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Lamb Wave Technique for Non- Destructive Evaluation of Structures”

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***Abstract* — In recent years there is a continuous rise in construction activities in the field of civil engineering. The life of a structure depends on initial strength and the maintenance of construction. Hence there is necessity of nondestructive evaluation (NDE) is emphasized worldwide. In this role, the PZT patches act as actuators and sensors and employ ultrasonic vibrations to find out a characteristic admittance ‘signature’ of the structure. Typically, their sensitivity is high enough to capture any structural damage at the incipient stage. The admittance signature encompasses vital information governing nature of the structure, and can be analyzed to predict the onset of structural damages.**

This new NDE technique is called the Lamb wave. Detection of incipient damage is quite critical for health monitoring of structures. In this study, through artificial damage created in the structures, it is found that the incipient level damage is very quickly detected by the lamb wave technique. For moderate to severe damages, the same PZT is capable of serving as the sensor of the global dynamic technique, and can suitably quantify such damages as well as locate them. Hence, PZT patches, which have so far been used largely with lamb wave technique, have been found suitable for global techniques in this study.

Damage ranging from incipient to near failure (severe) can be located and quantified using the lamb wave technique. Incipient damage is located using extracted equivalent parameter from the admittance signature of different sensors. Moderate to severe damages are determined by using RMSD. A new experimental technique developed to predict in situ aluminium plate of size 200mm×200mm×2mm, steel plate of size 200mm×200mm×2mm, hollow structure of size 1000mm×50mm×25mm & concrete cube of size 150mm×150mm×150mm strength non-destructively is then described at dry as well at humid condition.

Keywords— Structural health monitoring (SHM), Non -destructive evaluation (NDE), Piezoceramic Zirconate Titanate (PZT) patches, Lamb waves, Root mean square deviation (RMSD).

I INTRODUCTION

Structures are designed for certain life span, and it is assumed that during this period structure is maintained properly. By proper monitoring, it may be possible that the life of the structure be increased and serviceability enhanced, resulting in huge savings. Fatigue assessment can be determined, if continuous monitoring is done. It may possible that a new constructed structure may not be performing well with respect to design parameters, due to inferior material. This can be ensured by proper health monitoring.

Non-destructive evaluation (NDE) of concrete has historically been a niche discipline within civil engineering and a process carried out by an individual operator in the field to evaluate the extent of known or suspected flaws within a concrete structure. NDE techniques such as Ground Penetrating Radar, Ultrasound, and Eddy Current methods depend heavily on the expertise and diligence of the operator to maintain accuracy and are prone to producing sparse, subjective data. For these reasons, NDE methods such as eddy current methods, ultrasound, and ground-penetrating radar (GPR) are typically called upon by governing agencies and only to identify the extent of known defects or defects suspected to be present.

Concrete NDE techniques have shown the potential to reliably identify many forms of structural deficiency including poor material quality, poor consolidation, insufficient cover (thickness of protective concrete layer over reinforcing steel), and subsurface cracking and delamination due to damage. The application of such methods for quality control purposes, however, requires spatially dense, exhaustive data collection performed in an irrefutable manner suitable for holding construction agencies responsible for the product they produce. The list of NDE methods that have successfully been applied to concrete structures is incredibly long and is growing every day. While one of the main goals of the development of the automated system was to create a system capable of expansion to include new NDE instruments, a review of a myriad of potential instruments to be included in future research is not necessary for comprehension of this work. Nishanth R. and Maheshprabhu.R, et.al[1]: studied on structural health monitoring which is based on Lamb wave propagation. It has been developed especially for distinguishing different kinds of damages. The Lamb wave-based active SHM method uses piezoelectric (PZT) sensors to transmit and receive Lamb waves in a thin Aluminium plate. The Lamb wave modes travel into the structure and are reflected by the structural boundaries, discontinuities, and damage. By studying their propagation and reflection, the presence of defect in the structure is determined. Laboratory level experiments have been carried out on thin Aluminium plates with angular, horizontal and vertical defect. This study provides significant insight into the problem of identifying localized damages in the structure using PZT and dispersion of signal after they interact with different types of damage. Those small defect like the horizontal one that may be nearly missed in time domain analysis can also be clearly identified in the STFT analysis. Moreover the occurrence of So mode is also clearly seen. Thus, Lamb waves generated by PZT sensors and time-frequency analysis techniques could be used effectively for damage detection in aluminium plate. Hui-Ru Shih, Wilbur L. Walters et. al[2]: studied out on structural health monitoring (SHM) is an emerging technology that has multiple applications. SHM emerged from the wide field of smart structures, and it also encompasses disciplines such as structural dynamics, materials and structures, non-destructive testing, sensors and actuators, data acquisition, signal processing, and possibly much more.Shih-Lin Hung and C. Y. Kao[3]: studied on a novel neural network-based approach to detect structural damage. The proposed approach comprises two steps. The first step, system identification, involves using neural system identification networks (NSINs) to identify the undamaged and damaged states of a structural system. The partial derivatives of the outputs with respect to the inputs of the NSIN, which identifies the system in a certain undamaged or damaged state. This loosely defined unique property enables these partial derivatives to quantitatively indicate system damage from the model parameters. The second step, structural damage detection, involves using the neural damage detection network (NDDN) to detect the location and extent of the structural damage. Saurab Verma, Annamdas Venu Gopal Madhav et. al[4]: studied on gradual changes in the properties of concrete during the curing process of 30 days. For the purpose, a 150 x 150 x 150 mm^3 cubic concrete block was subjected to the test. Signatures were obtained using embedded and surface-bonded piezoelectric transducers (PZTs). The EM (admittance) signatures were processed using statistical indices like RMSD, for different periods of frequencies. But the conventional statistical tools did not serve the purpose in this situation. Hence, a new technique was devised (called RDSD) later. Ayaz Mahmood and Dr. S. K. Sahu[5]: studied on calibration of graph for Non destructing testing equipments like rebound hammer and ultra sonic pulse velocity tester and also obtained results for effect of reinforcement in columns, beams and slabs of double storied building. The use of combined methods produces true values when compared with other methods. C. Rainieri and G. Fabbrocino et.al[6]: studied Structural Health Monitoring systems network designed by University of Molise and University of Naples “Federico II”, and currently under implementation, is described, pointing out the solutions adopted to build a reliable SHM system. At completion, such a system will cover a wide range of structures over Molise and Neapolitan territories, taking advantage of its distributed infrastructure and of opportunities given by IT. Jordan D. Nelson[7]: studied different non-destructive evaluation techniques. His project work which is an expansive and comprehensive analysis system and the beginnings of an entire research program that could potentially advance the industry of concrete NDE and indeed the construction industry as a whole. It is a tool accessible to researcher and technician alike, with unique capabilities and unique applications. It is a powerful, flexible, and expandable software platform owned and operated by non-profit agency. It is recommended that the potential of the system for structural quality control applications be investigated and expanded upon, including statistical analyses of the system’s ability to reliably detect defects before a structural element enters service.

II METHODOLOGY

Experiments were conducted with a four different structure. In this specimen’s aluminium, steel, hollow beam, concrete structure were used to obtain result. For every structure PZT sensors were used as sender and receiver of lamb wave. One of the PZT (sender) is connected to the function generator and another PZT (receiver) is connected to the oscilloscope. The PZT actuator was excited by a signal constructed and transferred to an arbitrary function generator. This function generator could read the digital signal and output the corresponding analogue signal to the actuator. The measured signals were obtained with a digital oscilloscope for A/D conversion. Considered following cases.

Case 1 : Damage diagnosis for concrete cube 15×15×15cm

a. Damage diagnosis for concrete cube 150mm×150mm×150mm in dry condition.

b. Damage diagnosis for concrete cube 150mm×150mm×150mm in humid condition.

Case 2 : Damage diagnosis for hollow beam of size 1000mm×50mm×25mm with 1 mm thickness

a. Damage diagnosis for hollow beam of size 1000mm×50mm×25mm with 1 mm thickness in dry condition.

b. Damage diagnosis for hollow beam of size 1000mm×50mm×25mm with 1 mm thickness in humid condition.

As per regression analysis given by Dr. Bhalla, it is apparent from the figures that the first peak frequency increases with the strength of structure. This increase is on account of the additional stiffening action due to bonding with structure, the level of stiffening being related to the specimen's strength [10]. At least two plates were tested corresponding to each strength and the average frequencies were worked out. From regression analysis, the following empirical relationship was found between strength (S) and the first resonant frequency,

$$S = 0.0089 f^2 - 2.6657 f + 196.94$$

where,

$f \longrightarrow$ the resonant frequency, is measured in kHz &

S $\longrightarrow$ compressive strength, is measured N/mm^2.

This empirical relationship can be used to evaluate strength non-destructively for low to high strength concrete. It should

Compressive load(KN)	Changes in Peak frequency (KHz)	Resonant frequency (KHz)	Compressive strength (N/mm^2)	Stiffness K (N/mm)	Damping coefficient (C) (Ns/mm)	Damping ratio (ζ)
0	208.2	104.1	15.66	877781.6	8432.09	5418.40
100	212.6	106.3	14.56	915274.8	8610.3	5649.84
200	219.4	109.7	11.61	974761.3	8885.7	6017.04
300	258.6	129.3	10.78	1354197	10473.3	8359.24
400	298.3	149.15	10.01	1801904	12081.15	11122.86

be mentioned that good correlation was not found between concrete strength and the second and the third peaks.

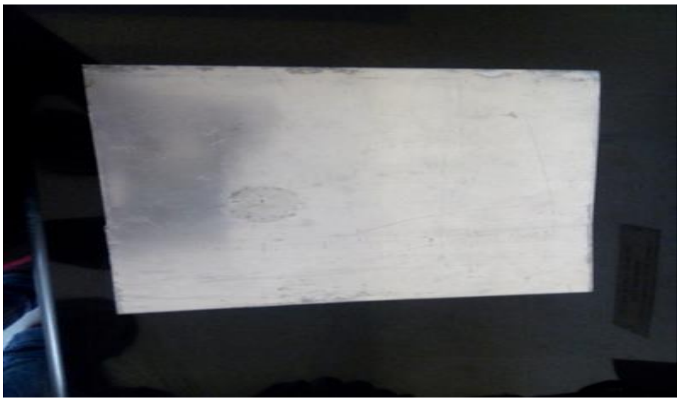
As expected, with damage progression, the stiffness or strength can be observed to reduce. The stiffness is reduced after the incipient damage. Thereafter, with further damage propagation, very small further drop/increase was observed in these parameters.

Experiments is conducted with a aluminium plate structure of size 400mm×200mm×2mm. In this experiment two PZT sensors are used as sender and receiver of lamb wave.

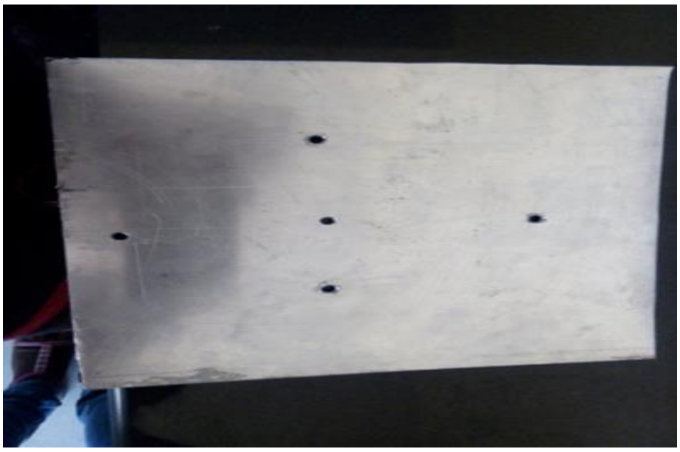
This signature is considered as baseline signature. Then damaged to the structure by drilling machine of Ø-5mm drill. This drill are gradually increased from incipient to severe near PZT sensors. Measured signals which obtained from DSO[39]. Compare the changes occurred in signature at different parameters as above mentioned for damage indication. Experimental set up is showed in fig.3.6. In fig. 3.7 shows aluminium plate structure for (a) undamaged condition and (b) damaged condition respectively.

As mentioned above in experimental set up, there first observed a baseline signature for in situ state of aluminium plate then damaged the plate by drilling machine to obtained damaged state of response. Compared the both response for dry condition as well as humid condition. Then observed changes occurred in signature for humidity, and also to study for protective measures taken to decrease electric permittivity of PZT patches for decrase in noise obtained in response.

Figure 1: Experimental Set Up



(a)Without damage



(b)With damage

III RESULT AND DISCUSSION

Damage diagnosis for M-15 concrete cube of size 150mm×150mm×150mm in dry condition.

This section describes a damage diagnosis study carried out on concrete cube of 150mmx150mmx150mm in size, that is identified using a ceramic transducer bonded on the surface. As shown in Table, the effect of these damages on the identified structural parameters- changes in stiffness and damping and mass and damping ratio.

Damage diagnosis of concrete cube for dry condition by inducing damages in structure with the help of obtained first peak frequency.

Changes obtained in parameters which mentioned in following table, from equation 3.1, 3.2 & 3.3 the effect of these damages on the identified structural parameters- changes in stiffness and damping and mass and damping ratio mentioned in annexure A.

All calculations are depends on first peak frequency of structure. Test results for M-15 concrete with Different parameter- Strength, Damping coefficient, Damping Ratio.

M-15 grade concrete for different parameters where mass of concrete remains constant.

a) Change in first peak frequency

In structure frequency should be observed to increase. Hence as expected, with damage progression, the first peak frequency can be observed to increase. The first peak frequency is increased after the incipient damage.

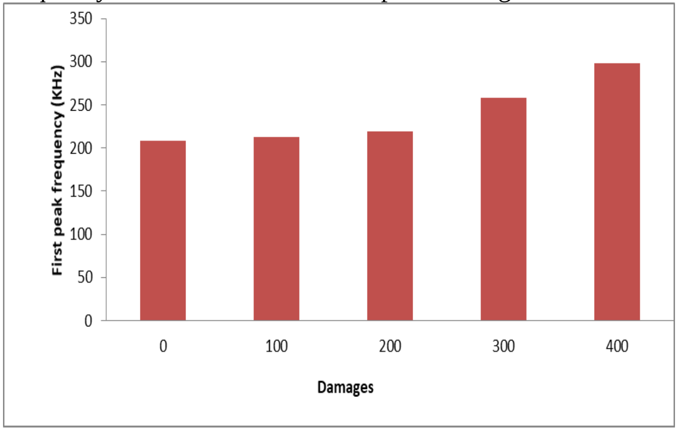


Fig. 2 First peak frequency for M-15 concrete.

From above fig.2 shown a plot between the observed first resonant frequency and measured aluminium hollow beam strength. The strength is reduced gradually- 25% for the incipient damage, 58% for the moderate damage and 78% for the severe damage.

b) Change in compressive strength

As per regression analysis mentioned in equation (1),plot relation between resonant frequency and compressive strength of concrete.

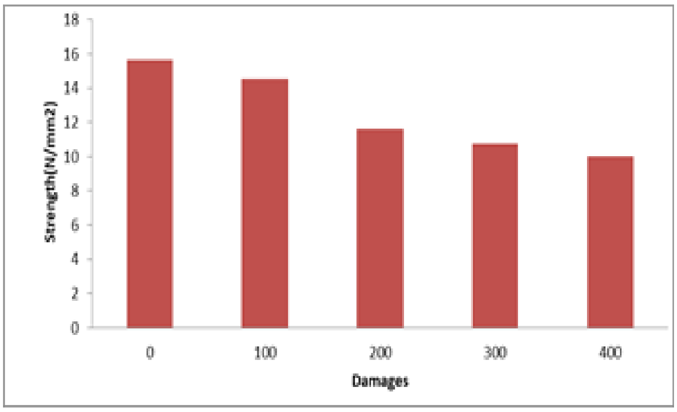


Fig. 3 Compressive strength for M-15 grade of concrete.

From fig.3 in structure stiffness should be observed as a strength. Hence as damage progression, the stiffness is observed to reduce. The stiffness is reduced gradually-7% for the incipient damage, 25% for the moderate damage and 56.6% for the severe damage.

c) Change in damping coefficient

As expected, with damage progression, damping can be observed to increase.

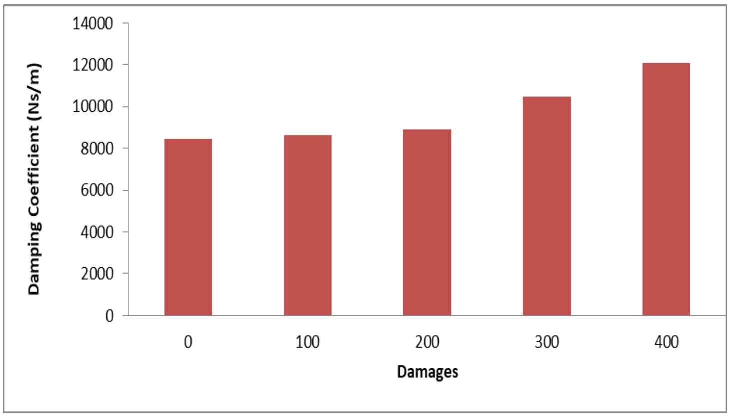


Fig.4 Damping coefficient for M-15 grade of concrete.

From fig.4 with damage progression, the damping coefficient observed to increase. The damping coefficient increased with damage severity- 2.5% for the incipient damage, 5.1% for the moderate damage and 30% for the severe damage.

d) Change in damping ratio

In this found that rational relation between damping ratios and damage. Damping ratio is subsequently increased with damage severity.

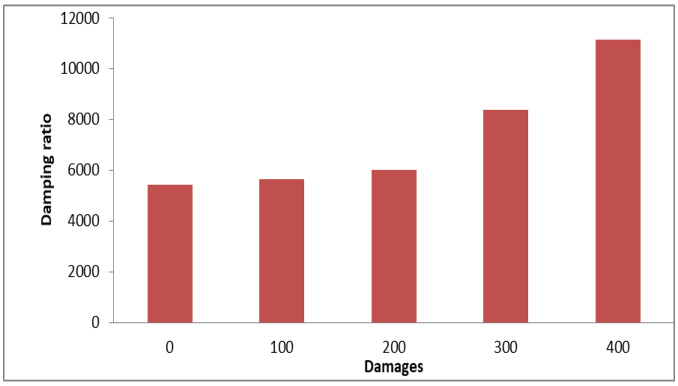


Fig. 5 Damping ratio for M-15 grade of concrete.

From fig.5 it is observed that damping ratio was increased with damage severity- 4% for the incipient damage, 9% for the moderate damage and 51% for the severe damage. Here clearly observed that damages are observed near sensors hence, damping ratio are increased from moderate to severe.

Damage diagnosis for M-15 concrete cube of size 150mm×150mm×150mm in humid condition.

This section describes a damage diagnosis study carried out on concrete cube of 150mmx150mmx150mm in size, that is identified using a ceramic transducer bonded on the surface.

Damage diagnosis of concrete cube for dry condition by inducing damages in structure with the help of obtained first peak frequency.

As shown in Table 2, from equation 3.1,3.2, &3. 3, the effect of these damages on the identified structural parameters- changes in stiffness and damping and mass and damping ratio in annexure A.

a) Change in first peak frequency

In structure frequency should be observed to increase. Hence as expected, with damage progression, the first peak frequency can be observed to increase. The first peak frequency is increased after the incipient damage.

As damage progression there is increased in first peak frequency, due to increase in vibration in structure. Hence increased in frequency of structure is observed.

All calculations are depends on first peak frequency of structure.

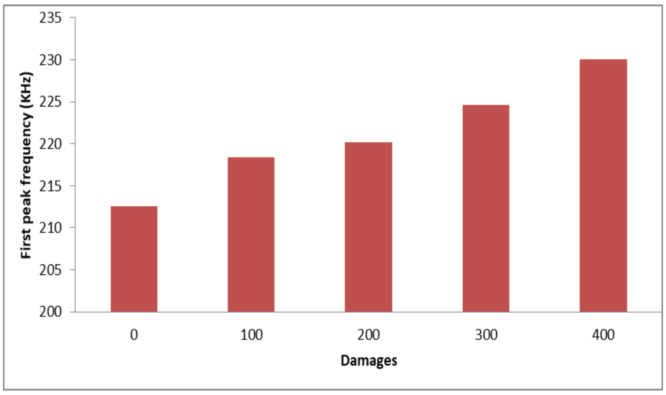


Fig.6 First peak frequency for M-15grade of concrete

From above fig. 6 shown is increased after the incipient damage. The frequency increased gradually-19.8% for the incipient damage, 27.8% for the moderate damage and 44.2% for the severe damage. Hence damages are occurred nearest to sensors.

b) Change in compressive strength

In structure stiffness should be observed as a strength. Hence as expected, with damage progression, the stiffness can be observed to reduce. The stiffness is reduced after the incipient damage. Thereafter, with further damage propagation, very small further drop/increase was observed in these parameters.

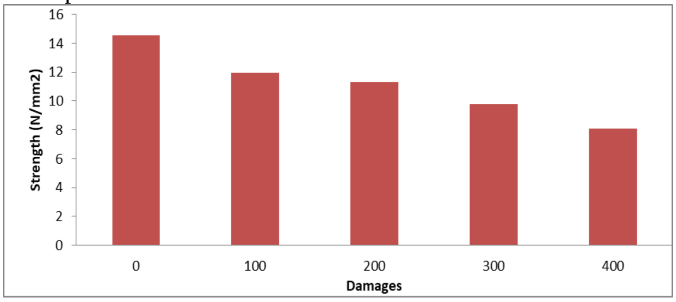


Fig.7 Compressive strength for M-15grade of concrete

From above fig.7 shown strength is reduced after the incipient damage. The stiffness reduced gradually-21.6% for the incipient damage, 28% for the moderate damage and 45% for the severe damage. Hence damages are occurred nearest to sensors.

c) Change in damping coefficient

As expected, with damage progression, damping can be observed to increase. The damping is increased after the incipient damage.

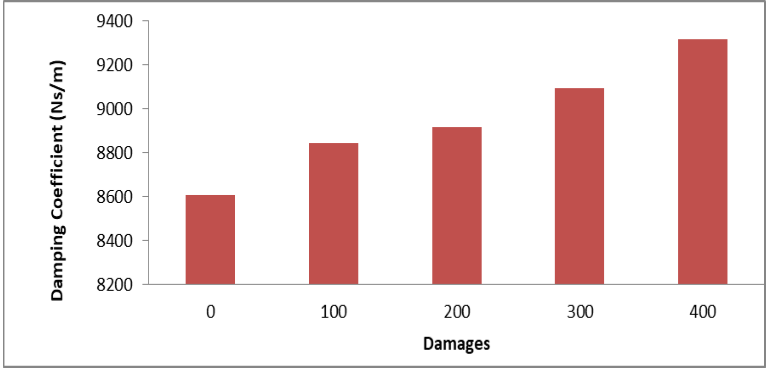


Fig 8 Damping coefficient for M-15 grade of concrete.

From fig.8 with damage progression, the damping coefficient observed to increase. The damping coefficient increased with damage severity- 2% for the incipient damage, 5% for the moderate damage and 7.5% for the severe damage.

d) Change in damping ratio

In this found that rational relation between damping ratios and damage. Damping ratio is subsequently increased with damage severity.

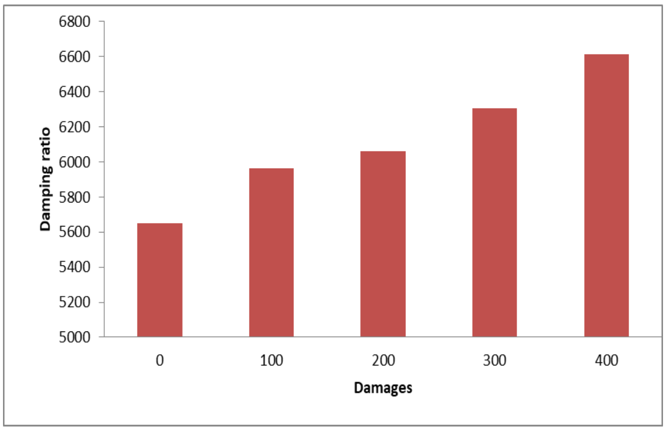


Fig. 9 Damping ratio for M-15 grade of concrete.

From fig.9 it is observed that damping ratio is increased with damage severity 5% for the incipient damage, 7% for the moderate damage and 15% for the severe damage.

From above signature for damaged and undamaged condition of concrete cube, it is found that very negligible changes in signature even after a long exposure to humid condition. Here it is observed that for compressive strength in dry condition is 7% more than humid condition which is very negligible. So this low frequency sensors gives better result for humid condition too.

IV CONCLUSION

Based on above case studies, following conclusions are drawn:

1. There is greater change in first peak frequency compared to other peak frequencies after damage.
2. It is certain that the there are negligible changes in frequencies after incipient damage. Hence, incipient damage cannot be surely detected using this techniques.
3. Frequency changes after damage also depends upon the span and geometry of the structure.
4. It may be possible that frequency changes for the same level damage in same structure are different, depending upon how the damage originated in the structure.
5. There are noticeable changes in frequencies for moderate to severe damage. Hence, this technique is suitable for prediction of presence of moderate to severe damage.
6. It may be further noted that the change in damping ratio will be more if the damage is located near the sensor but variation in damping ratio measured by different sensors for same level damage can be ignored. However, changes in damping ratio with damage for a sensor are noticeable. Hence, damping ratio can be treated as parameter to differentiate damage severity especially for moderate to severe damage. The main advantage here is that damping ratio can be measured without measuring the excitation force. The damping ratio is a representation of the region surrounding of the PZT patch.
7. It is observed that very negligible changes occurred in signature for humid condition as compared to dry condition hence it observed that PZT patches protected by plastic fiber gives better result for humid condition.
8. Hence that humidity has exercised adverse effect on the signatures is clearly evident by the substantial vertical shift in the signature as shown in all signature.

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