 23.00m.

The perimeter ring is formed by an ellipse.

5.4.3. Intersecting front plane

The intersecting rear plane is inclined β= 24º on the horizon line.

The height of the roof in the intersecting axis is 20.00m, and the plan projection regarding shell's springing axis is of 50.00m.

The perimeter ring is formed by an ellipse.

5.5. Structural Analysis and comparative study

We now proceed to analyse briefly the behaviour of the structure with the adopted new geometry and to compare structure built and the proposed solution.

5.5.1. Structural Analysis

" The state of stresses in a shell can be considered free of bending (approximately) if the following conditions are achieved: The mid surface should have, in general, a continuous bend; the thickness of the shell should not present abrupt variations; the loads acting on the surface should be distributed as uniformly as possible in a not too irregular way; the tangent forces in the edges should be directed to the indispensable mid surface so that the reactions originated will be absorbed also by tangent stresses to the mid surface "

(Girkmann, Flachentragwerke) Surfaces Structures in Building, Fred Angerer

In the cases where the previous conditions are not met the membrane theory (let us remember, stresses limited to the mid plane of the shell) does not yield correct results. For this reason it is necessary to apply a procedure that allows us to evaluate the bending stresses.

These additional stresses appear due to incompatibility of the imposed deflections with the deflections arising from the free edges of the shell.

The anomalies are limited to a narrow area and quickly disappear. The influence of these interferences shows up in the form of a damped oscillation.

In most occasions it is enough to reinforce the edges of the shell.

Regarding the global behaviour, we can make the following reflexion; while in the built structure, the structural behaviour was more similar to that of a great barrel vault, where the stresses derived from thrust line not being limited to the mid surface could only be resisted by developing bending resistance, in the shell due to its spatial behaviour, the internal forces are in equilibrium.

In our case and for the chosen geometry with Gauss negative curvature, the efforts in the longitudinal direction are compensated due to the inverse curvature in the transverse direction, establishing a new balance, without any bending.

Advantages of the double curvature

Following the Gaussian classification of the curvature obtained as the sign of the product K=K1xK2, there are surfaces with positive Gaussian curvature or sinclastic (revolution ellipsoid, revolution paraboloid) and with Gaussian negative curvature or anticlastic (hyperbolic hyperboloid, hyperbolic paraboloid).

If we also divide them in desarrollables and non desarrollables, the first structural advantage of the double curvature surfaces appears. The surfaces desarrollables are those that can be developed in a plan without suffering lengthenings. From a physic point of view, the surfaces non desarrollables (in general with double curvature) require more external energy than the desarrollables, to collapse and to transform itself into a flat form.

The main advantage of the surfaces with double curvature is its structural behaviour defined by two basic mechanisms:

Mechanism like cable: In the direction of the tensile principal stresses.

Mechanism like arch: In the direction of the compression principal stresses.

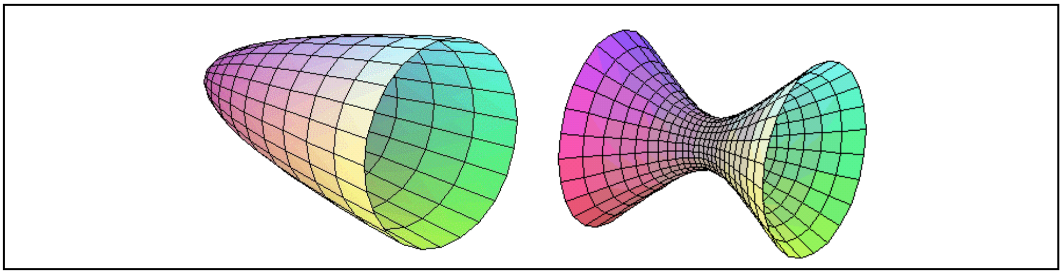

Figure 5: Eliptic paraboloid and hyperbolic hyperboloid

The cable and arch mechanisms, interact in an "opposed way": The applied loads induce compressions in the internal arch while at the same time they cause tension in the internal cable. The loads applied therefore are distributed among these two structural internal elements; the excess in compression of the arches is compensated by the cable effect that tends to lift the arches in each point; this effect increases the elastic stability of these surfaces.

5.5.2 Comparative study

We will proceed now to compare briefly the behaviour between the original structure and the proposed solution:

If we compare the global stability of each one of the structures, acting as shells, without structural secondary elements, this is without columns and without prestressed forces, the results obtained are the following ones:

Original Model:

Maximum displacement: -2.844 m

Alternative Solution Model:

Maximum displacement: -1.625 m

Of this first comparison it is observed that the original structure is unable to compensate the movement of the rigid solid due to its single curvature geometry. Its deformed shape is similar to the one associated with a free cantilever.

However, in the model of the proposed solution, the maximum displacement is almost 50% less, for the same span and a third of the thickness of the shell. The double curvature reduces the movement of the rigid solid and it compensates the maximum displacement of the cantilever whose point of maximum deflection is not the end but the central area adjacent to the end.

If we continue with the comparison in the next stage of design's process, which would be the consideration of tendons at the rear that would compensate the rigid solid movement and would give stability to the group, we obtain the following values corresponding to the maximum deflection and the reactions in the tendons:

Original Model:
Maximum displacement: -1.141 m
Alternative Solution Model:
Maximum displacement: -0.105 m

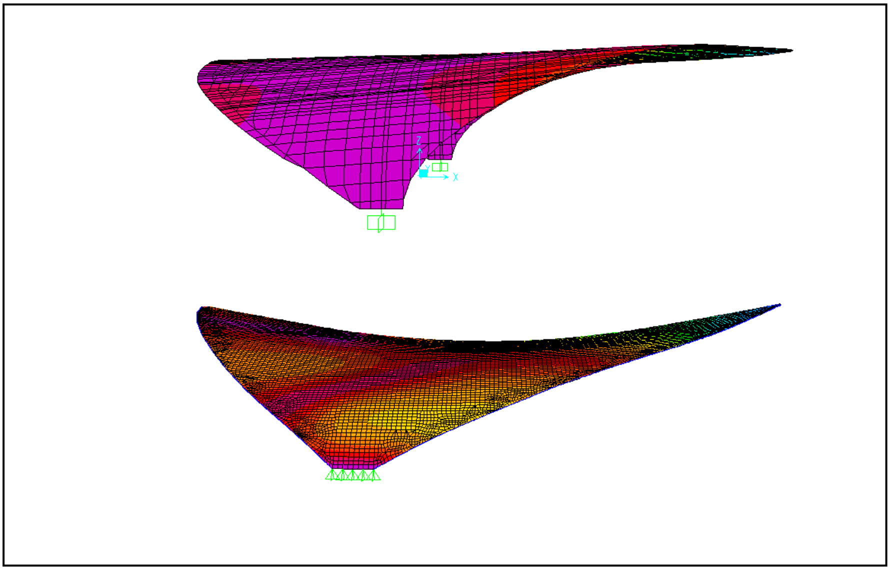

Figure 6: Comparative deformation between Original model (up) and Alternative Solution Model (down)

As shown, the behaviour is even more different if possible, in the first model the effect of the tendons reduces the value of the maximum displacement by half but does not change the behaviour of the structure and it is therefore not sufficient.

In the model of the proposed solution, the tendons compensate the movement of rigid solid and they reduce the maximum deformation to 0.105 m thanks to the truss effect created by the double curvature on the global structure.

The stress result is more than satisfactory, the variation of maximum stresses along the top and bottom face of the shell is so small that the minimum reinforcement required to counteract any shrinkage will be sufficient to resist the tensions stresses associated with load up to 30 kg/cm2.

This shows that the main stress on the structure is in compression, so the concrete solution chosen achieves its purpose, and the structural solution perfectly adequate.

6. Conclusions

The structure of the new Terminal of the Airport of Valencia, built by the construction company Fomento de Construcciones y Contratas with the architectural designed of the roof included in the project of the Architect Francisco Benítez, has been described and defined in this paper.

Also this paper has presented an alternative solution with the intention of showing, in the simplest possible way, that with a small variation in the geometry, the introduction of the double curvature, the structural behaviour changes completely allowing us to keep the same aesthetics.

It is not the intention of this paper to diminish the value of the structural solution developed, on the contrary, it is necessary to pay credit to the achievement as an engineer of being able to resolve, with an imposed geometry, the problems derived by it. In those circumstances it becomes necessary to apply all the knowledge acquired in the structural analysis to solve with ingenuity the difficulties inherited from the design phase.

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