Vibrating wire strain gauges of Ridracoli dam: analysis and interpretations

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Abstract. Safety and conservation of restraint structures are guaranteed by efficacy and efficiency of the monitoring system, particularly that controls the structure deformation state. A first verification of the correct functionality of monitoring system and of structure stability consists in check the correspondence of the recorded data trends with those expected, largely influenced by hydrostatic pressure and thermal variations. Any discrepancies between these values must be disclosed promptly and submitted to the analysis of control staff that must be able to recognize the causes of such anomalies to take the most appropriate initiatives. The technology currently most used for the control of deformations employs wire strain gauges embedded in the concrete. Deformation state control usually is based on simple static models or on empirical processes. In the last few years the evolution of numerical modeling has reached very high levels in reliability and portability. This allows to directly use these models in control centers in order to simulate in real time, or almost, the deformation status to be compared with the observed one. The reliability of the subsequent actions is therefore strongly influenced by the accuracy of the simulation model as a tool of interpretation. A system already widely tested is the one that operates at the Ridracoli dam which is a reference model to be taken into consideration in new achievements. The Ridracoli dam is an arch gravity dam characterized by an extensive and redundant monitoring system that consists of pendulums, strain gauges, piezometers, etc. Moreover in the control center, a decision support system called MISTRAL is in use, assisting operational decisions of control staff. This paper illustrates the correlations among the cause variables such as hydrostatic level and external temperature, and the effect variable, deformation of the concrete structure. The validated trends were employed to calibrate a preliminary finite element model of the structure in order to be used in the simulation of different load scenarios and to serve as a knowledge instrument.

Keywords. Deformations, Vibrating Wire Strain Gauges, Safety Dam

1 Introduction

The variables, acquired by means of the monitoring system of a dam, in order to fully describe the state of conservation of the structure, must necessarily be correlated each other and with the cause actions. In fact, the variability of some measures may be justified by the analysis of variations of cause quantities, such as the hydrostatic level and the temperature. Furthermore an asynchronous trend of the same size in different regions of the structure might depend on the operating principle of the same. An increase of specific values, not directly related to the cause variables, might instead serve as a wake-up call for the identification of ongoing processes that could affect on operation of the dam or even on its safety. Case study was the Ridracoli dam and its extensive and redundant monitoring system. The analysis focuses on the study of the deformation of the structure recorded by vibrating wire strain gauges embedded in the concrete. The state of deformation is influenced by cause variables as hydrostatic level and external temperature acquired respectively by dynamometric balance and electrical thermometers.

The reference to the theoretical behavior of an arch restraint structure subject to hydrostatic pressure and temperature loads allows to compare the observed data with that is theorized by the literature and to find so correspondence of the proper operation of the structure in the theoretical experience. Furthermore, the use of a finite element model of the structure, subjected to hydrostatic and thermal loading conditions similar to those observed in the period of analysis, allows to obtain a deformation state comparable to the real one thus having confirmation of a linear elastic behavior under ordinary loads. The calibration of the model on validated initial data enables to extend its use to situations of different loads and to estimate previously the behavior of the structure. The objective is to minimize the failed areas in the identification of possible critical states. Some papers on systems architectures used in the active control of civil structures and dams are those of Lazzari and Salvaneschi, Comerford et al. and Cade et al.. Similarly works of reference for the case study discussed in this paper are those of Lancini et al., Masera et al. and Marini et al.. Then a possible evolution of the study of correlation between cause and effect variables that affect restraint structures is discussed, by means the use of neural networks, by Mata J..

2 The Case of Study: The Ridracoli dam

2.1 Place and Structure

The Ridracoli Dam, owned by Romagna Acque Società delle Fonti S.p.A., is located in the Forlì-Cesena province, Emilia Romagna, Italy. The primary use of the reservoir is to provide drinking water through adjusting, during the year, of the Bidente river flow. The dam is the water supplier of 48 municipalities distributed in the Forlì-Cesena, Ravenna and Rimini provinces and, since 1989, of the Republic of San Marino. The secondary function is hydroelectric production. The Ridracoli dam is an arch gravity dam, in simple concrete, with an height 103.5 m and a crest length 432 m. The dam body is a double curvature structure, symmetric with respect to the main section, resting on a foundation pulvino which extends around the entire perimeter of the excavation. Both the upstream and downstream face are curved according to specific analytical laws, giving to the arcs along the horizontal sections from the center to the sides and to the vertical section from the top down thicknesses gradually increasing, in line with the gravity construction type. The dam body is made up of 27 ashlars with an independent static operation in such a way as to ensure the deformations of the structure as a result of the increase of the hydrostatic level and of other actions such as the temperature and to avoid in this way the concrete cracking.

2.2 The monitoring system

The control of the behavior of the structure, of the rock basement, of the banks of the reservoir and of the downstream rocky slopes is achieved through a complex monitoring system active since the construction phase. Most of the instruments and of the measuring points are located in five radial sections of the structure: the key section, the two lateral and the two intermediate. In the warden's house the centralized reading of about 284 instruments of a total of 985 takes place. Data acquisition is done, with different temporal frequencies, by automatic selection of panels placed in the tunnels of the dam, which are in contact with the individual measuring instruments and by manual measurements. The automatic data are stored in a computerized system called INDACO, active since 1992 it is connected in line with the centre CESI - ISMES of Bergamo. It allows the design of trend diagrams of variables, the storage of measurements and the comparison, in real time, of the current behavior of the structure with that provided by a theoretical model. The latter is contained in MISTRAL, a decision support system, which analyzes and filters the data from 42 automatic tools deemed significant for the identification of the state of the structure. In a dual way at the on-line control, a further off-line control is expected; it is based on the totality of the manual and automatic data stored in MIDAS system in order to validate the correct operation of the structure.

2.3 Analyzed Variables

As part of this work, the cause variables that have been taken into account are the hydrostatic level and the outside temperature, the effect quantity is instead the concrete deformation of the structure.

- Hydrostatic level

The primary tool that makes reading is the dynamometric balance, it detects, records and transmits hydrostatic level with great accuracy and extended measuring range. It is based on the lever principle of the first type, it presents the hydrostatic pressure outlet and the level meter disposed below the height of the reservoir minimum level. The tool allows the reading of the level at the installation place and in the warden's house. The validation of the measurement is also realized by reading staff gauges placed in the rock of the right side.

- Temperature

The temperature measurement is performed by electrical thermometers and also by vibrating wire tools used for other measures such as strain gauges. The temperature of the concrete, of air and of water is detected. Thermometers that detect the outside temperature are placed in the key section 1-2, and in the lateral ones 10-12 and 9-11, respectively in the right and left sides.

- Deformation

The measurement of the unitary deformation is carried out by vibrating wire strain gauge (Figure 1) embedded in the concrete and it is associated to the elongation of a vibrating wire of known characteristics. The strain gauges are applied in particular star configurations known as "rosettes" in such a way as to obtain values of strain along the application directions; within the structure are present rosettes of 2 or 4 instruments, arranged in the plane as shown in Figure 2. Rosettes, characterized by four instruments, control the deformations on the horizontal and vertical directions and on the two directions at 45°, the rosettes with two strain gauges analyze instead only the horizontal and vertical deformations. The tools are installed in the plane that is tangent to the surface of the dam and they are placed in the main section 1-2, Figure 3, in the left and right ones, respectively, 9-11, 15-17, 25-27 and 10-12, 16-18, 26- 28.

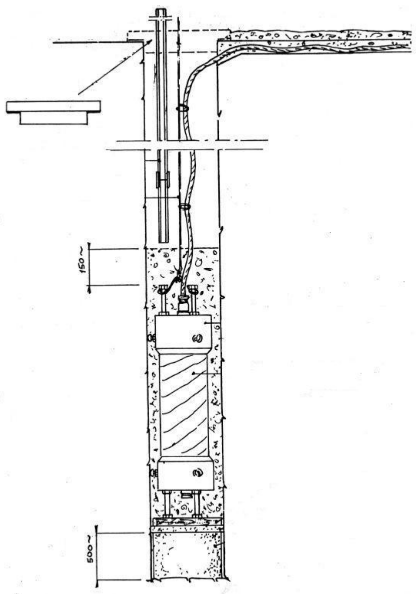

Fig. 1 Explanatory drawing of a vibrating wire strain gauge

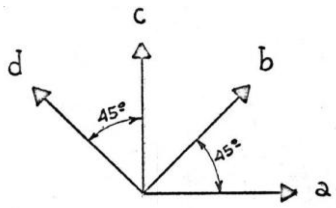

Fig. 2 Rosette scheme

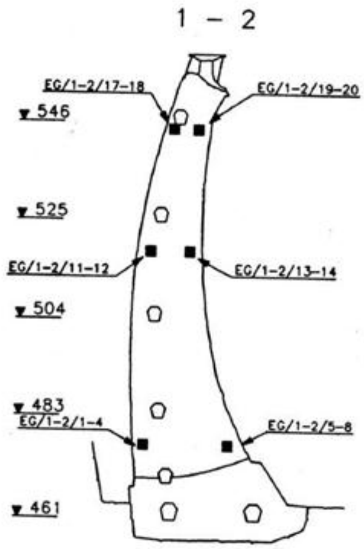

Fig. 3 Position of strain gauges in the main section 1-2

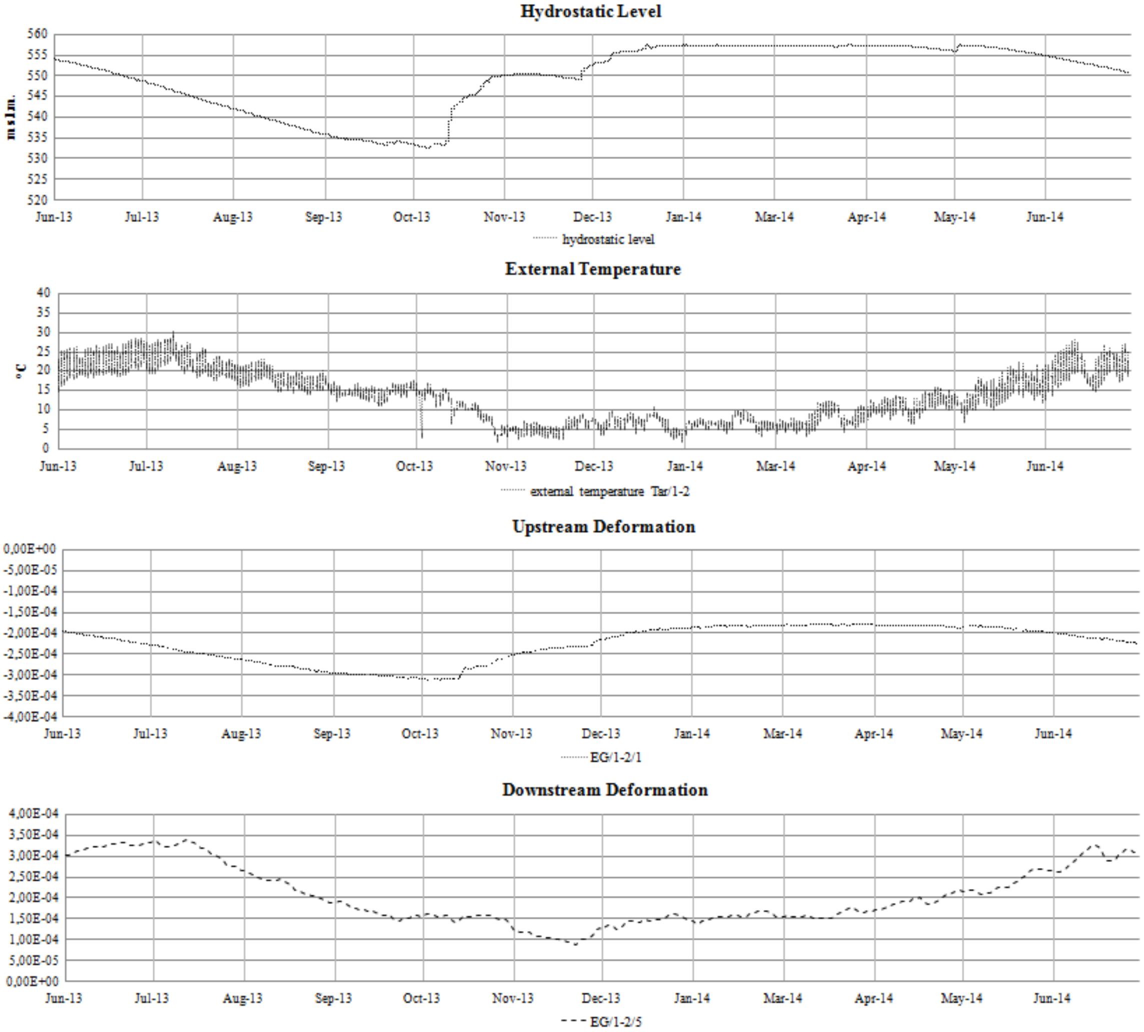

Fig. 4 Hydrostatic Level, External Temperature, Upstream Horizontal Deformation EG/1-2/1, Downstream Horizontal Deformation EG/1-2/5

2.4 Recall of descriptive analysis

Theoretical recalls of the method used to establish the correlation between two variables are exposed. Starting from the covariance and the standard deviations of two random variables X and Y, the index of Pearson quantifies the possible linear relationship between them. The Pearson's index is given by the ratio between the covariance of the two variables and the product of their standard deviations and assumes values between -1 and +1:

$$\rho_{XY}=\sigma_{XY}/(\sigma_X\cdot\sigma_Y) \qquad (1)$$

The extreme values are assumed only if a variable is a linear function of the other: in an inversely proportional manner(-1) or directly proportional manner(+1) with a probability equal to 1. The correlation index takes the value 0 if the two variables are independent, and therefore a variation of one does not influence the other and vice versa, and they are said to be uncorrelated.

2.5 Correlation between Hydrostatic Level – Temperature – Deformation

The structure deformations are mainly related to the variations of hydrostatic level and temperature. Their variability determines accordingly a change in the trend of the deformations that have different behavior depending on the area of the analyzed structure. The rosettes composed of four strain gauges are located in the lower part of the dam body both upstream and downstream while, those characterized by just only two strain gauges have been installed in the upper arcs. In the analysis of monitoring data, the strain gauges placed in the main section were used, they best explain the deformation behavior of the structure. In particular, the strain gauges placed along the horizontal direction within the rosettes of section 1-2 were taken into account, Figure 3. The analysis of the concrete temperature was performed using strain gauges that also act as thermometers. Figure 4 shows the trends, in the range 06/30/2013 - 01/07/2014, of: i) deformation of the strain gauges in the main section arranged along the horizontal direction; ii) hydrostatic level; iii) external temperature. The analysis of the performance and of the values assumed by the Pearson's index shows that the upstream deformations along the horizontal direction at 479 m s.l.m. (EG/1-2/1) are highly correlated with the hydrostatic level and they tend to decrease with increasing of the latter (ρ_{XY}=-0.98). The dependence of the deformation by the concrete temperature appears less evident (ρ_{XY}=0.48), probably due to the high thermal inertia of the dam body at this altitude as well water mass. However, it is clear the tendency that, at the increasing temperature of the concrete, the structure is affected in this zone by a decrease of compression translatable into an increase of the deformation. The strain gauge EG/1-2/5, near the downstream face at the same height, records instead a strain that does not appear correlate with the hydrostatic level (ρ_{XY}=0.00), perhaps influenced by the surface temperature; the correlation of deformations with air and concrete temperatures is much more evident, in accordance with the functioning theoretical principle of the structure which in this area provides for a decrease of the deformation due to the increase of temperature that means an increase of compression. The strain gauge EG/1-2/11 is placed at 519.50 m s.l.m. near the upstream face of the main section. It has, as its analogue placed at a lower level, a recording of the deformation strongly correlated to the hydrostatic level showing a decrease of the measure at increasing of the water height. The strain is weakly correlated with the temperature, although these two variables appear directly related. The strain gauge EG/1-2/13 has a deformation that shows an inverse correlation, even if moderate, with the hydrostatic level, although the theoretical principles suppose a tendency to decompression in the main section following the increase of hydrostatic pressure. The divergence causes of the results are to be found in the greatest influence on the data by the external temperature rather than by the hydrostatic level. The deformation is instead strongly inversely correlated to the temperature, also showing here a tendency to the compression of the structure at an increase of temperature. At 546 m s.l.m., the strain gauge EG/1-2/17, placed near the upstream face, measures a deformation still strongly inversely related to the hydrostatic level, although less than that detected by the corresponding strain gauges placed at lower altitudes; the cause of this reduction is to be found in the strong correlation between measured deformation and the temperature, in fact in this case, although the strain gauge is near the upstream face, the area is not more screen nor by a high thickness of the dam body, since it is located at high altitude, nor by water, being this area, for a certain period during the year, above the hydrostatic level. Moreover in this area there is a tendency to a decompression of the arc with increasing temperature, as witnessed by the strong positive correlation between strain and temperature. Finally the strain gauge EG/1-2/19 placed near the downstream face has the same discrepancy in the correlation between deformation and hydrostatic level that there was in the similar EG/1-2/13, compared to the latter, the dependence of the measured deformation by the temperature is even higher being the instrument in a more exposed position. As the similar strain gauges placed near downstream face at a lower altitudes, the EG/1-2/19 shows a deformation which witnesses a tendency to compression, evidenced by a decrease of the strain, at the increase of temperature, according to the principle of theoretical operation.

2.6 Preliminary solid modeling of Ridracoli dam

The three dimensional model of the dam body and of the foundation has been created by the digital reconstruction of project geometry. The creation of a mesh model allows to obtain the input file for a FEM program(Finite Element Method). The loads application, the characterization of materials and of constraints and the subsequent static analysis were made in the ABAQUS program post-processor. The material that summarizes the whole model has an elastic and isotropic constitutive law.

Tab. 1 Pearson Correlation Coefficient ρ – ε/Hydrostatic Level/External Temperature

	Hydrostatic level	External temperature TAr/1-2
EG/1-2/1	-0.98	0.19
EG/1-2/5	0.00	-0.93
EG/1-2/11	-0.97	0.28
EG/1-2/13	-0.56	-0.89
EG/1-2/17	-0.70	0.79
EG/1-2/19	-0.50	-0.92

Tab. 2 Pearson Correlation Coefficient ρ – ε/Concrete Temperature

	Concrete Temperature EG/1-2/4
EG/1-2/1 (upstream)	0.48
	Concrete Temperature EG/1-2/7
EG/1-2/5 (downstream)	-0.70
	Concrete Temperature EG/1-2/12
EG/1-2/11 (upstream)	0.24
	Concrete Temperature EG/1-2/14
EG/1-2/13 (downstream)	-0.96
	Concrete Temperature EG/1-2/18
EG/1-2/17 (upstream)	0.97
	Concrete Temperature EG/1-2/20
EG/1-2/19 (downstream)	-0.99

The mass density is 2470 kg/m^3, the Poisson's ratio is 0.2 and the elastic modulus is equal to the value of 30738 N/mm^2, resulting by the arithmetic mean of the values obtained by compression tests on concrete specimens. The model is stuck to the ground and is subject to gravity, thermal loads and hydrostatic loads. To quantify the effects of external actions on the deformation, two different hydrostatic levels were taken into account: 532.8 m s.l.m. (water height = 64.8 m) and 546.54 m s.l.m. (height water = 78.54 m), respectively, recorded at 8:00 am of 01/01/2008 (external temperature = 1 °C) and of 01/08/2008 (external temperature = 21.7 °C). The results appear to be consistent with the empirical findings derived by the registered data by the monitoring system analyzed in the paragraph §2.5. The variation of the reference deformation status was obtained from the measures acquired by the strain gauges placed in the main section along the horizontal directions at 8.00 am of 01/01/2008 and 01/08/2008. The zero reading of the deformation state is not known and the analysis of its absolute value is therefore meaningless, the variation Δε is therefore analyzed. The order of magnitude of the deformation, 10^{-06}, and the evolutionary trend are the same in the case of the observed data and in the case of those obtained from the finite element model. The response in the elastic range of the structure under ordinary loads as well the goodness of the preliminary model are confirmed. The difference that is found in the values of significant digits can however be justified in the approximations in terms of constraints and of rheology introduced in the schematization. Figures 5, 6 show the deformation states of the structure by the application of two different load scenarios in terms of hydrostatic level and temperature which were taken into account during the two days.

3 Conclusions

The study of the deformation state of restraint structures such as those real allows to calibrates solid finite element models to simulate their behavior during different load scenarios. The tendency of the strain state may be different depending on the area of the analyzed structure varying external stresses. A possible inconsistency of the measures by the expected behavior must be analyzed in a critical way, being able to be justified by the influence of a cause magnitude rather than another, or by any of those considered. The interpretation of each situation plays therefore a key role. Different scenarios may be simulated by means of finite element modeling programs. Reproduction definitely includes real situations already analyzed and monitored in order to calibrate the model and then be able to use, so suitably refined and validated, in the simulation of scenarios that have not yet affected the structure. The model presented here is definitely preliminary but demonstrates a behavior close to that of the structure, thus being able to allow, after further additions, the simulation of scenarios certainly more complex and of greater interest. The further objective of the work is to provide a finite element model that includes, in addition to the dam body, ancillary works of the structure such as the dissipation basin, the concrete blocks ballasting in the sides as well as a potion of soil for an extension at least equal to the height above ground of the structure; the representation of the spillways and the joints between the ashlars is just as important, in fact these singularities have a significant effect on the states of deformation and stress. An exhaustive calibration of the model on validated empirical data obtained by the measures of the monitoring system will make autonomous the simulation tool. Calibrating the model with the cause variables that acting on the dam, any anomalies of the monitoring system and of the behavior of the structure can be recognized with a large precision in the localization of the discrepancy through the high meshing degree of the model.

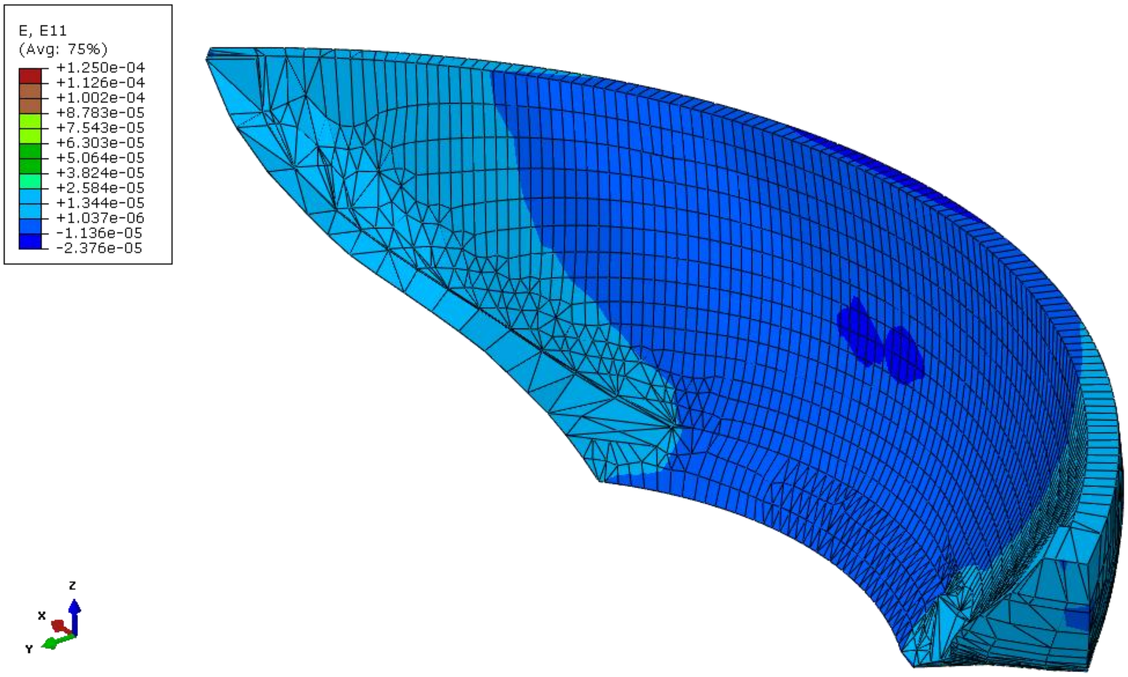

Fig. 5 Deformations along the horizontal direction E11 downstream face Step 2(78.54 m)

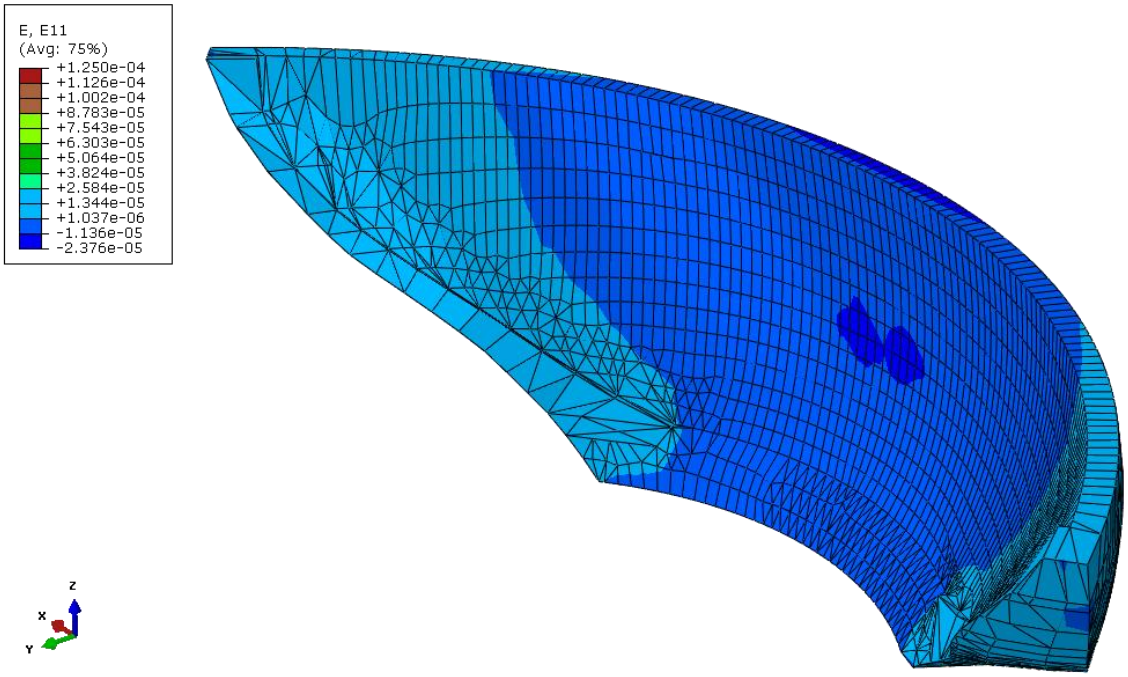

Fig. 6 Deformations along the horizontal direction E11 upstream face Step 2(78.54 m)

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