The behavior of Baserca and Llauset dams in the new energetic scenarios

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Summary

The growing energetic demands are promoting new business strategies in the operating of hydroelectric power plants. These are materialized by increasing the role of the reversible plants to produce high quality energy. This fact becomes in an abrupt and quick variation of the water level of the reservoirs. This influences at the temperature levels in the dams. Furthermore, since the dams have been working for years, temperature registers from them are available. This enlarges the initial hypotheses considered in the project calculation. This paper summarizes the results obtained in the enlargement of the operating system involving the Baserca and Llauset dams. The initial experimental data come from the measurements which have been taken in those dams after 30 years of operation.

Introduction

The Baserca and Llauset dams integrate the Moralets reversible fall. They were built in the 80's close to the sources of the Noguera-Ribagorzana river, between the provinces of Huesca and Lérida (Spain). Both of dams are practically equal, they show similar dimensions, two vaults of 87 and 89 m high from foundations respectively, and lengths of crowning level of 300 and 330 m respectively. During their lifetime – that's 30 years – the behaved as expected, without showing any anomaly or working problem from the functional and structural point of view. That's a proof of a good design, project and construction.

To drive the new business strategies an intensification of the pumping in the falls is needed to optimize their exploitation capacity. This new working plan for the dams implies the increase of the dam-undam cycles, which affects to the thermal actions on the dam. It's well known that these thermal issues affect in a significant way the response of the dam, especially vault dams, so a very precise method to calculate this response is needed.

This thermal analysis can be done nowadays in a much more realistic way than in the project stage, given the great amount of strain and thermal information acquired in the dams during their lifetime.

It's also important to take into account that the concrete of the dam has been spilt 30 years ago, which means that its mechanical properties have improved during this period.

Anyway, in this type of analysis, calculation is a necessary tool, even unavoidable, but it can't introduce numerical uncertainties in the structural behaviour of the vaults, especially when the response of the real dam is checked.

The best way to avoid fictitious incompatibilities from the computation stage is to keep the calculation hypothesis from the project phase, to preserve the structural principles unchanged, although modern technologies are used. According to these principles tridimensional lineal elasticity is assumed for the material constitutive behaviour, and Stucky method for the thermal response of the dam. These hypotheses have been used to reproduce the project conditions as well as the ones derived from the exploitation time.

For both dams different load cases have been considered, due to mechanical charges (self-weight, full dam or exploitation minimum level) and thermal (winter and summer with empty, full and oscillating dam).

These multiple hypotheses generate a great amount of results to sum up, present and treat in a friendly way, pointing the qualities and singularities of the structural response. The objective is to identify the maximum values of tensile and compression stress and their location. Some of the results present stresses localization with excessive values (2 MPa in extraordinary case) according to the "*Instrucción para el Proyecto, Construcción y Explotación de Grandes Presas de 1.967*" which is the instruction used in the project for both dams.

The numerical model

The study of the behaviour of these two dams present two different sides: mechanical problem and thermal problem. The Finite Element Method can solve the differential equations governing both problems, with the suitable boundary conditions for charges and temperatures [2,3]. This method offers a high flexibility to describe the geometry and build numerical models following the geometrical parameters and curves of the project [4].

The Baserca and Llauset vaults are defined in top view by three center archs. The angle of the central arcs is constant, and the centers are defined by parabolic curves. In the front view, the dam is divided in 20 and 17 cantilivers respectively, with the corresponding construction joints (Figure 1).

The body of the dam is completed with a block of soil, with a height, and width upstream and downstream similar to the dam's height. This dimension is considered representative enough to reproduce the effects of the boundary.

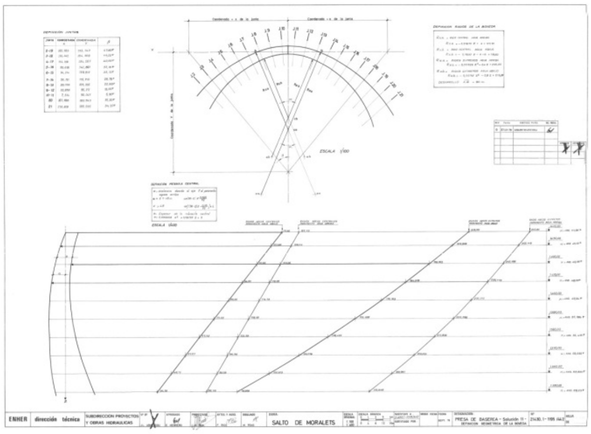

Figure 1.- Geometric definition (Baserca dam)

The vaults have been modelled as a tridimensional solid conformed by 2-node hexahedral serendipic elements well known and used for this type of analysis because of its efficiency (Figure 2).

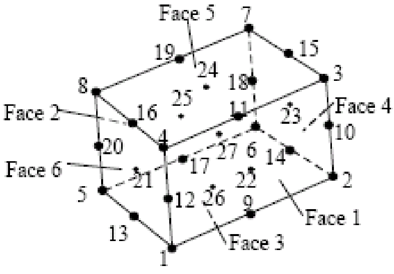

Figure 2.- 27 node hexahedral element

The geometry includes the vertical construction joints of the dam, defining every alternative block. The geometric definition of the dams eases the generation of two different numerical models: Isolated alternative blocks and continuum blocks model to treat the different behaviour of the structure.

The Baserca vault model includes upstream a soil layer along the base supporting the dam, which models the horizontal support acting in the construction phase (self-weight load). This layer behaves as an elastic spring with different coefficients for tension and compression. The numerical model is composed by 9.492 elements and 45.214 nodes (Figure 4).

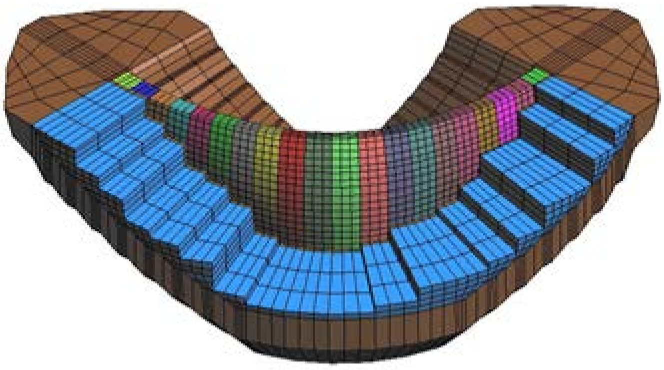

Figure 4: Numerical model for the Baserca dam

In the Llauset vault numerical model a short concrete wall has been added upstream, which supports the structure in the construction phase (self-weight load). The numerical model is composed by 9.852 elements and defined by 46.413 nodes (Figure 5).

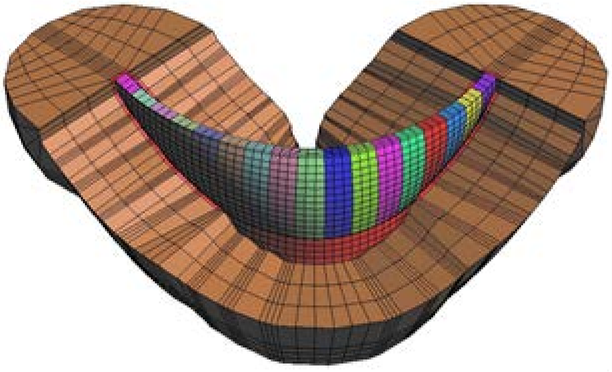

Figure 5: Numerical model for the Llauset dam

Basic loading cases

Three so called basic loading cases have been considered: self-weight, hydrostatic pressure and thermal effects. The right modelling of every case needs a well-defined numerical model in relation to the constructive process, and its structural consequences. The compound loading cases are obtained from the superposition of these three basic ones.

The model for the self-weight loading case reproduces the physical situation before and after the joints injection, according to the constructive process. To model this effect the structural response of the dam is calculated considering that the blocks behave with no interaction to each other before the joints are injected (alternative blocks). After the injection, that's the ordinary and exceptional situations, the structural response is obtained from a numerical model with the continuum domain where the blocks are joined (continuum blocks). Hence, two different stages are considered: first, calculation with non-interactive blocks and second, with continuum behaviour for the blocks.

Self-weight

The self-weight case is analysed using two different models with alternative blocks: odd and even blocks with the soil (figures 6 & 7). The final result is obtained by superposition of the cantilevers, with no contact to each other. This procedure means that there are nodes sharing coordinates in the block's interface with two different stresses values.

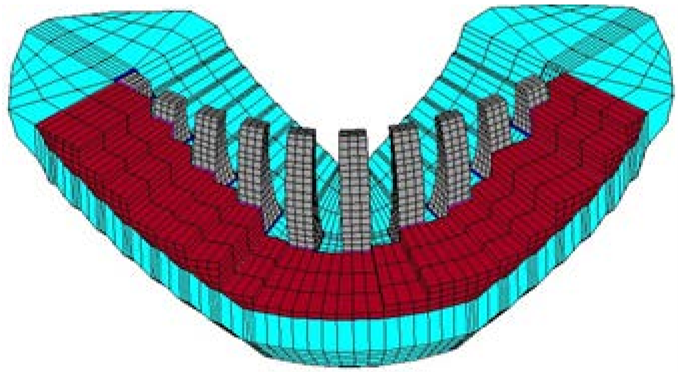

Figure 6: Odd blocks model. Baserca dam

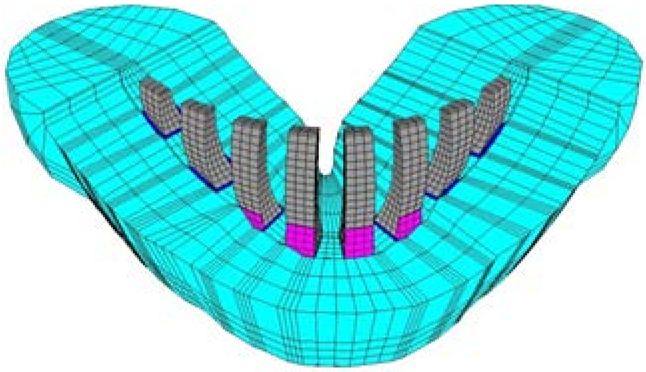

Figure 7: Even blocks model. Llauset dam

Hydrostatic pressure

The behaviour of the dams under hydrostatic pressure is calculated using a continuum block model (figures 4 & 5). The hydrostatic pressure is considered as a normal load in the upstream wall. Three water levels have been considered for reference: Maximum ordinary level (NMO), exploitation minimum level (NME) and extreme flood corresponding to the crowning level (NAE).

Thermal effects

Both dams have been working properly for more than 25 years, and both vaults have reached their stable working temperature long ago, and the thermal behaviour is governed by the environmental temperatures. In the present study the temperatures distribution in the body of the dams are based in the mean values of seasonal environmental temperatures.

The company responsible of the exploitation of the whole fall has stored physical data about the dams' response from the auscultation plan. Daily, monthly or seasonal measures have been registered during 1988–2011 period in the thermometers placed in the body of the dams, at different heights. These measurements have been used in this study to determine the thermal increments with respect to the initial temperature in the joint injection moment, which are the reference for the thermal response. To avoid that the environmental temperatures distribution are conditioned by daily variations or punctual changes, monthly averages have been considered softening the extreme values, taking into account the concrete thermal inertia.

These monthly averages have been grouped into three sets of values for the seasonal temperatures.

- Mean winter temperature distribution defined as the maximum, mean and minimum value of the average of the monthly means obtained in December – May period.
- Minimum winter distribution defined as the maximum, mean and minimum value of the minimum of the monthly means obtained in December – May period.
- Maximum summer distribution defined as the maximum, mean and minimum value of the maximum of the monthly means obtained in June – November period.

T Concrete	Average of the monthly means				
Minimum winter	0,99	Maximum winter	9,74	Mean winter	3,90
T minimum winter	Minimum of monthly means				
Minimum winter	-4,30	Maximum winter	7,19	Mean winter	0,56
T maximum summer	Minimum of monthly means				
Minimum summer	9,08	Maximum summer	19,95	Mean summer	15,95

Table 1.- Temperature variation in the upstream Wall of the Baserca vault

The temperature distribution in the body of the dam has been obtained from the environmental values using the Stucky method [1]. This method determines the temperature distribution inside the concrete from the annual or seasonal variation of the environmental temperatures registered in the walls. This distribution is normalised by linear function defined from the mean variation amplitude and the maximum increment of temperature between the walls. According to this method the following thermal cases have been analysed:

- Empty dam in winter and summer, with the same temperature variation in both walls.
- Empty dam in summer with insolation in downstream wall considering an increment of temperature in the opposite wall
- Full dam in winter and summer, with temperature variation in the water in the upstream wall and environmental temperature in the downstream wall.
- Full dam in summer with insolation in the downstream wall considering the variation of the temperature in the water in the upstream wall.
- Oscillating water level considering the minimum level of exploitation upstream, and an average of the temperatures for full and empty dam in the walls.

In figures 8 and 9 some of the singularities of the thermal cases are shown for each dam. The first corresponds to the temperatures distribution during the joint injection. The second corresponds to Llauset dam in the so called “Oscillating dam” situation to model a quick fill-spill of the dam.

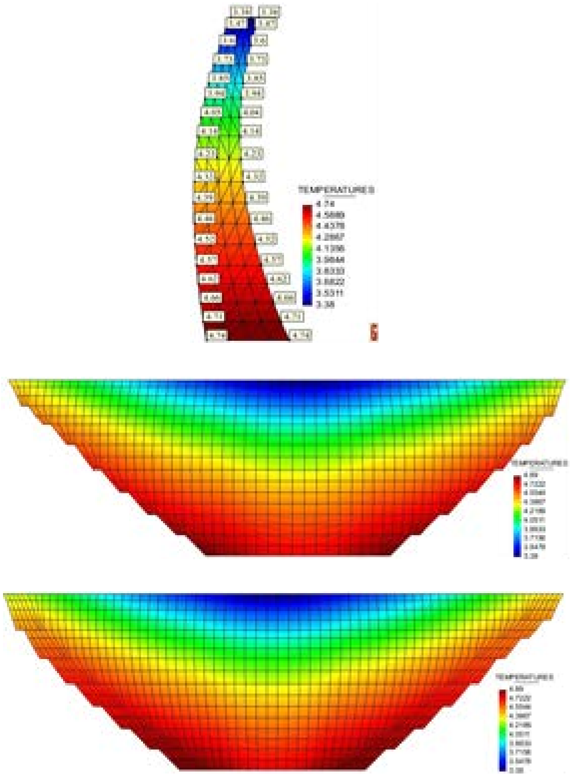

Figure 8: Temperatures distribution during the joints injection (Baserca dam)

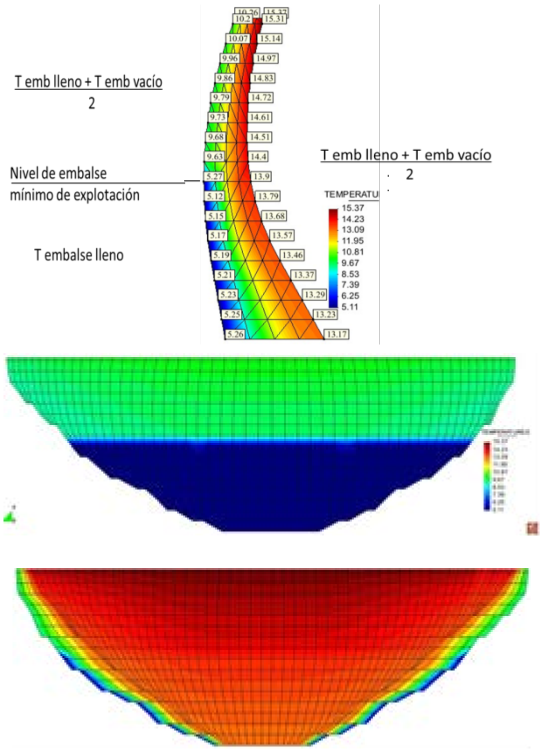

Figure 9: Temperature distribution in summer for Oscillating dam (Llauset dam)

Loading cases

Taking into account the basic loading cases for the Baserca and Llauset dams, the study of their behaviour involves four different loading cases:

- **Self-weight + Temperature empty dam**: This case represents the situation before the filling up of the dam when the upstream wall has been exposed to environmental conditions for long time.
- **Self-weight + Hydrostatic pressure for full dam + Temperature full dam**: this combination describes the state of the dam during exploitation time with full dam.
- **Self-weight + Hydrostatic pressure at minimum level of exploitation + Temperature for oscillating dam**: This combination describes quick variation of the water level between the minimum level for exploitation and full dam in the upstream wall.
- **Self-weight + Hydrostatic level for extreme flood**.

For the first and second loading cases, the thermal effect leads to three different situations to calculate:

- Minimum temperature in winter.
- Maximum temperature in summer.
- Maximum temperature in summer with insolation downstream wall.

In the case of oscillating dam two thermal scenarios have been considered for winter and summer.

Results

Results have been obtained for the different loading cases defined before, applying the superposition principle to the basic loading cases, from the linear elastic behaviour. This superposition has been performed in both dams with the continuum (monolithic) models, keeping the results obtained in the alternative blocks model for the situation before the joints injection.

For any case the stress results in traction and compression are shown in horizontal (arc direction σ_x) and vertical direction (σ_z) in both walls. In some cases the singularities of the numerical model produce stress localizations in a very small domain, which are negligible. In other cases, this stress localization (figure 10) shows a certain non-negligible dimension. These stresses are treated calculating an average in the horizontal and vertical direction, reproducing the real behaviour of the structure.

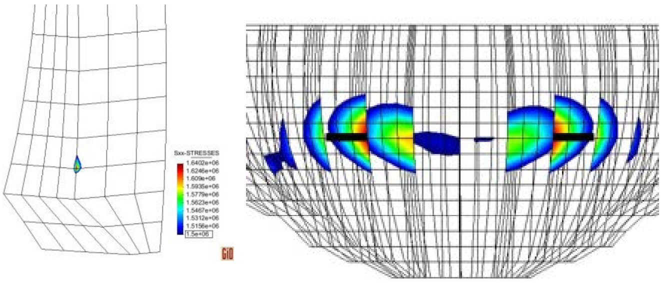

Figure 10.- Stress localization example

The results obtained are post processed in contour fill mode. The legend inside the stress diagrams considers tensile stress as positive, expressed in N/m^2.

BASERCA DAM

Taking into account the great amount of information obtained in the analysis of the nine calculation problems defined for every single dam, the results have been grouped according to exploitation criteria, that’s empty dam, full dam oscillating dam and extreme flood case.

Empty dam

In this case the main load is self-weight with different thermal scenarios. The maximum tensile stress is 1.47 MPa in horizontal direction, in the downstream wall for the minimum temperature in winter.

The maximum vertical tensile stress is 1.4 MPa located in downstream wall for the maximum temperature in summer. A bit higher values are obtained in the left abutment in the upstream wall. These values are very concentrated in vertical direction. The distribution of these stresses gives values under the maximum value.

The maximum compression stress is 7.8 MPa in vertical direction in the upstream wall for the maximum temperature in summer with insolation. The maximum compression horizontal stress is 7.9 MPa, in downstream wall for the maximum temperature in summer with insolation.

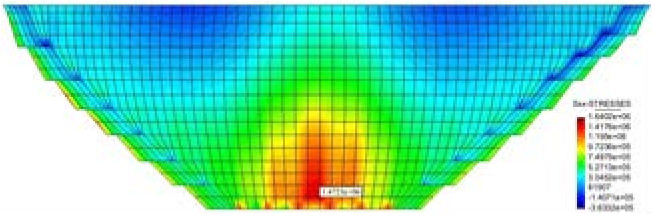

Figure 11: Maximum tensile stress in horizontal direction

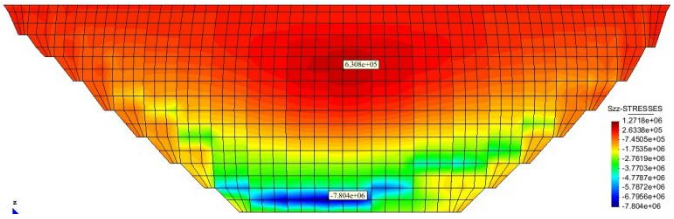

Figure 12: Maximum compression vertical stress in the upstream wall

Full dam

In this case the loads are the self-weight and the hydrostatic pressure with different thermal scenarios.

The maximum tensile stress is 1.46 MPa in horizontal direction, and is located in downstream wall for the minimum temperature in winter. The vertical maximum tensile stress is very similar, in the same thermal scenario but located in the upstream wall.

Some tensile stresses are obtained, with values over the maximum, concentrated n the crowning level. These stresses are distributed in horizontal and vertical direction, with resulting values under de maximum.

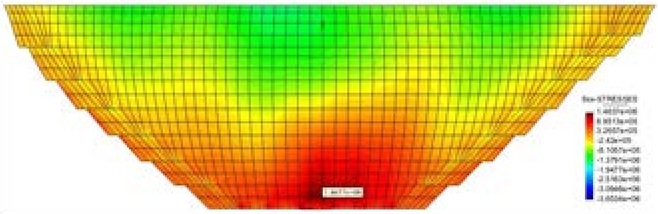

Figure 13: Maximum tensile stress in horizontal direction. Downstream wall.

The maximum compression stress is 4.6 MPa in horizontal direction, located in downstream wall for the maximum temperature in summer with insolation. The maximum compression vertical stress is 4 MPa, located in the same wall and thermal scenario.

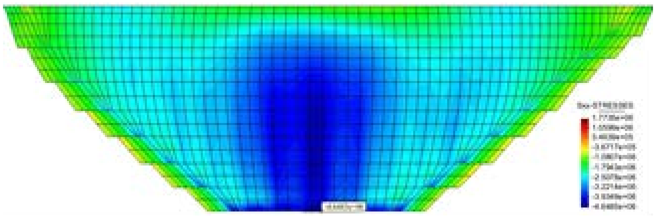

Figure 14**:** Maximum compression stresses in horizontal direction. Downstream wall.

Oscillating dam

In this case the loads are the self-weight and the hydrostatic pressure corresponding to the minimum level of exploitation for the different thermal situations considered.

The maximum tensile stress value is 1.9 MPa located in the upstream wall for the oscillating dam in summer. This stress is very concentrated in the crowning level.

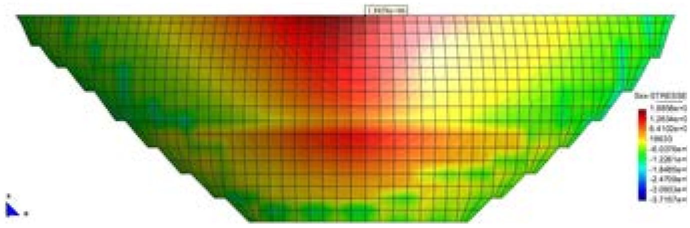

Figure 15**:** Maximum tensile stress in horizontal direction. Upstream wall.

This stress shows that the loading hypothesis is too strict; because the structure is able to hold out although it’s not been designed according to do so. The maximum vertical tensile stress is 0.8 MPa and is located in the same wall for the same thermal scenario.

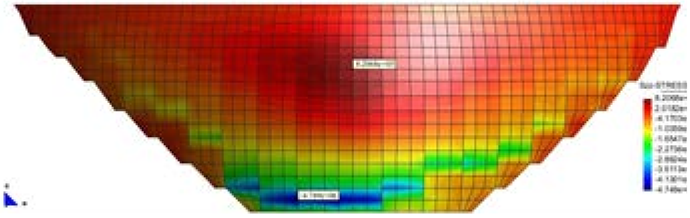

Figure 16**:** Maximum compression vertical stress. Upstream wall

The maximum compression stress is 4.7 MPa in vertical direction and is located in the upstream wall for the oscillating dam case in summer. The maximum compression in horizontal direction is 3.7 MPa and is located in downstream wall for the same thermal scenario.

Extreme flood

In this case the loads are the self-weight and hydrostatic pressure corresponding to the spilling over the crowning level.

The maximum tensile stress is 1.4 MPa in vertical direction, and is very concentrated in lower part of one of the central joints, upstream wall. The maximum tensile stress is 0.5 MPa in horizontal direction, in the same wall.

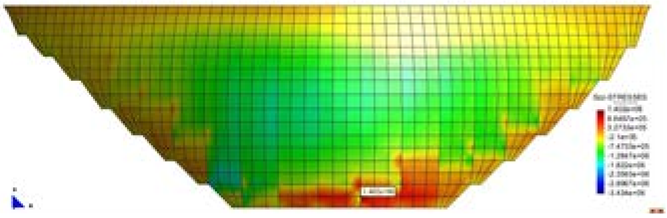

Figure 17**:** Maximum vertical tensile stress. Upstream wall

The maximum compression stress is 3.4 MPa in vertical direction, located in the downstream wall. The maximum horizontal compression stress is 3.1 MPa obtained in the upstream wall.

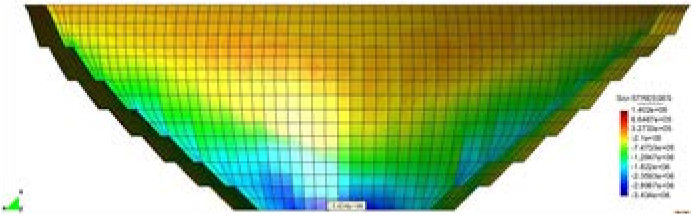

Figure 18**:** Maximum vertical compression stress. Downstream wall

LLAUSET DAM

Empty dam

In this case the main load is the self-weight in the different thermal scenarios considered.

The maximum vertical tensile stress is 1.6 MPa located in the dowsnstream wall fot the maximum temperature in summer with insolation. This maximum stress is very localized in the surface of the right abutment downstream. The maximum stress in horizontal direction reach 1.3 MPa located in the upstream wall for the minimum temperature n winter. This value is obtained after a vertical redistribution in the neighbourhood.

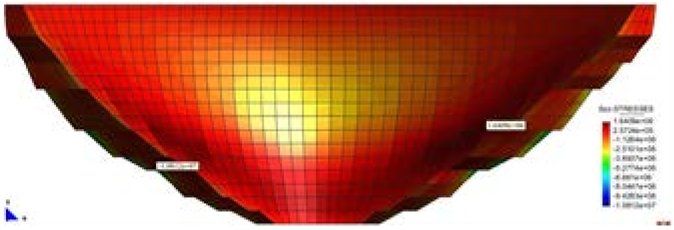

Figure 19**:** Maximum vertical tensile stress. Dowstream wall

The maximum vertical compression stress is 10.8 MPa located in downstream wall, very concentrated in the lower part of the left abutment, for the maximum temperature in summer. The maximum horizontal compression stress is 7.6 MPa located in downstream wall, very localised in the upper part of the left abutment, for the maximum temperature in summer with insolation.

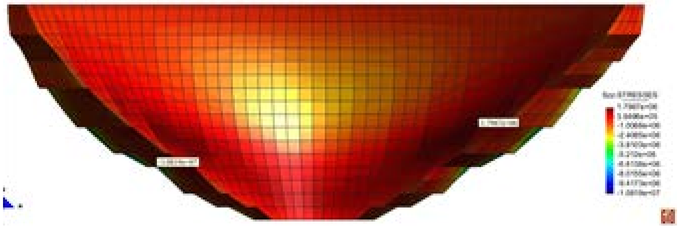

Figure 20**:** Maximum vertical compression stresses. Upstream wall

Full dam

In this case the loads are the self-weight and the hydrostatic pressure for the differents thermal scenarios.

The maximum horizontal tensile stress is 1.4 MPa located in upstream wall for the maximum temperature in summer with insolation. This value is the result of a redistribution of the a slightly higher stress but very concentrated in the crowning level, in a very small area.

The maximum vertical tensile stress is 1..5 MP and is located in downstream wall for the minimum temperature in winter.

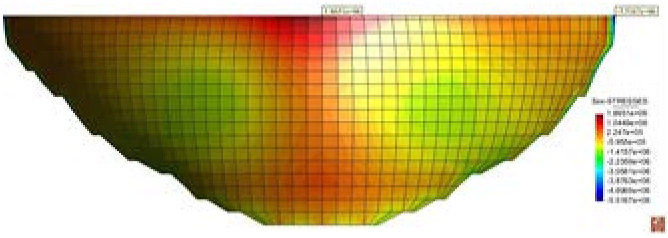

Figura 21.- Maximum horizontal tensile stresses. Upstream wall

The maximum vertical compression stress is 6.20 Mpa located in downstream wall concentrated in the lower part of the left abutment, for the maximum temperature in summer. The maximum horizontal compression stress is 5.5 MPa, located in upstream, very localized in the interface between the crowning level and the right abutment, for the maximum temperature in summer with insolation.

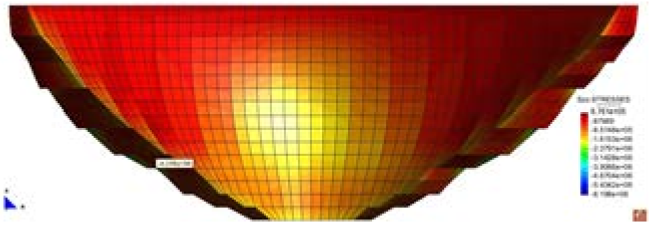

Figure 22.- Maximum vertical compression stresses. Downstream wall

Oscillating dam

In this case the loads are the self-weight and the hydrostatic pressure associated to the minimum exploitation level for the different thermal scenarios.

The maximum vertical tensile stress is 1.6 MPa located in downstream wall for the oscillating dam temperature in winter. The maximum horizontal tensile is 1.5 MPa obtained in upstream wall, very concentrated in the crowning level, for the oscillating dam temperature in summer.

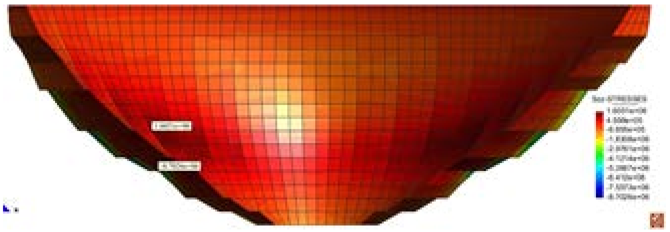

Figure 23.- Maximum vertical tensile stress. Downstream wall

The maximum vertical compression stress is 9 MPa located in the upstream wall, very localized and concentrated in the lower part of the right abutment, for the oscillating dam temperature in summer.

The maximum horizontal compression stress is 5.2 MPa obtained in the same wall, very concentrated in the upper part of the right abutment, for the same thermal scenario.

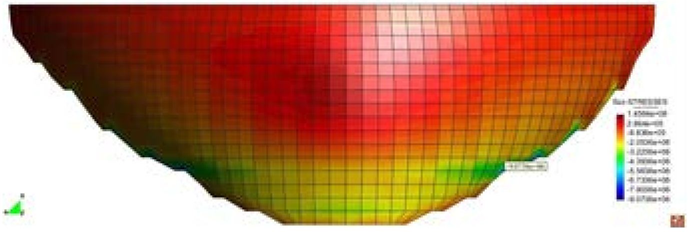

Figure 24.- Maximum vertical compression stresses. Upstream wall

Extreme flood

In this case the loads are the self-weight and the hydrostatic pressure associated to the situation of spilling.

The maximum horizontal tensile stress is 0.9 MPa located in the upstream wall, concentrated in the upper part of the left abutment. The maximum vertical tensile stress is 0.75 MPa obtained in downstream wall.

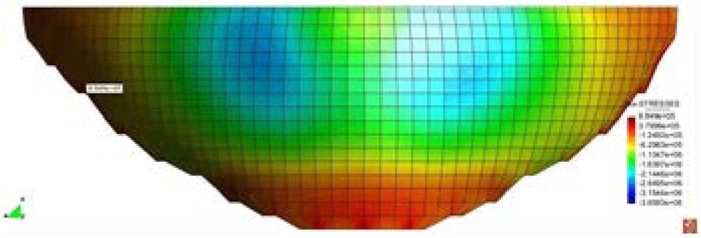

Figure 25**:** Maximum horizontal tensile stress. Upstream wall

The maximum vertical compression stress is 5.6 MPa located in downstream wall. The maximum horizontal compression stress is 3.7 MPa in the crowning level in downstream wall.

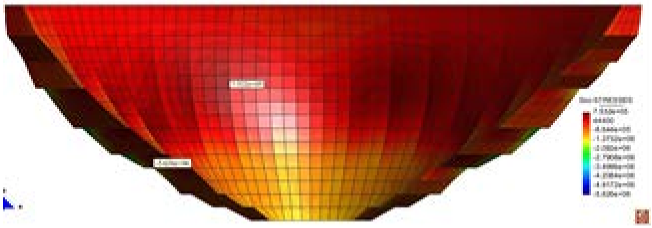

Figure 26**:** Maximum horizontal compression stresses. Downstream wall

Conclusions

For both dams – Baserca and Llauset – results have been obtained for different loading cases, self-weight before joints injection when every cantilever works independently, hydrostatic pressure, with the cantilevers working as a continum because of the joint injection, for different water levels and different thermal situations, defined from the measurements “in situ” in several points of both dams from 1.998.

All the values obtained in the calculation process are below the admissible limite of stress, altought in some small areas higher values appear, they’re concentrated or affect the surface of the dam. These concentrated stress are caused by the geometry of the numerical model. This conclusion is supported by the results obtained in the redistribution of stresses in vertical or horizontal direction in the zones affected, which weaken significantly the maximum values observed.

It’s well known that thermal loads are very restrictive with vault dams response. For this reason, to remove the uncertainties during the analysis and the interpretation of the results, the Stucky method has been used. This methodology is commonly used and accepted in the thermal analysis of concrete dams.

This methodology employs real thermal data form both dams, which permits particularize the thermal reference load (joints injection) and exploitation load in winter and summer seasons.

The oscillating dam scenario modelling the cycle filling–spilling up the dam, considering for both walls a mean temperature in each thermal scenario between empty and full dam is a novelty in this type of analysis and means a strict test for both vaults, which they pass reasonably well.

In both dams the case of extreme flood is not determinant because the maximum tensile and compression stresses observed are similar to the stresses obtained in other loading cases, altought in both cases in vertical direction and in opposite walls, upstream and downstream respectively.

Altought both dams are geometrically and functionally very similar, they show some particularities in its structural response. That’s possibly due to the different treatement for the questions related to self-weight modelling considering isolated blocks.

It’s also important to note that concrete used in both dams was put up approximately 30 years ago, and so its resistance has grown up during the dams lifetime.

Apart from the numerical calculation process the behavior of the dams has been checked in situ, to verify that both dams have supported similar loading states to the ones considered in this study and foreseen in the future. The behavior of the dams has been excellent according to the visual inspection performed and the auscultation results obtained from the dams.

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