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Monitoring Concrete Strength Parameters for Gravity Dam using Strain Energy Based Structural Health Monitoring Technique

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ABSTRACT: Monitoring of concrete strength parameter like Modulus of Elasticity during its phase of strength gaining is an important health monitoring strategy in order to comprehend its construction quality and overall health. On the other hand, reduction in concrete strength owing to the damage caused by fire, environmental agents, etc. also an important real-time observation - essential for regular monitoring of the structural health. Variation in the extent of the deviation for the intended strength parameter many a time calls for an appropriate and robust identification parameter for that specific case. In this article, four sets of vibration-based damage identification parameters such as Eigenfrequency, Displacement mode shape (DMS), Curvature mode shape (CMS) and Strain Energy mode shape (SEMS) are employed to detect as well as to localize the zone of strength reduction. Numerically the method is applied to the finite element model of the Koyna concrete gravity dam. The model, prepared in ABAQUS commercial software environment, is validated with the available data. Analyzing the results it is inferred that Eigenfrequency and DMS can detect the presence of damage or for that matter reduction in the strength but cannot localize the impaired elements or if at all not with adequate accuracy. Therefore, in case of strength gaining phase where the differential value of the strength parameter is significantly small, these two parameters are not the appropriate ones. While on the other hand, CMS and SEMS identify the strength difference up to the extent of localization. Among them, SEMS is found to be the most sensitive and therefore, the most appropriate parameter for initial damage or small strength deviation identification. In case of damaged structures for initial detection first three identification parameters are employable but for localization of damage at its premature state SEMS is the most suitable indicator. Although for real structure a large number of sensors have to be employed, the method is applicable for updating the model using the modal parameters of the structure obtained from the operational modal analysis at the site. Therefore, real-time monitoring of the structure from its construction stage to the stage of performance is possible using SEMS as the monitoring parameter.

1 INTRODUCTION

Identifying and monitoring the system of a mass concrete structure like Gravity Dam is difficult because of its huge size. On the top of it many a time they remain unattended because of their location; which is usually far away from the populated industrial zone or locality. But consequence of its failure has significant impact on the population that the structure serves. Therefore, a continuous monitoring of such structures from the very inception of its construction is essential to anticipate any form of strength discount whether owing to improper construction or damage thereafter. Traditionally, direct human involvement based structural health monitoring techniques like visual inspection, supervision of the static deformation employing geodetic tools, clinometers or plumb lines, piezometers, etc., are employed to keep track of the state of functionality. With the introduction of the automation technologies, popularly known as Civionics, vibration-based health monitoring methodologies are recently being used for real time monitoring. Although mostly ambient vibration-based output-only modal analysis are employed in this process, if the site is connected by the strong motion network a complete input-output based modal analysis is possible. Presently five dams in Switzerland are being monitored as a part of the Swiss National Strong Motion Network (Darbre,1995). Cantieni (2009) reported that for the first time four dams were tested in Italy in the year 1970 and till 2009 probably no real structure was being supervised using automated technology. Of late, numerical models of a number of arc as well as gravity dams are calibrated using experimental data. Cheng et al. (2015) reported that recent literatures show that a number of arc and straight gravity dams are modelled numerically and calibrated using testing data to identify their actual behavior. Achieving target strength for a concrete structure is challenging from the construction point of view. Therefore, it is necessary to identify a robust monitoring parameter which can be considered as an efficient signature of the structural strength parameter at any point of time after the construction. Usually modal parameters like Eigenfrequency and displacement mode shape (DMS) are studied to understand the state of the structure and its functionality. Pandey et al, (1991) shown that information pertaining to Eigenfrequency and DMS are not sufficient many a time to exactly identify the damage in a structure. To surmount this problem curvature mode shape (CMS) was introduced. As another advantage of CMS, Rucevskis et al., (2010 and 2016) indicated towards its baseline free method. In spite of the advantages of CMS Foti (2013) noted the difficulties associated with measurement. Although studies on the latticed structure have proved CMS as one of the efficient parameters for damage localization its applicability for the small strength variation in the mass structure like gravity dam is yet to be studied. Another alternative parameter suitable for damage identification is Modal Strain Energy, which Yang et al. (2003) have utilized for the off-shore structure.

In spite of these advantages found from the studies on the latticed structures the CMS method needs to be tested on the mass structure like gravity dam. In this article efficiency of all four parameters are studied for the mass concrete structure gravity dam with four different sets of concrete strength parameters. In subsequent two sections working methodology and numerical model are introduced in brief. Subsequently, the model is validated and results of the study are discussed. The article closes summarizing the findings of this study.

2 WORKING METHODOLOGY

As evident from the available literature, sensitivity of different modal parameters is different in identifying the extent of the reduction in strength. The exactitude involving three tire of sensitivity such as detection, localization and quantification of damage needs to be considered in order to comprehend the state of functionality of the structure. Depending on the information obtained from the real structure the numerical model can be calibrated which in turn can help to estimate the residual strength and corresponding lifespan of the structure. Present study used four different modal parameters to understand their ability in achieving the tire of exactitude as discussed above. Global as well as local modal parameters are chosen in order to understand the extent of sensitivity of the parameters for a comparatively small anomaly.

First, the sample model of Koyna Dam, available with the Abaqus Example Problems Guide (ABAQUS-EPG) is validated with the available data. Subsequently, the validated model is used to model different possible cases of real strength of concrete as per the empirical equations provided by the regression analysis done by Noguchi et al. (1993). Behavior of the dam structure is studied for four different cases to find the level of sensitivity of the parameters.

Deflection mode shape is directly available from the modal analysis. Variation of Eigenfrequency and DMS are studied to confirm their ability in identifying the strength inaptness. Curvature is given by Eqn. (1) where, ‘y’ denotes the height along the upstream face of the dam measured from its base and ‘u’ is the displacement along horizontal direction.

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

Therefore, CMS can be obtained by differentiating DMS twice numerically. Equation (2) expresses the node wise CMS value employing central difference formula for i^{th} node where ‘i' is any number between 1 and the number of nodes on the upstream face and ‘h’ is the distance between two consecutive nodes along that face.

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

Modal Strain Energy of the upstream face is plotted along the height. Elemental Strain Energy is given by Equation (3)

$$Element\ Strain\ Energy = \int_V (\sigma)^T(\varepsilon)dV \tag{3}$$

where σ and ε denotes elemental stress and strain respectively and *dV* is the volume of the element.

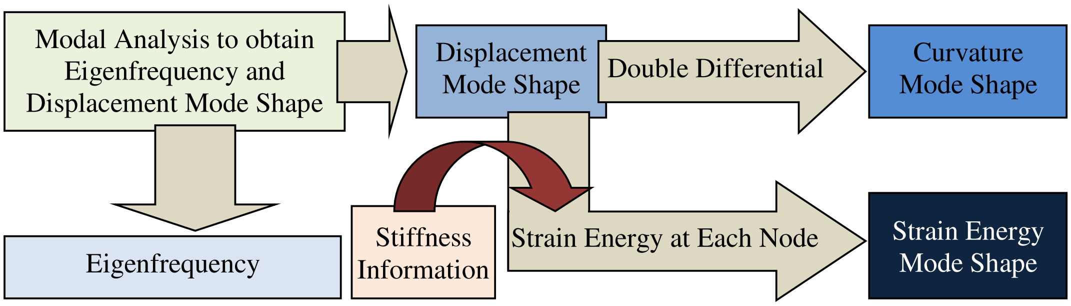


Figure 1. Flowchart showing relations between different modal parameters

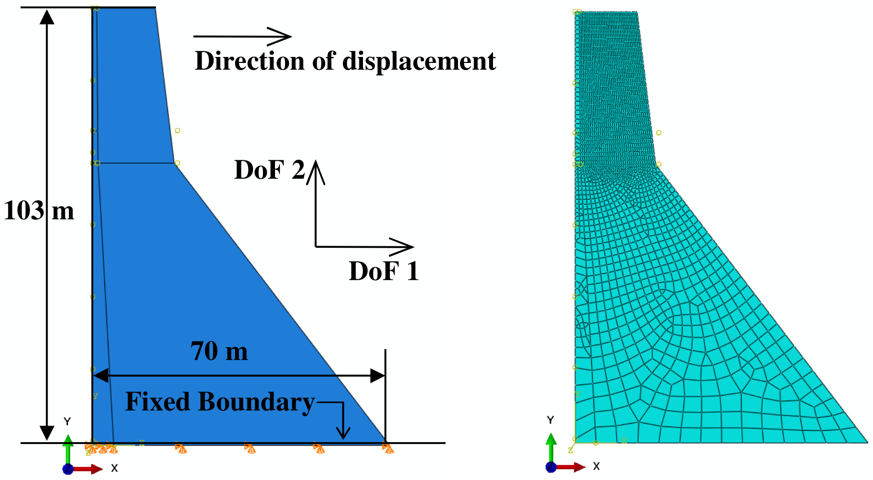
3 NUMERICAL MODEL

The cross section of Koyna dam is modeled numerically in 2D using the ABAQUS/CAE finite element software environment where the standard profile provided in the ABAQUS-EPG is used. The domain is discretized using 4-node, Plane stress, bilinear, reduced integration, quadrilateral, hourglass control (CPS4R) elements. Lanczos eigen solver is used to extract first four modes of free vibration in Linear perturbation technique. Eigen frequencies of those four modes obtained from the standard model are used to validate the model with the published data. As shown in the Figure 2, base of the dam is considered to be fixed along both the horizontal (DoF 1) and vertical (DoF 2) degrees of freedom. As the output of the simulation, following three parameters such as, Natural Frequencies, Modal Deflection (along DoF 1, i.e, U1), Total Modal Element Strain Energy (ELSE) are noted.

Material properties and the geometric behavior of the dam are presumed to be linear and elastic. Subsequently, the mechanical material properties of the model are varied as per the prescription of the Architectural Institute of Japan (AIJ) and the above-mentioned regression analysis. The general expression for the Modulus of Elasticity (E), considered in the current study, is given as follows by the Eqn. (4)

$$E = k_1 k_2 a \frac{\sigma_B^b}{m} \frac{\gamma^c}{n} \tag{4}$$

where, E = modulus of elasticity (MPa)
γ = unit weight of concrete (t/m^3 or kg/l)
σ_B = specified design compressive strength of concrete (MPa)
k_1 = correction factor corresponding to coarse aggregates
k_2 = correction factor corresponding to mineral admixtures.
b = exponent for design compressive strength (concrete)
c = exponent for unit weight (concrete)
m = normalization factor for design compressive strength (concrete)
n = normalization factor for unit weight (concrete)



(a) (b)

Figure 2. Koyna gravity dam: Numerical model; (a) Schematic representation of the structure with DoFs and Boundary, (b) Finite Element Model

The first model (Case – 1) uses the values as per prescribed by AJI where the factors for the aggregate and admixture are not used. As this equation overestimates the E value for the high strength concrete, for the mass concrete structure like gravity dam that may not be suitable. Therefore, following two models uses the values as per the results obtained from the regression analysis. Second model (Case – 2) also doesn't consider the factors for the aggregate and admixture but the final equation takes all of the factors into account. As the final equation, reported as a result of the regression analysis, is based on $\gamma = 2.4$ t/m^3 and $\sigma_B = 60$ MPa, values of m and n are chosen accordingly.

Table 1. Comparison of the first four eigen frequencies of the Koyna dam

Mode	Validation Case	Case - 1	Case - 2	Case - 3	Case - 4
Target Compressive Strength (σ_B) in MPa	< 30	36	60	60	60
Unit weight (γ) in t/m^3 or kg/l	2.643	2.643	2.643	2.643	2.643
Poission's ratio	0.15	0.15	0.15	0.15	0.15
Modulus of Elasticity (E) in MPa	31027	34454	44480	40638	40627

4 VALIDATION

The first four eigen frequencies of the structure, obtained from the simulated model, matches with those of the published data ($\text{Error}_{|\max} = 2.05\%$). Therefore, the model can further be employed for damage identification purpose.

Table 2. Comparison of the first four eigen frequencies of the Koyna dam

Mode	Standard Model (Hz)	Reference Model (Hz) Chopra et al, (1973)	Error (%)
First	03.04	03.07	00.88
Second	08.09	08.20	01.35
Third	10.97	10.75	**02.05**
Fourth	15.96	15.87	00.52

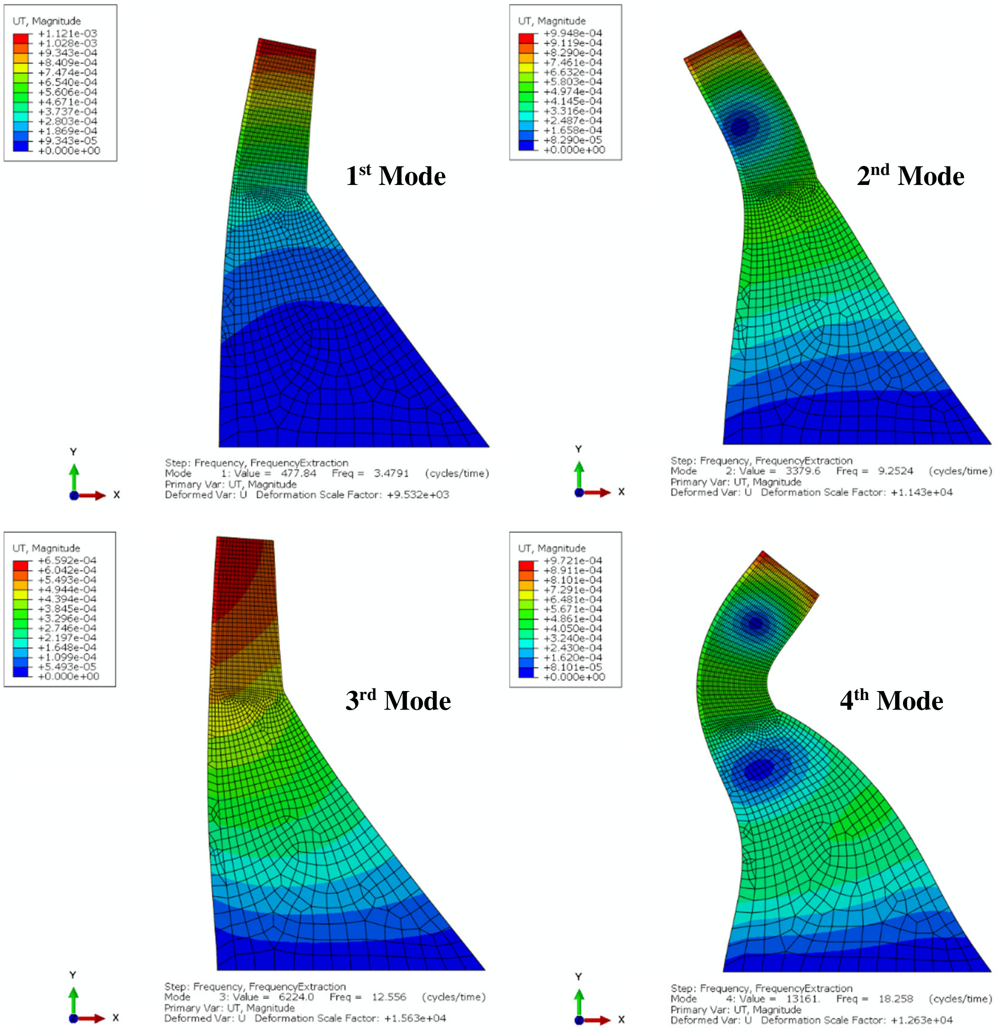


Figure 3. Koyna gravity dam: First four modes of vibration

5 RESULTS AND DISCUSSION

As stated, modal behavior of the Koyna gravity dam for the four sets of concrete properties are compared to understand the sensitivity of the damage identification parameters. In this section, case wise signature values of the four parameters, i.e., Eigenfrequency, DMS, CMS, SEMS are presented and discussed critically.

5.1 Eigenfrequency

Natural frequencies of the four cases are presented in the Table 3. It is evident that in spite of significant difference between the target compressive strength and corresponding E value difference in the natural frequencies are very minimum between the first two cases. Following the same trend for the last three cases the differences are even smaller because for those cases target compressive strength is same for all (60 MPa). Therefore, it is legitimate to infer that Eigenfrequency is not able enough to identify the variation in the concrete strength.

Table 3. Comparison of the first four eigen frequencies (in Hz) of the Koyna dam for the four cases

Mode	Case -1	Case - 2	Case - 3	Case - 4
First	03.204	03.640	03.480	03.479
Second	08.521	09.681	09.254	09.252
Third	11.563	13.138	12.558	12.556
Fourth	16.814	19.104	18.261	18.258

5.2 Displacement Mode Shape

Displacement mode shapes of first four eigenmodes are presented in the Figure 3. Modal displacements clearly indicate that the behavior of the dam structure is significantly different from that of prismatic cantilever beam. It is also evident that Modal displacement of the up-stream face cannot differentiate at all between the cases.

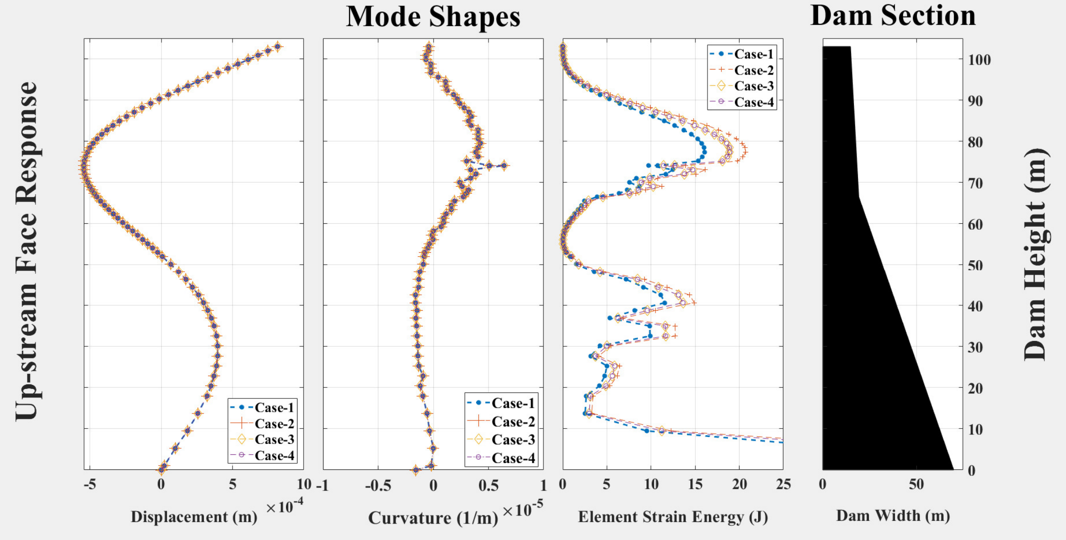


Figure 4. Modal response (Forth mode) of Koyna gravity dam: Displacement, Curvature and Element Strain Energy Mode shapes for the Up-stream face.

5.3 Curvature Mode Shape

The third modal parameter, i.e., CMS is employed to identify the strength variation because DMS is found to be quite insensitive to the target compressive strength. Unfortunately, as evident from the Figure 4, CMS also found to be not appropriate to differentiate between them.

5.4 Strain Energy Mode Shape

Elemental strain energy (ELSE) is found to be able to differentiate between different concrete E values even when the target compressive strength is same for them. It is to be noted that Case-3 and Case-4 have both σ_B and E values almost same but E value of Case-2 is slightly different from the later two cases. As ELSE is capable to differentiate between them in spite of slight variation in E value, SEMS is the better parameter for identification in strength inadequacy.

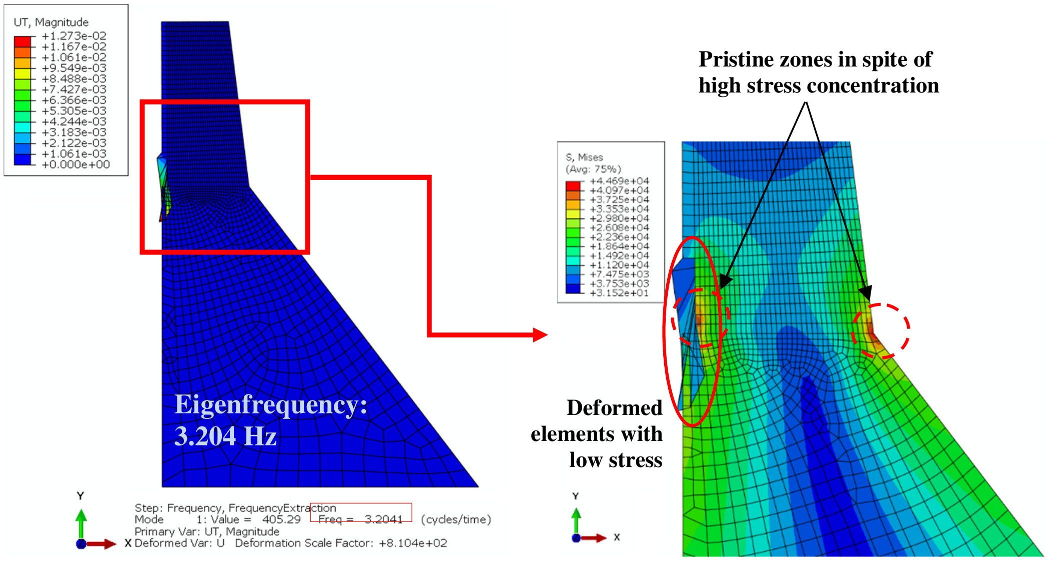


Figure 5. Koyna gravity dam: Damaged element for low Modulus of Elasticity region (First eigen frequency Same as Case – 1).

6 CONCLUSIONS

This article studies the sensitivity of different modal parameters such as Eigenfrequency, DMS, CMS and SEMS against four possible cases of concrete strength using the 2D Finite element model of Koyna gravity dam. The inferences of this study are summarized in this section.

First of all, it is concluded that neither Eigenfrequency nor the DMS-CMS are capable of identifying the strength inadequacy in the structure. Eigenfrequency can be different in same amount even for a large reduction in E value at a very small location, which practically represents the case of local damage. As shown in the Figure 5, even a small localized damage can be responsible for the reduction in the Eigenfrequency. In this case deformed elements experienced much smaller amount of stress than some other zones of the structure where elements are yet to undergo any deformation. It is to be noted that the model in Case -1 and the model with the damaged element have same Eigenfrequency (3.204 Hz) but for the former the compressive strength is 36 MPa while for the damaged one overall compressive strength is as high as 60 MPa. Sensitivity of Element strain energy parameter is tasted against both E and σ_B. Unless both of them are matched to the sufficient exactitude ELSE will indicate the strength anomaly. Element strain energy is found to be the appropriate parameter to identify the structural system and therefore the structure can be tuned to match the real system behavior using this parameter as the target.

The modal strain energy responses of the structure presented in this study are numerical. In case of practical application upstream face of the dam has to be quipped with enough displacement/strain sensors, which at times may not be economically viable. Additionally, in reality strength of the concrete may not be as homogeneous as modeled. Therefore, in that case the modeled E value will be representative of the equivalent strength parameter of the concrete.

7 ACKNOWLEDGEMENT

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