DEPARTMENT OF CIVIL ENGINEERING

IIT DELHI

# FATIGUE DAMAGE DIAGNOSIS IN STEEL/ RC STRUCTURES


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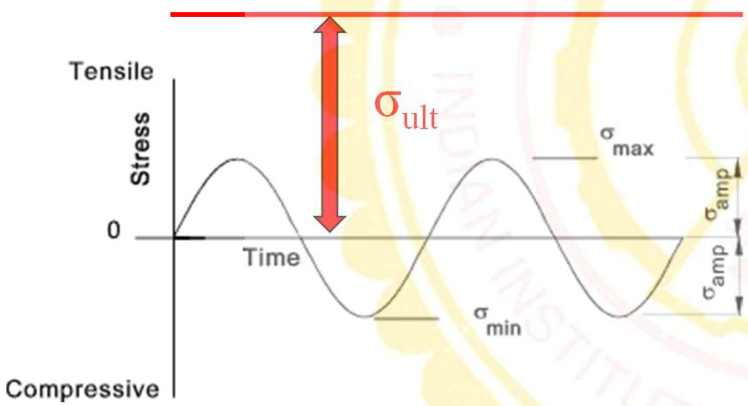
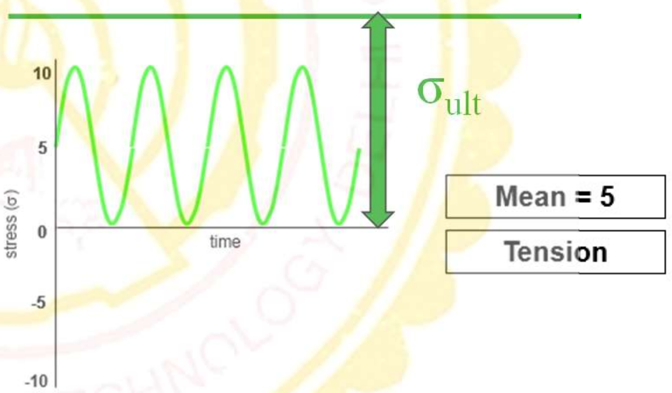
# WHAT IS FATIGUE?

**'Fatigue', is a weakened condition in structures caused by repeated loading, ultimately resulting in fracture at a stress much lower than that necessary to cause fracture in static application.**




Several major failures across the world have been found to be initiated by fatigue, such as the Seongsu Bridge in Seoul.

# FATIGUE IN METALS

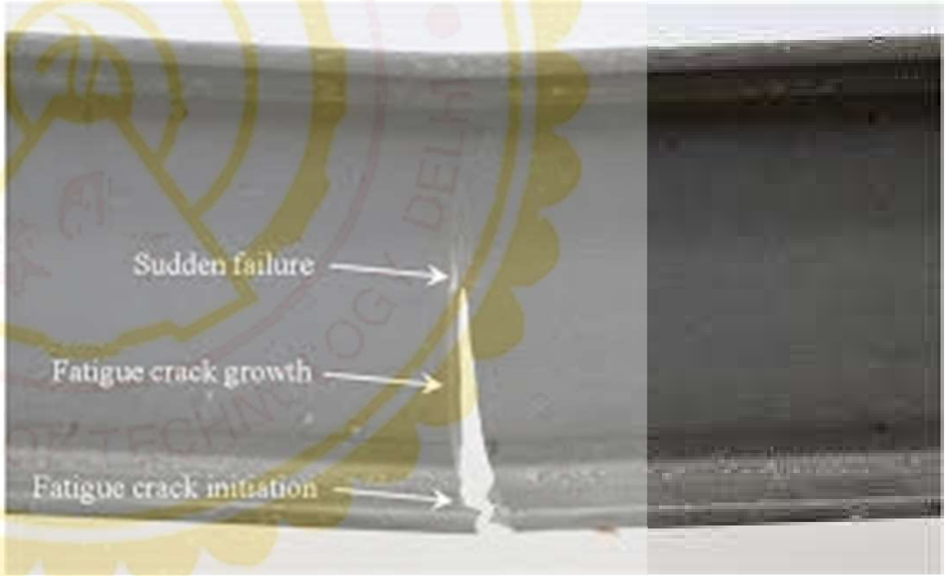
Fatigue begins as a well-demarcated crack.

The crack progressively advances in three phases –

(a) initiation/nucleation,

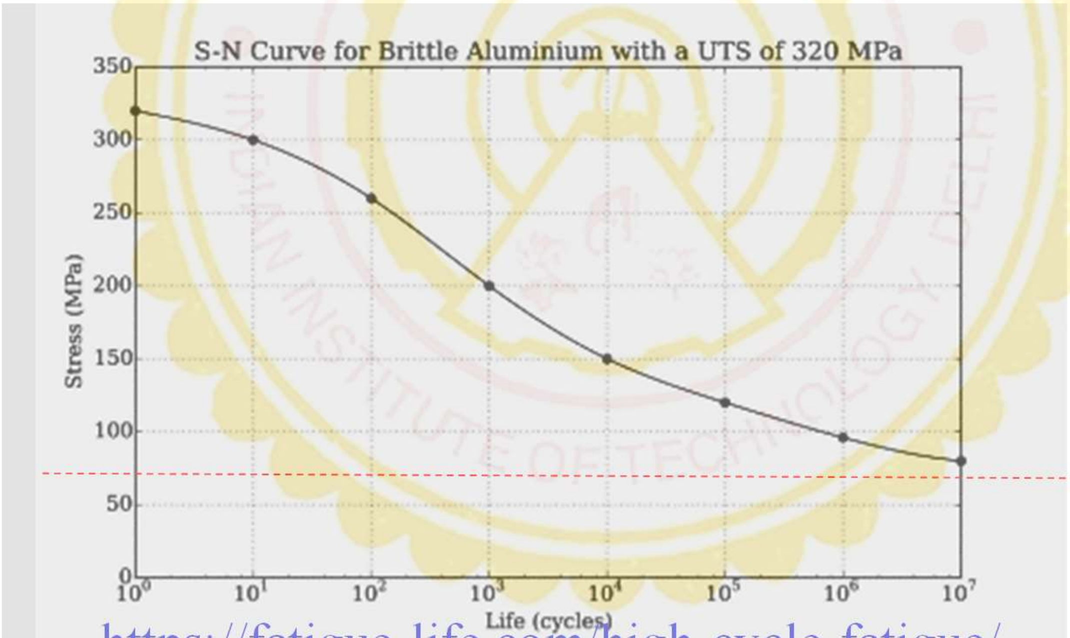
(b) slow sustained growth, and finally,

(c) culminating in abrupt failure .



# S-N CURVE

Fatigue in metals can be represented in terms of the plot of the maximum induced stress versus the number of load cycles to failure, commonly called as the S-N or the Wohler curve.



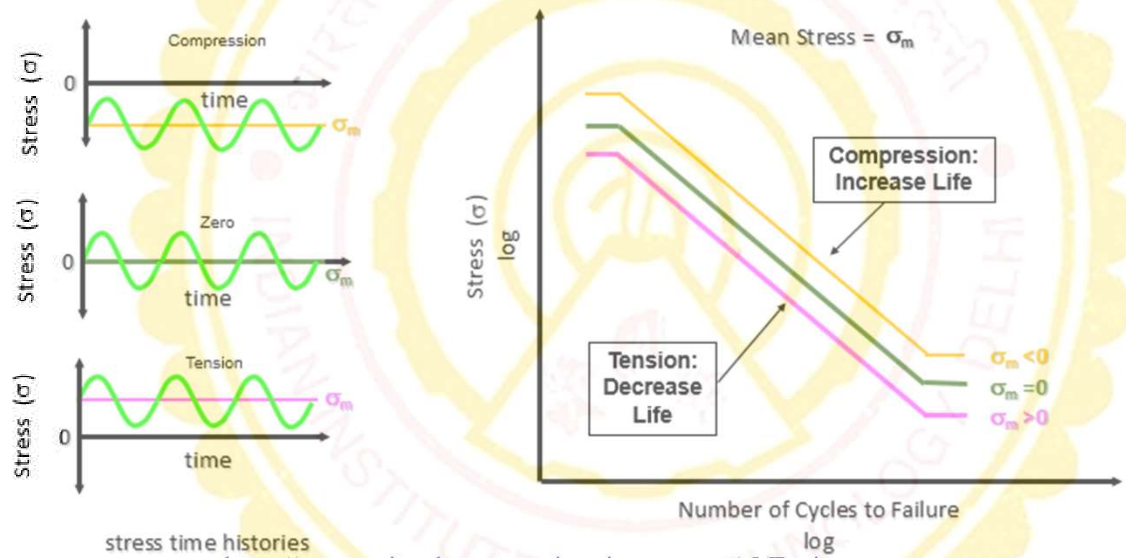

https://fatigue-life.com/high-cycle-fatigue/

**Fatigue limit or**

**Endurance limit**

# REMAINING LIFE PREDICTION

SN curves can be used for making some degree estimation about the service life of a metallic component when subjected to a known amplitude of cyclic loads.




https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/What-is-a-SN-Curve/ta-p/355935

Most metals have SN curves asymptotic to a definite stress value, called as the 'fatigue limit' or "endurance limit"…i.e the stress level below which an infinite number of loading cycles can be applied to a material without causing fatigue

# HOW TO MONITOR FATIGUE INDUCED DAMAGE?

Fatigue damage can be monitored by observing changes in specimen's stiffness as a function of the number of loading cycles.

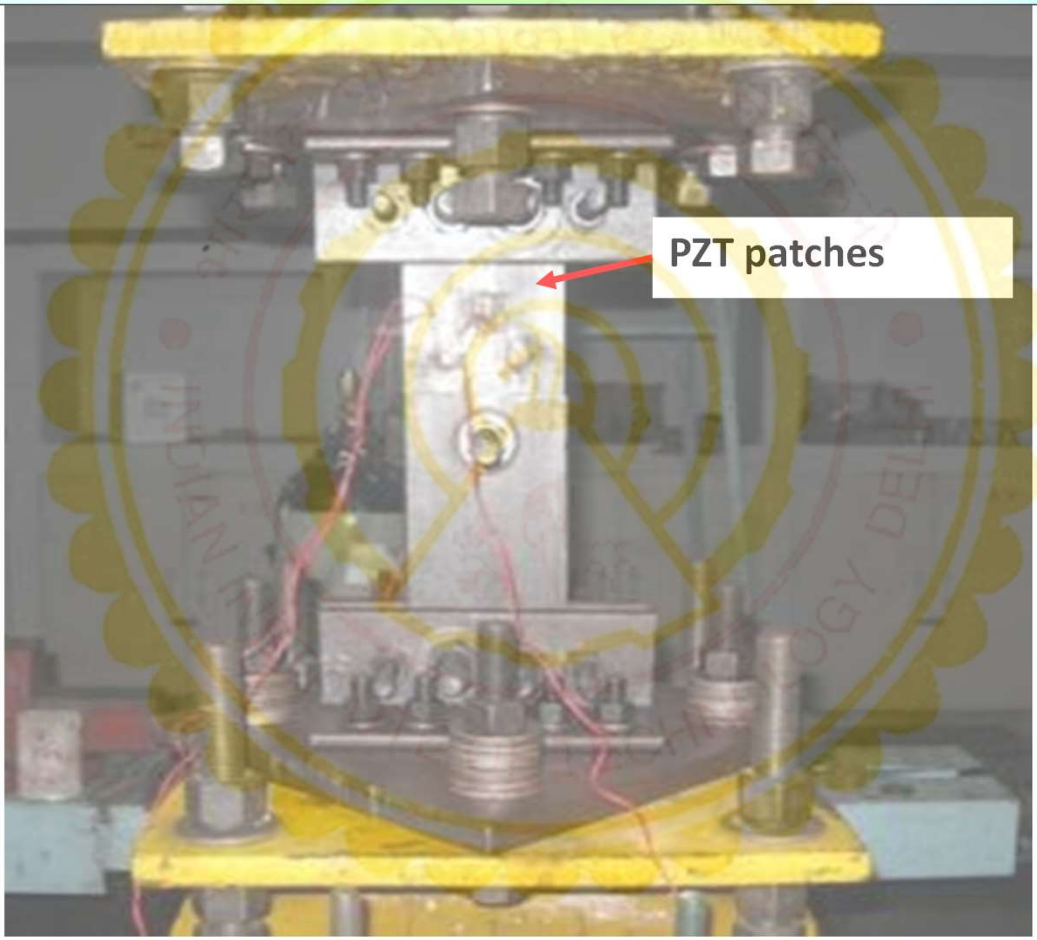
However, in a structural component under service (say a large bridge joint), it is in general not possible to determine the residual stiffness while the component is under service.

Also, difficult to estimate the number of cycles of loading undergone till now.

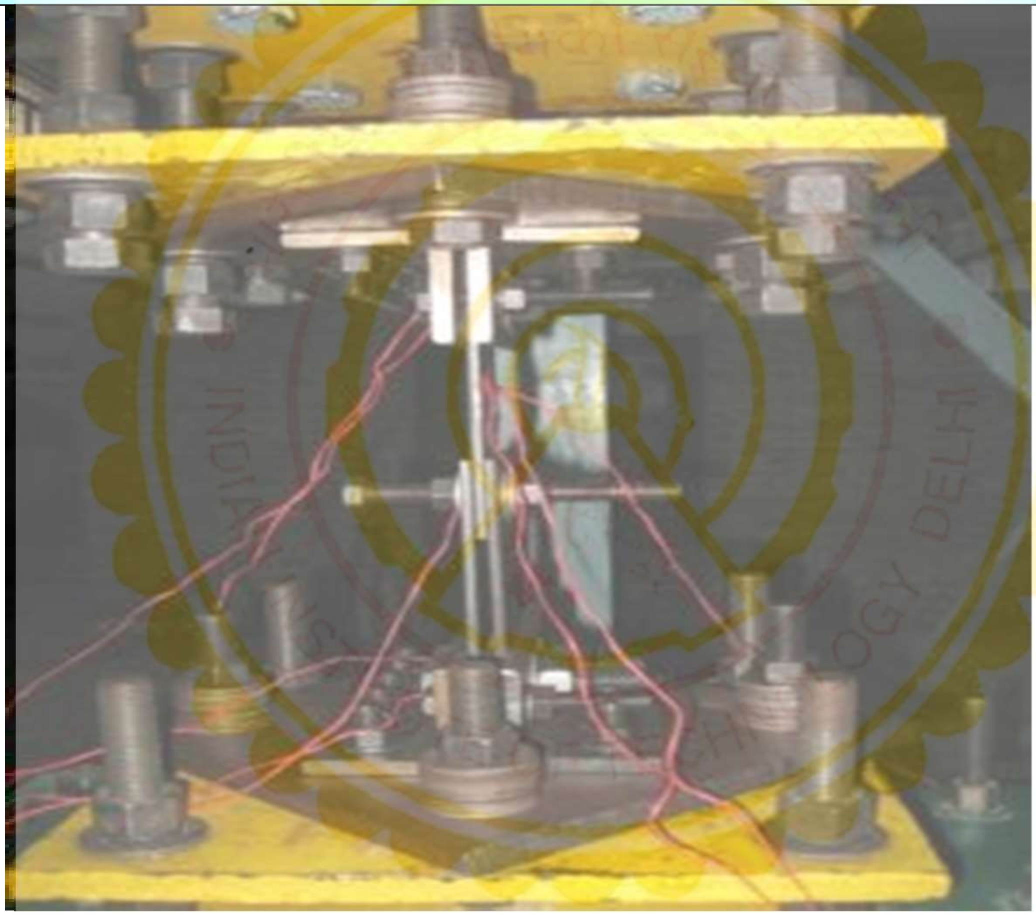
## CASE STUDY(I)

# IMPEDANCE-BASED DAMAGE ASSESSMENT OF STEEL JOINTS

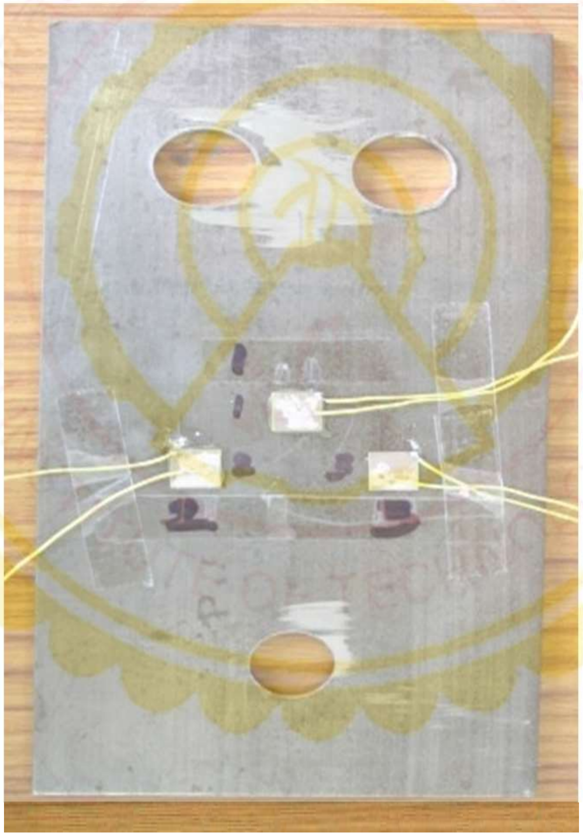
# SPECIMEN 1



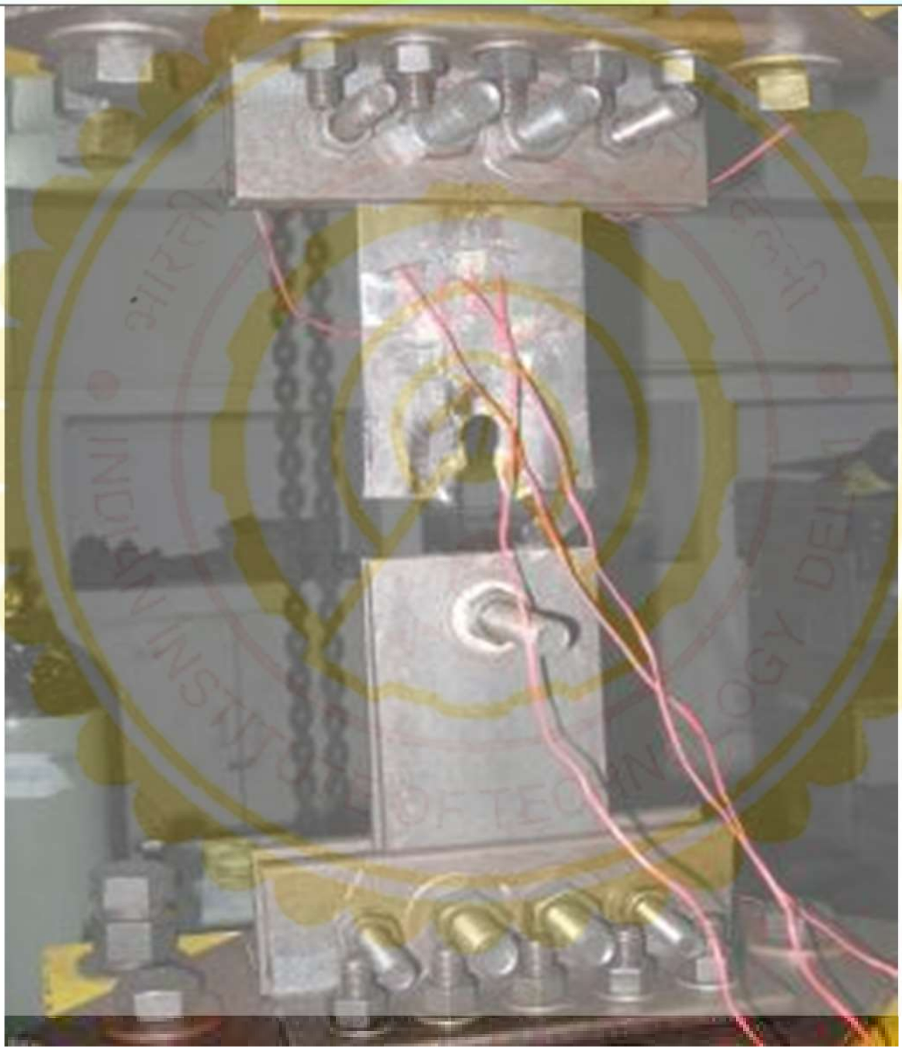
# SPECIMEN 1



| CYCLES | CYCLE RATIO CR (= $N/N_o$) | OPERATING FREQUENCY | STRESS EXTREMES |
|---|---|---|---|
| 0-26000 | 0-0.409 | 3 Hz | $0.08f_y$-$0.64f_y$ |
| 26001-58500 | 0.409-0.92 | 4 Hz | $0.216f_y$-$0.608f_y$ |
| 58501-63586 | 0.92-1 | 5 Hz | $0.314f_y$-$0.664f_y$ |



# SPECIMEN 1: FAILURE PATTERN



# SPECIMEN 2

# SPECIMEN 2: FAILURE PATTERN

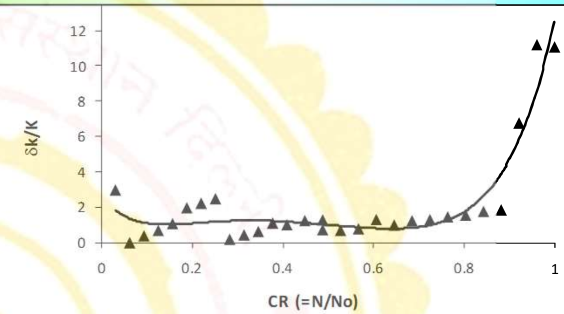
| CYCLES | CYCLE RATIO CR (= $N/N_o$) | OPERATING FREQUENCY | STRESS EXTREMES |
|---|---|---|---|
| 0-17351 | 0-1 | 5 Hz | $0.08f_y$-$0.88f_y$ |

# SPECIMEN 3

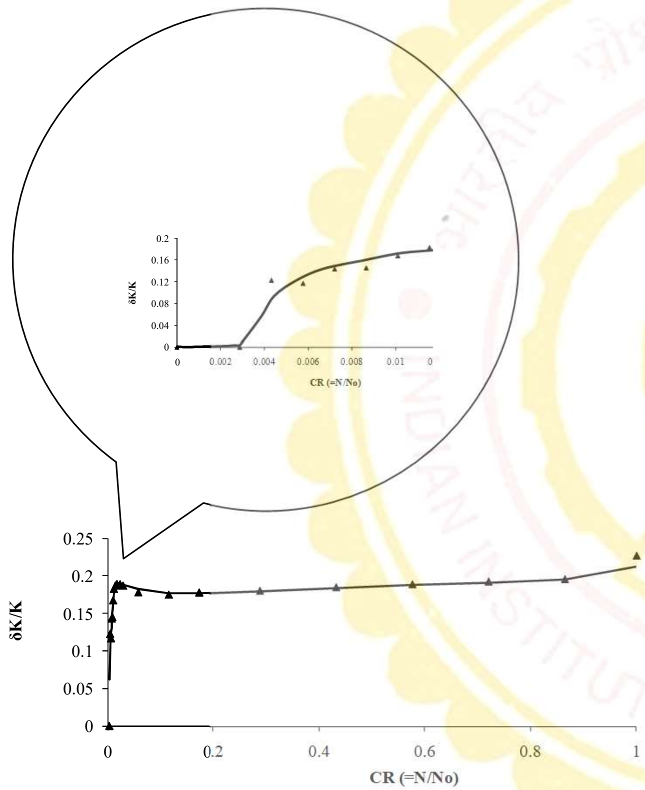
# SPECIMEN 3: FAILURE PATTERN

| CYCLES | CYCLE RATIO CR (= $N/N_o$) | OPERATING FREQUENCY | STRESS EXTREMES |
|---|---|---|---|
| 0-40,000 | 0-0.308 | 5 Hz | $0.062f_y$-$0.7f_y$ |
| 40,001-90,000 | 0.308-0.692 | 5 Hz | $0.0625f_y$-$0.8f_y$ |
| 90,001-13,0000 | 0.692-1 | 5 Hz | $0.0625f_y$-$0.94f_y$ |

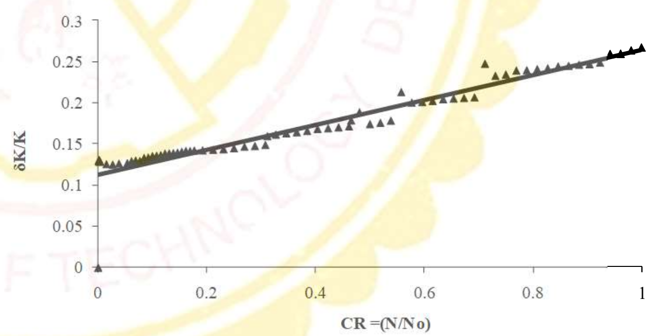
# STIFFNESS LOSS WITH DAMAGE




SPECIMEN 1




SPECIMEN 2




SPECIMEN 3

# STATISTICAL DAMAGE QUANTIFICATION

Root Mean Square Deviation (RMSD)= $\sqrt{\dfrac{\sum_{i=1}^{i=N}(w_i - u_i)^2}{\sum_{i=1}^{i=N} u_i^2}}$

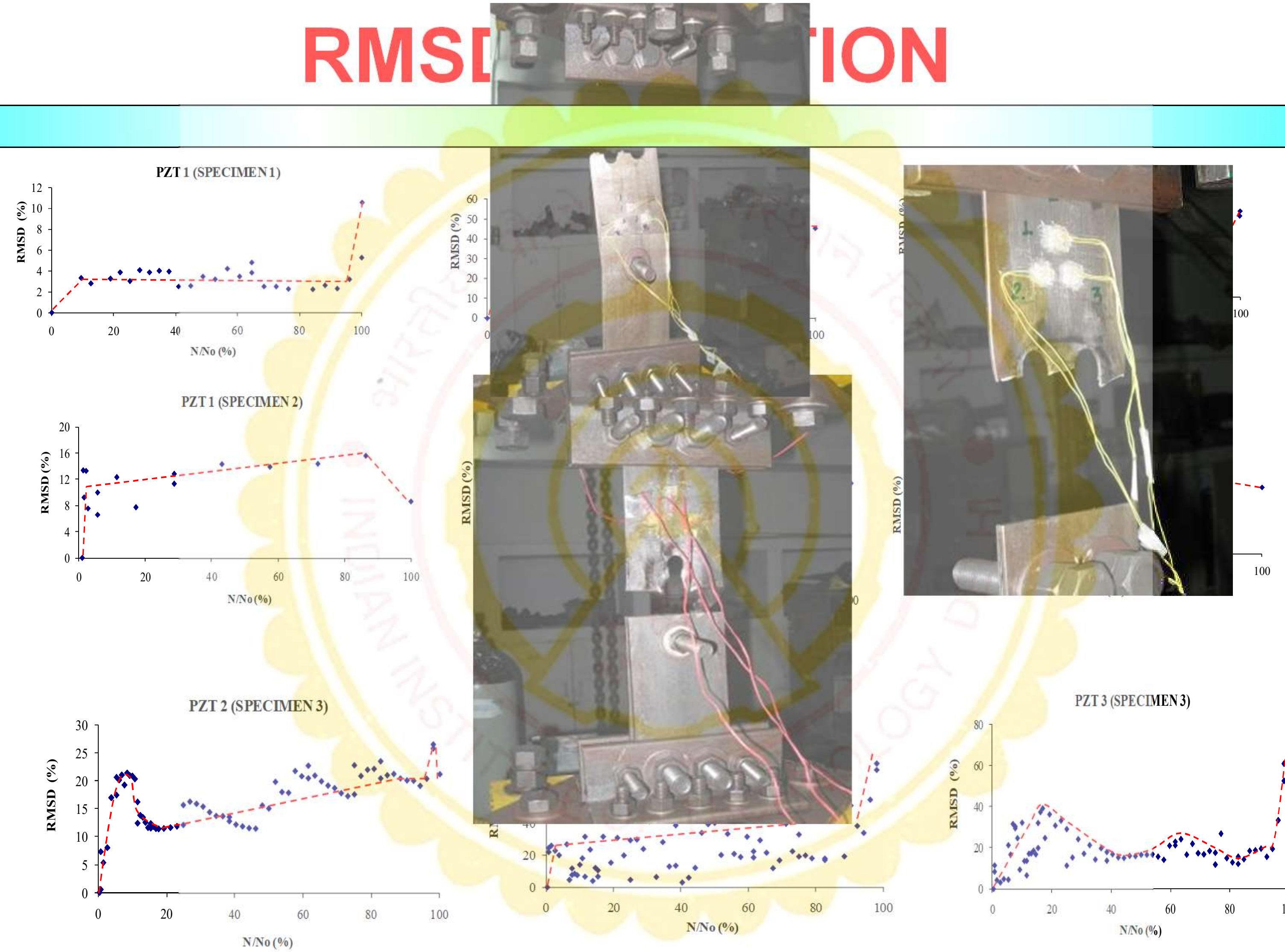
**Signature before damage**= $[u_i]$,

**Signature after damage** = $[w_i]$ ;

i= 1,2,3,....

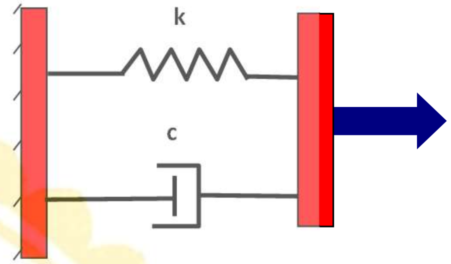
**Non- Parametric Damage Quantification**

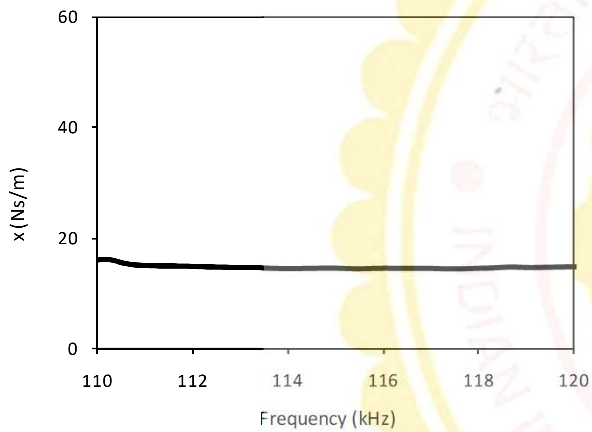
# RMSD TION




**Conclusion:** Largely scatter, no good correlation with damage, no uniform scale

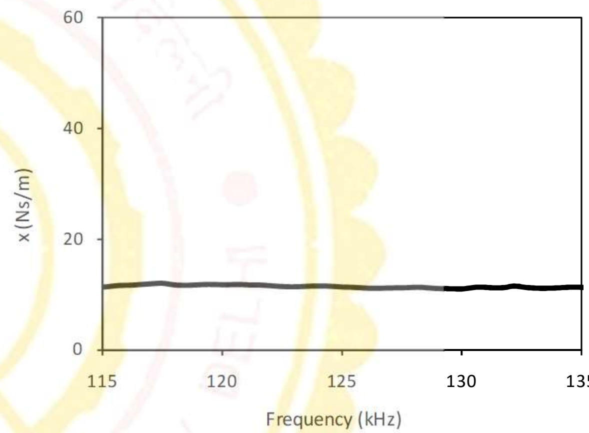
# MECHANICAL IMPEDANCE APPROACH.....HOW BETTER?

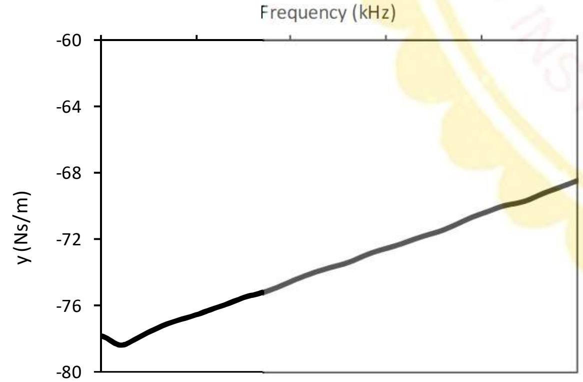


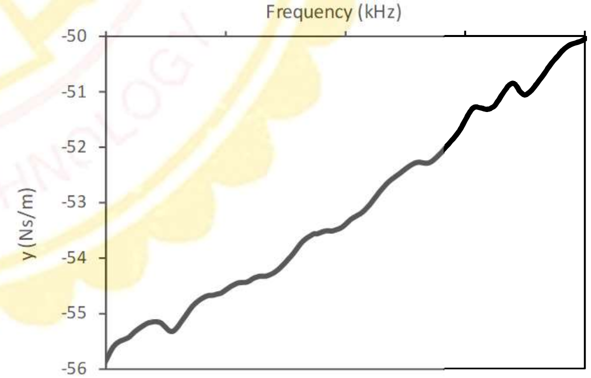




$$x = c$$

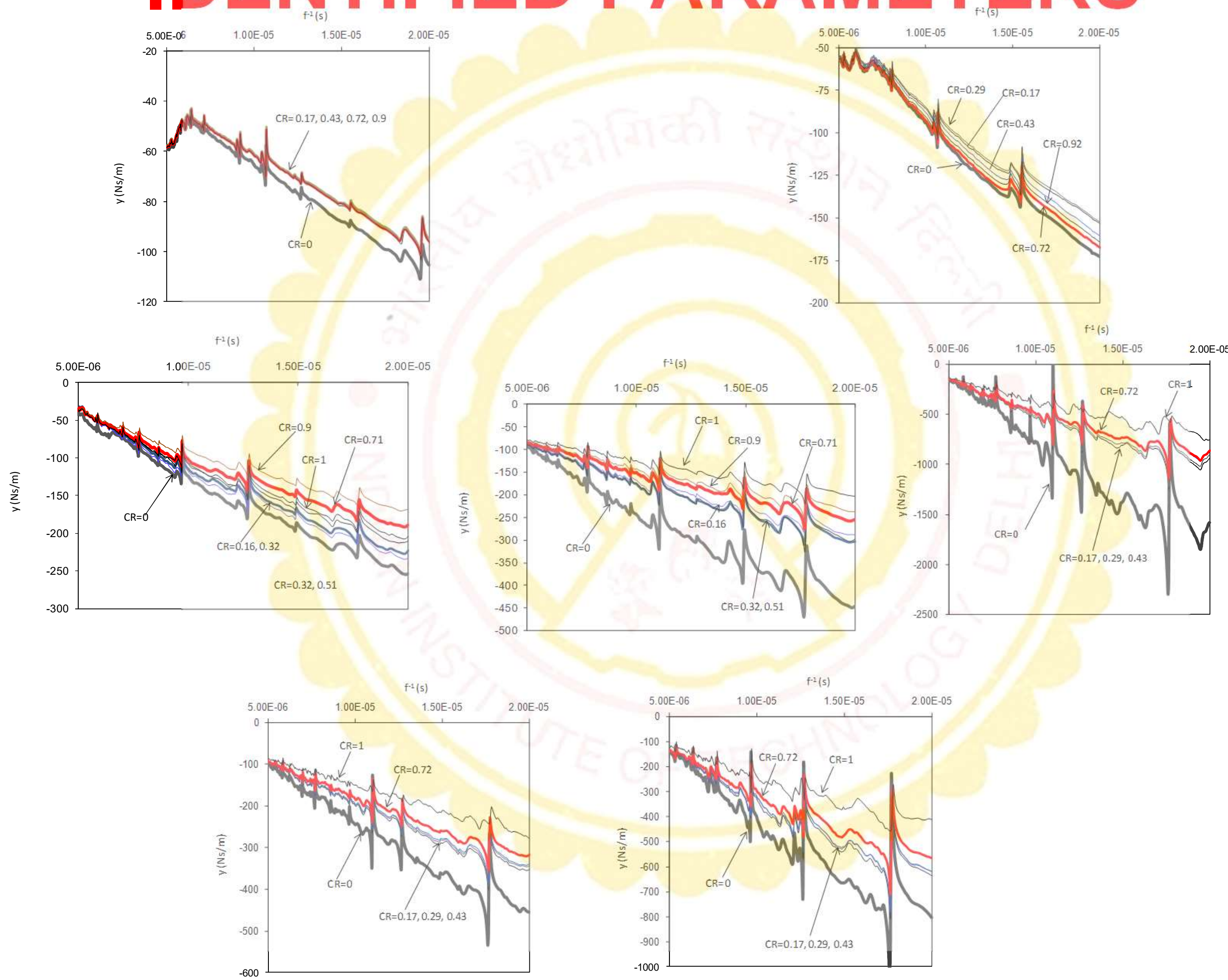
$$y = \frac{-k}{\omega}$$



# IDENTIFIED PARAMETERS



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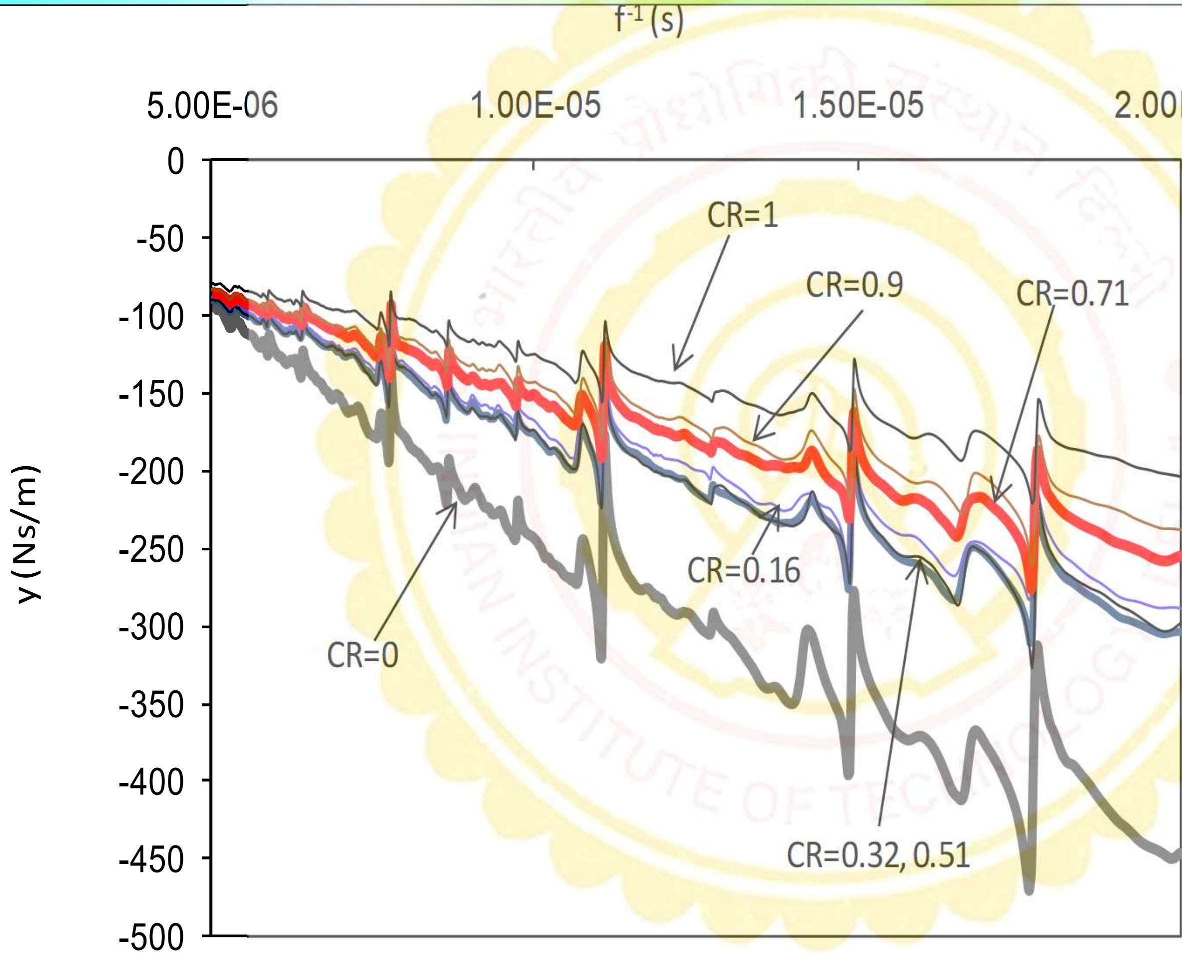
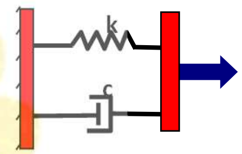


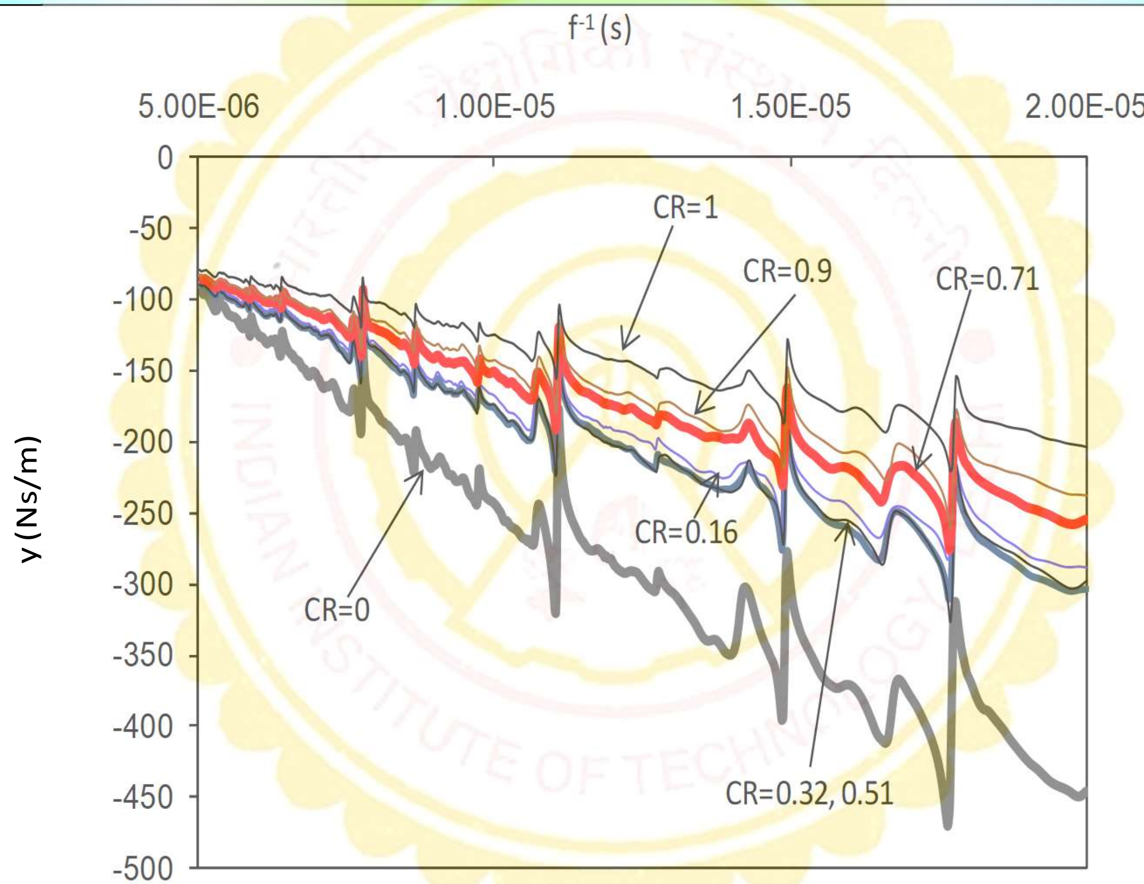

$$x = c$$

$$y = \frac{-k}{\omega}$$

$$k = avg(-2\pi f y)$$

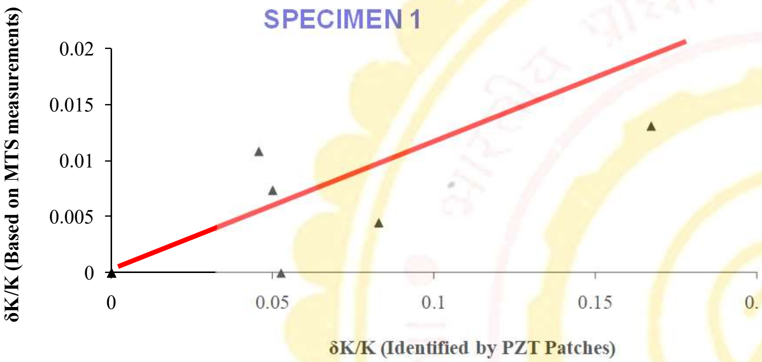
$$c = avg(x)$$

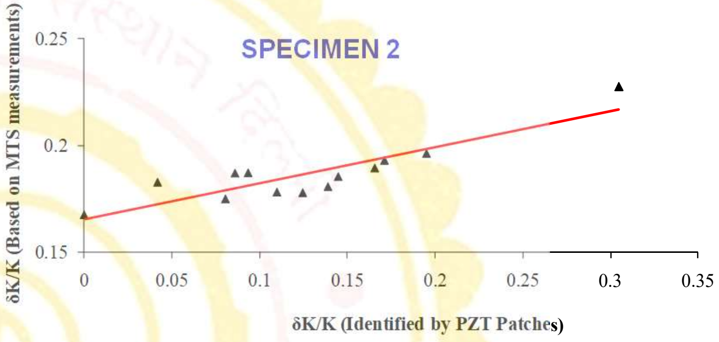
# PIEZO-IDENTIFIED STIFFNESS

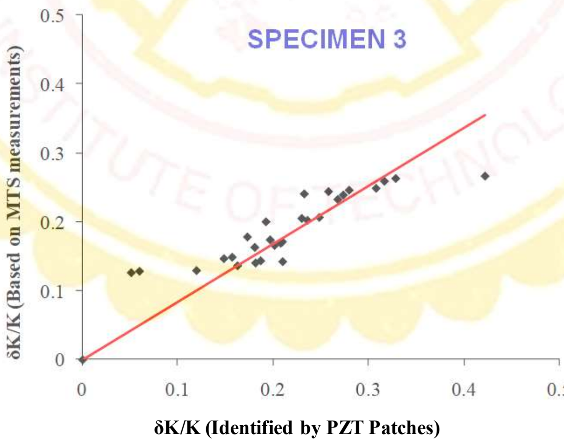



**Consistent performance of equivalent stiffness parameter in terms of reduction in piezo-identified stiffness**

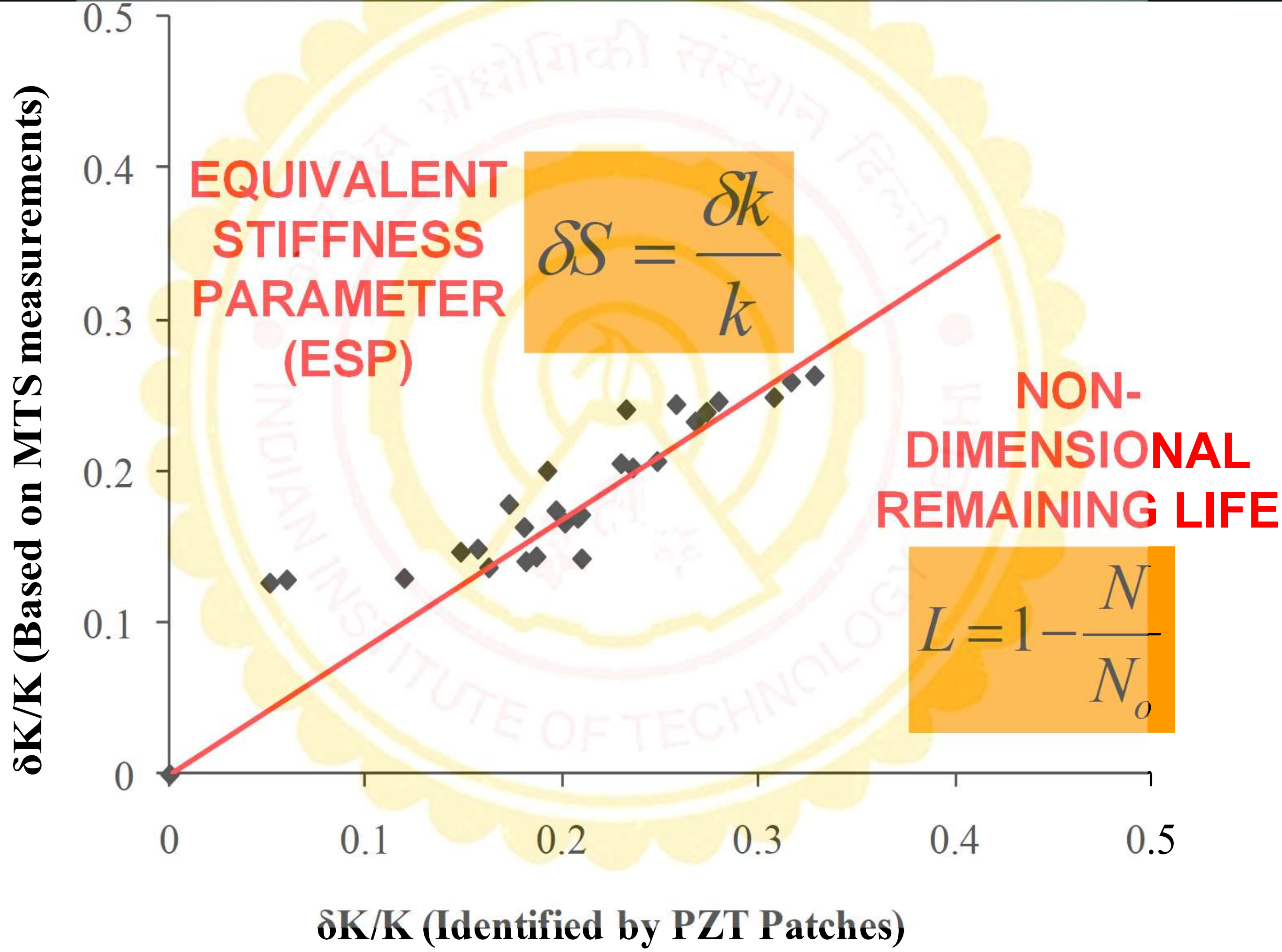
# CORRELATION OF PIEZO-IDENTIFIED STIFFNESS WITH ACTUAL STIFFNESS



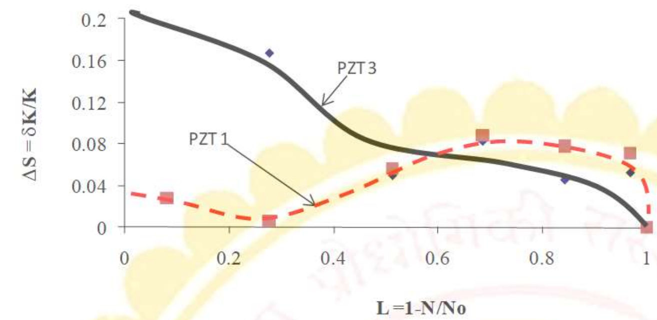



## VERY STRONG EMIPIRICAL CORRELATION BETWEEN NORMALIZED "IDENTIFIED STIFFNESS" AND "ACTUAL STIFFNES" IN NON-DIEMNSIONAL TERMS

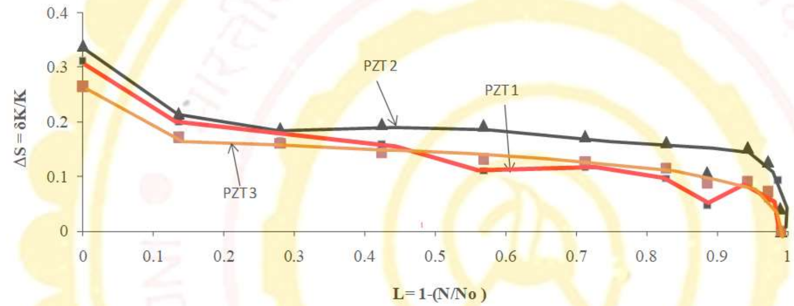



$$\delta S = \frac{\delta k}{k}$$

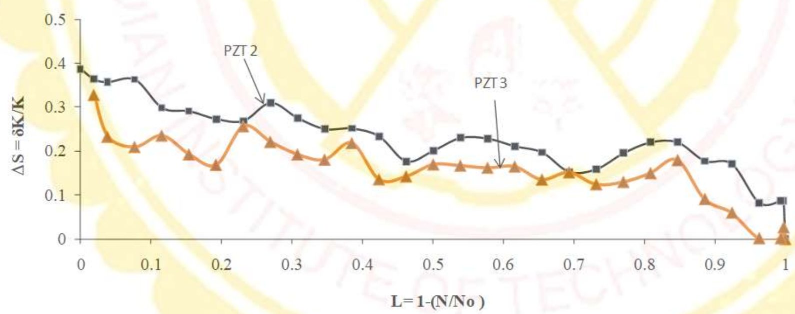
$$L = 1 - \frac{N}{N_o}$$




SPECIMEN 1




SPECIMEN 2



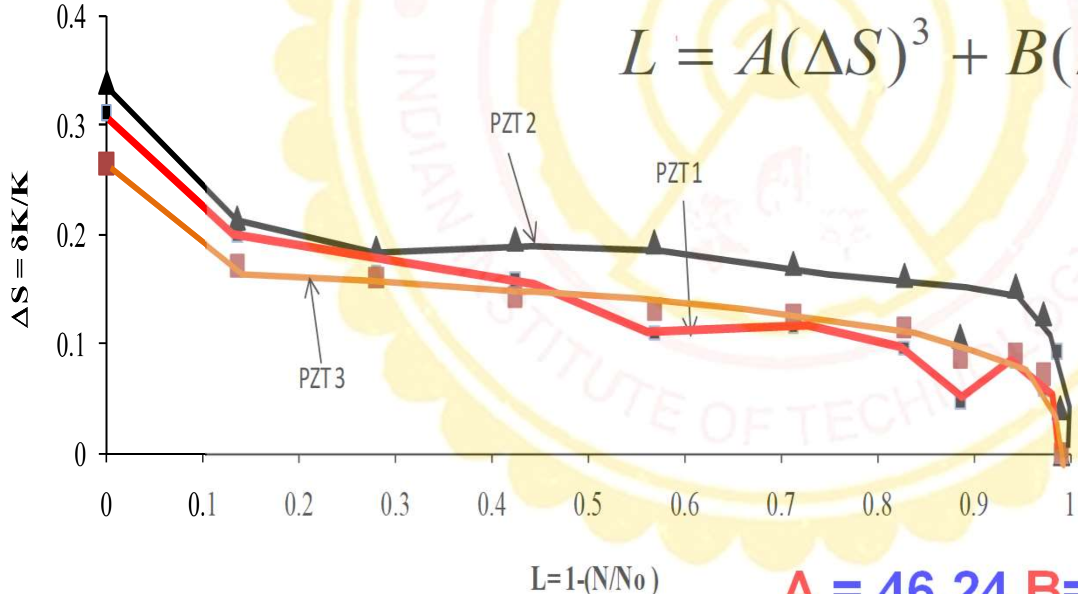

SPECIMEN 3

$$L = A(\Delta S)^3 + B(\Delta S)^2 + C(\Delta S) + 1$$

# EMPIRICAL MODEL FOR RESIDUAL LIFE DETERMINATION FROM PIEZO-IDENTIFIED STIFFNESS LOSS

$$\delta S = \frac{\delta k}{k} \qquad L = 1 - CR = 1 - \frac{N}{N_o}$$

$$L = A(\Delta S)^3 + B(\Delta S)^2 + C(\Delta S)$$




A = 46.24 B= 225.64 C =0.463

# EQUIVALENT STIFFNESS PARAMETER (ESP)

- **PZT IDENTIFIED STIFNESS CORRELATES WELL WITH ACTUAL STIFFNESS**
- **RESIDUAL LIFE CAN BE ESTIMATED FROM LOSS OF EQUIVALENT IDENTIFIED STIFFNESS.**
- **THE PROPOSED APPROACH FACILITATES RESIDUAL FATIGUE LIFE WITHOUT DETERMINING ACTUAL STIFFNESS OF THE COMPONENT**

**Bhalla, S.**, Vittal, A. P. R and Veljkovic, M. (2012), "Piezo-Impedance Transducers for Residual Fatigue Life Assessment of Bolted Steel Joints", Structural Health Monitoring, *An International Journal*, Vol. 11, No 6 (Nov), pp. 733-750. **DOI: 10.1177/1475921712458708.**

## Suggested reading:
## Bhalla et al. (2012)

**(downloadable links at:**
**http://web.iitd.ac.in/~sbhalla/journals.pdf )**

# CASE STUDY(II)

# IMPEDANCE-BASED DAMAGE ASSESSMENT OF STEEL JOINTS

# FATIGUE IN REINFORCED CONCRETE

In the context of concrete, which is a composite material consisting of rocky aggregate in a cement-mortar matrix, the phenomenon of fatigue manifests somewhat differently.

Here, the beginning of fatigue damage is marked by the development of micro-cracks, which, in contrast to metals, are widespread throughout the matrix.

Further damage progression leads to the appearance of larger cracks, but not as localized as in the case of the metals.

# FATIGUE IN CONCRETE

In contrast to metals, the fatigue limit cannot be explicitly defined for concrete.

Rather, fatigue limit is expressed as the strength after undergoing a specified number of cycles, say a million.

Another distinguishing feature of concrete fatigue, as opposed to metals, is the phenomenon of temporary recovery during the rest periods.

# LOW AND HIGH CYCLE FATIGUE

**Low-cycle fatigue (high-strain fatigue):**

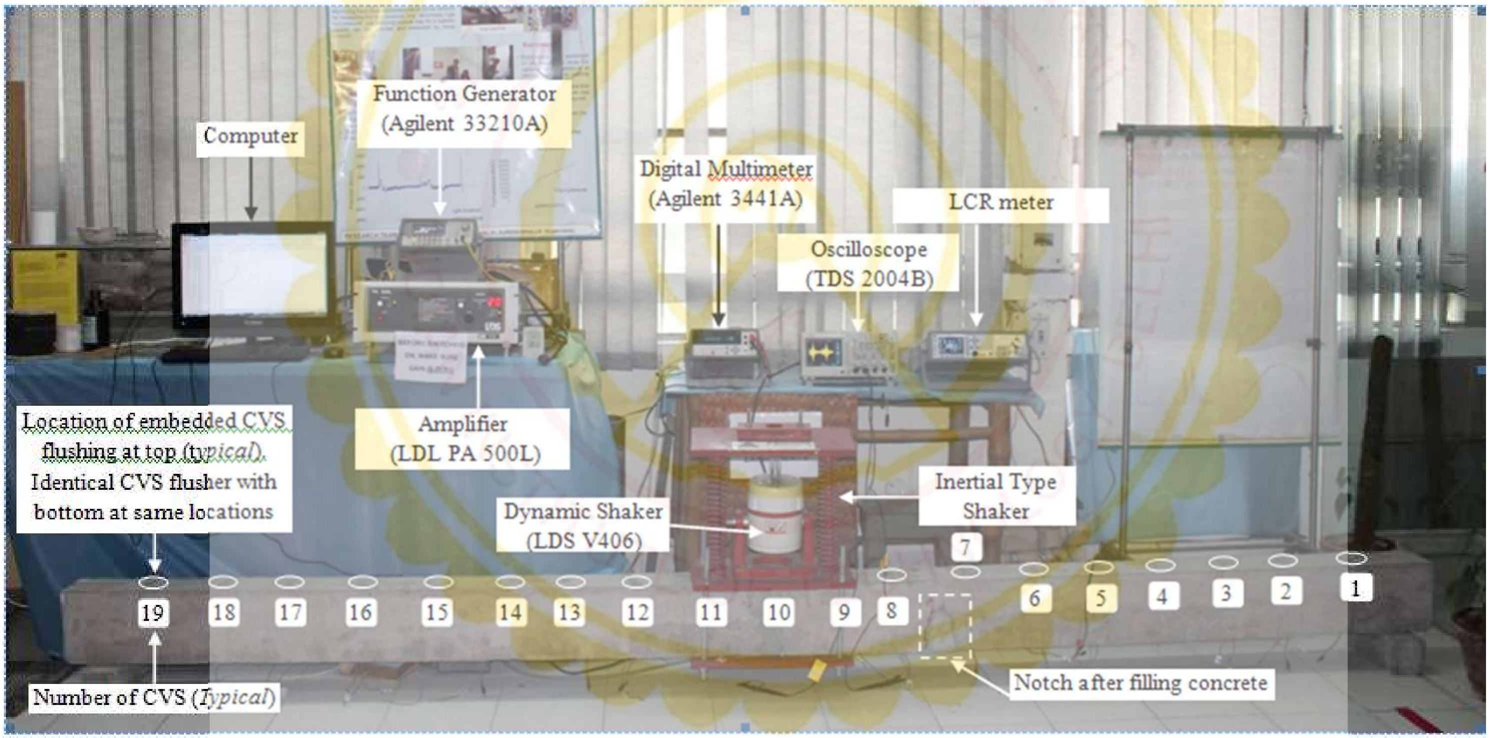
**The component fails in relatively small (< 10,000) cycles**

**High-cycle fatigue (low-strain fatigue):**

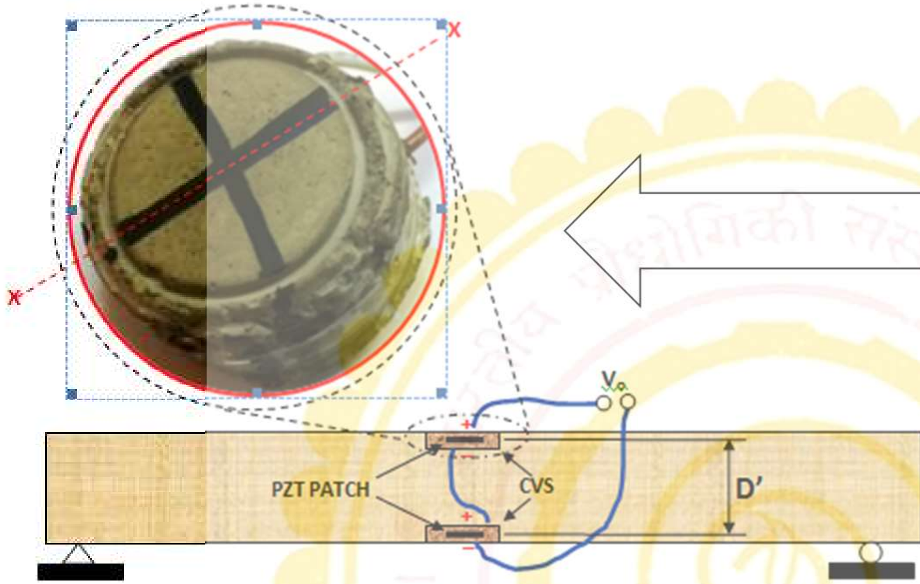
**The component fails in > 10,000 cycles**

# CASE STUDY: DAMAGE PROGNOSIS OF RC STRUCTURES UNDER LOW-STRAIN FATIGUE

4m long RC beam subjected to over 8 million cycles with extreme fibre strains restricted to 50 microns. PZT patches acting as Concrete Vibration Sensor (CVS) monitored damage

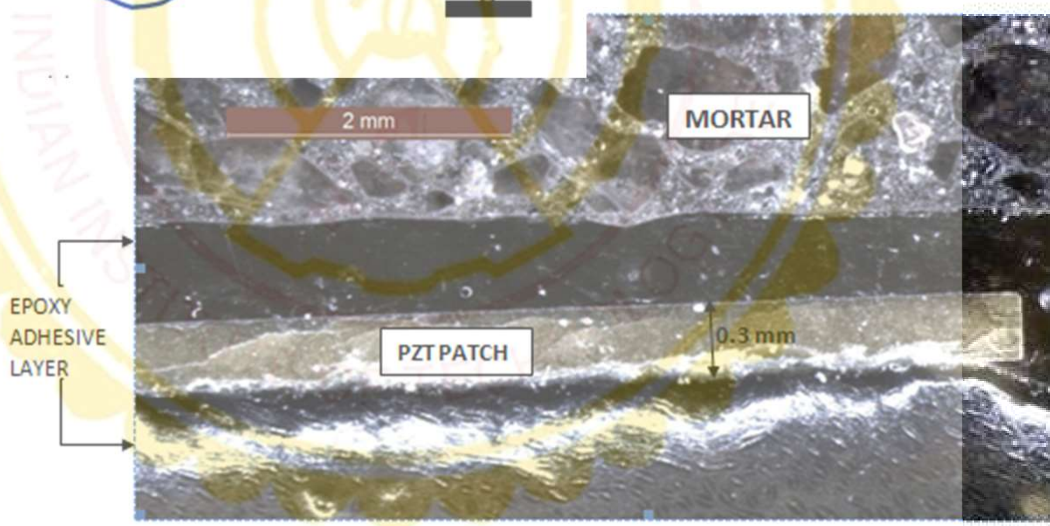



**Bhalla, S.** and Kaur, N. (2018), "Prognosis of Low-Strain Fatigue Induced Damage in Reinforced Concrete Structures Using Embedded Piezo-Transducers", International Journal of Fatigue, Vol. 113 (Aug), pp. 98-112. **DOI: 10.1016/j.ijfatigue.2018.04.002**



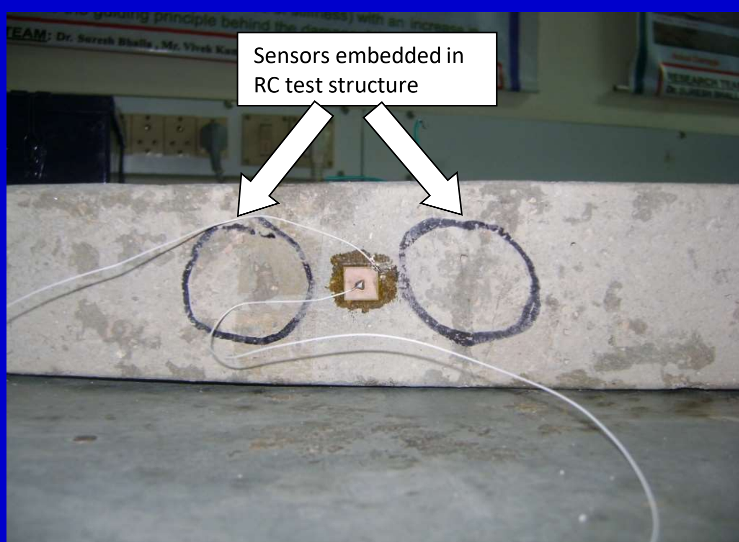

# CVS

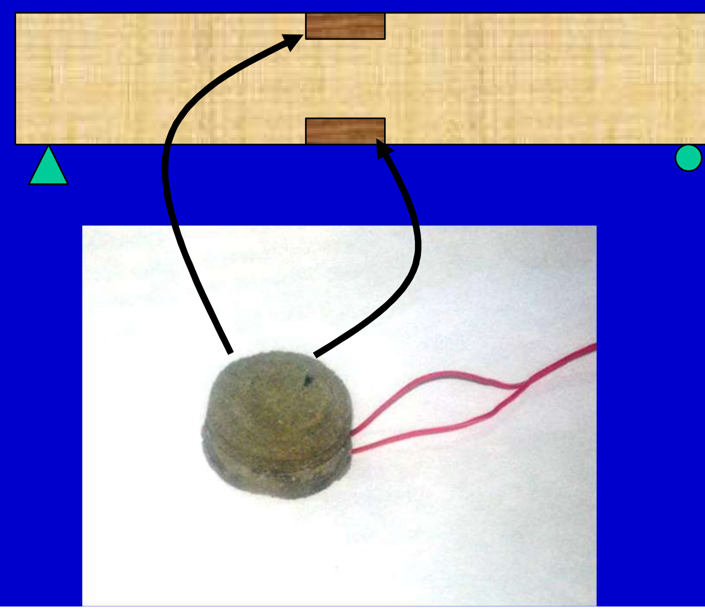
**Optical image of sensor structure**



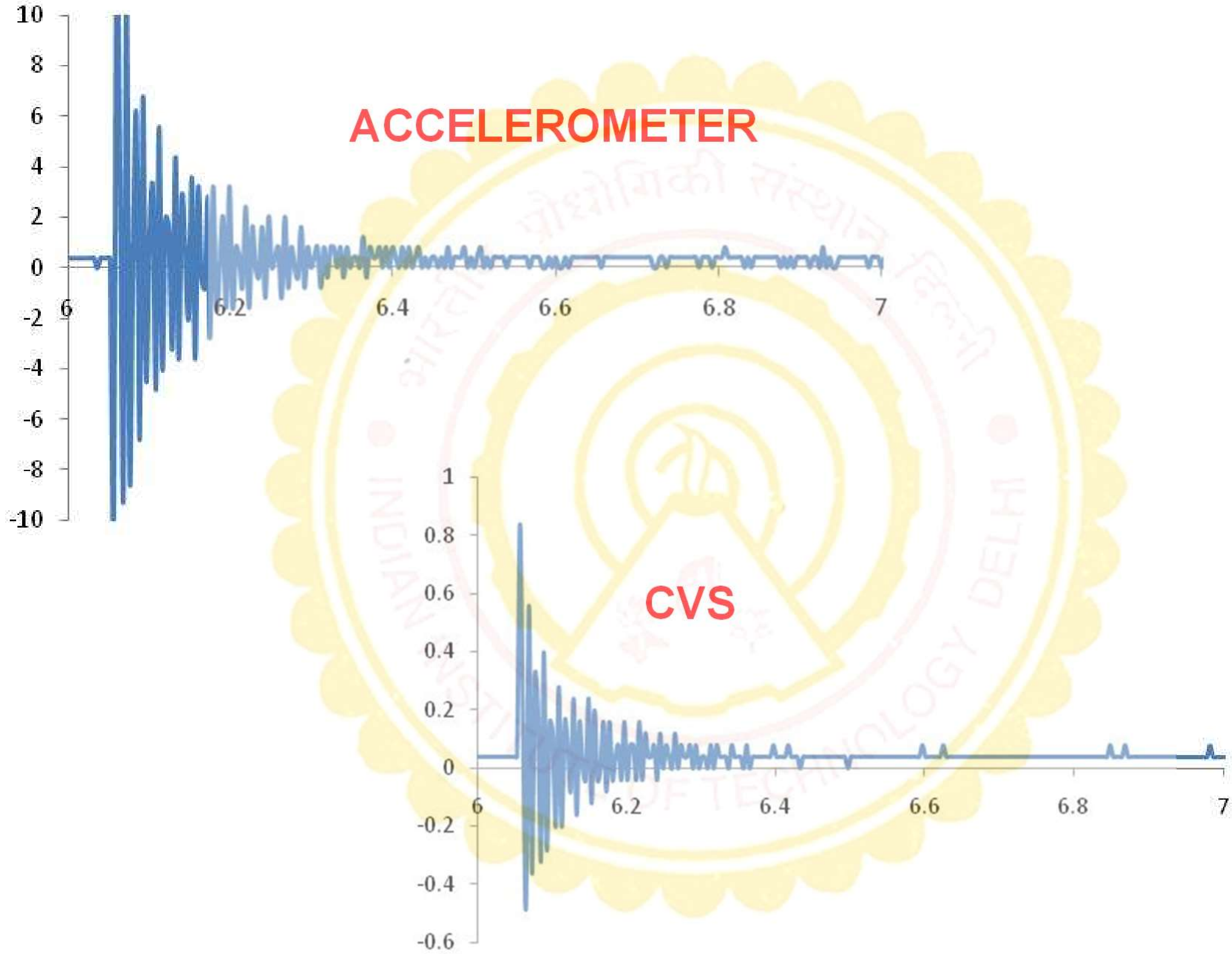
# CONCRETE VIBRATION SENSOR (CVS)

CVS is a ready to use packaged sensor for dynamic response measurement developed especially for reinforced concrete structures such as buildings and bridges.



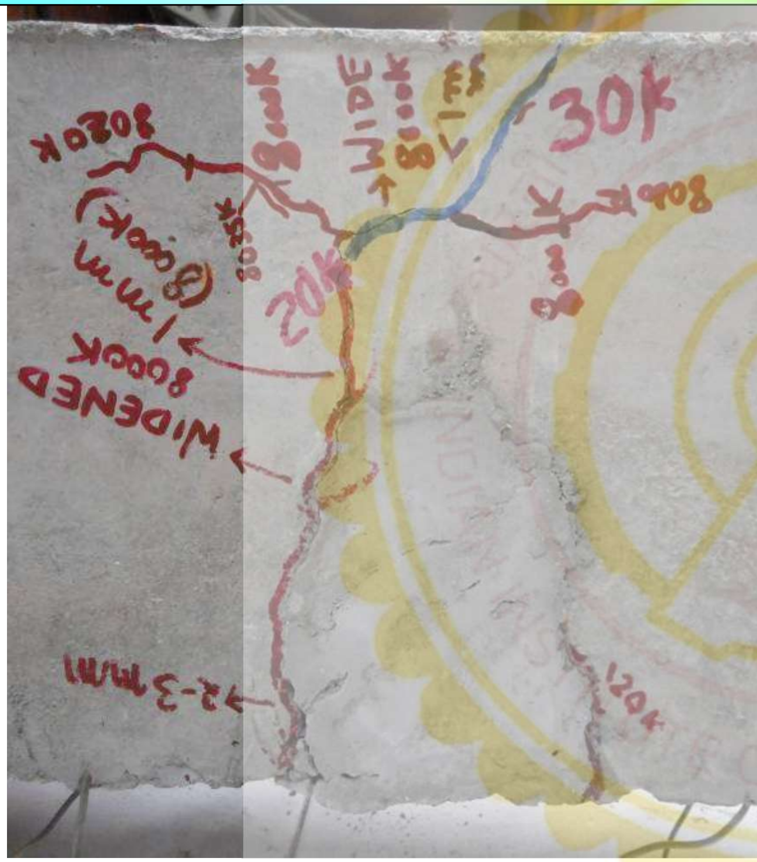




EXPT 5
BEAM 2.

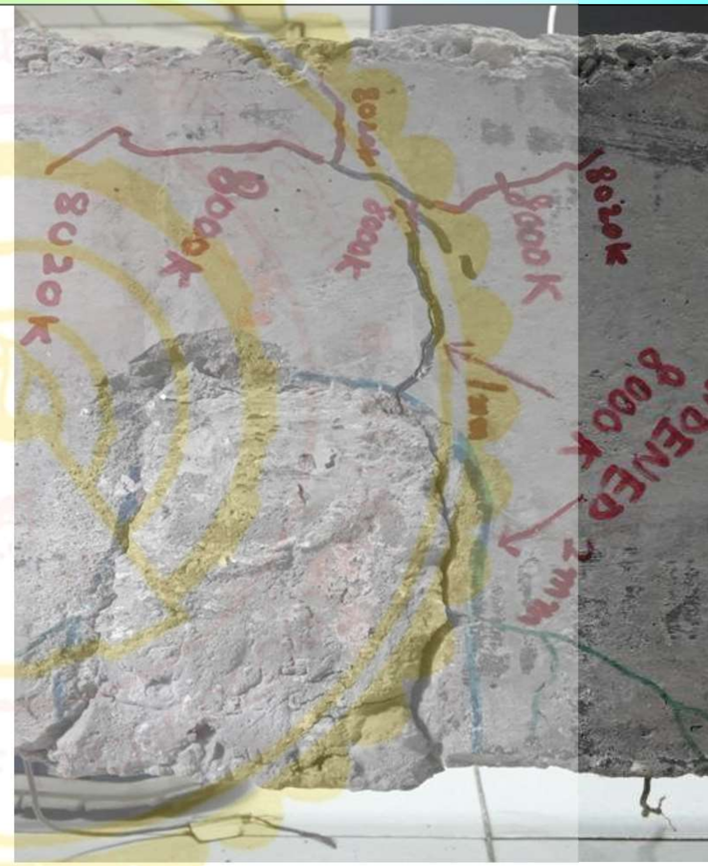

ACCELEROMETER
10
8
6
4
2
0
-2
-4
-6
-8
-10
6
6.2
6.4
6.6
6.8
7
CVS
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
6
6.2
6.4
6.6
6.8
7

# CRACK FORMATION PATTERN (900 K CYCLES)


# FINAL CRACK PATTERN

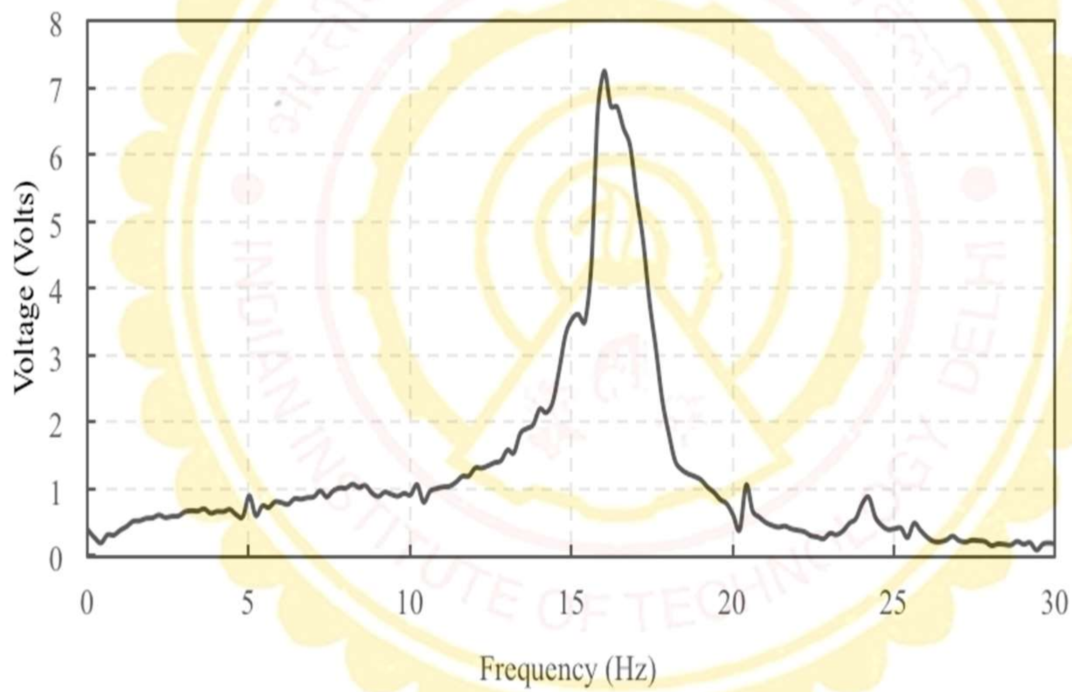


FRONT (NEAR NOTCH)



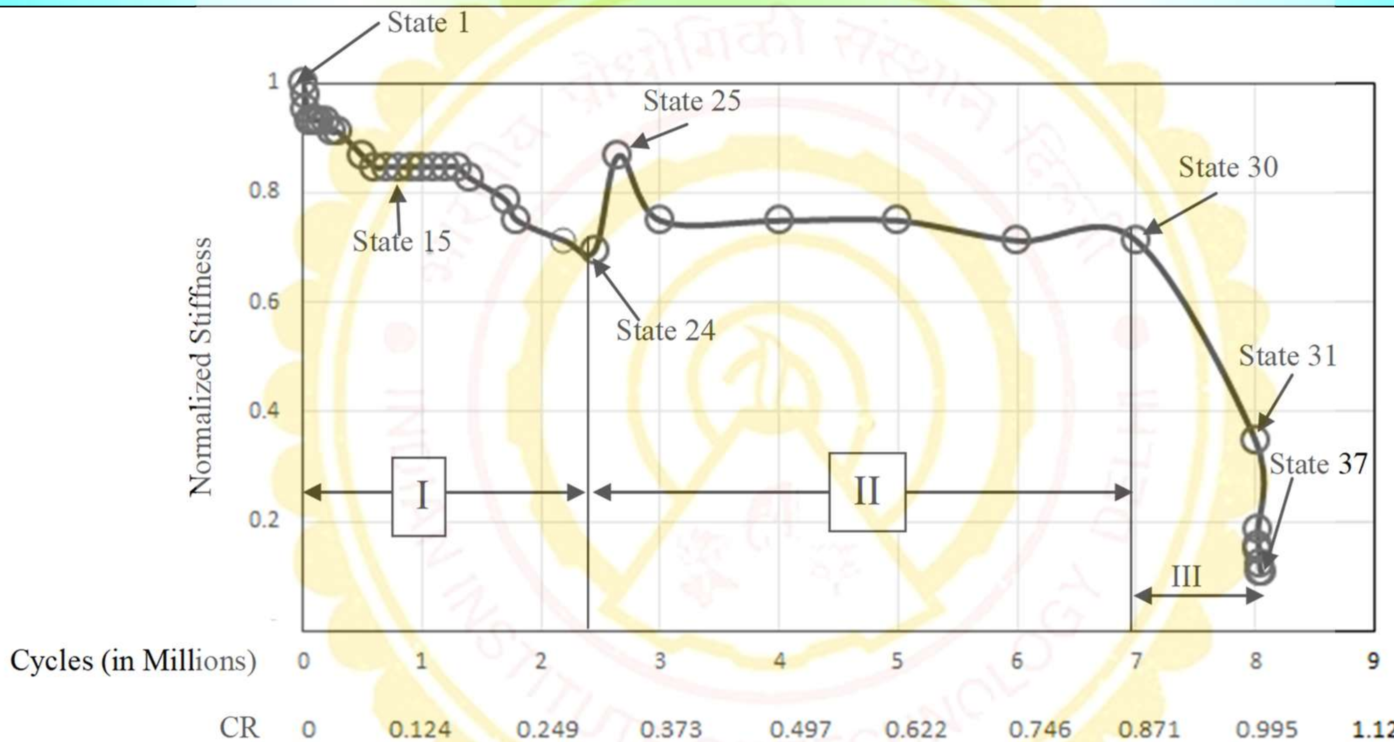
REAR (NEAR NOTCH)

# FREQUENCY (STIFFNESS) MEASUREMENT USING GLOBAL DYNAMIC TECHNIQUE (CVS)



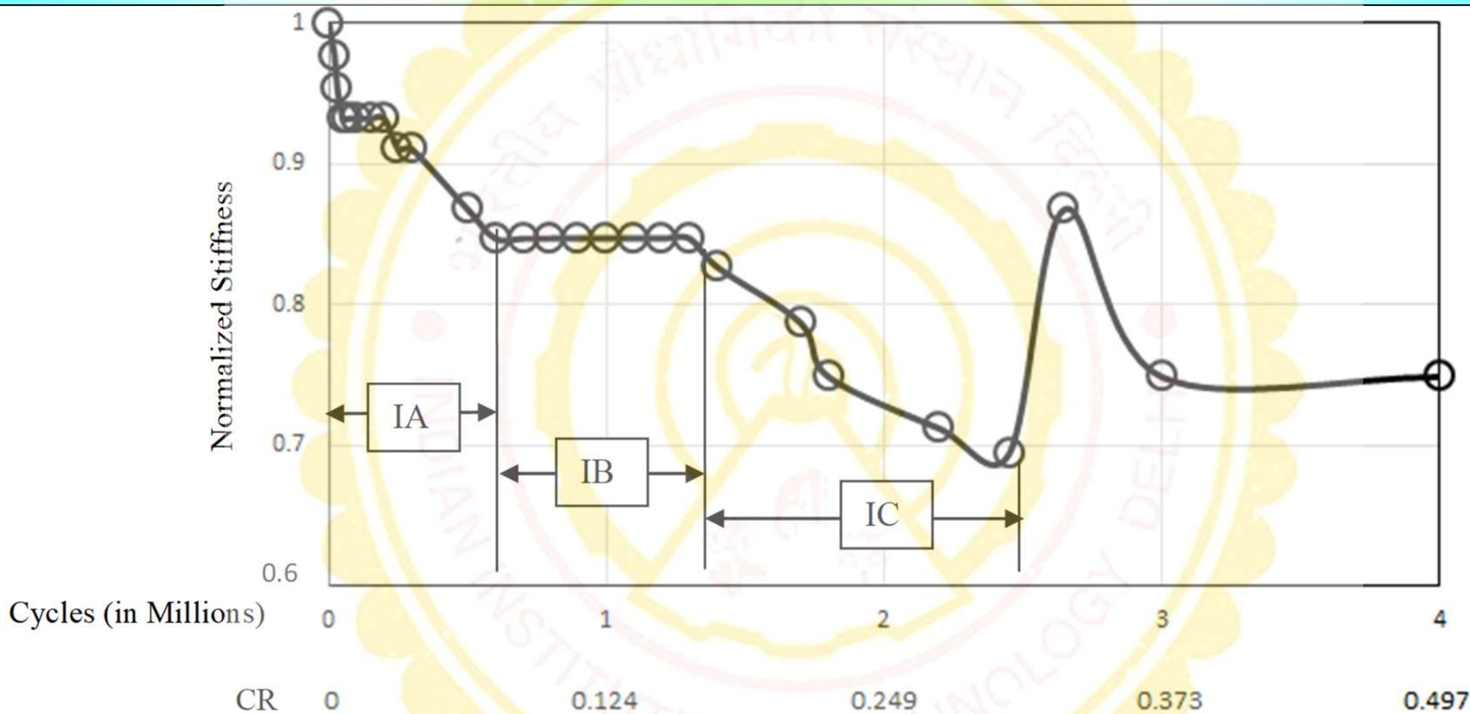
| State | Cycles | Cycle Ratio (CR) | Natural Frequency |
|---|---|---|---|
| 1 | 0 | 0.000 | 17.2 |
| 2 | 20,000 | 0.002 | 17.1 |
| 3 | 30,000 | 0.004 | 17 |
| 4 | 50,000 | 0.006 | 16.9 |
| 5 | 70000 | 0.008 | 16.9 |
| 6 | 100000 | 0.012 | 16.9 |
| 7 | 150000 | 0.018 | 16.9 |
| 8 | 2,00,000 | 0.025 | 16.9 |
| 9 | 2,50,000 | 0.031 | 16.8 |
| 10 | 3,00,000 | 0.037 | 16.8 |
| 11 | 5,00,000 | 0.062 | 16.6 |
| 12 | 6,00,000 | 0.075 | 16.5 |
| 13 | 7,00,000 | 0.087 | 16.5 |
| 14 | 8,00,000 | 0.100 | 16.5 |
| 15 | 9,00,000 | 0.112 | 16.5 |
| 16 | 10,00,000 | 0.124 | 16.5 |
| 17 | 11,00,000 | 0.137 | 16.5 |
| 18 | 12,00,000 | 0.149 | 16.5 |
| 19 | 13,00,000 | 0.162 | 16.5 |
| 20 | 14,00,000 | 0.174 | 16.4 |
| 21 | 17,00,000 | 0.211 | 16.2 |
| 22 | 18,00,000 | 0.223 | 16 |
| 23 | 22,00,000 | 0.273 | 15.8 |
| 24 | 24,50,000 | 0.304 | 15.7 |
| 25 | 26,50,000 | 0.329 | 16.6 |
| 26 | 30,00,000 | 0.373 | 16 |
| 28 | 50,00,000 | 0.622 | 16 |
| 30 | 70,00,000 | 0.871 | 15.8 |
| 31 | 80,00,000 | 0.995 | 13.2 |
| 32 | 80,20,000 | 0.998 | 11.26 |
| 34 | 80,30,000 | 0.999 | 10.7 |
| 35 | 80,35,000 | 0.999 | 10.2 |
| 36 | 80,40,000 | 1.000 | 9.9 |

# DAMAGE SEVERITY ASSESSMENT USING CVS AS GLOBAL VIBRATION SENSOR

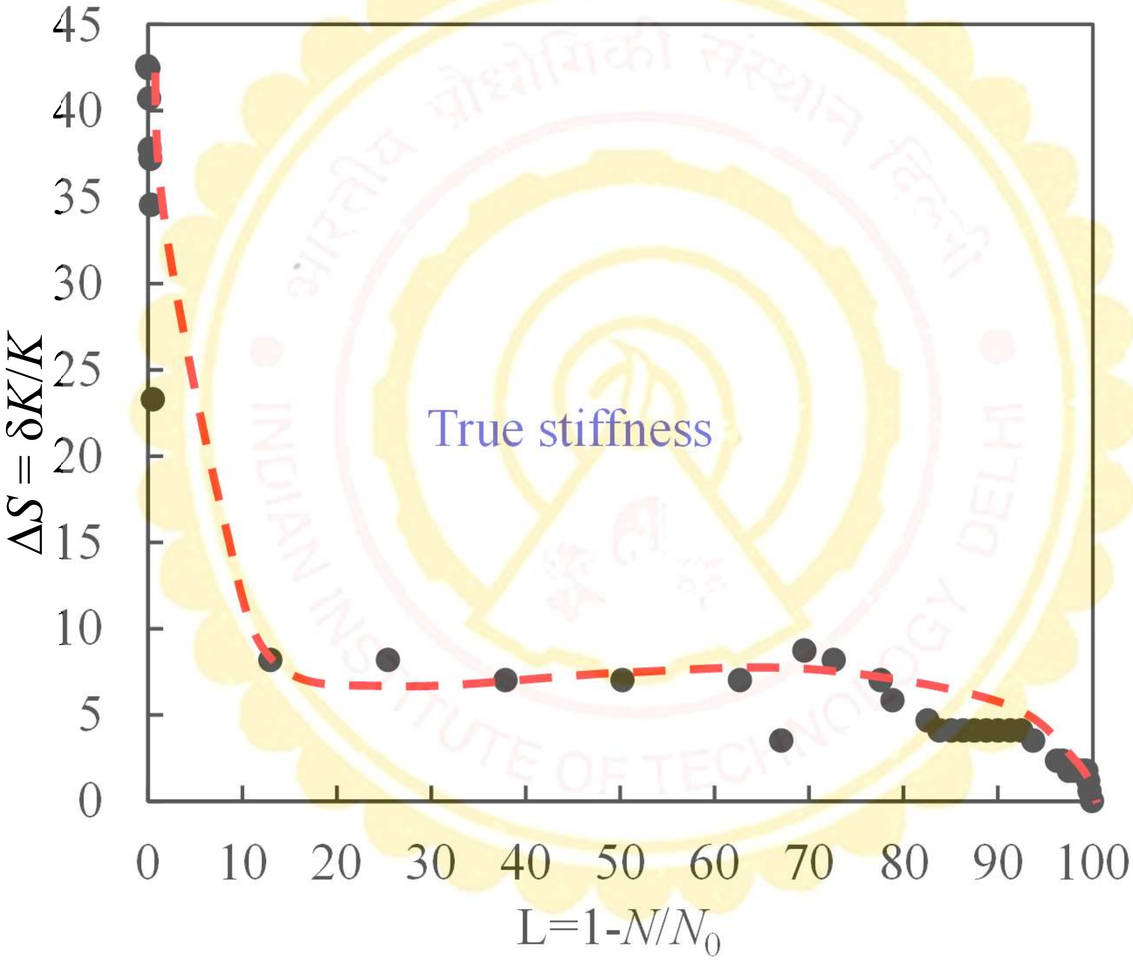



$$EI = \frac{4\rho A f_1^2 L^4}{\pi^2}$$

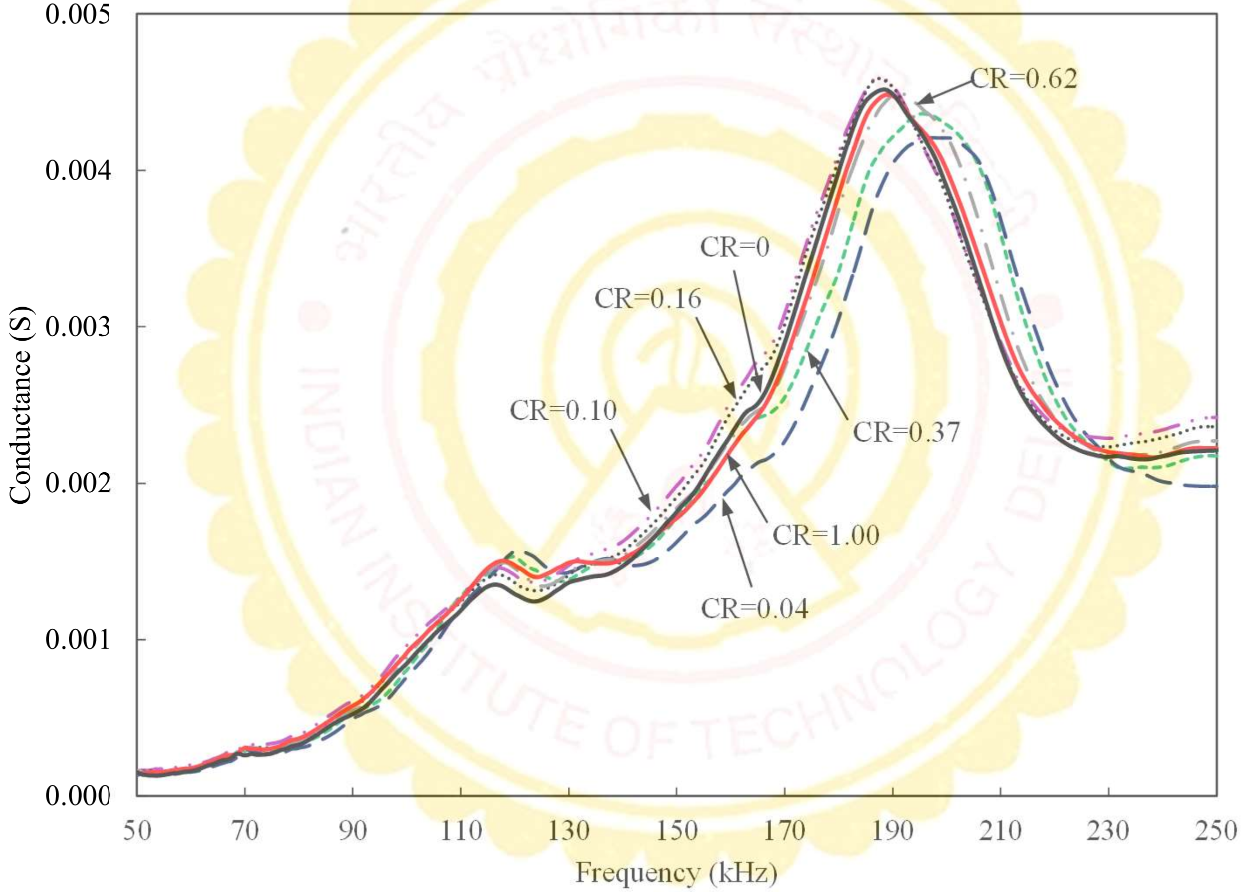
# CLOSE UP VIEW OF REGION I



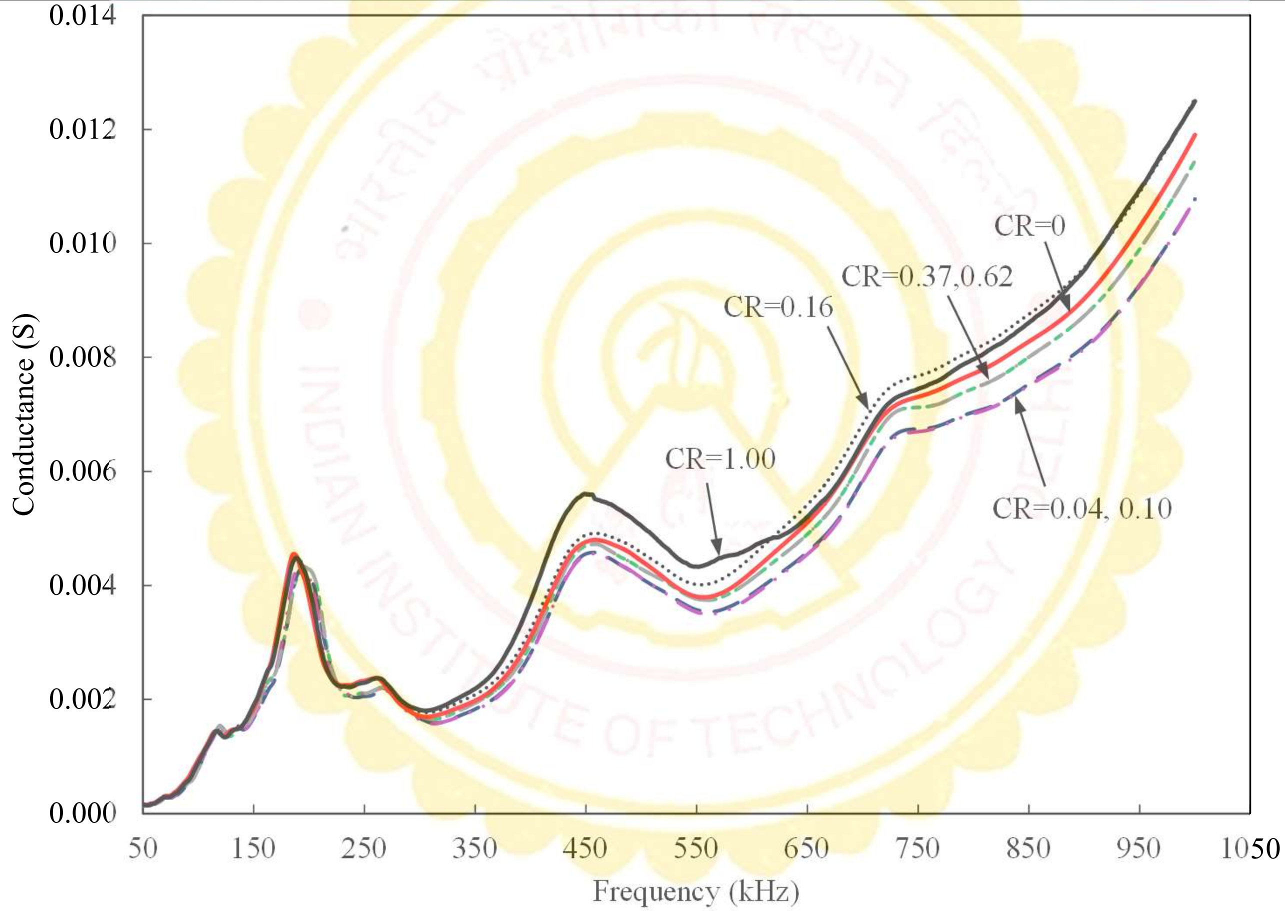
# REMAINING SERVICE LIFE



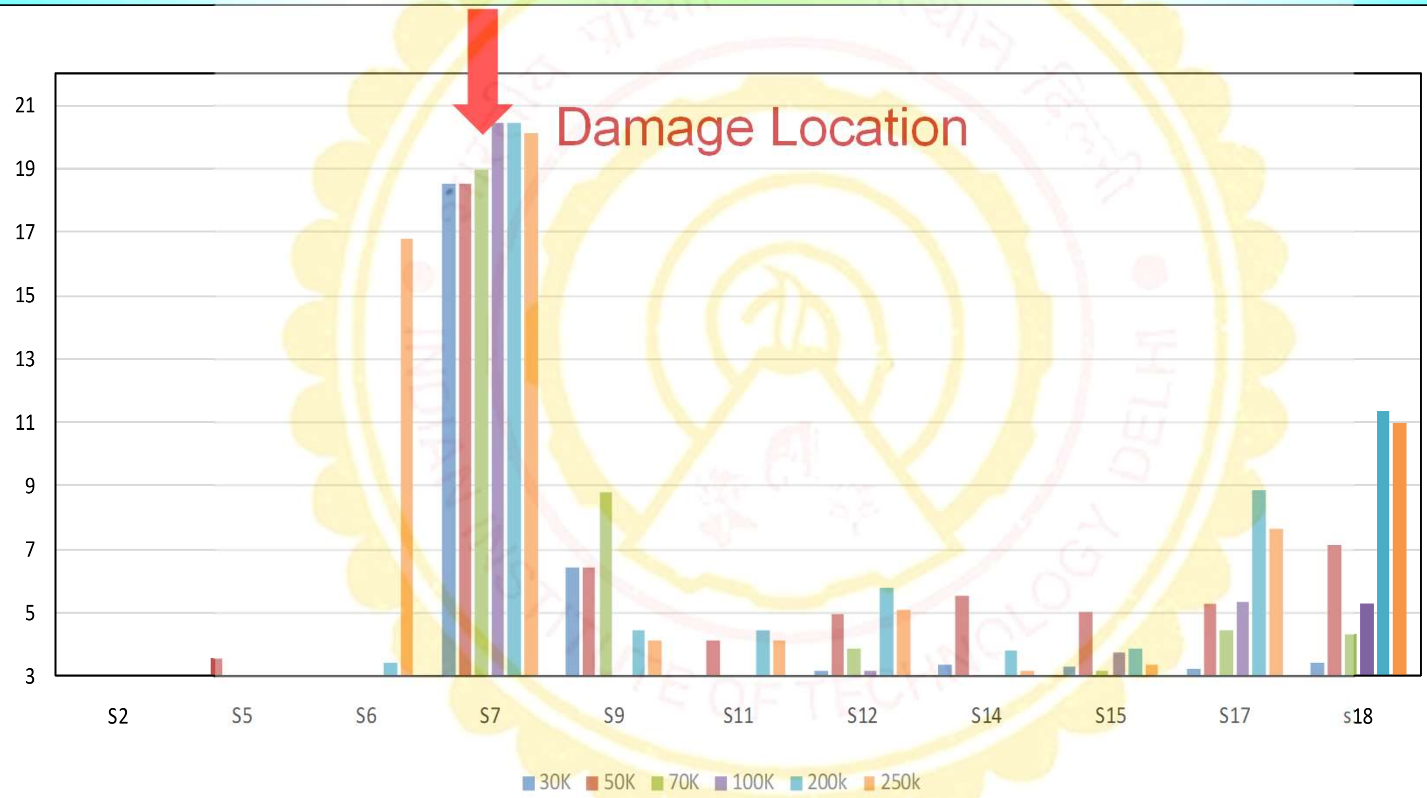
# SIGNATURE ACQUISION USING EMI TECHNIQUE 50-250 kHz



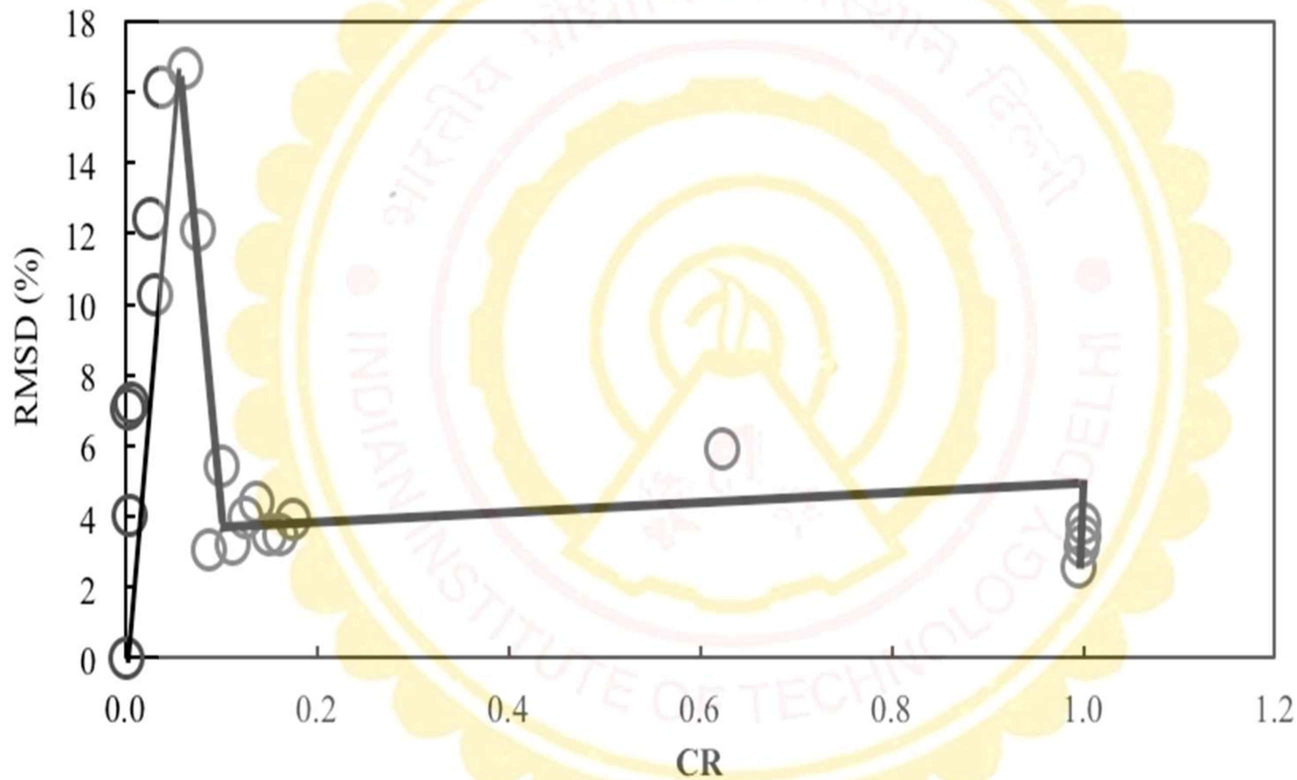
# SIGNATURE ACQUISION USING EMI TECHNIQUE 50-1000 kHz



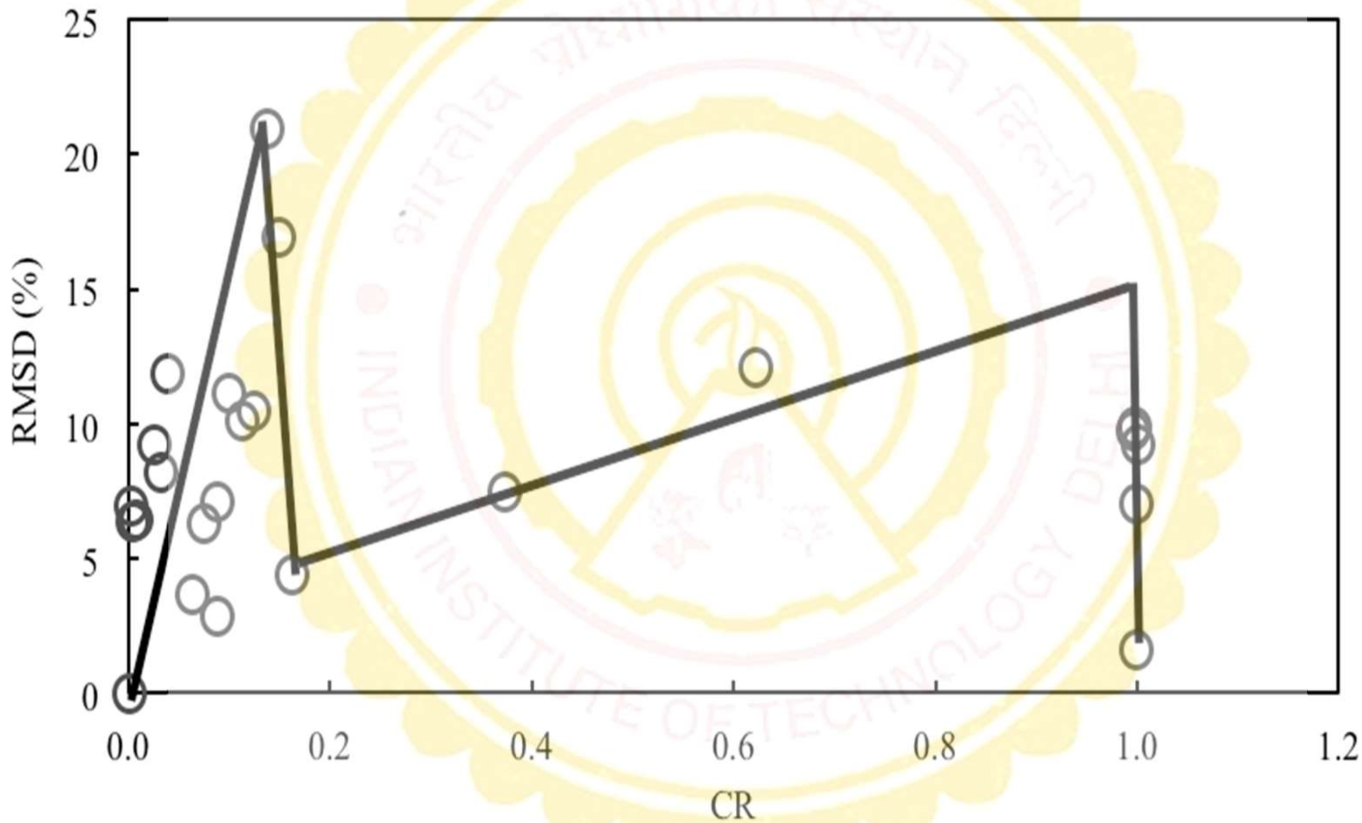
# DAMAGE LOCALIZATION USING EMI TECHNIQUE (50-1000 kHz)



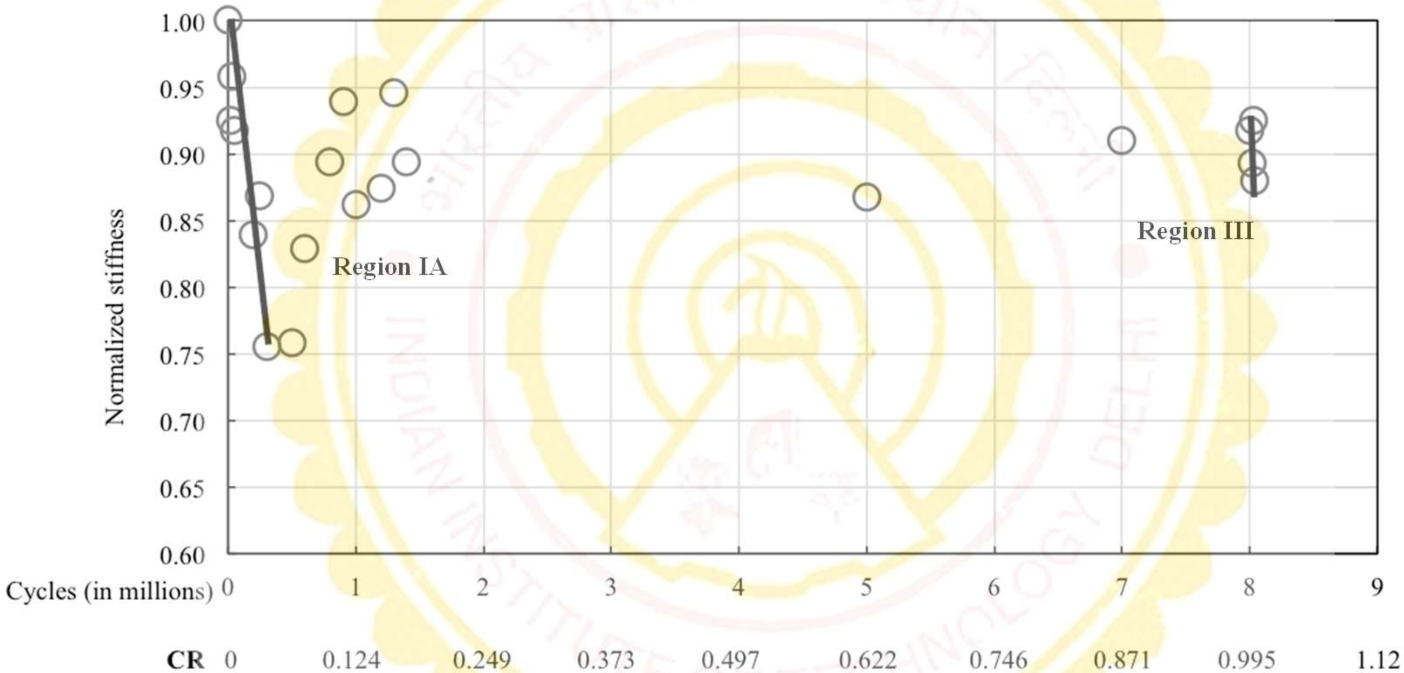
# RMSD 50-250 kHz



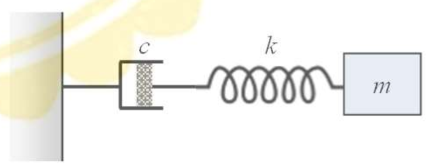
# RMSD 50-1000 kHz



# IMPEDANCE BASED IDENTIFICATION

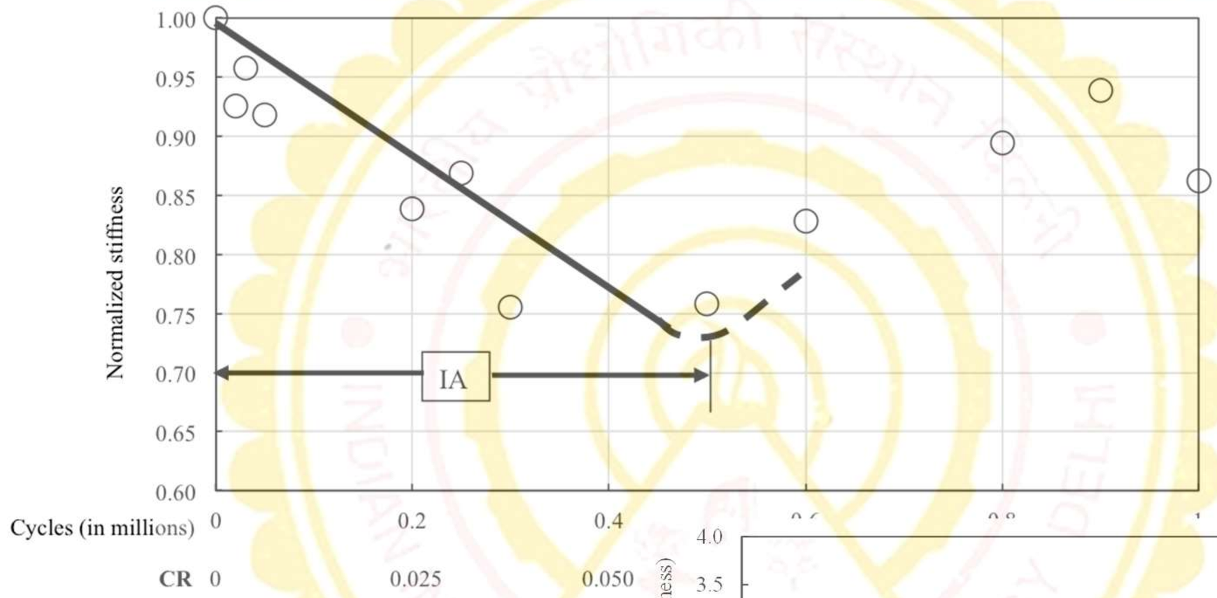


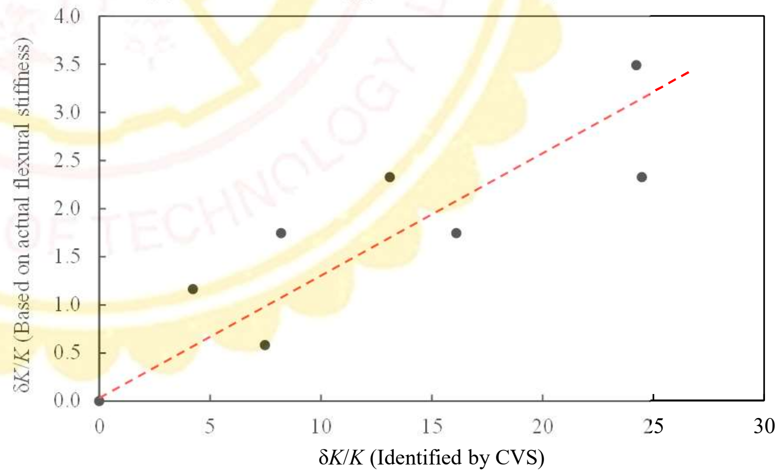

Not very effective in Region II




(a)

# IMPEDANCE BASED IDENTIFICATION: REGION I



# IN CONCLUSION……

- **EMI TECHNIQUE CAN FACILITATE CAPTURE OF FATIGUE INITIATION.**
- **IT CAN ALSO ENABLE DAMAGE LOCALIZATION.**
- **FURTHER ADVANTAGE OF THE EMI TECHNIQUE CEASES AFTER THE PROPAGATION PHASE.**
- **FATIGUE PROPAGATION PHASE CAN BE REALISTICALLY QUANTIFIED BY GLOBAL VIBRATION TECHNIQUES.**
- **BOTH TECHNIQUES MEANINGFULLY COMPLEMENT EACH OTHER.**

# THANK YOU

## SUGGESTED READING:

**Bhalla and Kaur (2018)**

**Moin et al. (2020)**

**(downloadable link at:**
**http://web.iitd.ac.in/~sbhalla/journals.pdf )**