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# Investigation of Damage Influence on Modal Participation Ratio in Experimental Modal Test

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For many years rapid visual screening was the only approach used for health monitoring of infrastructures. Developing new modern metropolises, huge structures such as bridges has become a ground for new requirements for up to date methods as a probe for authority figures to be able to decide logically for rehabilitation or rebuilding vulnerable structures.

Many new approaches have been developed in recent years, for health monitoring of civil structures, using different global factors such as natural frequency or damping ratio or modal shapes. In this study, based on some experimental and laboratory test results Modal participation ratio showed a good relation with damage and damping in concrete slabs, new approach is proposed , for screening of damage in existing concrete post-tension bridges. This provides global information of structural health, to make further decisions. For specimens where the test carried out using experimental modal analysis, high identification accuracy and confidence of this method is shown.

## 1 INTRODUCTION

In past century, the major effort of structural engineers was the development and application of new and numerical approaches to use in the static and dynamic analysis of huge civil engineering structures. The quick development of finite-element techniques accompanied by tremendous technological experience in the computers allowed structural engineers to utilize extreme calculation software for robust simulation of structural elements.

Also, the design and construction of complex and huge civil structures, like skyscrapers, large cable stayed and suspension bridges, or other complicated structures have made engineers to evolve new experimental tools to provide the accurate identification of the most usual dynamic properties. These tools should enable trusted data to maintain calibration, updating, and validating of structural analysis numerical models.

In addition, the continuous ageing and subsequent structural corrosion of many existing structures have made the development of efficient dynamic-based damage detection techniques provided by structural health monitoring systems. Gharighoran & Nematollahi(2012)

At present, periodic structural condition monitoring of reinforced concrete structures is necessary to ensure that they provide a continued safe service condition. Conventional assessment procedures usually rely on visual inspection and location dependent methods. Damage may also be defined as any deviation in the structure’s original geometric or material properties that may cause undesirable stresses, displacements, or vibrations on the structure.

These weakening and deviations may be due to cracks, shrinkage, broken welds, corrosion, fatigue, and so on.

Nondestructive Damage Test (NDT) techniques such as modal analysis tests, acoustic emission and X-ray inspection, provide facilities to detect the occurrence of damage. These methods are local inspection approaches. In NDT, the structure undergoes a dynamic input, such as the tap of a hammer or a controlled impulse. Key properties, such as displacement or acceleration at different points of the structure, are measured as the corresponding output. This output is recorded and compared to the corresponding output given by the transfer function and the known input. Differences may indicate an inappropriate model (which may alert engineers to unpredicted instabilities or performance outside of tolerances), failed components, or an inadequate control system. The methods are usually based on the fact that structural damage leads to a reduction in stiffness, which changes the dynamic characteristics of the structure. Dynamic properties-based damage identification methods have drawn world wide attention due to their infrastructural roles.

Reduction in stiffness is one of the major keys which could outline structural damages. However it will not cover all kind of damages which structures undergo during their service life. For instance it will not represent alternations in damping factor.

Past researches show that increasing damage will increase higher modes participation ratio. Accordingly, obvious relationship can be found between damage and modal participation ratio of first five vibration modes in a concrete slab.

In this study, using a pioneer test setup, output data will demonstrate enough agreement between first modes participation ratio and damage ratio. Test setups, that will be discussed later, include some concrete slabs which will be loaded statically and then will resist dynamic loads to reveal changes in dynamic properties.

## 2 THEORETICAL CONSIDERATIONS

### *2.1 Damage measure*

The change of global behavior of a structure should be related to local parameters describing the damage. For this purpose, it is important to select damage indicators that are sensitive to structural changes due to the damage. Damage patterns should be described by suitable parameters, which in principle, not only will identify the damage location, but also reflect the damage severity.

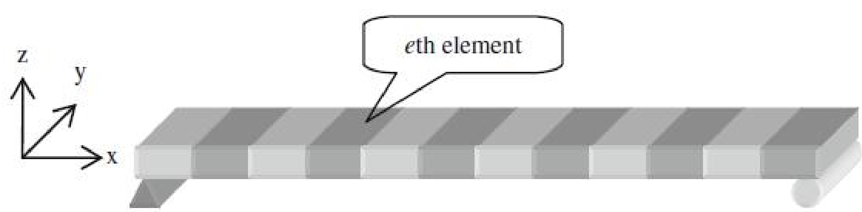


Figure 1. Finite element model of a simply supported beam..

In the context of discredited finite elements, damage to a structure may be represented by a decrease in the stiffness of the individual finite-elements as shown in Fig. 1. The damage identification is then carried out at the element level. It is assumed here that the stiffness matrix of the whole element decreases uniformly. The change in stiffness of an element can be expressed as

$\boldsymbol{k}_{Se}$=$\boldsymbol{k}_{\boldsymbol{e}}$-$\widehat{\boldsymbol{k}}_{\boldsymbol{e}}$(1)

in which $k_{se}$ is the change of the e*th* element stiffness matrix after damage. $\boldsymbol{k}_e$ is the eth element stiffness matrix of the undamaged structure. $\alpha_{De}$ is the e*th* element stiffness matrix of damaged structure $\hat{k}_e$ and can be written as

$\alpha_{De}$= $\frac{(\hat{E}\hat{I})_e}{EI_e}$ (2)

In Eq. (2) only variation of bending stiffness has been taken into account. This equation can be applied in beams under one direction bending, but in slabs under two direction bending, moments of inertia in every direction should be distinguished. In this test setup owing to elements geometrical ratios (length to width ratio) which will be shown later, considering variation of bending stiffness will provides enough accuracy. Local damage index $\alpha_{se}$ can be written as

$\alpha_{Se}$=(1- $\frac{(\hat{E}\hat{I})_e}{EI_e}$ ) (3)

In which, the local stiffness before and after damage are $(EI)_e$ and $(\hat{E}\hat{I})_e$, respectively. The global damaged stiffness matrix $\hat{K}$ is the assemblage of each element damaged stiffness matrix $\hat{k}_e$. Using Eqs. (1,2 and 3), we have

$\widehat{\boldsymbol{K}}$= $\sum_{e=1}^{m}\widehat{\boldsymbol{k}}_e$=$\sum_{e=1}^{m}(1-\alpha_{Se})\widehat{\boldsymbol{k}}_e$= $\sum_{e=1}^{m}(\alpha_{De})\boldsymbol{k}_e$ (4)

Where m is the total number of finite elements.

## 3 EXPERIMENTAL TESTS

In this research, five post-tensioned concrete slabs are tested. To establish the relation between damage and changes of dynamic characteristics, tests which include static and dynamic tests, are performed. To produce damage, a concentrated point load is used in many consequent steps. After each static load step, the beam is gradually unloaded and a modal test is performed to obtain dynamic characteristics. The dimensions of the reinforced concrete beams are 400 mm wide and 100 mm thickness as shown in Fig. 2a. The beams are simply supported across an effective span of 3800 mm.

On concrete blocks as shown in Fig. 2b, the applied post-tension forces are 0, 50, 80, 115, and 150 kN. The beam is reinforced and additionally pre-stressed with two stretch cables with nominal diameter of 5.2 mm and a yield stress of 1810 N/mm2, after the solidification of the concrete by two hydraulic jacks. These beams are called St10P0, St10P5, St10P8, St10P11.5 and St10P15, respectively. It should be noted these names represent the pre-stressing forces.

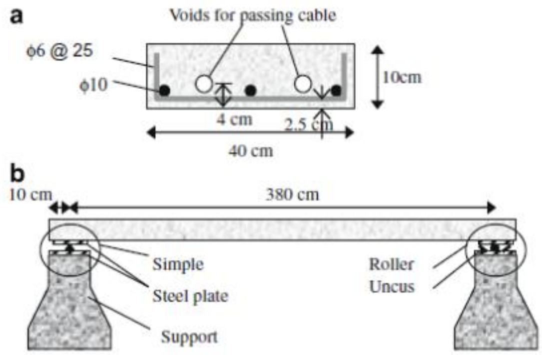


Figure 2. Experimental test setup.

### *3.1 Static tests*

The concentrated point load was applied at the middle point of span as shown in Fig. 3a. The static load is applied in six steps that are labeled with W and shown in Table 1. Each load step includes loading and unloading applied incrementally from 0 N to maximum loading and from maximum loading to 0 N. To ensure that there are no dynamic effects, maximum loading speed was limited to decrements of approximately 100 N each time. The force is generated by one hydraulic jack and transferred via one steel plate to the beam. The static tests are performed to produce successive damage to beams

Crack locations and crack depths are recorded for each beam after each static load step. Measurements for crack are recorded from both side faces as well the bottom of beams using a lens.

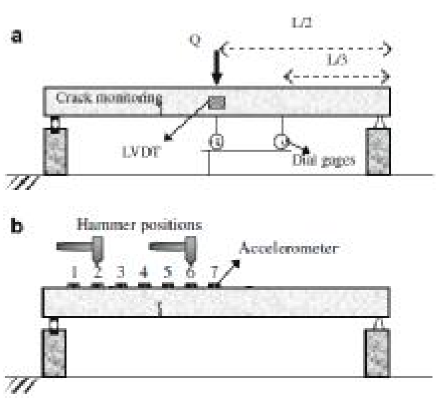


Figure 3. Experimental setups: (a) static test and (b) modal test .

Table 1. Load steps of static tests.

Load steps of static tests.

| Load Step | W0 | W1 | W2 | W3 | W4 | W5 | W6 |
|---|---|---|---|---|---|---|---|
| Load(N) | 0 | 1150 | 2400 | 3700 | 5000 | 6300 | 7600 |

### 3.2 Dynamic tests

Fig. 3 represents the static and dynamic test setups. After each static load step, a dynamic test (modal analysis) is performed. An impact loading is created using a falling weight on a specified point of the beam, for each load step. In order to excite the bending modes and to enhance the accuracy of each dynamic test, the exciting hammer is applied to points 2 and 6 as shown in Fig. 3b. The accelerations are measured by means of piezoelectric sensors.

In order to get a detailed measurement of mode shapes, 13 sensors + 1 reference sensor are used. They are placed on top of the beam in one row (central axis) to measure bending modes (see Fig. 3b). The excitation resulting from the input force is measured using a force transducer that is pitched to the hammer. A Bruel & Kjaer 12-channel analyzer type 3040 is used to acquire the signals and to obtain the Frequency Response Functions (FRFs) from the modal test. By using modal analysis software, curve fitting process is performed on the transfer function spectra to extract modal parameters such as natural frequencies, mode shapes and damping ratios. A total of five normal bending modes are acquired in this manner. In this research, a hammer is constructed for excitation of beams as shown in Fig. 3. More details of two hammers that are made for excitation of beams and bridges are presented in Gharighoran & Daneshjoo (2009).

### 3.3 Modal mass participation ratio

In experimental test, output data can be found for a sort of vibration modes for a structure which have unlimited degrees of freedom. In civil structures, most of the time, using some of the first vibration modes is enough to obtain accurate results.

For the purpose of evaluation of modal participation ratio in total vibrating mass, using Modal analysis method we have ,Chopra A.K.(2001),

$$m*_{ij} = \frac{(\sum_{j=1}^{n} \phi_i m_{ij})^2}{\sum_{j=1}^{n} \phi_i m_{ij}^{\ 2}} \tag{5}$$

In which $M_n$ is n*th* mode mass and $\phi_n$ is n*th* modal shape. And modal mass participation factor is,

$$MMPF_i = \frac{m*_{ij}}{\sum_{j=1}^{n} m^*_{ij}} \tag{6}$$

In an ideal condition which we have all of the vibrating mode shapes,

$$\sum MMPF_i = 1 \tag{7}$$

Practically, only some of the vibration modal shapes can be found, so summation of modal participation ratios will be less than 1.0. If we assume that 10 percent error is acceptable, one can obtain number of modes which will result in 90 % of total dynamic response.

Utilizing eqs. 6 and 7, in the experimental test; MMPF is calculated for different loading conditions in all the slabs which are utilized in this study. Results show that the modal participation ratio of first five vibration modes are more than 90 percent which means,

$$MMPF_i \geq 90\% \rightarrow n = 5 \quad (12)$$

### 3.4 Experimental results and discussion

The experimental results contain both static and dynamic results in which, beams are considered as simply supported members. Results of these tests include static deflections and crack patterns (Fig. 4). The dynamic measurements are aimed to obtain dynamic characteristics of undamaged and damaged beams. The dynamic experimental results (e.g., natural frequencies and mode shapes) are extracted using rational fraction curve fits (RFCF) method in frequency domain. Ewins DJ(2000).

Summary of modal mass participation ratios for 3 specimens are shown in fig. 5 to 7 . In all test slabs 2nd ,4th modes participation ratio are zero and summation of mode numbers 1st ,3th ,5th modes participation ratios are more than 90 % .First vibration mode participation ratio is at least 82 % which shows that first mode has the largest participation ratio.

Review of graphs in fig 5 to 7 shows that summation of modal mass ratios for 1st, 2nd, and 3rd vibration modes in all of the specimens are reduced respect to damage ratio. So often, in first modes, it is decreases, then in second mode increases and then decreases and in the 5th mode, participation ratio increases .As the participation ratio of first mode is more than the others, it will govern the summation. Decline in summation of modal participation factors is clearly shown.

From results in the figures 5 to 7, one can conclude that decline rate for post-tension specimens is increasing by decreasing of post tension load. So in the specimen without any post tension loading ,we have maximum decrease in modal participation ratio. Also it is clear that there is a good relationship between modal participation ratio and damage ratio.

In spite of the frequency and stiffness, modal participation ratio combines influence of more than one dynamic parameter. So technically it can be utilized as a damage index which will be apparent evident of the structural health. This relationship may be a result of amplification of participation of last vibration modes by increasing in damage ratio in a specimen.

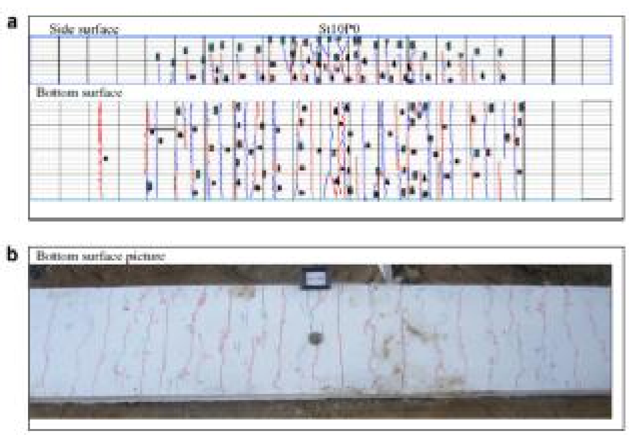


Figure 4. Crack patterns: (a) drawn and (b) picture.

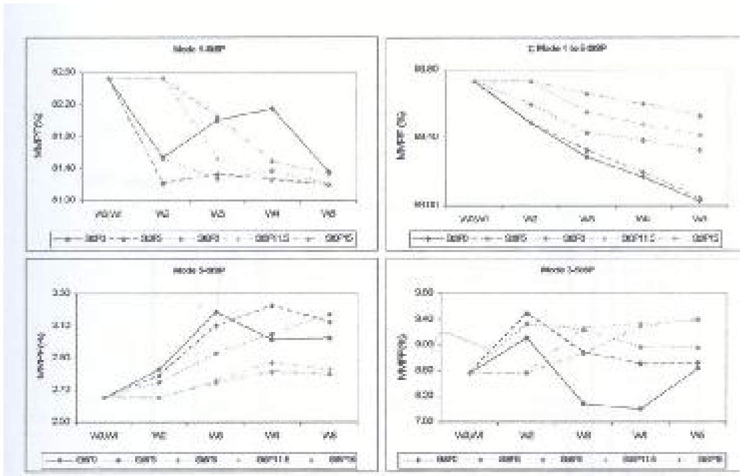

Figure 5.modal mass participation ratio and damage ratio for St8P specimens.

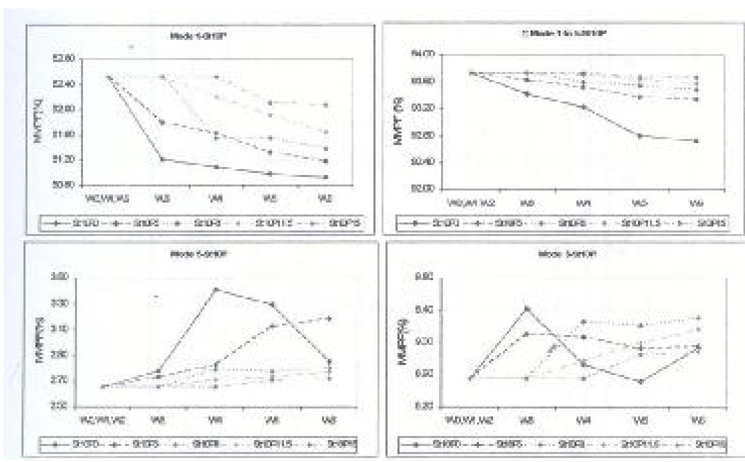

Figure 6.modal mass participation ratio and damage ratio for St10P specimens.

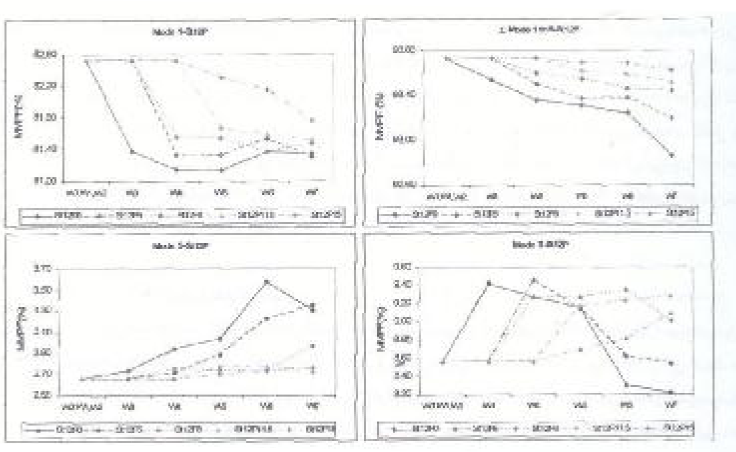

Figure 7.modal mass participation ratio and damage ratio for St12P specimens.

## 4 CONCLUSION

Using frequency or stiffness is a normal approach to find damage ratio in structures. In this study, as shown in figures 5 to 7, there is a good relationship between damage ratio and modal mass participation ratio. Modal mass participation ratio is a combination of more than one dynamic parameter. It can be utilized as a better damage index to estimate structural health. While damage ratio in a specimen increases, this relationship seems to be a result of increase in participation of latter vibration modes. Further study with more specimens is required to develop this theory.

## References

Cawley P, Adams RD. The locations of defects in structures from measurements of natural frequencies. *J. Strain Anal.* 1979;14:49–57.

Chopra AK. Dynamics of structures theory and applications to earthquake engineering. *Prentice Hall International Inc.*; 2001.

Ewins DJ. Modal Testing: Theory, Practicing, and Application. Hertfordshire England: Research Studies Press Ltd., Letchworth; 2000.

Farrar CR, Lieven N. Damage prognosis: the future of structural health monitoring. *Philos Trans Roy Soc* 2007;A365:623–32.

Gharighoran,AR And Nematollahi, R. 1993. Experimental Modal Test of Civil Concrete Bridges.*Conference Proceedings of the Society for Experimental Mechanics Series* Volume 26, 2012, pp 173-187

Gharighoran,AR, Daneshjoo,F And Khaji,N. Use of Ritz method for damage detection of reinforced and post-tensioned concrete beams. *Construction and Building Materials*, Elsevier, 23 (2009) 2167–2176.

Hamed E, Frostig Y. Free vibrations of cracked prestressed concrete beams. *Eng. Struct. 2004;26(11):1611–21.*

Kam TY, Lee TY. Detection of cracks in structures using modal test data. *Eng. Fract. Mech* 1992;42:381–7.

Maeck J, De Roeck G. Damage assessment of a gradually damaged RC beams by dynamic stiffness determination. In: *Proceeding of 17th international modal analysis conference*; 2001. p. 1289–95.

Zou Y, Tong L, Steven GP. Vibration-based model-dependent damage (delamination) identification and health monitoring for composite structures - a review. *J. Sound Vib.* 2000;230(2):357–78.