CONCRETE SWELLING IN A DOUBLE CURVATURE DAM

J. Rodríguez, P. González, F. Martínez, and J. Martí

Principia Ingenieros Consultores
javier.rodriguez@principia.es

Abstract

Several chemical reactions are able to produce swelling of concrete for decades after its initial curing, a problem that affects a considerable number of concrete dams around the world. The object of the work reported is to simulate the underlying mechanisms with sufficient accuracy to reproduce the past history and to predict the future evolution reliably. Having studied the available formulations, that considered to be more promising was adopted and introduced via user routines in a commercial finite element code. It is a non-isotropic swelling model, compatible with the cracking and other non-linearities displayed by the concrete. The paper concentrates on the work conducted for a double-curvature arch dam. The model parameters were determined on the basis of some parts of the dam's monitored histories, reliability was then verified using other parts and, finally, predictions were made about the future evolution of the dam and its safety margin.

KEYWORDS

Concrete dams, Concrete swelling, Alkali-aggregate reaction.

1 INTRODUCTION AND BACKGROUND

There are a number of chemical reactions that may cause delayed swelling in concrete. The reactions generally involve the aggregate, the cement matrix and water. The process is very slow, as it typically arises from more than one reaction, with the second one feeding on the results of the first one. Also, water must be available, which migrates only slowly in a concrete mass. In any case concrete swelling, whenever it takes place, entails deterioration and potentially catastrophic consequences for the structure concerned.

Investigations of this problem have taken place at least from the late thirties [1] and many structures are known to suffer from this problem today. In particular it affects a considerable number of concrete dams built towards the middle of the 20th century in many places of the world. The application discussed in the present paper is a double-curvature arch dam dating from that period. Because of its widespread occurrence and its potential consequences, the phenomenon has been extensively studied by various institutions like the International Commission for Large Dams (ICOLD), the American Concrete Institute (ACI), the International Union of Testing and Research Laboratories for Materials and Structures (RILEM), etc.

A review of the state-of-the-art is outside the scope of the present paper, but an interested reader may wish to peruse the proceedings of previous International Conferences on Alkali-Aggregate Reaction in Concrete, of which the 13th and more recent one was held in 2008 in Trondheim, Norway [2]. Another recent example, reflecting the difficulties involved in accurate numerical simulation of these phenomena is evinced by the recent Numerical Benchmark for the Finite Element Simulation of Expansive Concrete [3], jointly sponsored by the ICOLD Committee on Concrete Dams and the RILEM TC 219-ACS Alkali Aggregate Reaction in Concrete Structures.

Various types of remedial measures have been attempted in the past, ranging from the treatment of the structure with lithium [4] to the vertical slicing of the dam to relieve the compressive stresses caused by concrete swelling or provide allowance for future expansion. It seems clear though that the proposal of useful strategies must rely on a sound understanding of the process and an ability to model it reliably, so that informed predictions can be made about the future of the structure and the effects of mitigating measures.

Based on the results of past investigations, it can be concluded that the factors that have a major influence in the swelling process are the following:

- Material components: reactive aggregates and alkali-rich cements are needed, additives may also influence the process.
- Time elapsed: the formation of a hydrophilic gel is not instantaneous, it has a latency time; also, once formed, its swelling via an alkali-aggregate reaction (AAR) involves a characteristic time.
- Environmental conditions: as in many chemical reactions, temperature accelerates the process and, since swelling occurs by absorbing water, moisture conditions play a significant role as well.
- Stress state: high compressive or tensile stresses may affect swelling because of their effects on water pathways, e.g.: by closing cracks or creating spaces for the expanded gel.

The significance of other factors can be considered smaller in comparison with those listed above.

2 CONCRETE BEHAVIOUR AND EXPANSION MODELS

Following an extensive literature review, the more promising mathematical formulations appear to be the one proposed by Ulm et al. [5], subsequently modified and extended by Saouma and Perotti [6]. Both theories will be described briefly below, since they will be incorporated into a finite element code and used for analyzing the dam. The constitutive behavior assigned to the concrete was a damaged plasticity model for tensile cracking and compressive crushing. It is in this mechanical framework that the expansion is assumed to take place.

2.1 Model by Ulm et al.

The model by Ulm et al. assumes that the reaction develops following an equation of the type:

$$1-\xi = t_c(\xi,\theta)\frac{\mathrm{d}\xi}{\mathrm{d}t} \tag{1}$$

where ξ is the extent of the reaction, t_c is the characteristic time of the reaction, θ is the absolute temperature, and t is the time elapsed. The characteristic time decreases as the reaction progresses:

$$t_c(\xi,\theta) = \tau_c(\theta)\lambda(\xi,\theta) \tag{2}$$

$$\lambda(\xi,\theta) = \frac{1+\exp\left(-\tau_L(\theta)/\tau_c(\theta)\right)}{\xi+\exp\left(-\tau_L(\theta)/\tau_c(\theta)\right)} \tag{3}$$

where τ_c is a characteristic time constant.

The latency and characteristic times are both a function of temperature, following the Arrhenius law that governs thermally activated processes. It may be noticed that the above differential equation can be solved analytically in the isothermal case. The parameters involved in the model, with the values proposed by Larive [7], are listed below:

- unidirectional expansion at infinite time: 0 to 0.004
- activation energy of the characteristic time: 5400 ± 500 K
- activation energy of the latency time: 9400 ±500 K

The activation energies are already divided by the Boltzmann constant, thus their K units. Figure 1a shows the physical meaning of the two time constants involved. The latency time is the time elapsed to the point of inflection of the curve that depicts the development of the reaction; it is near, but slightly differs from, the time when 50% of the reaction has taken place. The characteristic time is half of the incremental intercept produced by a tangent drawn at the inflection point. Figure 1b shows the effect of temperature in the progress of the reaction.

2.2 Model by Saouma and Perotti

The model by Saouma and Perotti was initially developed to represent the progress of the AAR and its temperature dependence is taken from the model by Ulm et al. They propose that the effects of the volumetric reaction in one space direction will be affected by the others, that the preferred directions for expansion will be the least compressed ones, and that high normal stresses will influence the reaction through mechanisms such as providing space for gel expansion, sealing or opening pathways for water migration, etc.

The effects of the stress level are reflected through its influence on the latency time:

$$\tau_L(\theta,\bar{\sigma}) = f(\bar{\sigma})\tau_L^{\mathrm{ULM}}(\theta) \tag{4}$$

$$f(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \geq 0 \\ 1+\alpha\bar{\sigma} & \text{if } \bar{\sigma} < 0 \end{cases} \tag{5}$$

where $\bar{\sigma} = -(\sigma_I + \sigma_{II} + \sigma_{III})/(3f_c)$ is the normalized pressure, α is an empirical coefficient, for which Saouma and Perotti propose using 4/3 based on the tests by Multon [8], f_c is the compressive strength, and τ_L^{ULM} is the latency time from Ulm et al.

For the evolution of swelling the following equation is proposed:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{vol}}}{\mathrm{d}t} = \Gamma_t(u_{\mathrm{ck}})\Gamma_c(\bar{\sigma})\xi(t,\theta)\varepsilon_{\mathrm{vol}}^{\infty} \tag{6}$$

where Γ_t accounts for the reduction of swelling caused by cracking with crack opening u_{ck}, Γ_c accounts for the reduction of swelling by compression with a normalized pressure $\bar{\sigma}$, and $\varepsilon_{\mathrm{vol}}^{\infty}$ is the free expansion at infinite time.

The dependence on tensile cracking is incorporated by:

$$\Gamma_t(u_{\mathrm{ck}}) = \begin{cases} 1 & \text{if } u_{\mathrm{ck}} \leq \gamma_t w_c \\ \Gamma_r + (1-\Gamma_r)\dfrac{\gamma_t w_c}{u_{\mathrm{ck}}} & \text{if } u_{\mathrm{ck}} > \gamma_t w_c \end{cases} \tag{7}$$

where γ_t governs the reduction of expansion in tension, Γ_r is the coefficient of residual expansion in tension, w_c is the maximum crack opening in the tensile softening curve. The effect of compression is introduced as:

$$\Gamma_c(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \leq 0 \\ 1 - \dfrac{e^{\beta}\bar{\sigma}}{1+(e^{\beta}-1)\bar{\sigma}} & \text{if } \bar{\sigma} > 0 \end{cases} \tag{8}$$

where β is taken as 0.5 based on the experiments by Multon and Toutlemonde [8].

Apart from determining the volumetric expansion, the model must also distribute it among the three space directions. For example, in uniaxial tension, the amount of chemical swelling would be identical in all directions; but in uniaxial compression, with the stress above a certain threshold, the chemical expansion would only occur in the two transverse directions. Figure 2 shows how the model distributes the expansion in the various stress states.

3 NUMERICAL IMPLEMENTATION

The model by Saouma and Perotti described in the previous section was implemented in Abaqus/Standard [9]. For this purpose a user subroutine was created to determine incrementally the imposed deformations caused by both the expansive chemical reaction and thermal dilation. Such increments are a function of temperature, progress of the reaction, pressure, and crack opening.

The calculation requires information about the principal stresses and directions and must be combined with the plasticity and the continuous damage model of the concrete. State and field variables are updated in another user subroutine and moisture is introduced as an independent field variable. The rest of the variables are updated at the beginning of each time step, thus in an explicit scheme, but are extrapolated to mid-step from their most recent values. The size of the time step may therefore play an important role and the sensitivity to this parameter should be studied for each specific application. For cases such as discussed in the present paper, experience indicates that 2 weeks is an adequate time step. Other subroutines were also written to impose yearly periodic boundary conditions for thermal analyses and to vary the hydrostatic pressure.

Many analyses were carried out on a single element of 25 MPa concrete to ascertain that the model was working as intended. Figure 3a shows the progress of the reaction at 15ºC for various stress conditions, slowing down as pressure increases; apart from the rate of progress, the final volumetric expansion is also affected by pressure, as can be seen in Figure 3b. The distribution of expansion between the various directions is shown in Figure 4, which corresponds to different stress conditions and 37ºC, a temperature that is typical of the accelerated swelling tests conducted in the laboratory. The latter figure confirms that, even under considerable compression in all directions, swelling decreases but does not vanish.

4 APPLICATION TO A DOUBLE-CURVATURE ARCH DAM

The Belesar dam is a 132 m dam built roughly 50 years ago on the river Miño in northwest Spain. The facility is owned by Gas Natural Fenosa for hydroelectric power generation. A general view of the dam is provided in Figure 4. Swelling phenomena were recognized from a relatively early stage and continue today. The early identification of the problem caused the installation of additional instrumentation, thereby producing a wealth of detailed monitoring data that would not exist otherwise.

4.1 Available data and methodology

The dam has several thousand channels of instrumentation, many of which have been producing data for almost 50 years. For the present purposes, some of them are especially significant:

- records of the demands imposed and the prevailing environmental conditions, such as air and water temperatures at various depths, as well as elevations of the water surface in the reservoir.
- records of the response of the dam, such as temperatures, displacements and other variables at many locations within the body of the dam.

The parameters used for describing the mechanical and thermal behaviour of the concrete concrete were Young's modulus 30 GPa, Poisson's ratio 0.22, compressive strength 30 MPa, tensile strength 3 MPa, density 2300 kg/m^3, thermal conductivity 1.7 W/mK, and specific heat 750 J/kgK. The coefficient of thermal expansion, initially believed to be 1.0 x 10^{-5} K^{-1}, had to be increased later, based on the monitored data, to 1.5 x 10^{-5} K^{-1}.

The data were first used to obtain average years for the evolutions of temperatures at specific locations and of the water level in the reservoir. The heat conduction equation was then solved, based on the temperatures at some points, to obtain complete temperature histories at all points in the dam, using temperature records at other points for verification.

Having done this, the parameters of the swelling model were calibrated using the displacement records of one single point at the top of the dam. With these parameters one can then trace the history of the dam, calculate the displacements at all points and verifying the model against data not used in the calibration.

4.2 Results obtained

A representative yearly evolution of the water levels in the reservoir was determined averaging and fitting with Fourier series. For the thermal analyses, Figure 5a shows the mesh used, made of about 90,000 linear tetrahedral elements. The thermal analysis is marched forward sufficiently to remove the influence of the unknown initial conditions; the resulting distribution of temperatures in the dam appears in Figure 6. Because of its more southerly orientation, the downstream face tends to be hotter near the left embankment.

The parameters of the expansion model were fitted to match the displacement trend at one location. The analyses were conducted with the mesh shown in Figure 5b, which uses about 30,000 elements (second order hexahedrons and first order tetrahedrons). The expansion parameters obtained were:

- swelling at infinite time: 0.001
- latency time: 20,000 days
- characteristic time: 5,000 days

Based on those parameters the model was then used to reproduce the history of the dam and thus generate the expected evolution of displacement at other locations. Figure 7 presents comparisons with recorded histories at points at the top of the dam. Since the history at point no. 4 had been used for calibration, a good match could be expected there; but the excellent agreement obtained at the other locations, in spite of the asymmetries displayed by the dam, can only arise because the expansion model represents well the physics of the problem and the parameters are well calibrated. Similarly good agreements occur when comparing the displacements at intermediate elevations in the dam.

The model was also used to determine the extent of the chemical reaction and the mean expansion at different times, as well as for predicting the crack patterns. The compressive stresses in 2012 and 2042, shown in Figure 8, indicate that the expected swelling will not lead to dangerous conditions. Figure 9 presents the cracking at those same dates; the current crack patterns are consistent with the predicted ones in spite of the degree of uncertainty inevitably linked to the tensile strength of concrete.

5 CONCLUSIONS

Following a review of the state-of-the-art in relation with long term, chemical swelling of concrete and its effects on existing dams, a swelling model was adopted and a subroutine was programmed to implement it in Abaqus/Standard. The newly generated tool and procedures were used to investigate the current situation and to predict the future evolution of a double-curvature arch dam known to be affected by this problem.

The conclusions reached as a result of the work performed are presented below:

a) The swelling model that appears to be more realistic is that initially proposed by Ulm et al., but incorporating the later modifications by Saouma and Perotti.

b) The model has been programmed in a user subroutine in Abaqus/Standard, which has been extensively validated to ensure that it performs its intended function.

c) Excellent agreement was observed when modelling a double-curvature arch dam, suffering from a concrete swelling pathology. The evolution of displacements at a single point was used to calibrate the parameters of the swelling model, which subsequently provided excellent predictions of the displacements at all other locations of the dam, in spite of the large asymmetries and other differences. It is thought that key to this success, apart from the correctness of the theoretical model, is the availability of detailed temperature data in the body of the dam.

d) The calculations allow concluding that the dam can be expected to behave well at least for the next 30 years.

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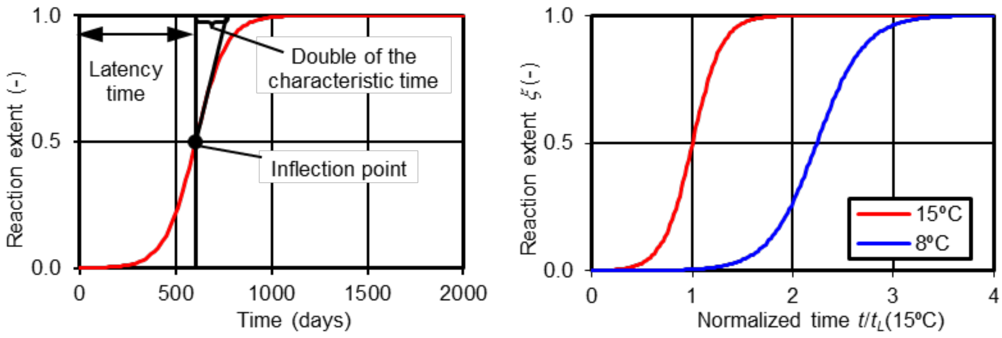


a) Reaction extent at constant temperature

b) Effect of temperature

FIGURE 1: Reaction extent according to Ulm et al. [5]

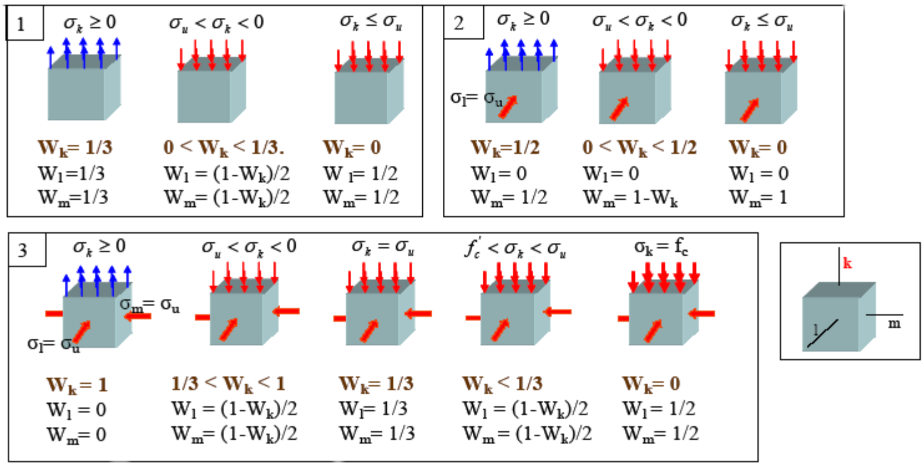
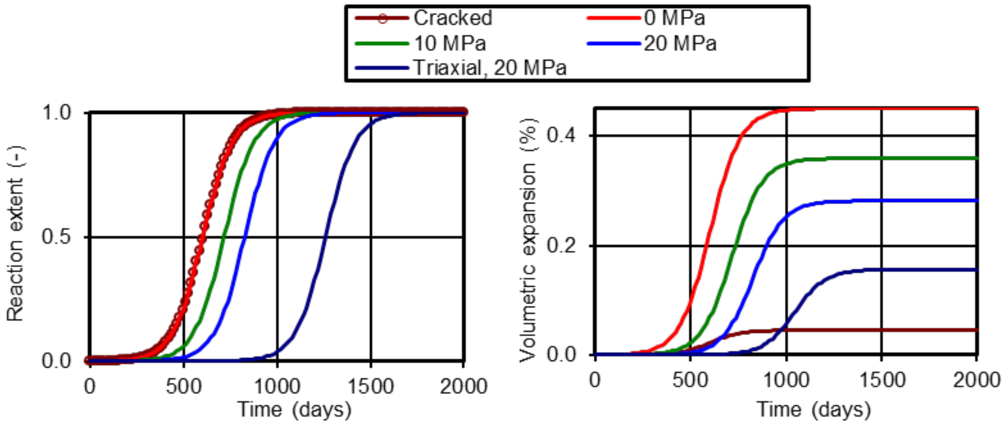


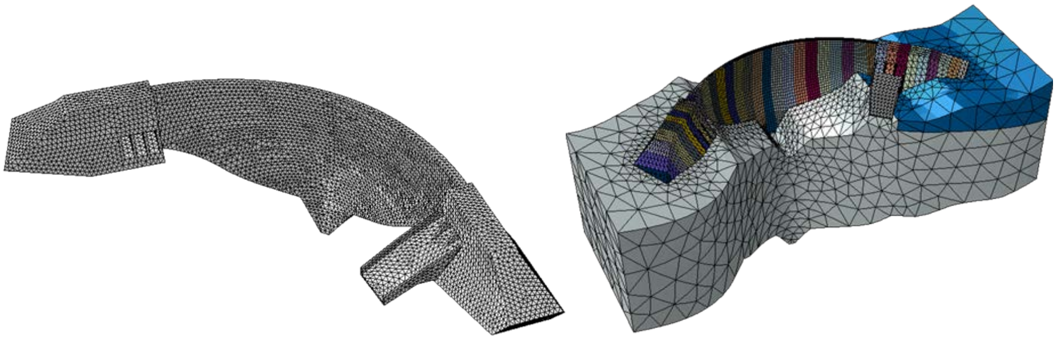
FIGURE 2: Distribution of expansion afterSaouma and Perotti [6]



a) Reaction extent b) Volumetric expansion

FIGURE 3: Reaction extent and volumetric expansion by Saouma and Perotti [6]

FIGURE 4: General view of the double curvature arch dam



a) Thermal analysis b) Mechanical analysis

FIGURE 5: Finite element meshes

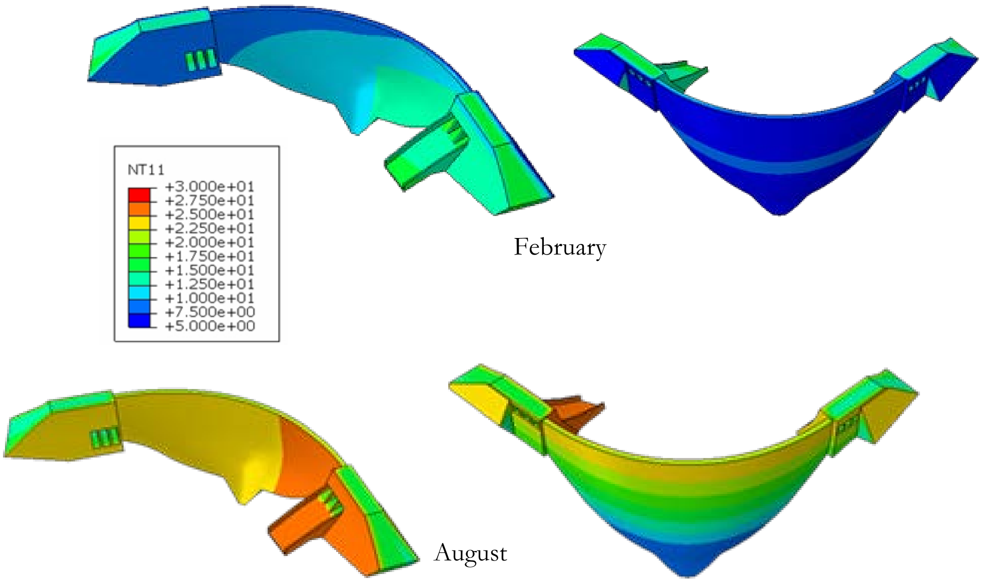
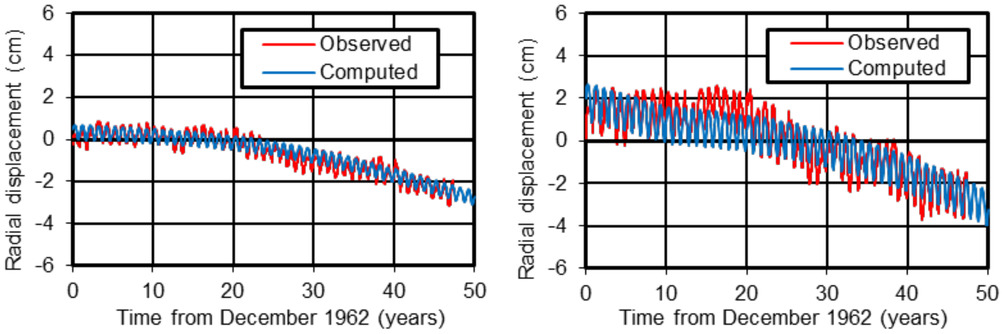
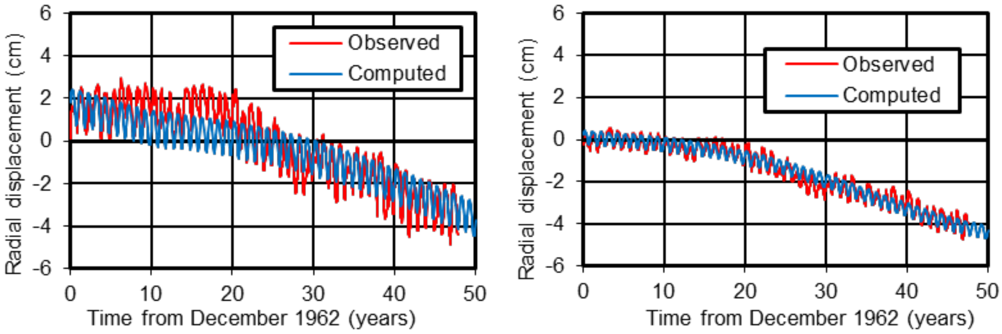


FIGURE 6: Distribution of temperatures

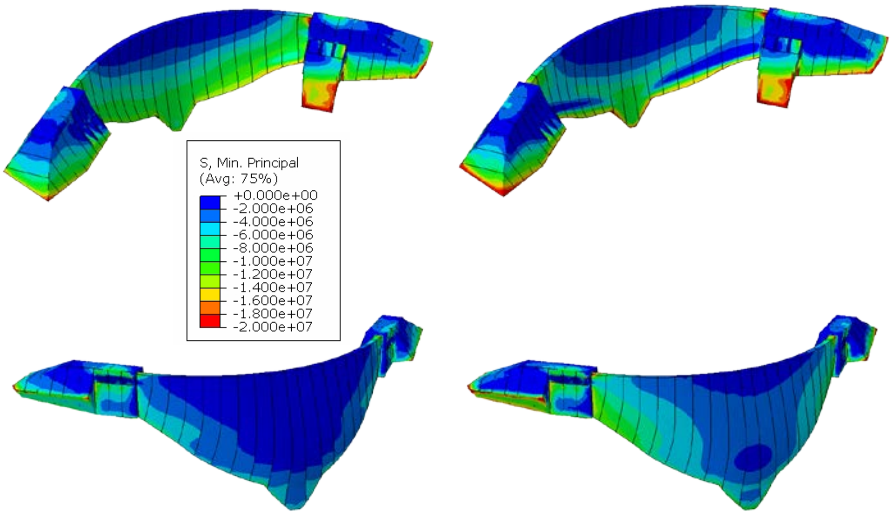


a) Point no. 1 b) Point no. 2



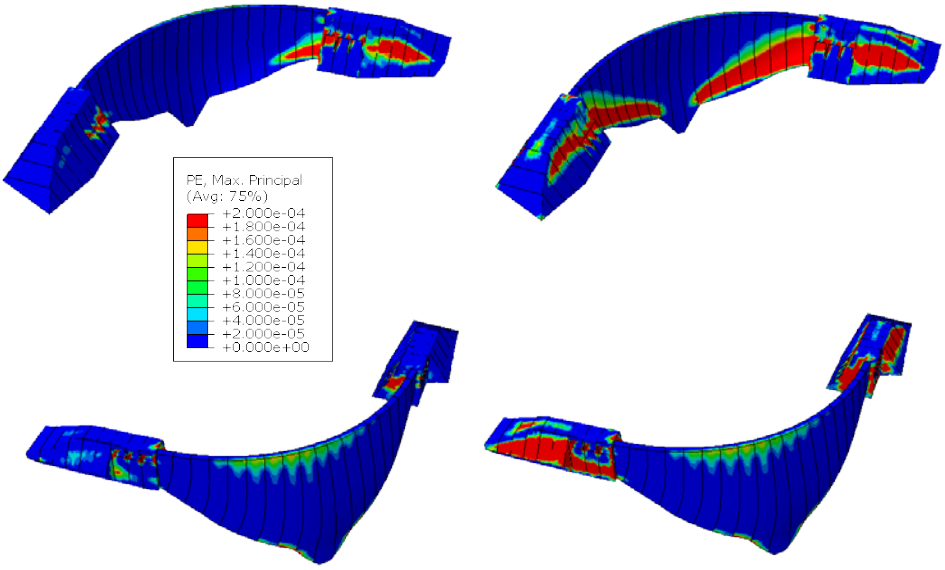
c) Point no. 3 d) Point no. 4

FIGURE 7: Comparison of recorded and computed displacements



a) year 2012 b) year 2042

FIGURE 8: Compressive stresses (Pa)



a) year 2012 b) year 2042

FIGURE 9: Equivalent plastic strains for cracking