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MULTIPLE DAMAGE LOCALIZATION OF GRAVITY DAM: STRAIN ENERGY BASED APPROACH USING RANDOM DATA

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Abstract: Continuous monitoring of large-concrete structures like Dam, using information obtained using the health monitoring system, is necessary for the prognosis of its premature degradation. In this study, Koyna dam, is modeled in 2D using ABAQUS software. Material properties of the dam material are assumed to be linear and elastic. The model is first validated against the available results for Koyna Dam. As real-time vibration data is sparse for the structures like Dam due to its size and location, White Gaussian Noise is used for generating the simulated ambient response. Damage is incorporated in the numerical model introducing suitable change in the modulus of elasticity of the elements at some specific locations. The dynamic properties of both the pristine as well as the damaged structures, including the natural frequency, Displacement Mode Shape (DMS), Curvature Mode Shape (CMS) and Strain Energy Mode Shape (SEMS) are compared to identify the appropriate parameter that can identify the damage up to the tire of quantification. Studying the modal responses of the numerical model of the gravity dam it is inferred that the neither natural frequency nor DMS or CMS are capable of identifying the region of the stiffness change with acceptable accuracy. While on the other hand, 1st eigen mode shows that SEMS can identify the damaged location with sufficient accuracy. Therefore, in this study Strain Energy based damage index is used for quantifying the damage.

1 INTRODUCTION

Gravity dam being a mass-concrete structure calls for regular structural health monitoring and performance evaluation to anticipate any premature degradation. Due to its huge size and remote location many a time they are monitored by some such procedures that involve human intervention such as, visual inspection for crack or seepage, measuring static deformation using geodetic tools, etc. Geotechnical investigations like inspection of uplift and drainage or pore pressures are also adopted often. Civionics, facilitated a very timely need for these structures by enabling real-time monitoring even from a remote location. Strong motion networks are found to be very useful to monitor Dam with its site. It is reported that, as a part of the Swiss National Strong Motion Network five dams in Switzerland are under continuous surveillance (Darbre 1995). It is reported that most probably till 2009 there was no real structure under the fully automated supervision system for the purpose of its health monitoring. Non-destructive testing is the most used method for the Structural Health Monitoring (SHM) of dam. As observed by Cantieni, for the first time in the year 1970 four dams were tested in Italy (Cantieni 2009). With increasing research in computational mechanics off late quite few a number of straight and arc gravity dams are modelled numerically and updated using data obtained from the real structure in order to identify their system health and performance (Pandey et al. 1991 and Cheng et al. 2015).

Identification of damage is one of the major purposes of SHM that includes detection, localization, quantification and estimation of residual life based on the information obtained in the previous three steps.

Reduction in strength of the structure or of its part are associated to the reduced elastic modulus, which in turn affects the stiffness and therefore the modal properties of the structure changes. Among the said modal properties natural frequency and Displacement Mode Shape (DMS) are often used to identify the characteristics of the solid mechanical system. Panday et al. (1991), observed that similar damages at different locations in the structure can be responsible for the similar alteration of these two parameters. Therefore, it is rational to hold that these two are the global parameters consequently not suitable for damage localization purpose. Moreover, Modal Assurance Criteria (MAC) and Co-ordinate Modal Assurance Criteria (COMAC) are well known for their tendency of averaging the damage information throughout the structural body, which makes them also inefficient to localize the damage. Curvature being the second differential of deflection, plot of its modal values, i.e., Curvature Mode Shape (CMS) is relatively more sensitive to the location of perturbation in the solid continuum. On the other hand, while agreeing on its relatively location sensitive nature, Foti (2013) observes that because of the difficulty in measurement CMS probably is not that suitable for experimental methods. As of now CMS is mostly applied on the latticed structure while its applicability on the mass structures are yet to be explored extensively. Yang et al. (2003) shows that another parameter namely, Strain Energy based Damage Index, is quite sensitive to the change in the elastic properties of a solid body. Modal strain energy is used in this study to extract modal information like natural frequencies, mode shapes and corresponding damping ratios and from the response data. The method is applied to identify damage of an off-shore structure where two methodologies such as, Eigen-system realization algorithm and Natural excitation technique are applied and two types of strain energy ratios relating to flexure and compression are estimated to quantify the damage. Strain energy method also is known to be efficient for the latticed structures. Modal Strain Energy based method have been improved by Moradipour et al. (2015) in order to attain better estimation of damage in complex structural systems. Bagchi et al. (2018) have shown that for damage localization and quantification of gravity dams Modal Strain Energy is a better parameter than CMS.

In this article finite element model of Koyna Gravity Dam is studied for its modal responses to identify a number of known damages. Objective of this study is to identify appropriate parameter capable of at least two tire damage identification of gravity dam for multiple damage scenario. Further the chosen parameter is employed to quantify the damage. In the following sections first, the formulation of working methodology is described briefly followed by the description of the numerical model, its two-step validation, reporting of the results with critical discussion and conclusions.

2 WORKING METHODOLOGY

In the preceding section it is briefed that the available technical literature indicates the varying level of sensitivity of the modal parameters in identifying the structural damage. Not only detection rather localization and quantification of damage are also to be performed in order to identify the state of functionality which actually helps to estimate the remaining service life of the structure. Current study examines the sensitivity of the four modal parameters up to the extent of localization of damage. Further an estimate of damage is presented in terms of strain energy-based damage index.

The undamaged model is first validated with the published data (Chopra et al. 1973) which provides with the base line model. The second step validation is done employing hypothetical random excitation. Damage is incorporated into the validated model by suitably modifying the young's modulus of the material at the intended elements. Therefore, the elements at various locations represent damaged zones those are intended to be localized.

DMS is the plot of the modal displacements values of the dam faces along the height. Change in Natural frequency and DMS are noted in order to comprehend their sensitivity to the damage. Curvature is given by Equation 1 where, 'y' is the height of the dam from the base and 'u' is the displacement along x direction.

$$[1] \kappa = \frac{d^2u}{dy^2}$$

As given by Equation 2, CMS is calculated by differentiating DMS twice employing central difference method.

$$[2] \kappa = (u_{i+1} - 2u_i + u_{i-1})/h$$

Modal Strain Energy of the structure for both the faces is plotted along the height. Element Strain Energy and Nodal Strain Energy Density of the structure are given by the Equations 3 and 4.

$$[3] \int_V (\sigma)^T (\varepsilon) dV$$

$$[4] \int_0^\varepsilon \sigma d\varepsilon$$

here 'σ' and 'ε' denotes stress of the element and average strain respectively and 'dV' is the volume of the element.

3 NUMERICAL MODEL

Cross section of Koyna dam is idealized in Two-dimension through the finite element model in the ABAQUS/CAE software. Linear-elastic material properties are considered for the dam structure. As discussed in the preceding section, hypothetical damage is incorporated in the base line structure by changing the Modulus of Elasticity at the multiple locations. Locations of the affected elements are shown in the Figure 1(c). Values of the Young's modulus for the un-damaged and the damaged elements are $3.1027 \times 10^{10} \text{ N/m}^2$ and $3.1027 \times 10^8 \text{ N/m}^2$ respectively. Unit weight of the concrete is taken as 2643 kg/m^3 and the Poisson's ratio as 0.15. Bilinear, 4-node, plane stress, quadrilateral elements are used with reduced integration, hourglass control (CPS4R) and controlled mesh to discretize the model. It is assumed that the base of the dam is fixed in both horizontal (DOF 1, i.e., 'X') and vertical (DOF 2, i.e., 'Y') directions [Figure 1(a)]. Lanczos eigen solver is chosen to extract first four modes of free vibration using linear perturbation technique. The output parameters noted for further calculation or direct plot are Natural Frequencies, Modal deflection along 'X' (U1), total modal Element Strain Energy (ELSE) and modal Elastic Strain Energy Density (SENER).

4 VALIDATION

The structure is excited by random excitation acceleration in the form of White Gaussian Noise (WGN) shown in the Figure 2. Response of the structure is noted at seven locations along the height on the upstream face. Frequency domain decomposition (FDD) technique is used in ARTeMIS software to extract the eigen frequencies. As shown in the Table 1, first four eigen frequencies of the structure, obtained from the simulated Abaqus model and ARTeMIS Extractor Pro software model matches with those of the published data ($\text{Error}_{\text{max}} = 3.05\%$ for the 2nd Mode). Therefore, the model can further be employed for damage identification purpose.

Table 1: Example table caption

Eigen modes	Abaqus Model (Standard) (Hz)	Error (%)	Abaqus Model (Discretized)* (Hz)	Error (%)	ARTeMIS Model (Hz)	Error (%)	Reference Model Reported (Hz) (Chopra et al. 1973)
1 st	03.00	2.28	03.04	0.98	03.03	1.30	03.07
2 nd	07.95	3.05	08.09	1.34	08.01	2.32	08.20
3 rd	10.85	0.93	10.97	2.05	10.84	0.84	10.75
4 th	15.64	1.45	15.96	<u>0.57</u>	15.63	1.51	15.87

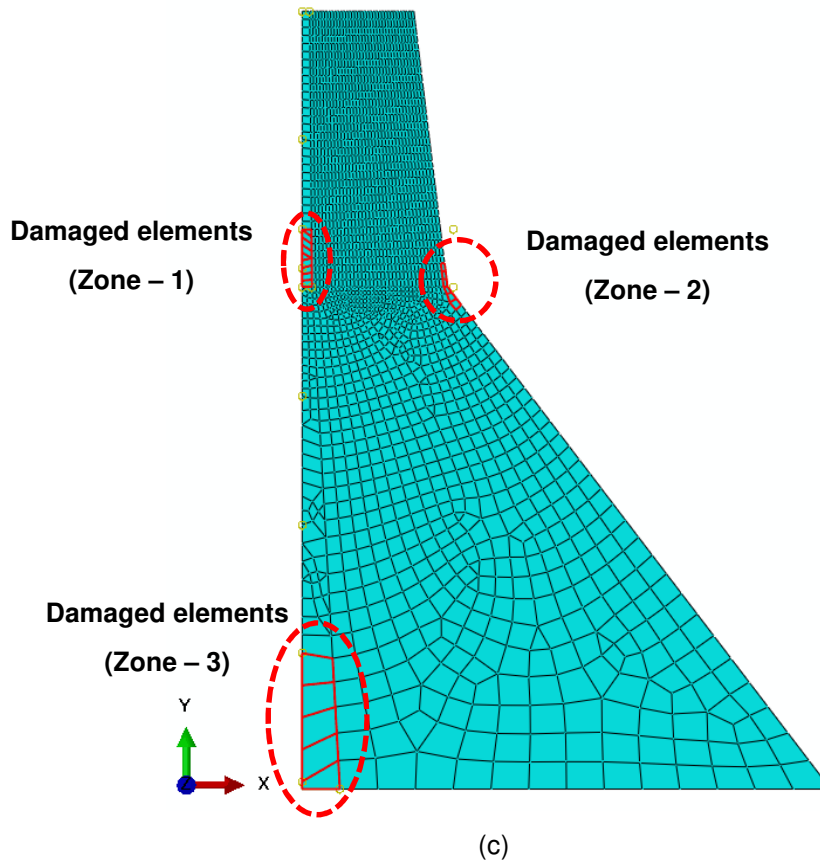
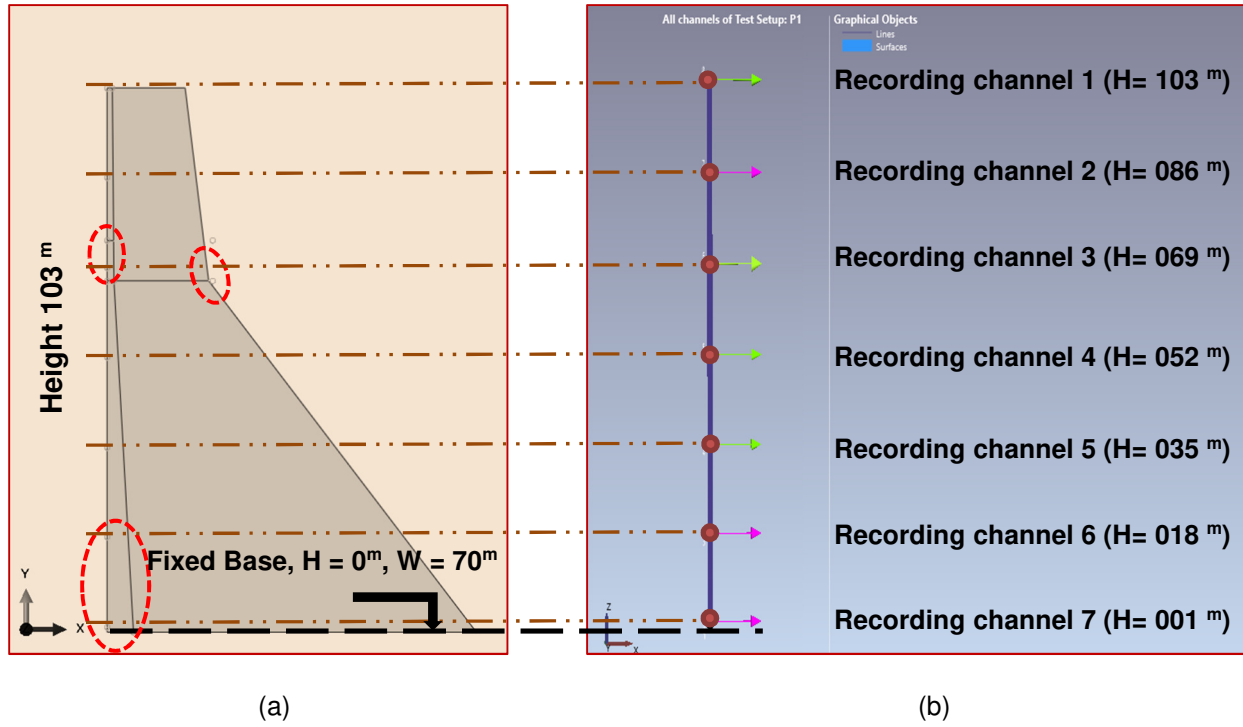


Figure 1: Numerical model of Koyna gravity dam; (a) Schematic diagram (showing partitions of the Abaqus 2D shell type part), (b) ARTeMIS 1D idealization (indicating the recording channel locations), (c) Finite Element Model (showing the location of the hypothetical damages).

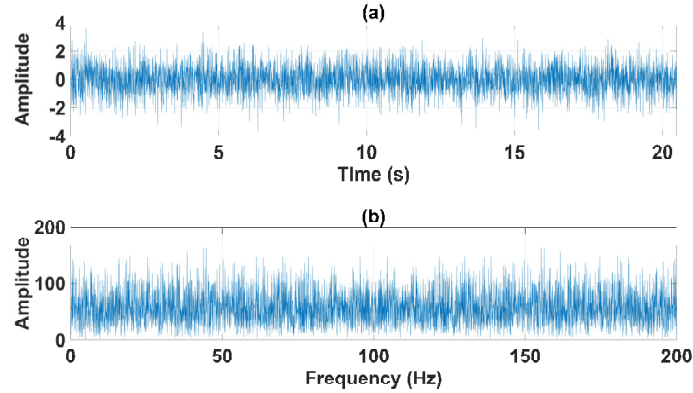


Figure 2: White Gaussian Noise (WGN) used as Random Excitation; (a) Time History (b) Frequency-wise amplitude distribution

5 RESULTS AND DISCUSSIONS

As the sensitivities of different modal parameters are different, the simulated and/or calculated values of the natural frequencies, displacement, curvature and strain energy mode shapes of the structure for the pristine as well as damaged cases are compared to comprehend the efficiency and appropriateness of the modal parameters in identifying the strength inaptness.

5.1 Natural Frequency

Simulated values of the first four natural frequencies of the Koyna dam, for the pristine as well as the damaged cases are presented in the Table 2. It is observed that due to damage there is 5% -10% reduction in the natural frequency for the first two modes. There is a very minor reduction in the third natural frequency; in reality which may not be attributed to the strength reduction. The fourth natural frequency shows significant change (~ 20%). Therefore, in line with the accepted understanding it can be concluded that significant alteration (~ > 5%) in the modal frequencies may be an indicator of damage but this is not the appropriate parameter to confirm small strength anomalies.

Table 1: Eigen Frequencies of the Dam for the Pristine and Damaged cases

Eigen modes	Pristine Case (Hz)	Multiply Damaged Case (Hz)	Error (%)
1 st	03.04	2.84	6.58
2 nd	08.09	7.43	8.16
3 rd	10.97	10.77	1.82
4 th	15.96	12.84	19.55

5.2 Deflection Mode Shape (DMS)

As natural frequency is not conclusive enough to identify the damage, DMSs are plotted for the first four eigen modes of the Koyna dam. As illustrated in the Figure 3, comparison between the modal displacements in the pristine (Bagchi et al. 2018) as well as in the damaged state indicates that there are little differences in the mode of vibration in the first and the third modes. Whereas, fourth mode is the most sensitive the damage at the heel location, which paralyzes the structure in such way that the rest of the structure refrains from participating in the vibration itself. DMSs presented in the Figures 4 (a), (b) and 5 (a), (b) also confirms the above interpretation. The behaviour observed studying the DMSs are mostly in agreement with those of the natural frequencies. However, although DMS indicates the location of the damage, it doesn't provide the information with sufficient accuracy.

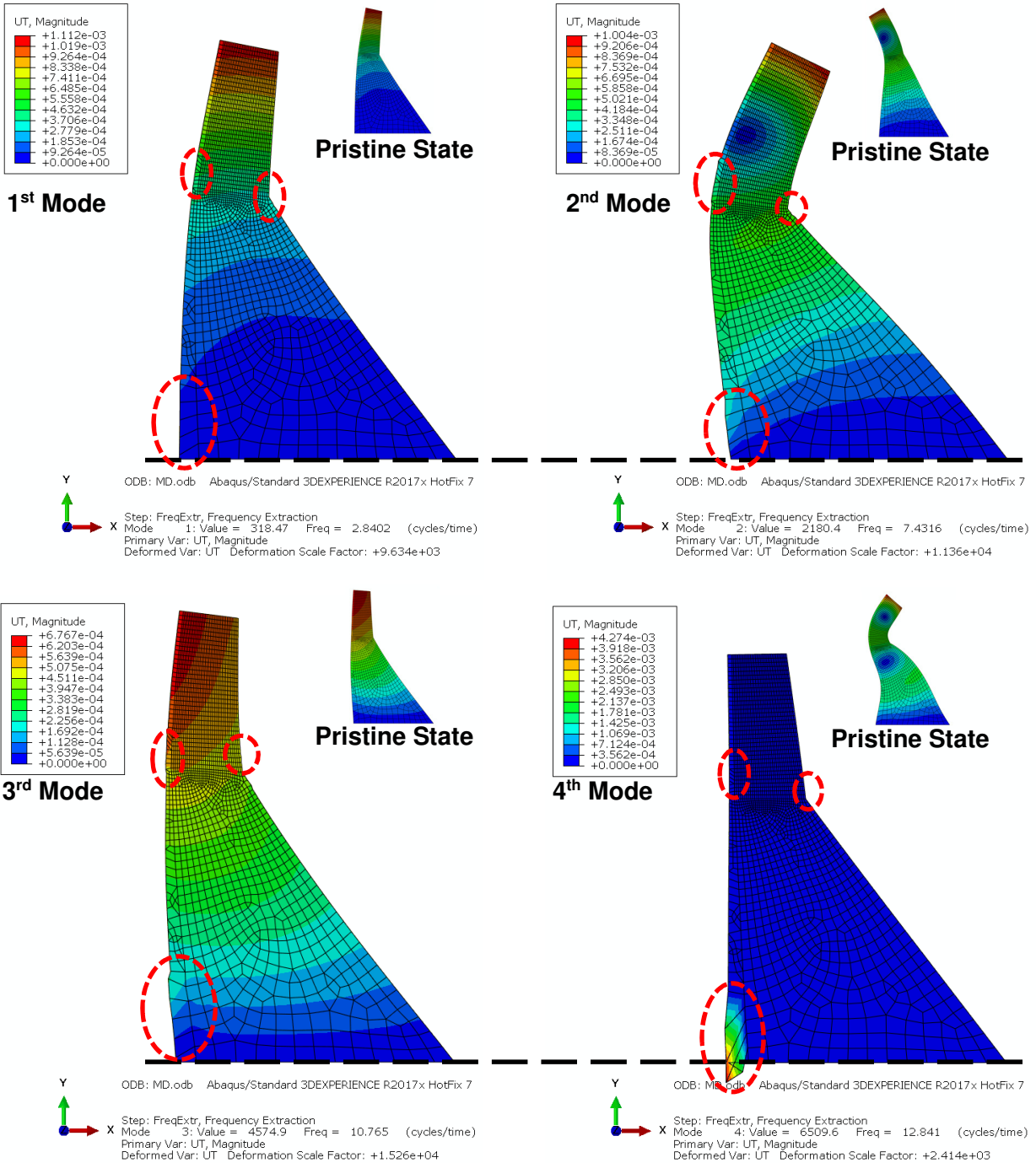


Figure 3: Modal Displacement [along DoF – 1 (x)] of the Damaged (Multiple) Structure [Inset: Corresponding Modal response of the Pristine State (after Bagchi et al. 2018)].

5.3 Curvature Mode Shape (CMS)

Plot of the modal curvature values (CMS) are presented in the Figures 4 (c), (d) and 5 (c), (d), which also fails to clearly differentiate between the pristine and the damaged cases indicating the zone of damage clearly unless there is a large change in the strength parameter over significantly wider zone, i.e., the case of zone – 3. However, CMS is found superior to the DMS in terms of locating the zone of strength reduction.

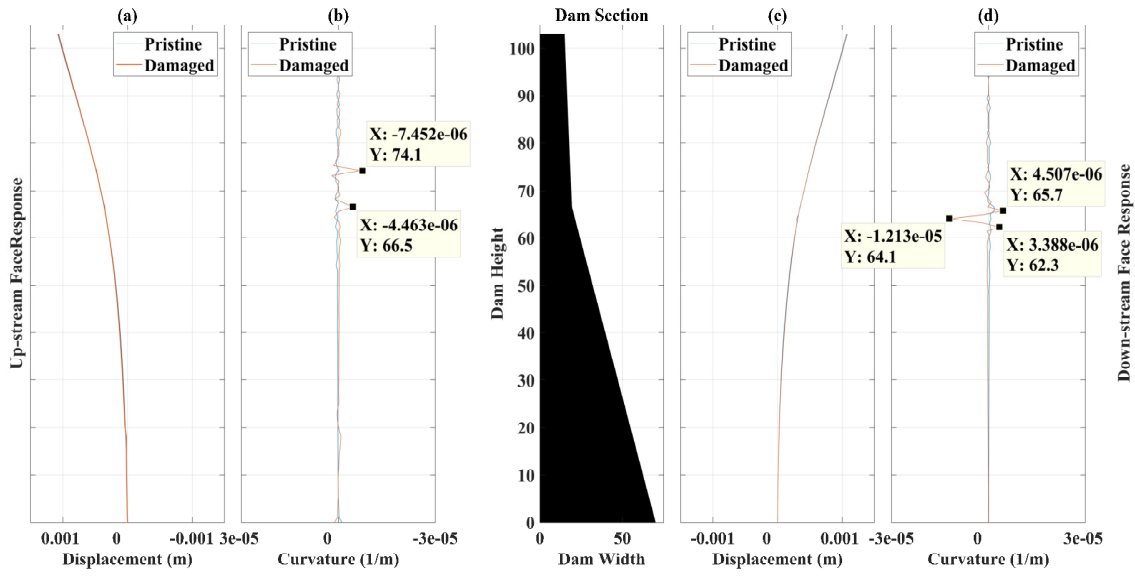


Figure 4: Displacement and Curvature mode shapes (Mode – 1) of the Koyna gravity dam; (a), (b) Up-stream face, (c), (d) Down-stream face.

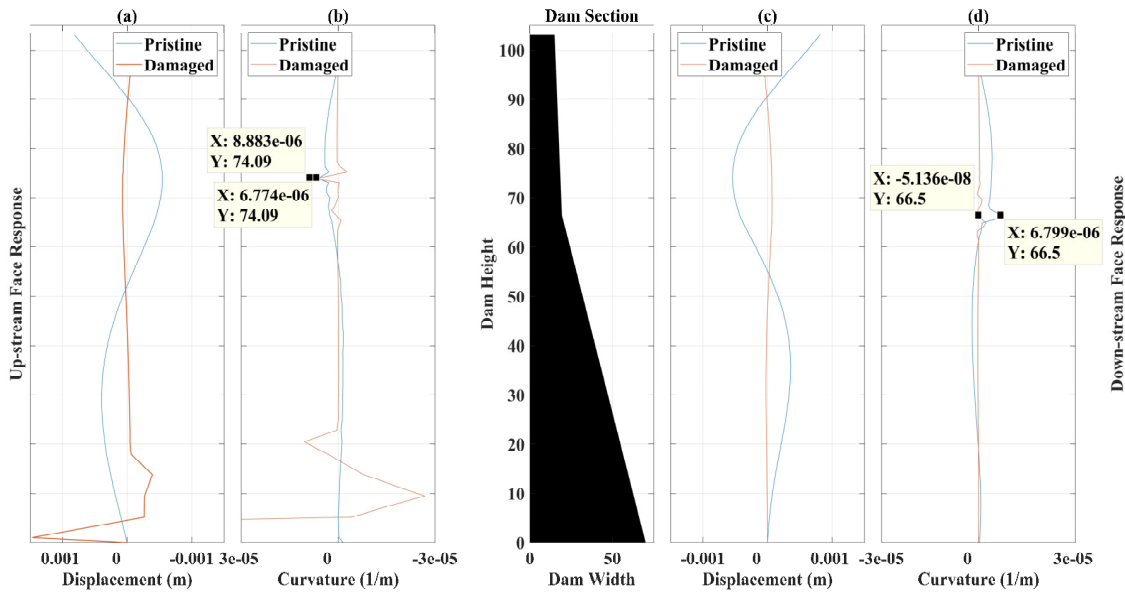


Figure 5: Displacement and Curvature mode shapes (Mode – 4) of the Koyna gravity dam; (a), (b) Up-stream face, (c), (d) Down-stream face.

5.4 Strain Energy Mode Shape (SEMS)

As mentioned in the third section, strain energy of the cantilever structure is obtained using a couple of parameters such as; Element strain energy (ELSE) and Nodal strain energy density (SENER). As illustrated in the Figure 6, SEMS for the first mode is evidently the much clearer indicator of the damaged location. It clearly indicates that the largest zone of damage is the zone – 3, i.e., the five elements near the heel up to

the height of 18 m. On the other hand, in the case of fourth mode due to excessive damage in the heel region the rest part of structure does not participate in the vibration. As evident from the Figure 7, there are large differences in both the strain energy parameters at the zone – 3 but rest of the structure is not responding to the perturbation. Therefore, response of this mode can be neglected.

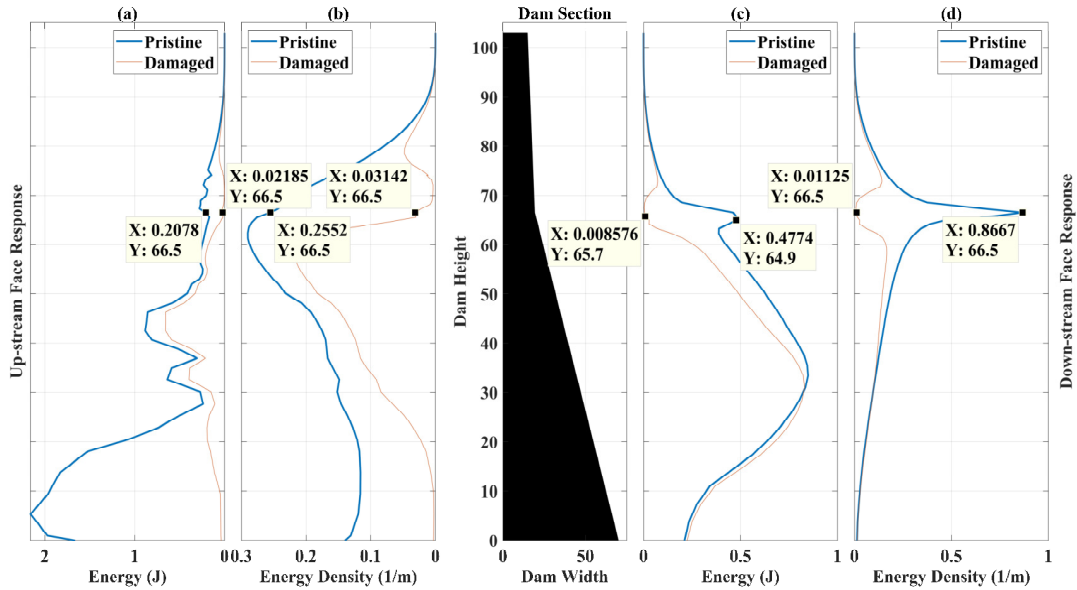


Figure 6. Strain Energy and Strain Energy Density Mode (Mode – 1) of the idealized Koyna gravity dam; (a), (b) Up-stream face, (c), (d) Down-stream face.

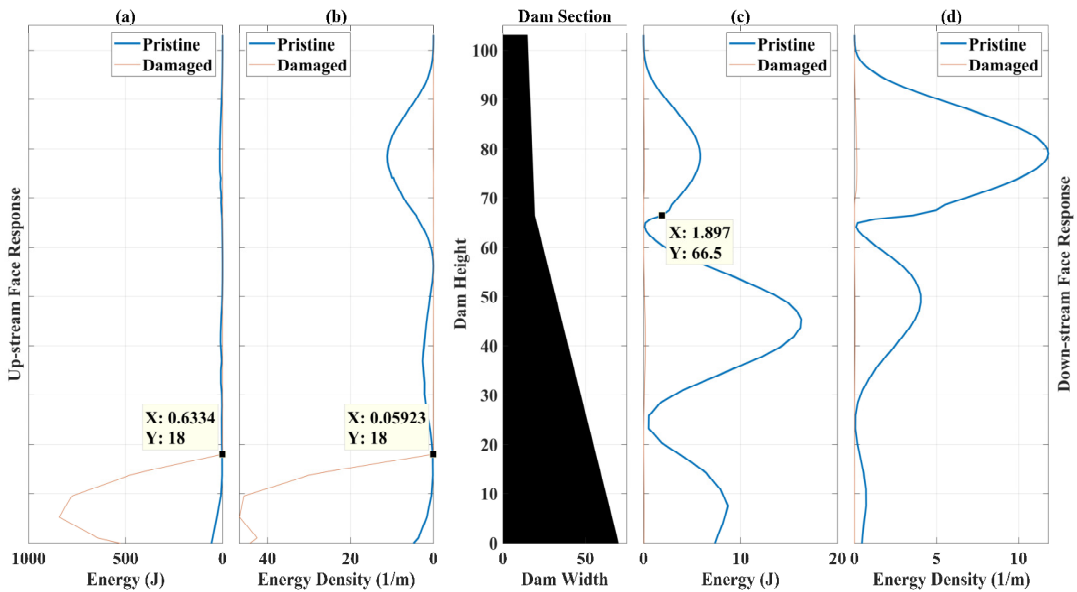


Figure 7. Strain Energy and Strain Energy Density Mode (Mode – 4) of the idealized Koyna gravity dam; (a), (b) Up-stream face, (c), (d) Down-stream face.

6 CONCLUSIONS

The idealized Koyna gravity dam profile, validated using linear perturbation based modal dynamic analysis and spectral response of the random excitation, is employed in this exercise to study different modal parameters' sensitivity to the strength reduction in the body of the structure. It is inferred unequivocally that neither the natural frequency nor the DMS and CMS are the appropriate parameters which can detect, localize and quantify the damage precisely. It is well known that the natural frequency being the global parameter of a structural system may detect the presence of a damage with certainty only if there is a significant variation in structural strength. The current study shows that in spite of strength variation at three critical positions of a gravity dam, third eigen mode shows negligible change in corresponding natural frequency (1.82%).

On the other hand, DMS is able to indicate the location of damage with at least acceptable clarity only if there is a significant displacement. Therefore, it is also insensitive to the damages at the early stage. CMS, however, is found to be moderately sensitive parameter in terms of the location of strength anomaly. One important observation of this study, which needs systematic furtherance, is the relation of depth or width with the sensitivity of CMS. Near the region of narrow cross section, i.e., near zone – 1 and 2 this parameter seems to be responding better to the strength reduction.

As noted before, SEMs are the most appropriate parameters to indicate the damage even if the differential strength is very minimum. It is evident from the response of both the SEMs that it can both detect and localize damage. Therefore, ELSE is employed to quantify damage through normalized ELSE value as shown in the Figure 8. It is to be noted that wherever there is differential strength there is a corresponding difference in the normalized Element Strain Energy value which distinguishes the damaged location with the pristine neighbourhood.

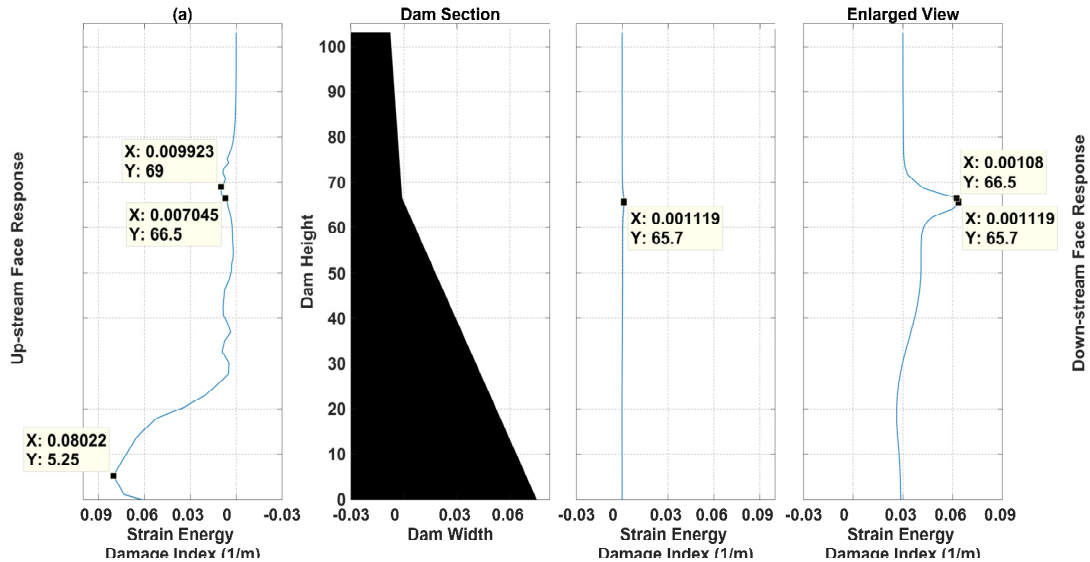


Figure 8. Quantification of damage: Normalized Element Strain Energy.

7 ACKNOWLEDGEMENT

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