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Vibration based damage identification of concrete arch dams by finite element model updating

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Abstract. Vibration based damage detection is very popular in the civil engineering area. Especially, special structures like dams, long-span bridges and high-rise buildings, need continues monitoring in terms of mechanical properties of material, static and dynamic behavior. It has been stated in the International Commission on Large Dams that more than half of the large concrete dams were constructed more than 50 years ago and the old dams have subjected to repeating loads such as earthquake, overflow, blast, etc.,. So, some unexpected failures may occur and catastrophic damages may be taken place because of theloss of strength, stiffness and other physical properties of concrete. Therefore, these dams need repairs provided with global damage evaluation in order to preserve structural integrity. The paper aims to show the effectiveness of the model updating method for global damage detection on a laboratory arch dam model. Ambient vibration test is used in order to determine the experimental dynamic characteristics. The initial finite element model is updated according to the experimentally determined natural frequencies and mode shapes. The web thickness is selected as updating parameter in the damage evaluation. It is observed from the study that the damage case is revealed with high accuracy and a good match is attained between the estimated and the real damage cases by model updating method.

Keywords: concrete arch dam; damage detection, finite element modeling, modal testing, model calibration, modelupdating

1. Introduction

It has been reported that more than half of the large concrete dams were constructed more than 50 years ago according to the International Commission on Large Dams (ICOLD). The dams have subjected to repeating loads such as earthquake, overflow, blast, etc., and unexpected failures could be occurred. It can be said that the main reason of the failure is the deterioration of concrete, which means loss of strength, stiffness and other physical properties of materials. Therefore, many dams need major repairs in order to preserve structural integrity.

Ardito and Cocchetti (2006) stated that the causes of damage were of different nature; one of

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the most important is the alkali–silica reaction (ASR). The reaction produces an expansive gel, which diffuses in the connected pores and generates local micro-cracks and global expansion. The presence of ASR implies negative effects on overall mechanical properties of structural importance such as strength in tension and compression and stiffness. The ASR can reduce initial values of compressive and tensile strength down to 60% and 80%, respectively. In any case, the reduction of the elasticity modulus is widely recognized as the most representative indicator of the degradation induced by ASR (Swamy and Al-Asali 1988, Ahmed *et al*. 2003). It is of paramount importance in order to keep under strict control the mechanical performances of the materials used in dam body. The identification of material properties covers in situ and laboratory experimental investigations such as penetrometric tests, concrete coring and over-coring, flat jacks; permeability, chemical analyses and tomography through acoustic or ultrasonic measurements. But the investigations only provide local information about the concrete.

Dynamic vibration test is very powerful in the overall performance evaluation of dams. By the vibration test, the dynamic characteristics, such as natural frequencies, mode shapes and modal damping ratios, can be determined for current case. If the dam is damaged, the dynamic behavior is changed depending on the location and size of the damage. The changes come up in the natural frequencies, mod shapes and modal damping ratios. The dynamic characteristics are used in order to identify the distribution of elastic stiffness as a meaningful parameter representative of structural damage by model updating method. Therefore, model updating according to the modal testing results is perhaps the most versatile method fordamage identification in many fields of structural engineering (Salawu 1997, Cerri and Vestron 2000; Alvin *et al*. 2003).The main idea in model updating is to reduce the differences between the finite element and experimental dynamic characteristics by changing structural parameters such as material properties, boundary conditions, etc (Roy *et al*. 1990, Imregun and Visser 1991, Modak *et al*. 2002, Bayraktar *et al*. 2011). It should be noted that the results of dynamic tests on dams can be significantly influenced from the fluid–structure interaction (can significantly change the natural frequencies and the mode shapes), the foundation deformability (characterized by anisotropy and uncertain parameters) and non-linear behavior of artificial joints. Sevim *et al.* (2011) showed that the dynamic characteristics of dams considerably influenced by water level and length.

In this paper, the effectiveness of the model updating method for global damage detection is showed on a laboratory arch dam model. Ambient vibration test with Operational Modal Analysis method is used in order to determine the dynamic characteristics under environmental vibrations. The initial finite element model is updated according to the determined natural frequencies and mode shapes. The updating parameter is selected as web thickness due to identify the distribution of this parameter as damage indicator. By this method, a good match is attained between the estimated and the real damage cases.

2. Damage detection

Many studies on damage detection were performed by using full-scale vibration test results. It was stated in these studies that a complete damage evaluation requires both finite element modeling and experimental investigation (Jaishi and Ren 2006, Perera and Ruiz 2008, He and Zhu 2011). Also, Salehi *et al*. (2010) introduced that according to the process to treat the measured data, the vibration-based damage identification methods can be classified as model based and non-model based. The model-based methods identify the damages by correlating a finite element model, which is usually based on the finite element theory, with test modal data of the damaged structure. Comparisons of the updated model to the original one provide an indication of damage and further information on the damage location and its severity. Considering the main theme in the damage detection, four level damage identifications were defined by Rytter (1993):

Level 1- Identification the existence of damage

Level 2-Identification the location of damage

Level 3- Identification the severity of damage

Level 4- Evaluation of the effects of damage on the structural behavior.

The construction of the finite element model usually includes some uncertainties. It is important to recognize the sources and types of uncertainty. With respect to variability, it is useful to understand how small variations in input parameter propagate through the structure and manifest itself in the output. Uncertainty in simulation results manifests itself in two main classes: physical uncertainty and numerical uncertainty (Dascotte 2007). The physical uncertainties are namely the boundary and initial conditions, material properties (modulus of elasticity, yield stress, local imperfections, etc.), and geometry (shape, thickness, manufacturing and assembly tolerances, etc.). Also, the main numerical uncertainties are conceptual modeling uncertainty (lack of data on the physical process involved, lack of system knowledge), mathematical modeling uncertainty (accuracy of the mathematical model validity), discretization error uncertainties (the choice of element types, mesh density, level of geometrical detail), numerical solution uncertainty (rounding-off, convergence tolerances, integration step), and human mistakes (programming errors in the code or wrong utilization of the software, mistakes in data or units) (Friswell and Mottershead 1995, Ewins 2000, Dascotte 2007). Therefore, the finite element models need to the calibration in order to remove the uncertainties in the initial model. The process is named as model calibration. The damage detection should be made on the calibrated finite model to reflect the real case. In view of these studies, the damage detection based on the vibration test result consists of the following three steps:

Step 1: Creating initial finite element model

Step 2: Calibrating the initial finite element model according to the undamaged case

Step 3: Updating the calibrated finite element model according to the damaged case

3. Model updating

Model updating is defined as a process of quantifying the differences between finite element dynamic characteristics and corresponding experimental data, and then modifying the numerical values of the input parameters, such as elasticity modulus, mass density, boundary condition, in the model to obtain a valid model. Uncertainty is mainly caused by lack of knowledge and may exist in all aspects of the modeling process. In practice, physical element properties (material, geometry) are selected as updating parameters to improve accuracy. They may also be used as indicators for stiffness or mass modifications that are required because of deficiencies in the model caused by inadequate meshing or level of detail. Variability, which can be considered as a specific type of uncertainty, refers to the variation of the physical input parameters that is mainly caused by manufacturing tolerances or in-service operation conditions (Femtools, 2003a; Dascotte, 2007).Model updating process consists of many steps which are defined below:

Step 1: Creating initial finite element model

Step 2: Matching the nodes of experimental and analytical models

Step 3: Comparing the experimental and numerical natural frequencies and mode shapes
Step 4: Defining convergence criteria for the natural frequencies and mode shapes
Step 5: Selecting parameters for model updating and defining the limit values
Step 6: Sensitivity analysis for the selected parameter
Step 7: Step by step solution until the convergence criteria is achieved

4. Applications

In this study, an arch type dam model wasselected for identification of damage case.The dam model was an arch type and the damages on this model were created randomly by impact hammer. Therefore, the physical properties of the damage were considered to be unknown.In the investigations on the dam model, the numerical dynamic characteristics were calculated by using SAP2000 finite element analysis software (SAP2000 2008), the experimental dynamic characteristics were identified by PULSE and OMA softwares (PULSE 2006 OMA 2006) and model updating was performed by Femtools software (Femtools 2003b).

4.1 Definition of the dam model

The dam model is a prototype of a concrete arch type dam. The model has 60cm height and the average length of the crest is 165.67cm. The plan and front views and the dimensions are given in Fig. 1.

The web thickness of the dam model is constant and it is 6 mm. The length of the bottom is 40cm. The initial finite element model was created on SAP2000 software by using solid elements. As boundary conditions, the border of the dam body was considered as fully fixed. A refined mesh distribution was developed on the initial model as given in Fig. 2.

In the initial finite element model, the elasticity modulus and mass density of the concrete was considered as constant on the whole of the model. The initial values of these parameters are given in Table 1.

The first five natural frequencies of the initial finite element model are given in Table 2. Also, the mode shapes of the model are demonstrated in Fig. 3. The modes were bending modes in the transverse direction.

Table 1The initial values for the material properties of the dam model

Elasticity modulus (N/m2)	2.8*1010
Mass density (kg/m3)	2300
Poisson ratio	0.20

Table 2The first five natural frequencies of the dam model for the initial case

Mode number	Natural frequencies (Hz)
1	423.09
2	432.92
3	594.46
4	730.43
5	867.64

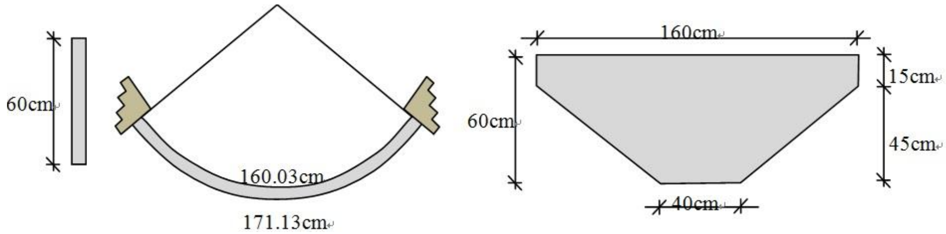


Fig. 1 The arch type dam model and its dimensions (Sevim, 2010)

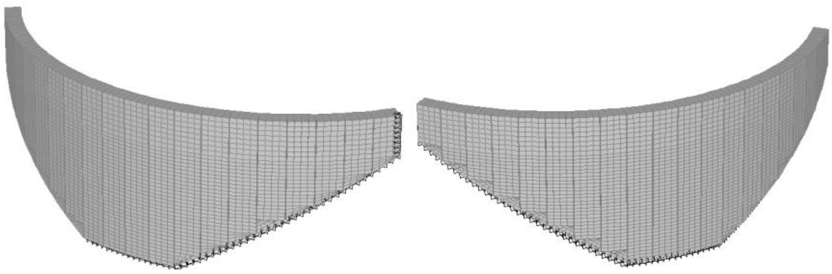


Fig. 2 The initial finite element model of the dam

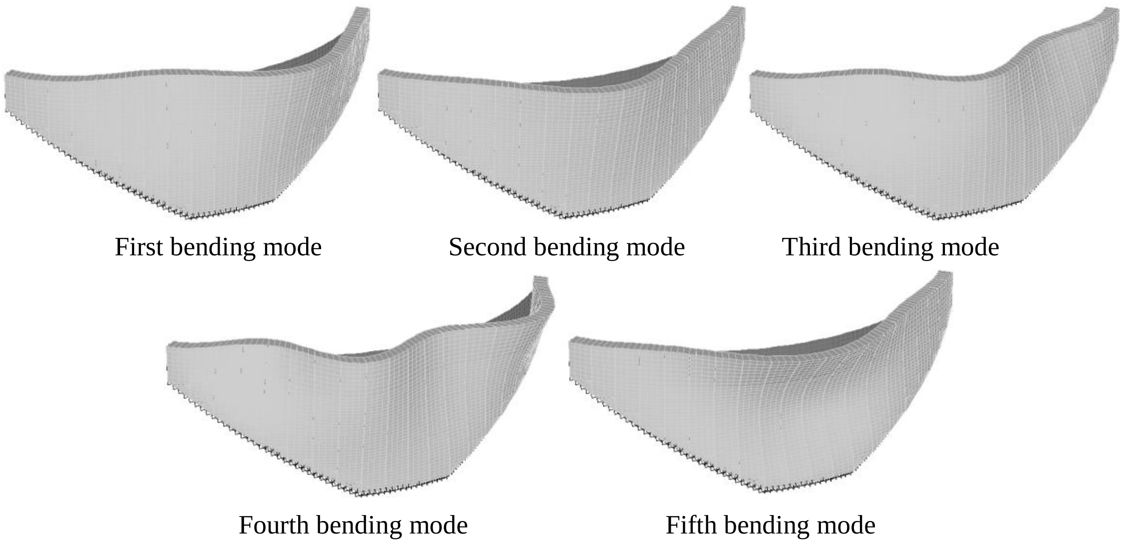


Fig. 3 The mode shapes of the dam model for initial case

After initial finite element modeling, the model was constructed in the laboratory. Huge side walls and a heavy foundation were created to provide fixed boundary conditions as shown in Fig. 4. Specialized concrete mixing ratios were used to attain smooth and non-cracked dam body.

The undamaged modal parameters were identified by ambient vibration test by Operational Modal Analysis method. Single axis accelerometers were used in the measurement. Totally eleven accelerometer were employed. The accelerometers were placed to the crest level of the dam in the normal direction of each point. The measurement configuration used in the test is given in Fig. 5.

The measurement was performed on a simple model, which reflects the crest line of the dam model, by PULSE software as shown in Fig.6. The accelerometer points and directions were defined as laboratory case so that the mode shapes were accurately attained. In that measurement, the frequency range was selected by considering the initial finite element results as 0-800Hz. The responses of the dam model were recorded during 10 minutes.

The recorded signals were analyzed by Stochastic Subspace Identification method and the stability diagram and the spectral density plot for each singular values were attained as given in Figs. 7-8, respectively.

Fig. 4The laboratory model of the arch dam

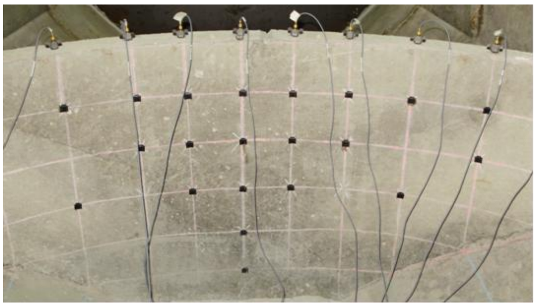


Fig. 5 A typical view from the accelerometer connection and direction on the dam model

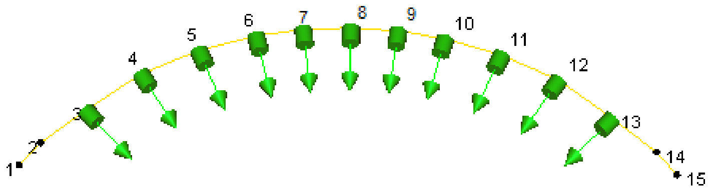


Fig. 6 The measurement configuration for the dam model on the PULSE program

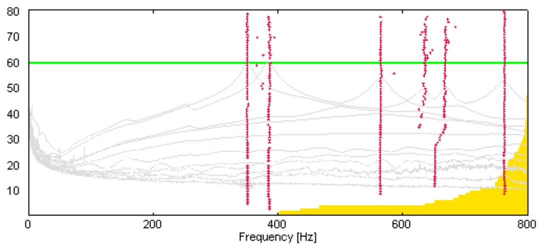


Fig. 7 The stability diagram for the undamaged case of the dam model

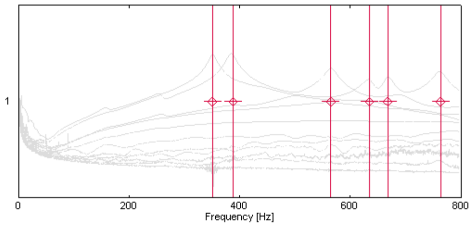
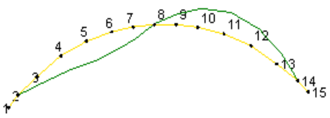
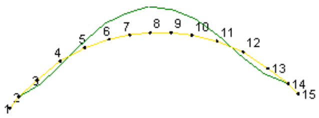


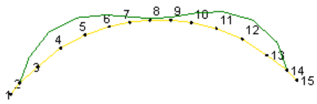
Fig. 8 The spectral density plots of each singular values for the undamaged dam model



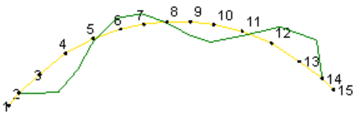
First bending mode



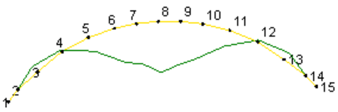
Second bending mode



Third bending mode



Fourth bending mode



Fifth bending mode

Fig. 9 The first five mode shapes of the dam for the undamaged case

Table 3 The first natural frequencies and modal damping ratios of the dam model for the undamaged case

Mode number	Natural frequency (Hz)	Modal damping ratio (%)
1	315.1	1.442
2	341.3	1.538
3	501.9	1.119
4	573.1	0.961
5	683.1	1.482

Table 4 The experimental and initial analytical natural frequencies of the dam model

Mode Number	Natural frequencies (Hz)		
	Undamaged	Initial	Difference (%)
1	315.1	423.09	34.27
2	341.3	432.92	26.85
3	501.9	594.46	18.44
4	573.1	730.43	27.45
5	683.1	867.64	27.02

Table 5 The calibrated natural frequencies of the dam model

Mode number	Natural frequencies (Hz)		
	Undamaged	Calibrated	Difference (%)
1	315.10	315.09	0.00
2	341.30	341.27	0.01
3	501.90	501.86	0.01
4	573.10	573.08	0.00
5	683.10	683.07	0.00

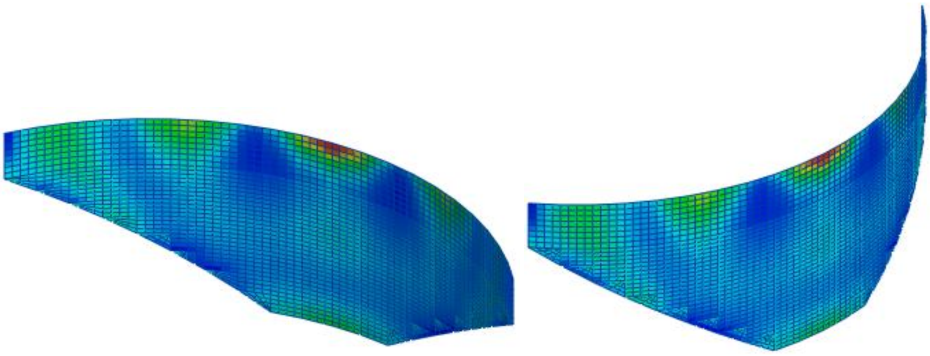


Fig. 10 The distribution of the elasticity modulus in the calibrated finite element model

Fig. 11 The observed damage distribution on the dam model

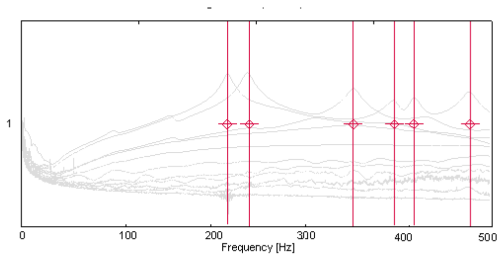


Fig. 12 The spectral density plot for each singular value of the damaged dam model

The first five modal parameters were extracted from these spectra. The natural frequencies are given in Table 3 and the mode shapes are demonstrated in Fig. 9.

It was observed that there were big differences between the experimental and numerical natural frequencies. The maximum difference was occurred in the first mode on the order of 34.27% as shown in Table 4.

To decrease the differences, the initial finite element model was calibrated by considering the elasticity modulus of each member as variable parameter. In the calibration process, it was aimed that the differences between the natural frequencies and the mode shapes were smaller than 1%. For this purpose, the iterative solutions were started by considering the change of elasticity values as 10%. After the iterative solutions, the initial finite element model was calibrated and the natural frequencies were calculated for this case as given in Table 5.

It was attained good correlations between the experimental and calibrated numerical natural frequencies. The differences were completely put away. For the calibrated case, the distribution of elasticity modulus changes is plotted in Fig. 10.

Table 6 The natural frequencies and modal damping ratios of the damaged dam model

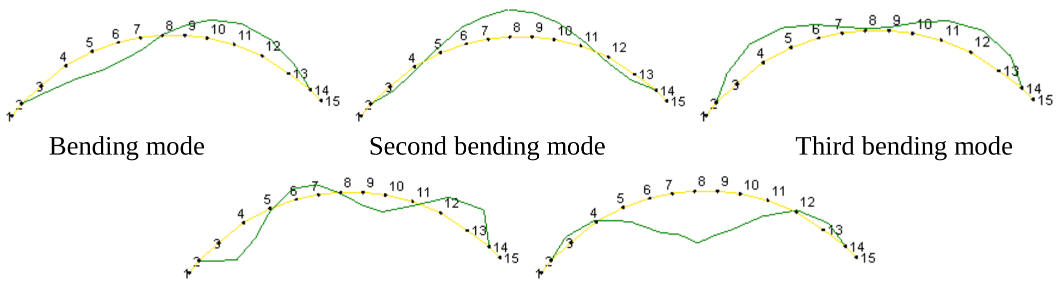
Mode number	Natural frequency (Hz)	Modal damping ratio (%)
1	211.30	1.047
2	223.70	1.497
3	293.80	1.644
4	374.70	1.355
5	410.40	1.406

Table 7 The calibrated and damaged natural frequencies of the dam model

Mode Number	Natural frequencies (Hz)			Modal assurance criteria
	Damaged	Calibrated	Difference(%)	
1	211.30	315.09	49.12	1.000
2	223.70	341.27	52.56	0.999
3	293.80	501.86	70.82	0.996
4	374.70	573.08	52.94	0.997
5	410.40	683.07	66.44	0.991

Table 8 The updated and damaged natural frequencies of the dam model

Mode Number	Natural frequencies (Hz)			Modal assurance criteria
	Damaged	Updated	Differences (%)	
1	211.30	211.28	0.01	1.000
2	223.70	223.99	0.13	0.999
3	293.80	294.19	0.13	0.996
4	374.70	374.70	0.00	0.997
5	410.40	410.46	0.01	0.990



Bending mode / Second bending mode / Third bending mode / Fourth bending mode / Fifth bending mode

Fig. 13 The first five mode shapes of the dam for the damaged case

The figure showed that the maximum changes were occurred on the mid of the crest level. It was expected because of the segregation of the aggregates in the concrete.

After calibration of the initial finite element model, an unknown damage distribution was developed on the dam model by a hammer with steel tip. Because the amplitude and direction of the applied load was not measured, the exact parameters of the damage such as location, severity, etc., were not known. Only a visual damage inspection was performed and the identified damages were highlighted as shown in Fig. 11.

The measurement on the damaged dam model was repeated and the responses were recorded the location and direction during 10 minutes. The signals were analyzed by Stochastic Subspace Analysis method. The spectral density plot for each singular value are presented in Fig. 12.

The identified natural frequencies and the modal damping ratios are given in Table 6 and the corresponding mode shapes are demonstrated in Fig. 13 for the damaged dam model.

The first level of damage detection is to identify the existence of damage as stated by Rytter (1993). The simplest way is to compare the natural frequencies and the mode shapes of the calibrated analytical with the current measurement results. Table 7 presents the calibrated and the damaged natural frequencies of the dam model.

Before the damage case, the experimental and analytical natural frequencies were approximately the same as presented in Table 5. After the damage, the experimental natural frequencies were decreased considerably. The maximum difference in the natural frequencies is occurred in the third frequency as 70.82% while the minimum difference is in the first mode as 49.12%. The changes are the sign of damages on the dam body or restraints.

After deciding the existence of damage, the location of the damage can be identified. For this purpose, the model updating is very effective and provides highly realistic estimates. To estimate damage location of the dam model, the web thickness of dam body was taken into consideration as variable parameter which shows the damaged member. By aiming to minimize the differences between the natural frequencies and mode shapes, the iterative solutions were performed. At the end of these solutions, the changes of the web thickness on the whole model are plotted in Fig. 14.

The maximum web thickness change was occurred in two sides of the midpoint of the crest level. The estimated damage case in Fig. 14 matches with the created damage case in Fig. 11 perfectly.

The natural frequencies after model updating are compared with the experimental values in Table 8. The maximum difference was 70.82%in the third frequency before model updating while the value is 0.13% after model updating. The differences in the first natural frequencies are smaller than 1%.

The third level in the damage detection is identification of damage severity. Fig. 14 shows the severity of damage as well as the damage location. The scale in this figure represents the change ratio. It can be said that the most damaged members of the dam model are in the crest level and highlighted by circles.

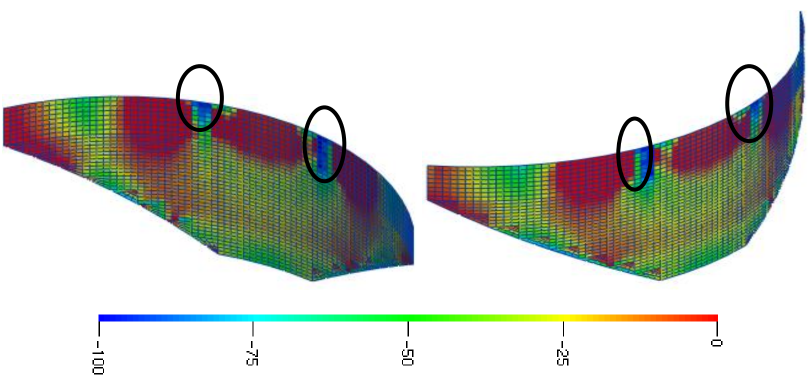


Fig. 14 The web thickness change after model updating on the dam body

5. Conclusions

In this study, a good application of damage detection was presented on a concrete arch dam model. The used damage detection method bases on model updating of finite element model according to the experimental modal test results. A random damage case was taken into consideration and the web thickness was selected as damage parameter. The investigation was carried out on the first five natural frequencies.

The used damage detection approach consists of three levels: initial finite element modeling, model calibration and model updating. It is assumed that the updated model represent the real damaged model. From the initial finite element modeling, the first five natural frequencies were attained in 423.09-867.64Hz frequency range and the modal behaviors were bending modes. From the experimental measurements on the undamaged dam model, the first five natural frequencies were identified in the 315.1-683.1Hz frequency range and the modal behaviors were extracted as initial modeling. It was observed that the initial natural frequencies were bigger than the experimental frequencies generally and the minimum difference was 18.44% in the third natural frequencies. The initial finite element model was calibrated to minimize the difference by considering the elasticity values as variable parameters and a good correlation was attained for the first five natural frequencies. The calibrated model met the expectations such as segregation on the crest level. After random damage effects which created by steel hammer, the natural frequencies were decreased considerably and the maximum change was occurred in the third frequency on the order of 70.82%. To identify the damage location, the calibrated finite element model was updated according to the damaged experimental test results by considering the web thickness as variable parameter. By this way, both the location and severity were determined. It was observed that the estimated damage case by model updating perfectly matched with the real damage case.

It can be generally said that the applied method based on model updating is very powerful in the full-scale damage detection of concrete arch dams. By this method, the updated finite element models which include damage effects can be developed and used for safety evaluations of concrete arch dams.

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