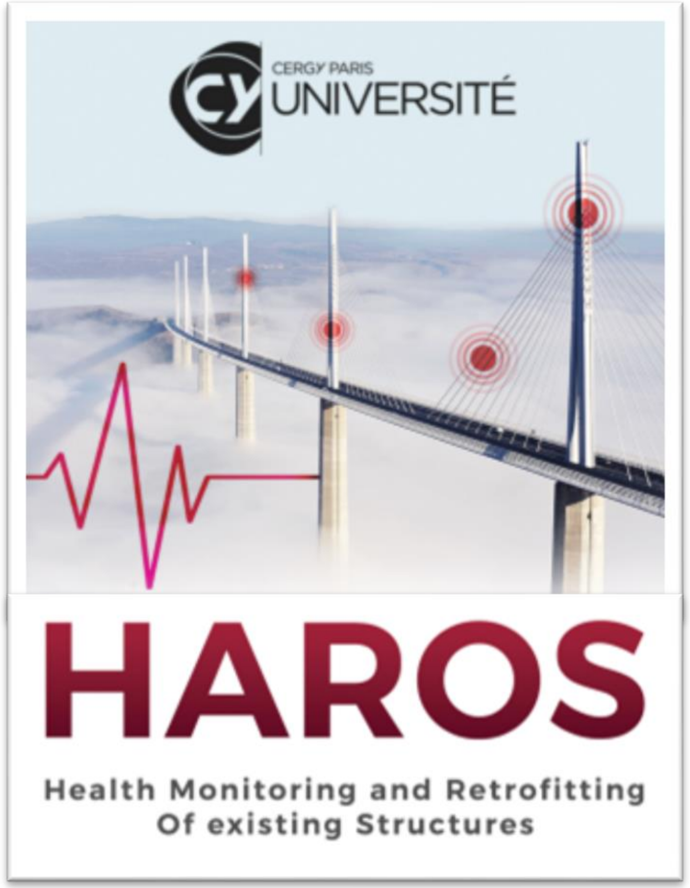
Damage Detection using Structural Health Monitoring

Science Behind Safety of structure



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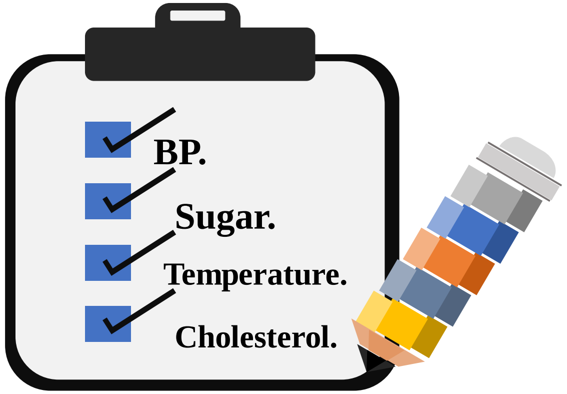
- Human Health Monitoring

Sick Person

Doctor

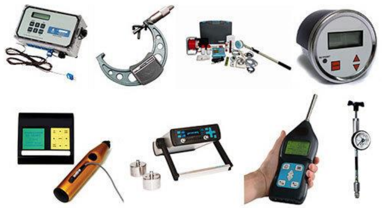
Medical equipment

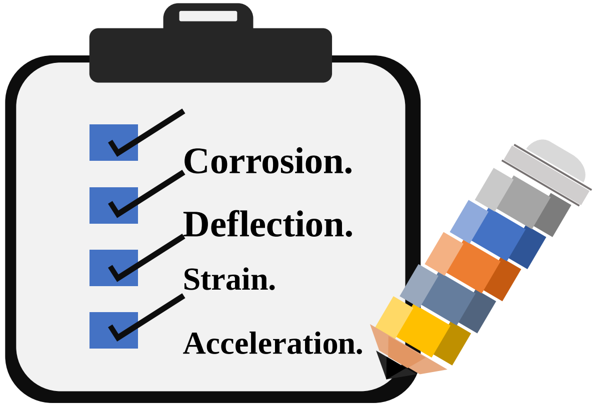


Test Parameters

Treatment

- Structural Health Monitoring





OUTLINE

- Introduction
- SHM techniques
- Smart materials
- Piezoelectric materials
- EMI techniques
- Experimental test frame and results
- Conclusions

What SHM

Estimating the state of structural health and detecting the changes in structure that has affected the performance of structure is defined as SHM

Condition Monitoring

- Asses the present condition
- One-time; subset of long-term SHM
- Particular purpose e.g. strength, integrity, load carrying capacity

Structural Monitoring

- Monitor Condition Continuously
- Maintain the functional utility of the structure

Structural Control

- Controlling Dynamic response of structure

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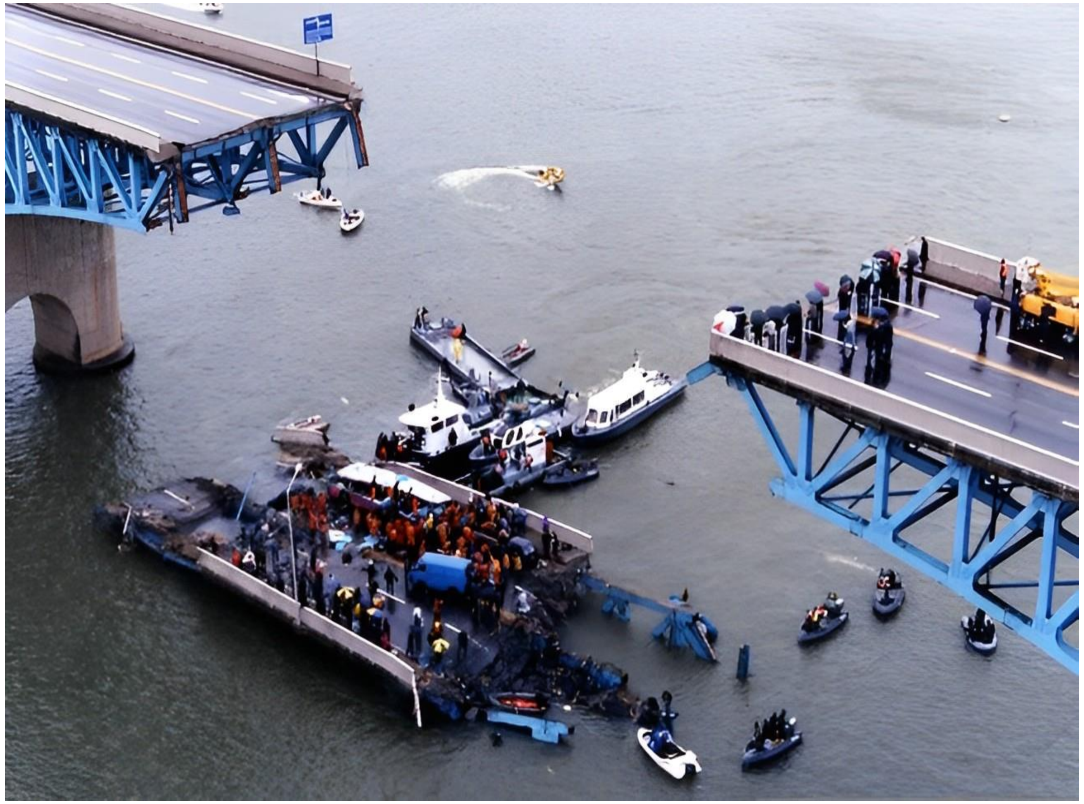
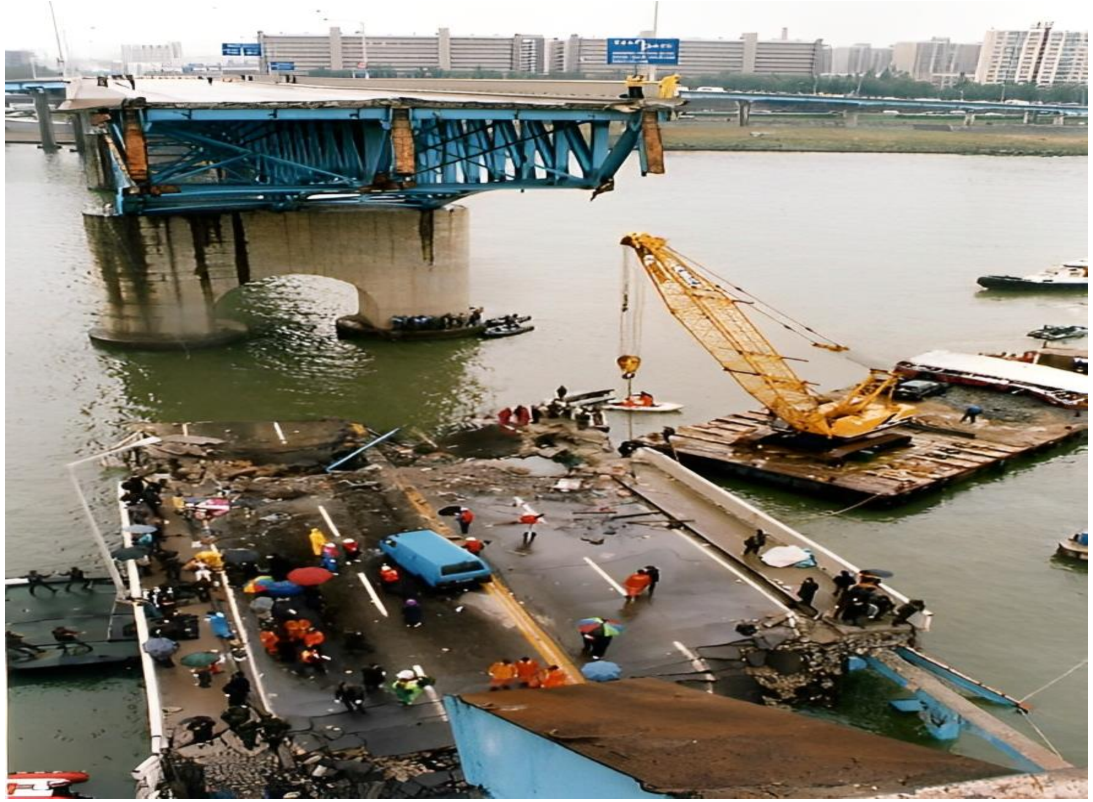
Why SHM ?





Seongsu Bridge, South Korea 1994

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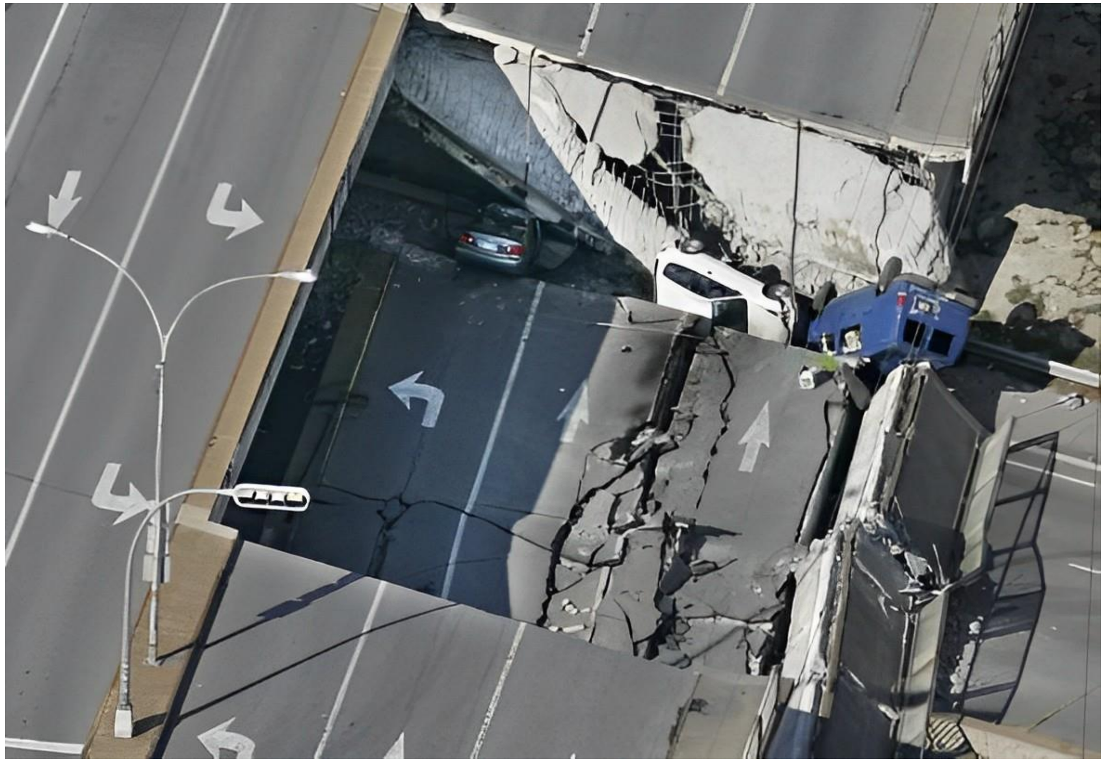
Why SHM ?



De la Concorde overpass collapse, Canada, 30 Sep 2006

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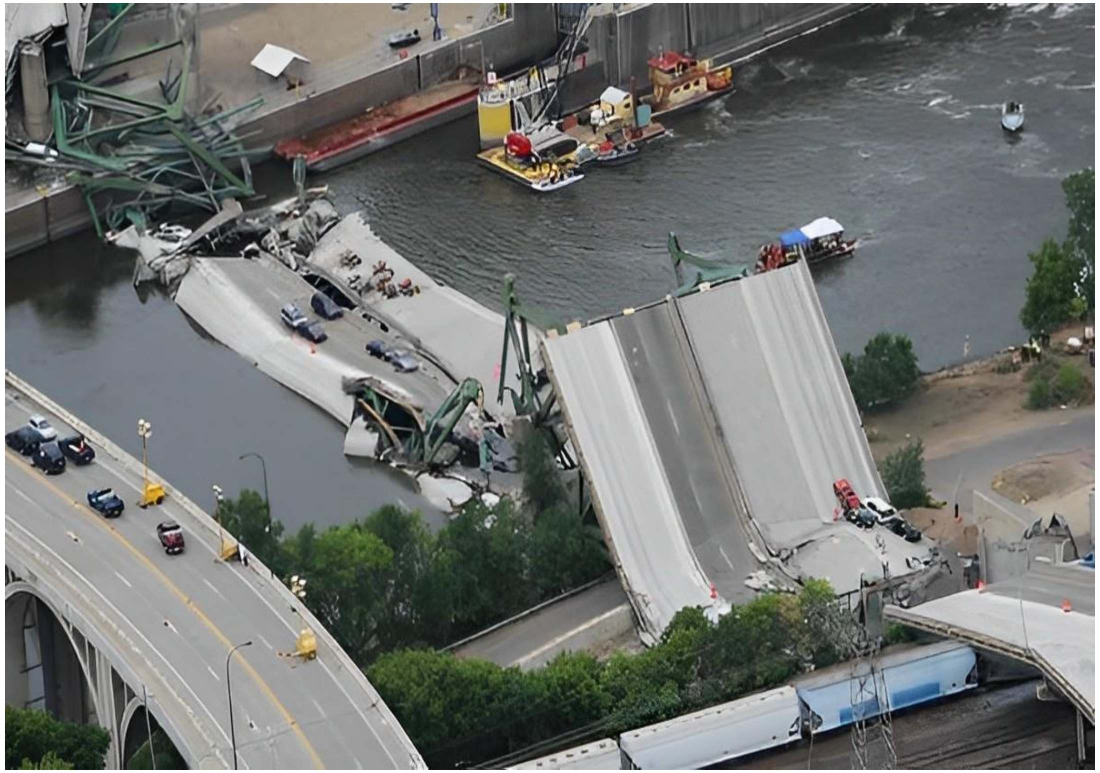
Why SHM ?



I-35W Bridge, U.S.A, 2007

Why SHM ?

Morbi Bridge, Gujrat, India, 30 OCT 2022 (150 people died)

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Why SHM ?

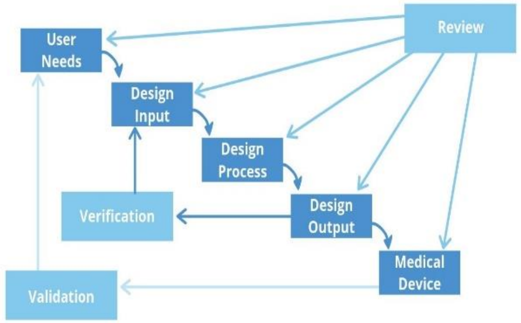
Structural safety

Risk reduction in excavation

Avoiding leakage

Replacement of visual inspection

Retrofitting Evaluation



Design validation

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SHM TECHNIQUES

Global Techniques

- Global static response
- Global dynamic response
(Freq. < 100 Hz) used when level of damage is high

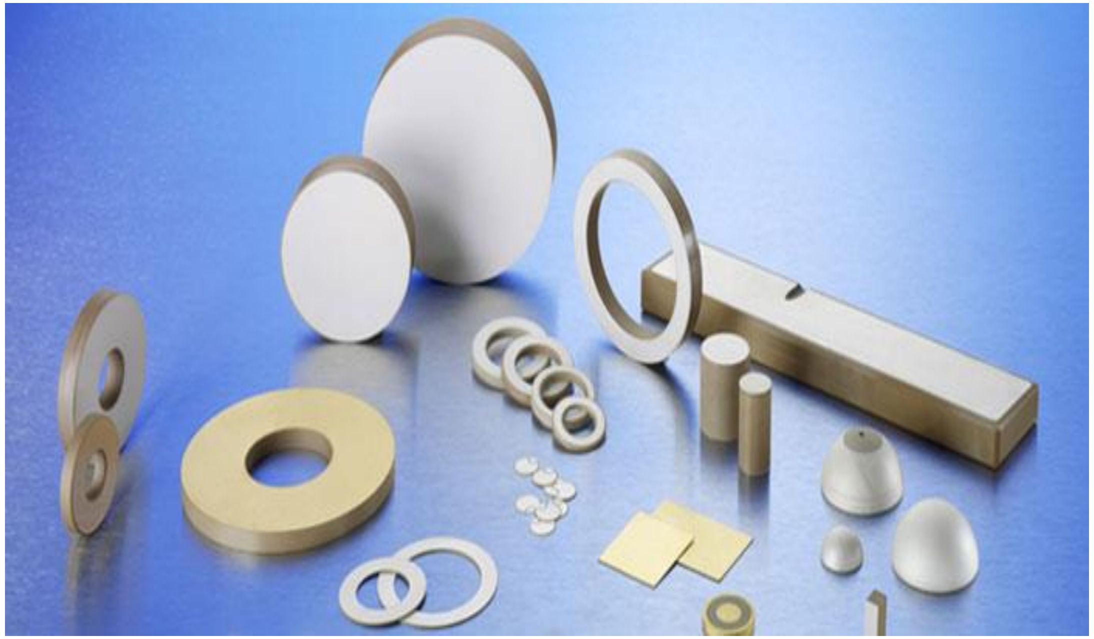
Local Techniques

- Ultrasound wave propagation
- Acoustic emission
- Eddy Currents
- Impact echo

- **EMI technique is the interface between local and global**
- **Principle = similar to the global variation techniques but in a high-frequency range of 50kHz - 500kHz**
- **Sensitivity = As high as ultrasonic techniques**

Smart materials for SHM

1. Piezoelectric materials
2. Shape memory alloy
3. Electrorheological fluid
4. Optical fibre
5. Magneto-strictive materials



Piezoelectric materials

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Working principle of Smart materials for SHM

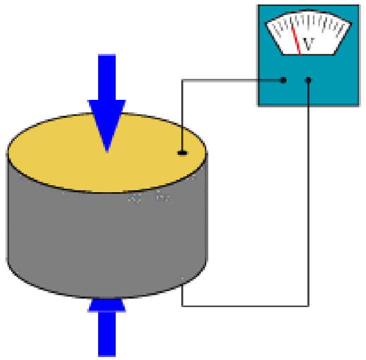
Input	Smart material	Output
(1) Stress (2) Electric field	**Piezoelectric materials**	(1) Electric charge (2) Mechanical strain
Heat	**Memory Alloy**	Original Memorized Shape
Electric field	**Electrorheological fluid**	Change in viscosity (Internal damping)
Temperature, Pressure, Mechanical strain	**Optical Fibre**	Change in opto- electronic signal
Magnetic field	**Magneto-strictive materials**	Mechanical strain

PIEZO ELECTRIC MATERIALS

Piezo + Electricity

Piezo → Greek root → PIEZEN : To Press

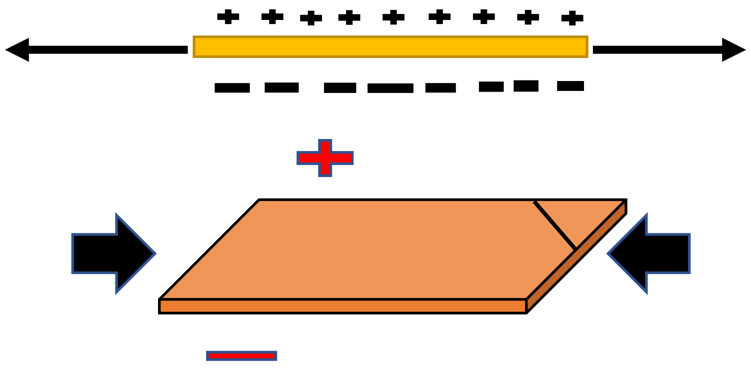
Electricity → Latin root → Electrum : Amber



PIEZO ELECTRIC EFFECT

Direct Effect

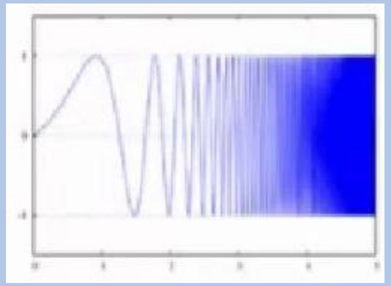
Mechanical Stress → Electric Charge



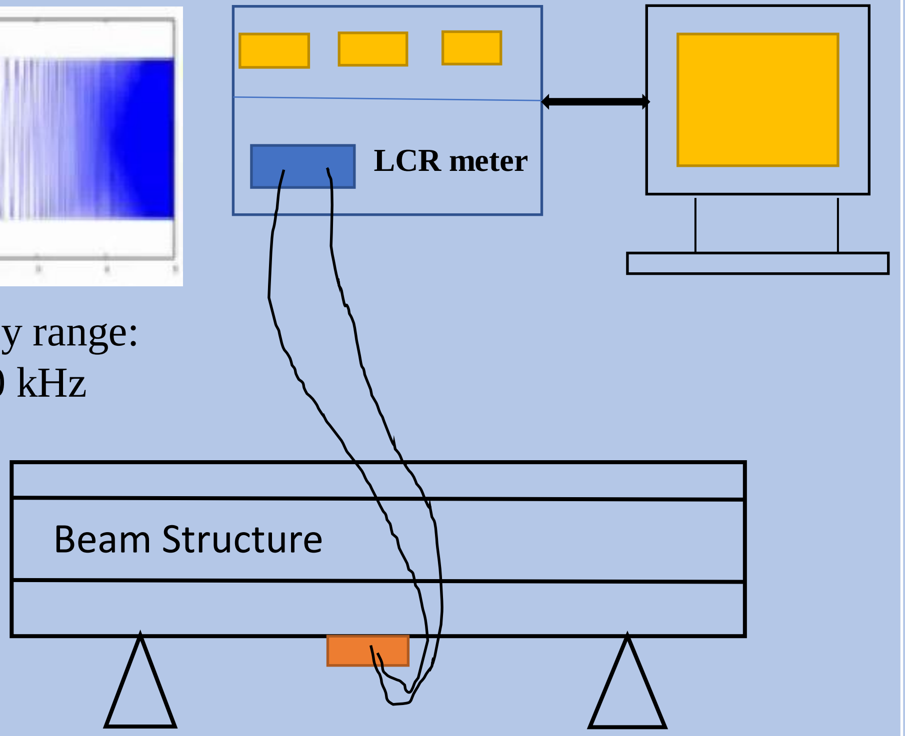
Converse Effect

Electric Field → Mechanical Strain

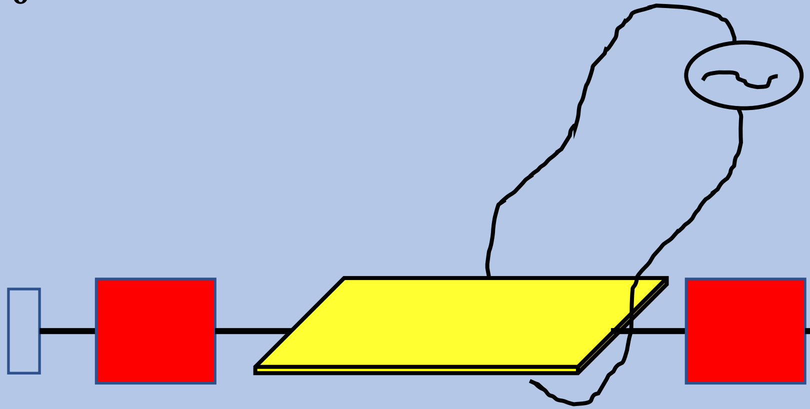
ELECTROMECHANICAL IMPEDANCE TECHNIQUE (*EMI TECHNIQUE*) DTU



Frequency range:
30 - 400 kHz



$$\bar{Y} = \frac{I_o e^{j(\omega t - \emptyset)}}{V_0\, e^{j\omega t}} = I_o e^{-j\emptyset} = G + Bj$$



A simple physical model of system (Liang et. al, 1994)

Electromechanical admittance,
Y = G + B j

Beam subjected To PZT patch	**Mathematical impedance modal of the structure**

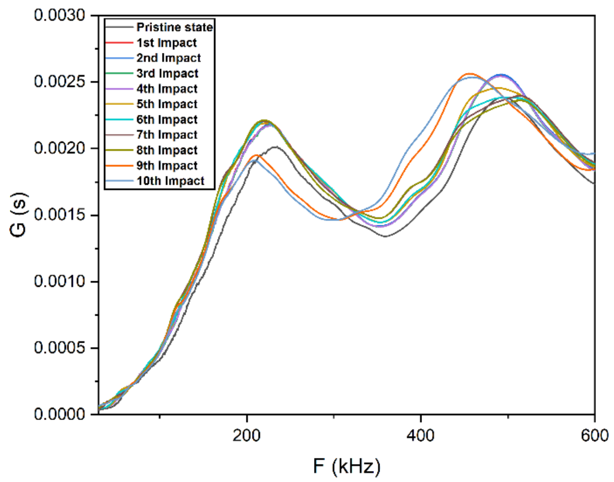
Authors – Dr. Shilpa Pal & Indrajeet Singh

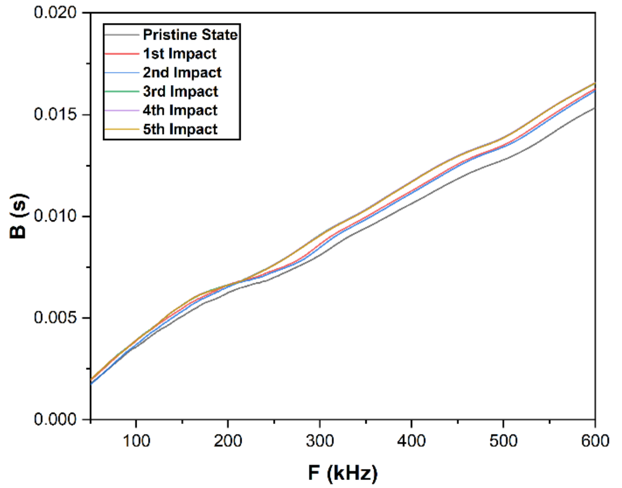
- Electrical admittance $Y = \dfrac{1}{Z_{electrical}} = G + Bj$

Conductance (Real part) **Suseptance (Imaginary part)**

Electrical impedance $(Z_{electrical}) = R + Xj$ $\dfrac{Voltage}{Current}$

Mechanical impedance $Z = \dfrac{F}{V}$





Mechanical impedance is a unique function of structural stiffness, damping and mass

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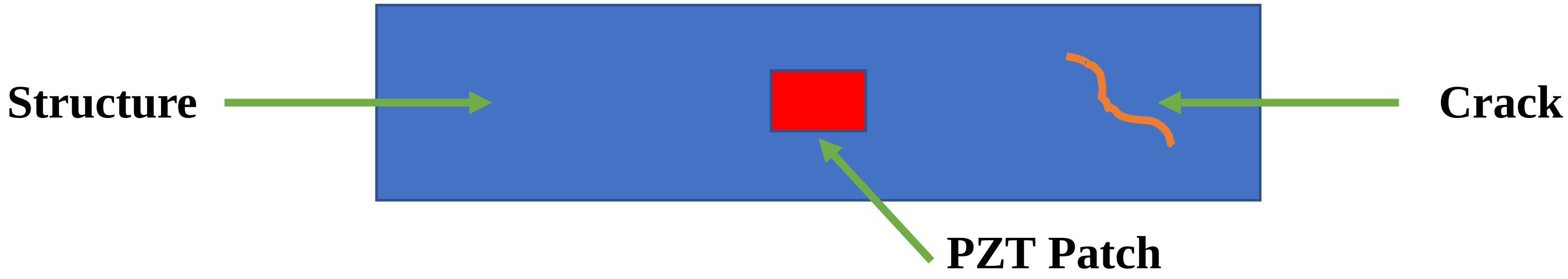
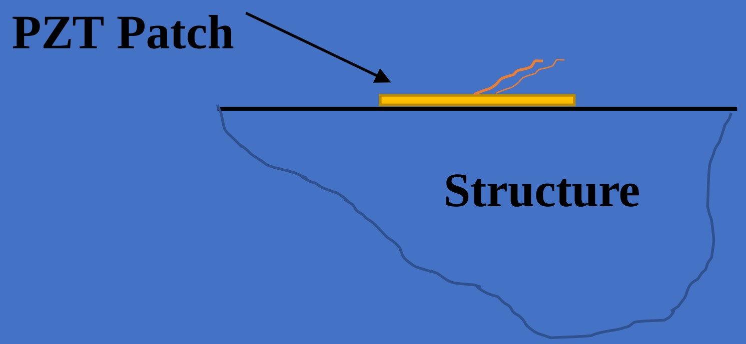
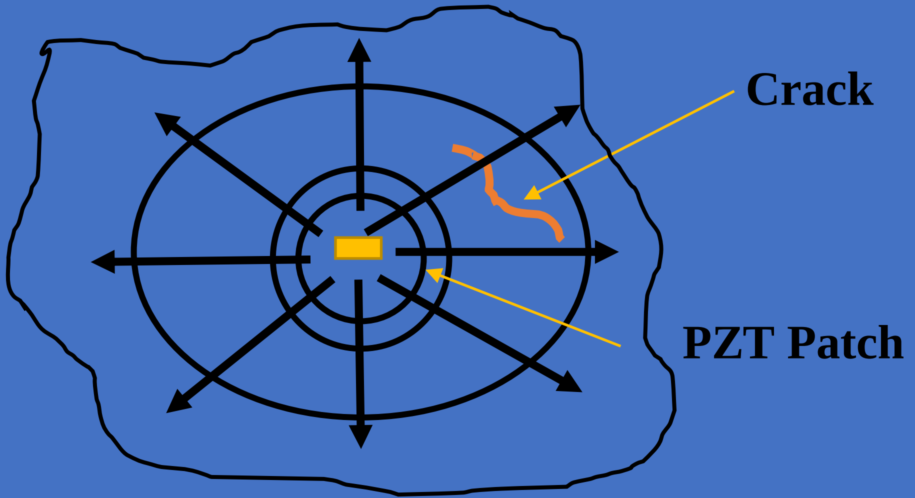






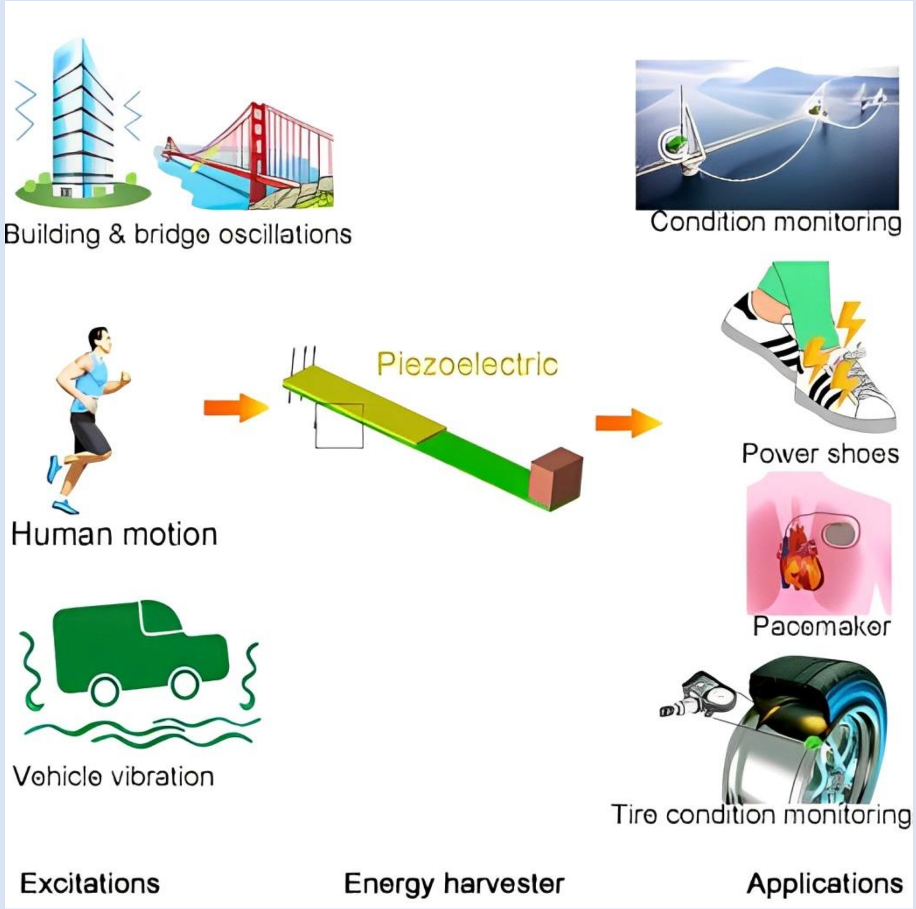
Cracks disrupts wave propagation

Structure —Damage→ **Change in stiffness, damping** → **change in Z**

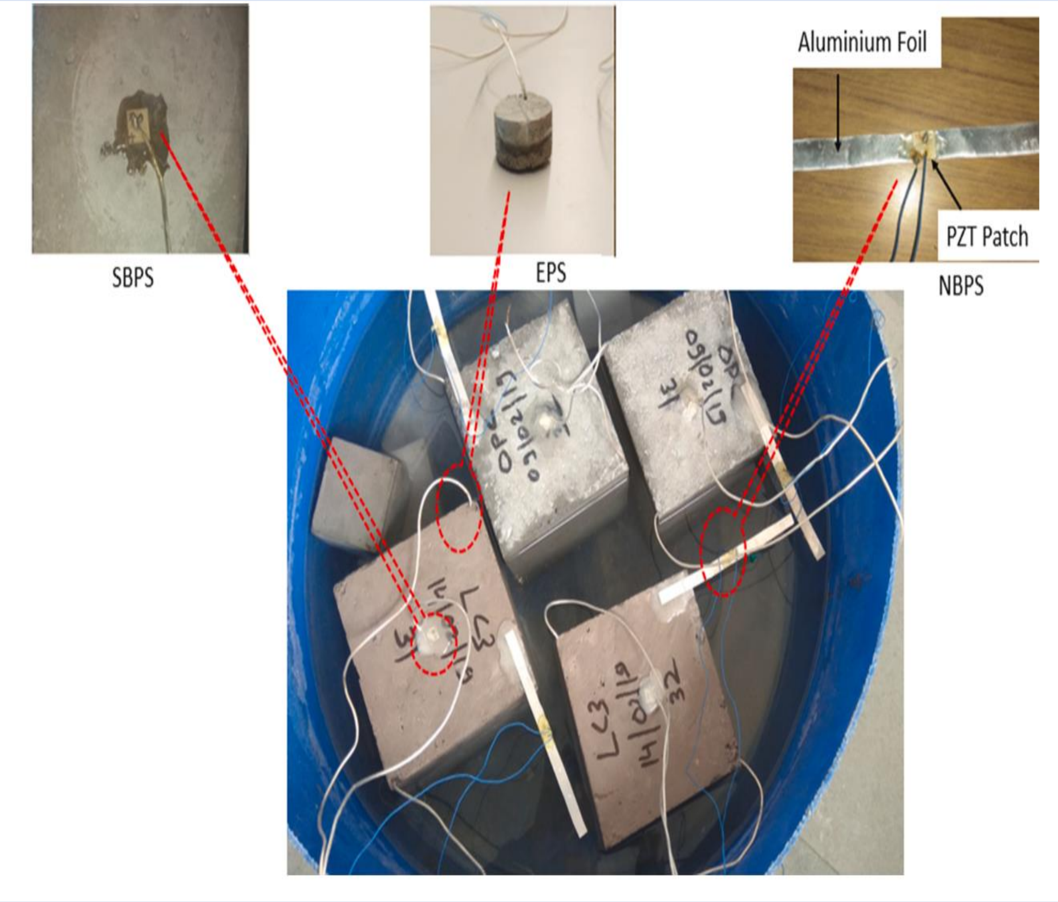
Change in Z → **Change in Y** → **Indication of damage**

Source: Dixit et.al 2018

Energy Harvesting

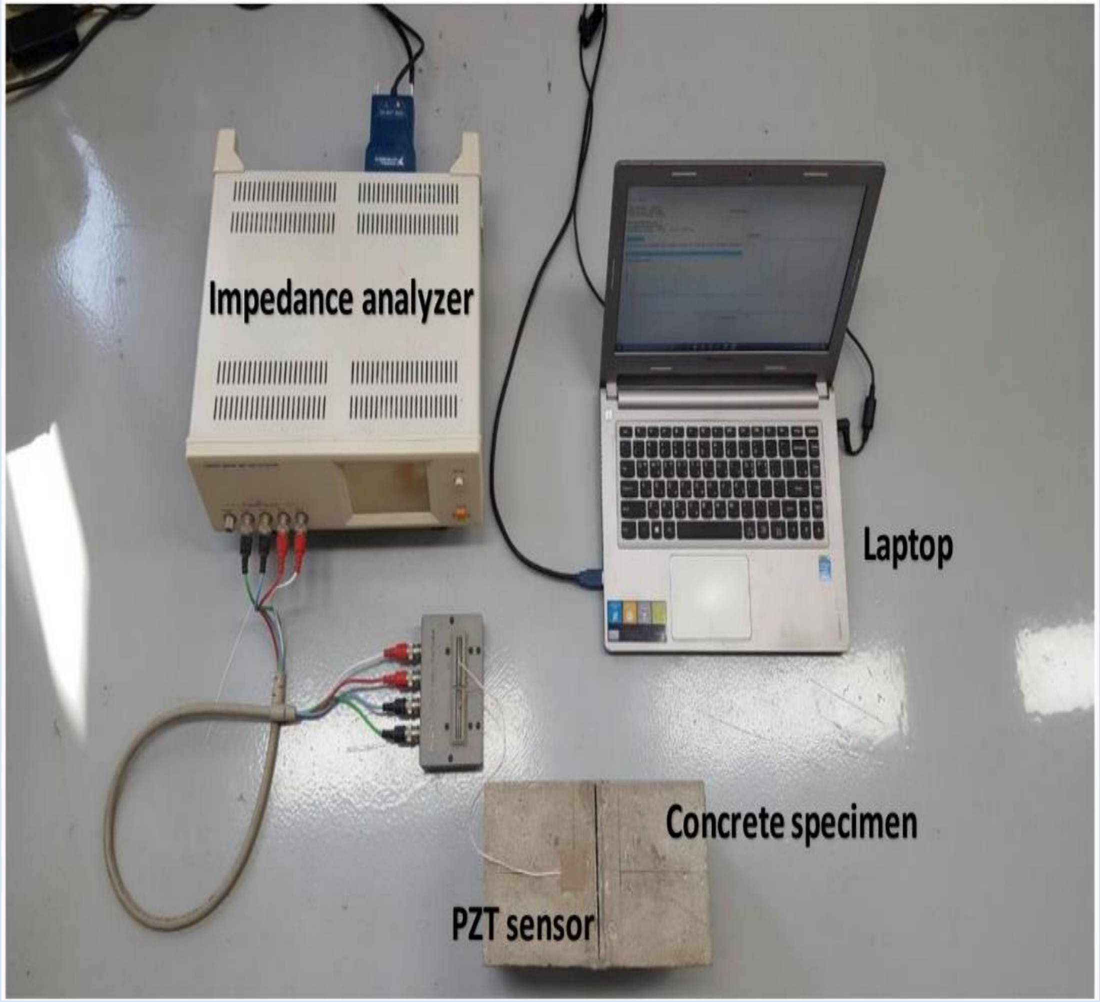


Strength Monitoring



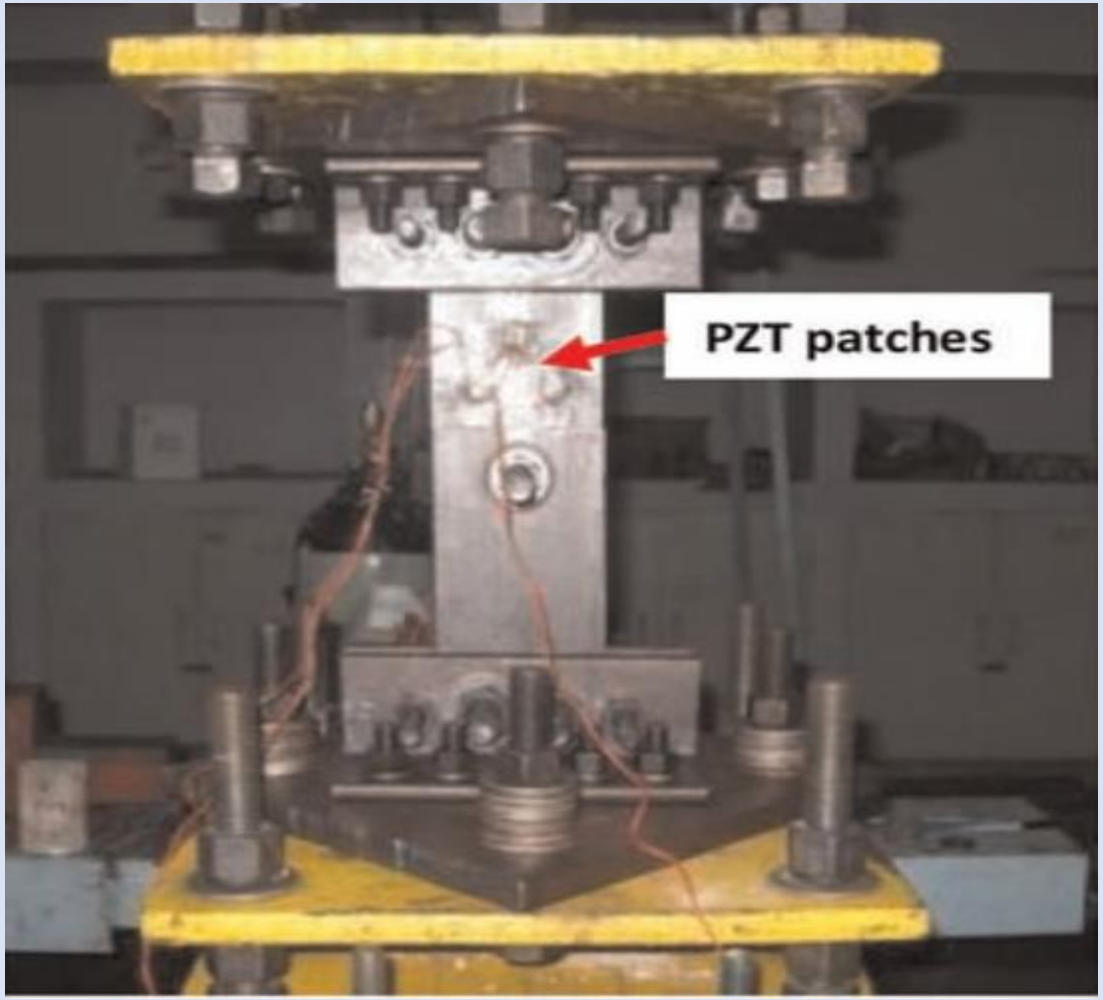
Source: Bansal .T et.al

Damage identification



Source: Kim et.al 2019

Creep and fatigue monitoring



Source: Bhalla et.al 2012

Corrosion Assessment

Source: Bansal et.al

DETAILS OF TEST FRAME

Experiment Topic

DAMAGE ASSESSMENT IN CONCRETE UNDER IMPACT LOADING AT VARYING TEMPERATURES

Parameter studied

- **FABRICATION OF PIEZO SENSORS**
- **PLACING OF PIEZO SENSORS ON CONCRETE**
- **SIGNATURE EXTRACTION**
- **STATISTICAL INDICES LIKE RMSD AND MAPD**
- **EQUIVALENT STIFFNESS PARAMETER**
- **REMAINING LIFE ESTIMATION**

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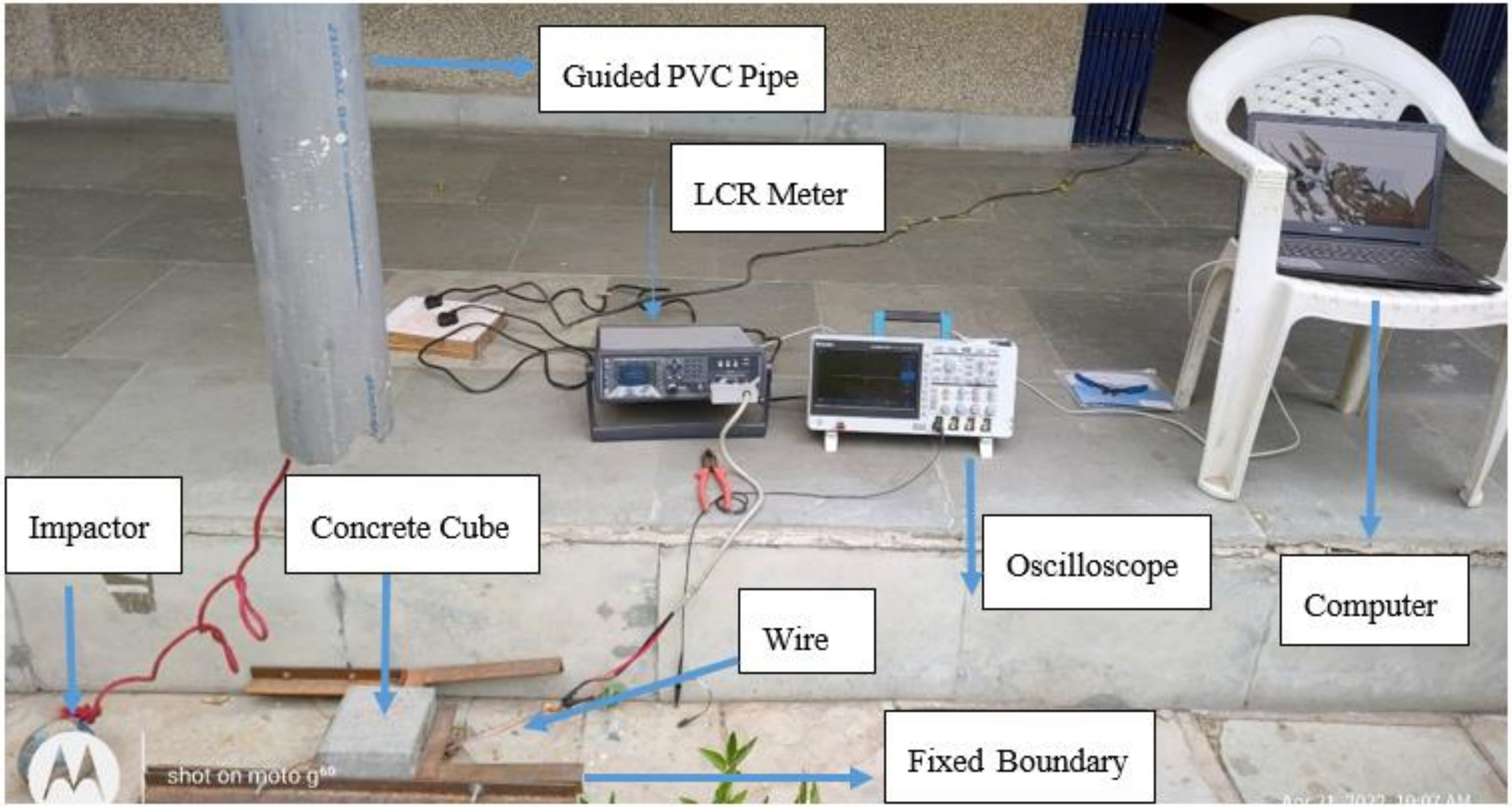
DAMAGE ASSESSMENT IN CONCRETE UNDER IMPACT LOADING AT VARYING TEMPERATURES

S.No.	Parameter	Description
1	Type of sensors configuration	Embedded, surface bonded and non bonded
2	Impact height	3 and 3.5 m
3	Impactor size and type	Steel ball with 13 cm diameter
4	Temperature variation	50^{o}C, 100^{o}C and 150^{o}C
5	Boundary condition	Free and Fixed
6	Instruments	LCR meter, oscilloscope, guided pipe
7	Grade of concrete	M30

DETAILS OF TEST FRAME



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FABRICATION OF PIEZO SENSORS

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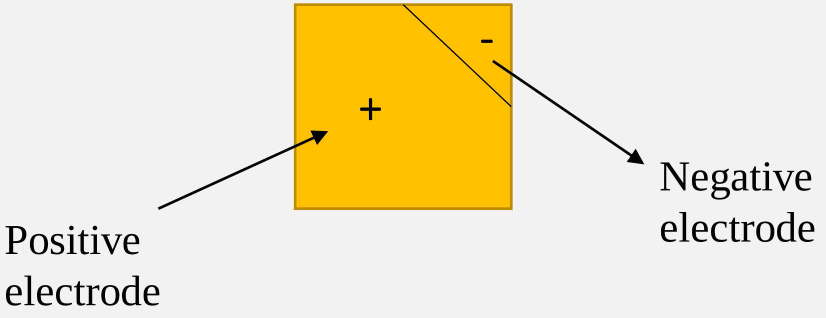
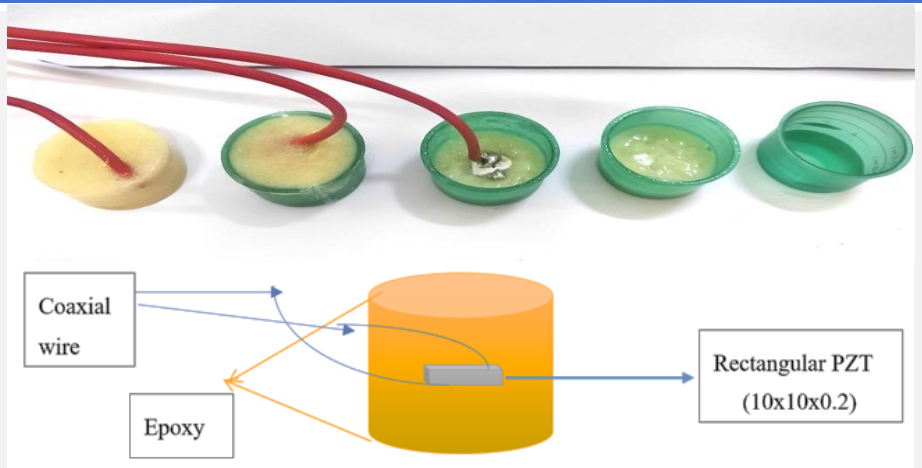
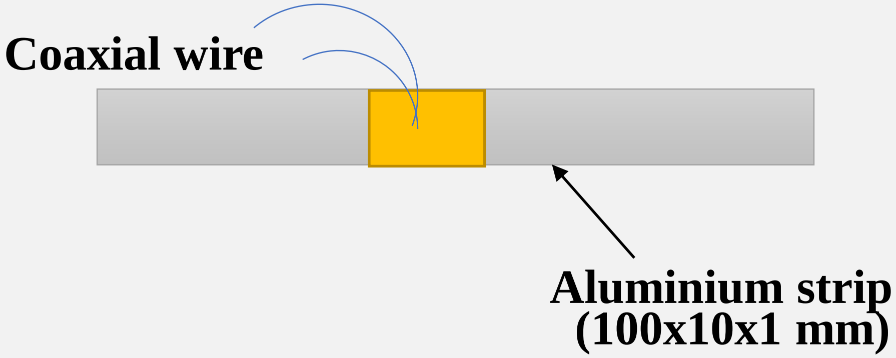
Free PZT(10x10x0.2 mm)	Fabrication of JKTPS (Jacketed piezo sensors)
	
SBPS (Surface bonded piezo sensors)	**NBPS (Non bonded piezo sensors)**
	

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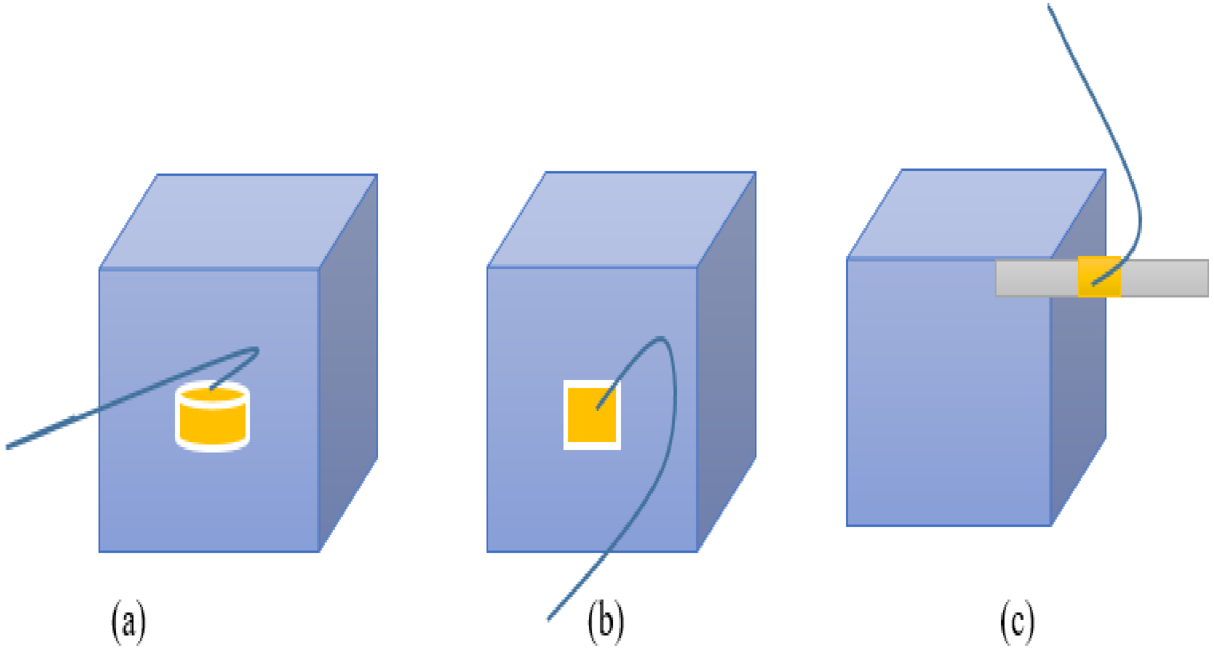
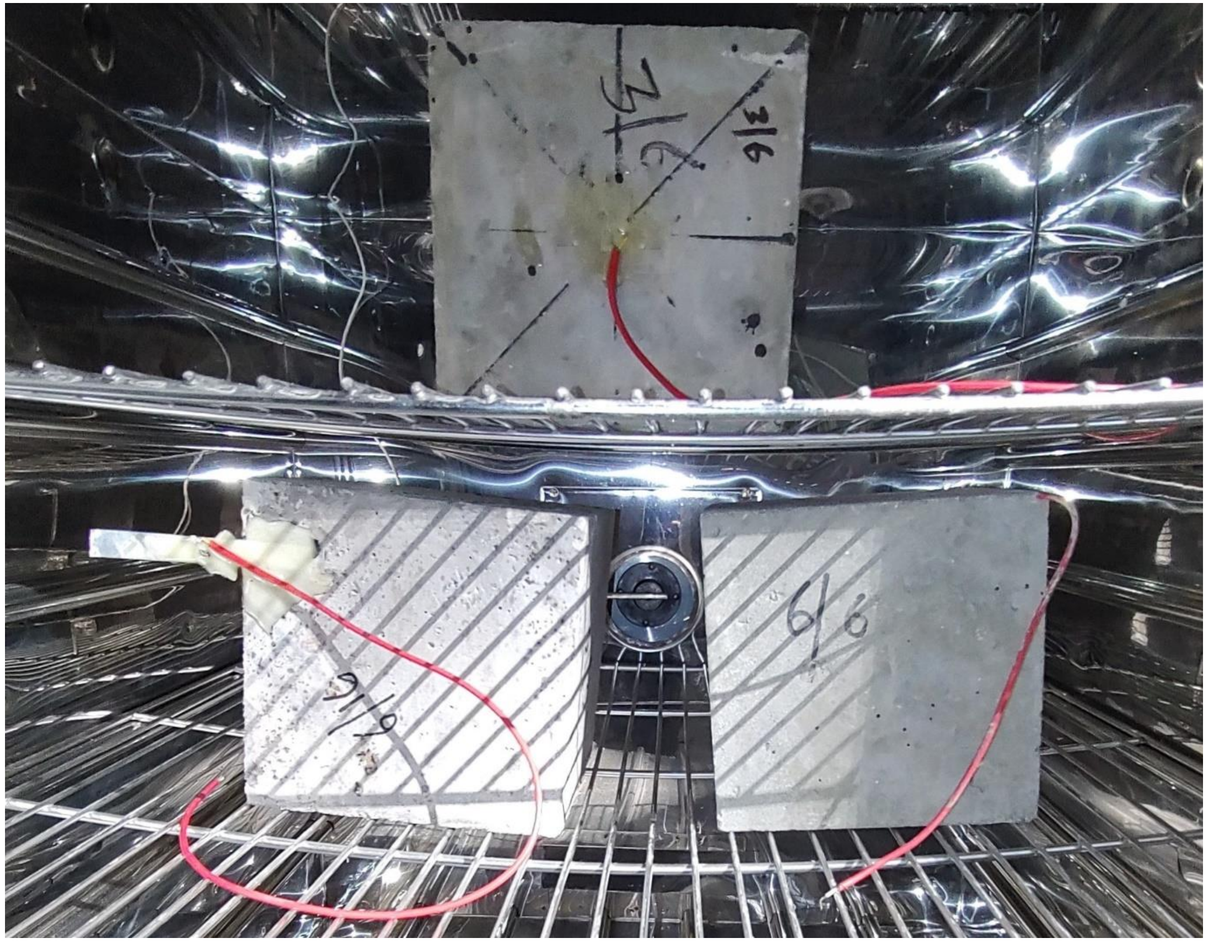
PLACING OF PIEZO SENSORS ON CONCRETE



(a) JKTPS **(b) SBPS** **(c) NBPS**



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Inspection of Visible Surface Cracks at Increasing Impact

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With the increase in impact the width of the cracks becomes wider

Cracks were developed at the centre first and then propagated towards the edge


Pristine State


1st Impact


2nd Impact


3rd Impact


3rd Impact side face


4th Impact

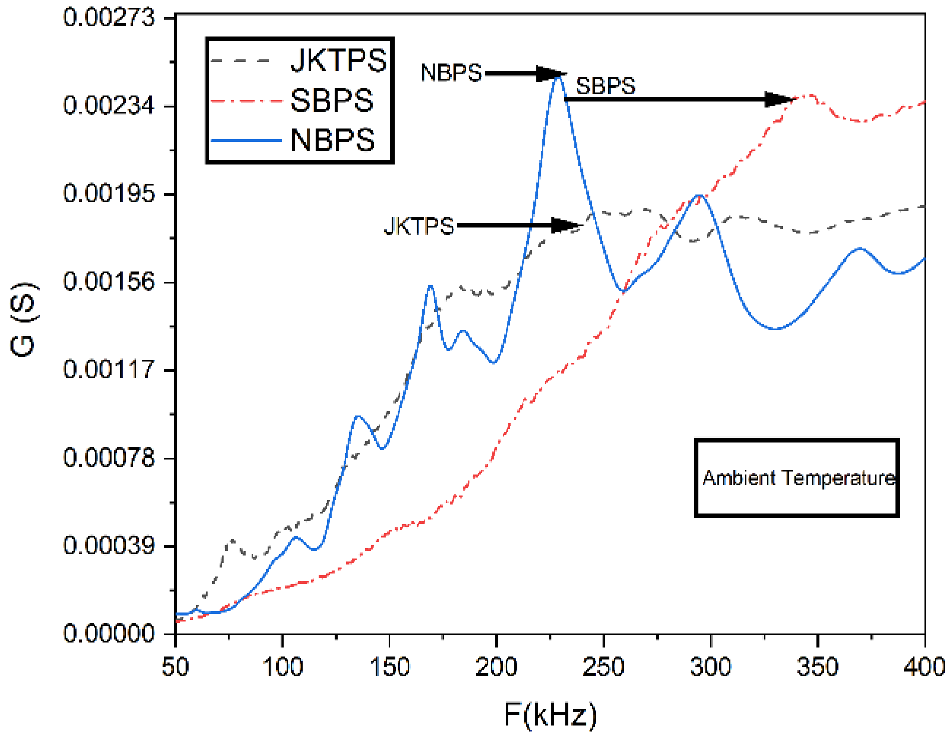

5th Impact


6th Impact

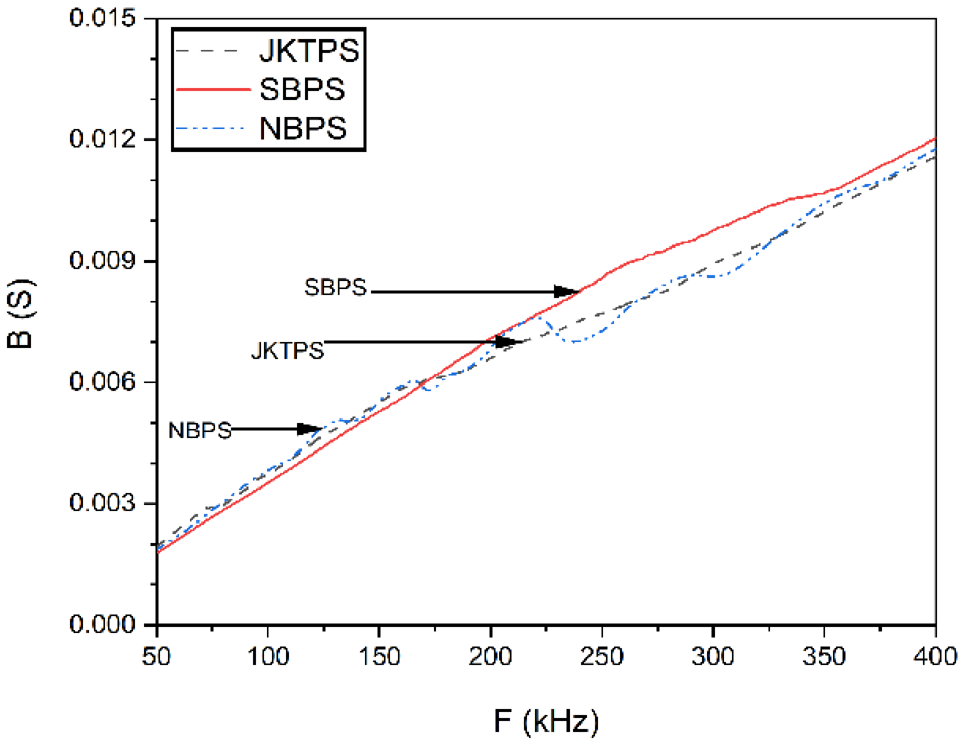
A typical example of a concrete cube under each impact for Inspection of visible surface cracks at increasing impact

Authors – Dr. Shilpa Pal & Indrajeet Singh

Baseline (healthy state)conductance and susceptance signature for different sensors configuration



For change in structure



For change in PZT

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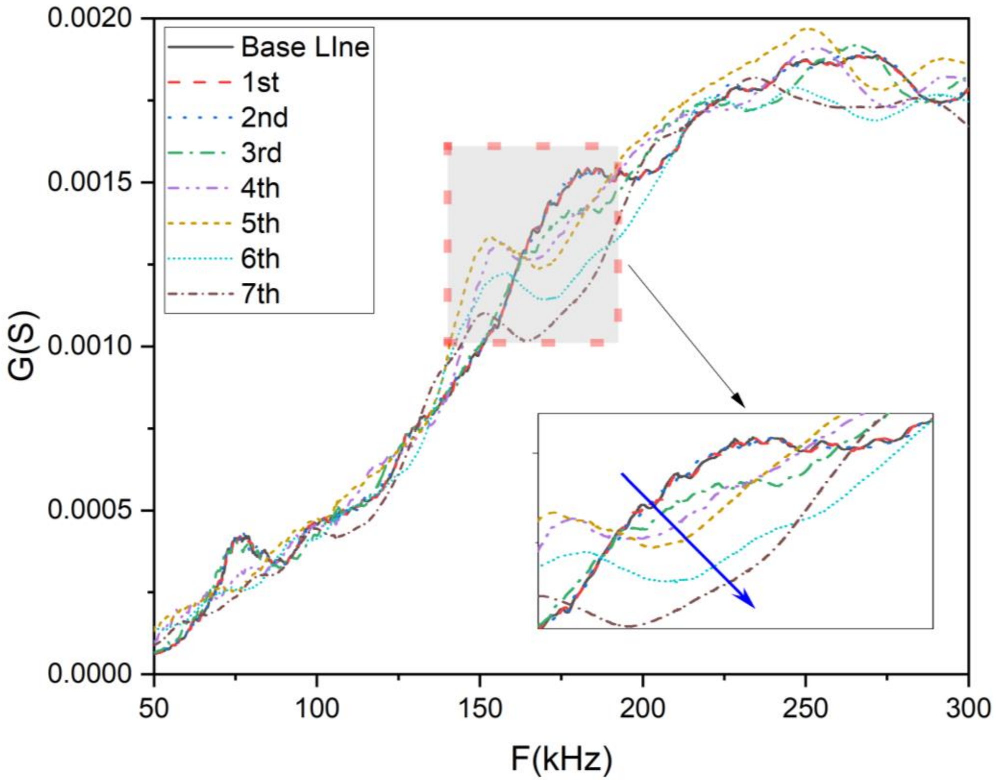
JKTPS → Jacketed piezo sensors (Embedded)

Variation of the Conductance signature with the frequency for increasing impact in comparison to the baseline signature at ambient temperature

With the increase in number of impacts, the conductance signature shifts in the downward directions



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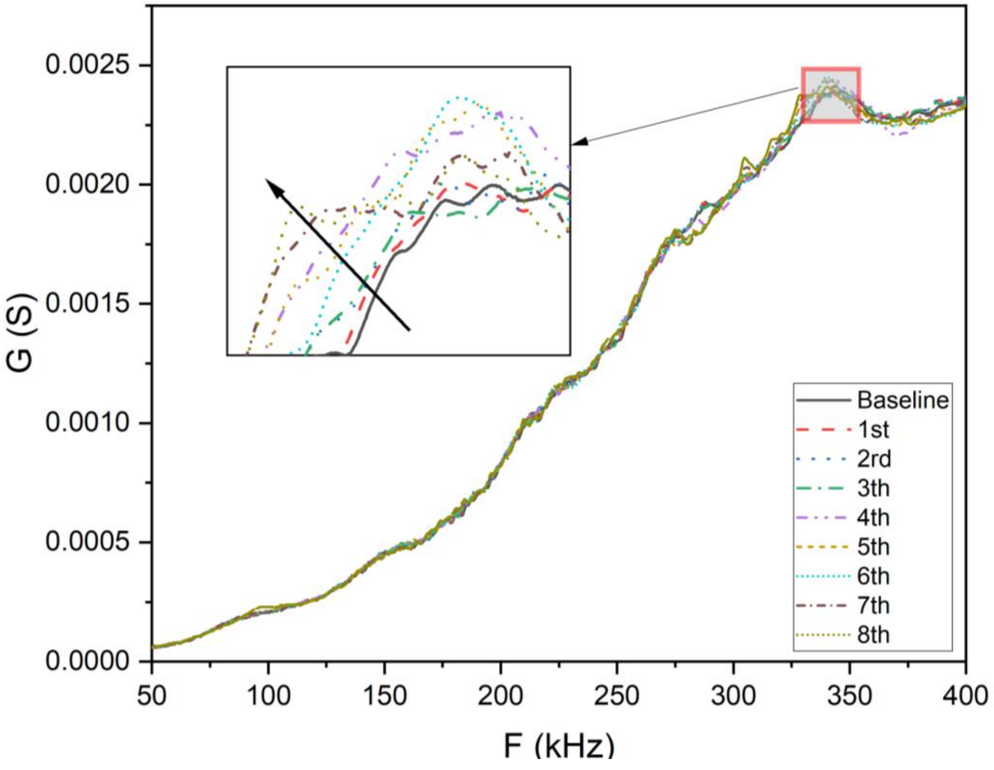
SBPS → Surface bonded piezo sensors



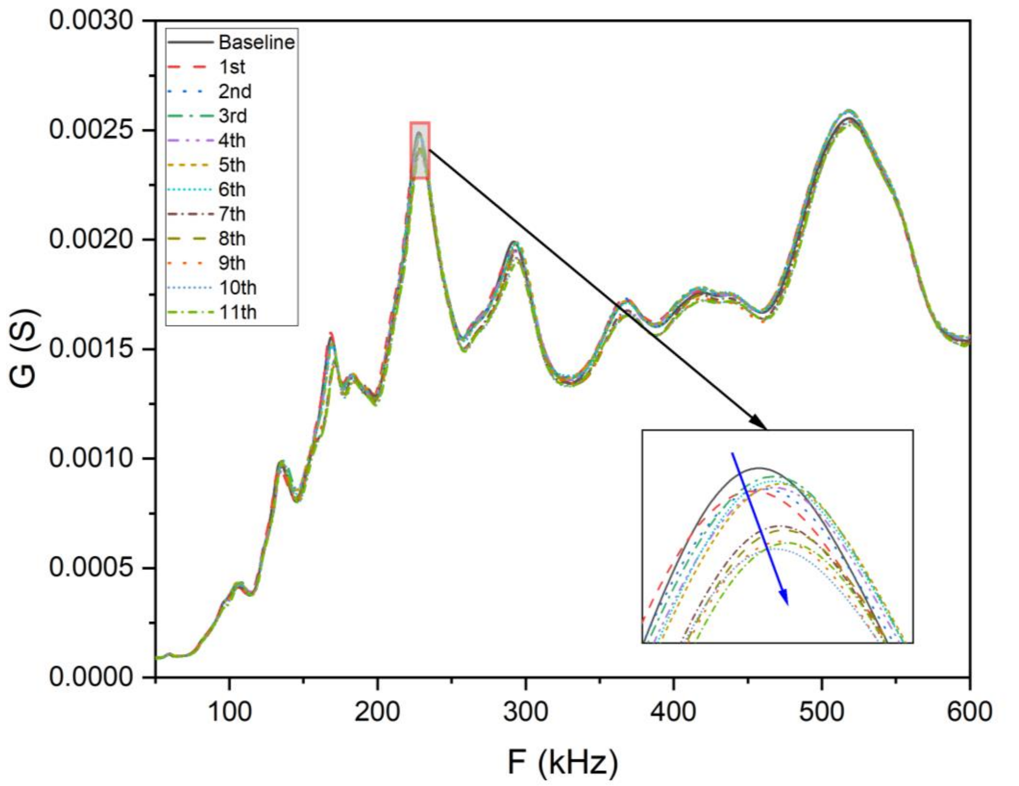
Variation of the Conductance signature with the frequency for increasing impact in comparison to the baseline signature at ambient temperature

With the increase in number of impacts, the conductance signature shifts in the upward directions

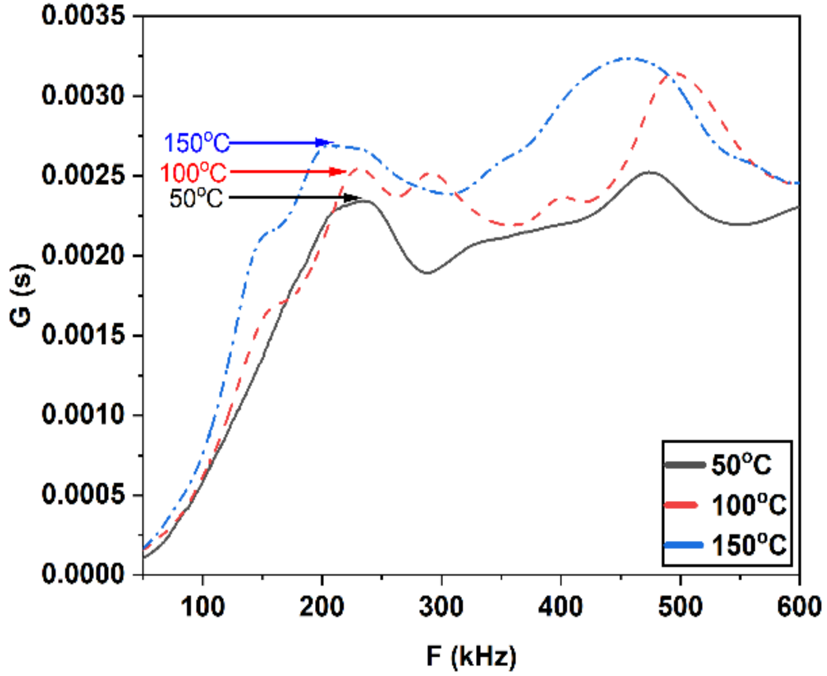
NBPS → Non bonded piezo sensors

Variation of the Conductance signature with the frequency for increasing impact in comparison to the baseline signature at ambient temperature

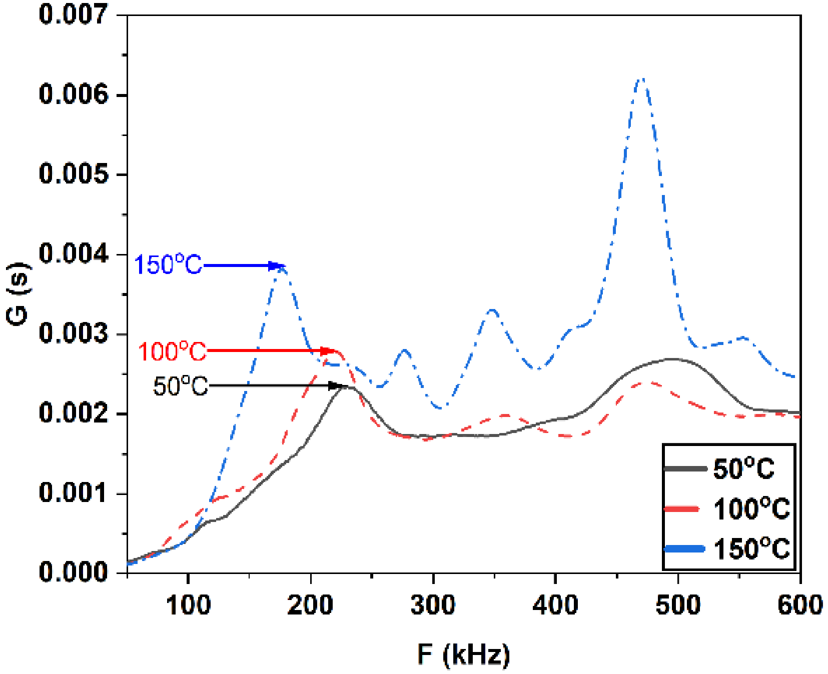
With the increase in number of impacts, the conductance signature shifts in the downward directions



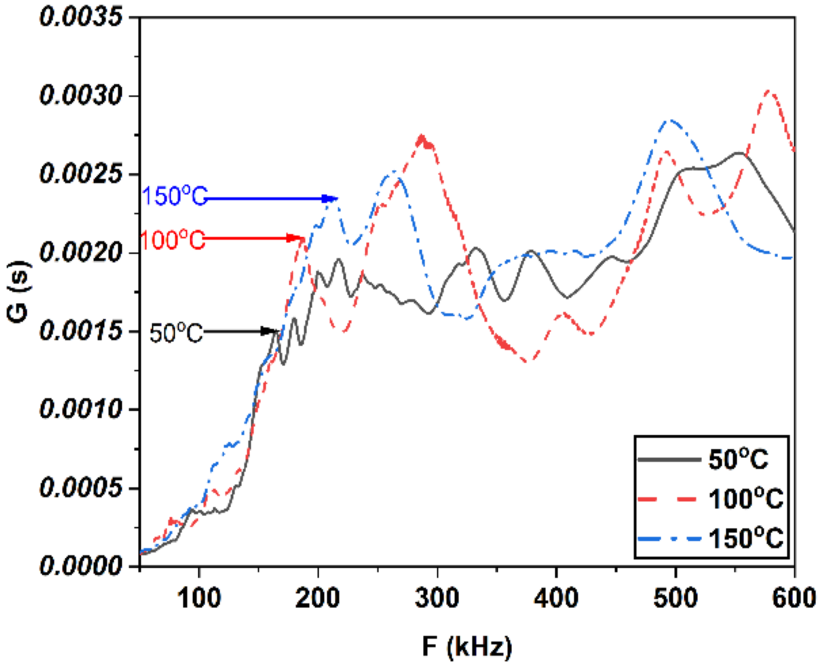
Heated at 50 ºC, 100 ºC and 150 ºC



JKTPS



SBPS



NBPS

COMBINED EFFECT OF IMPACT AND TEMPERATURE

SIGNATURES UNDER TEMPERATURE & IMPACT LOADING

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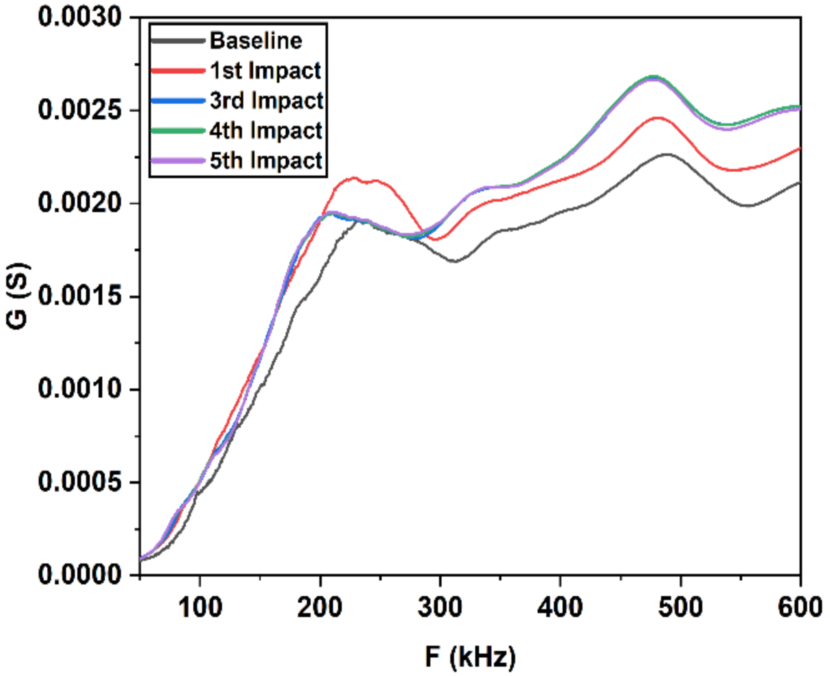
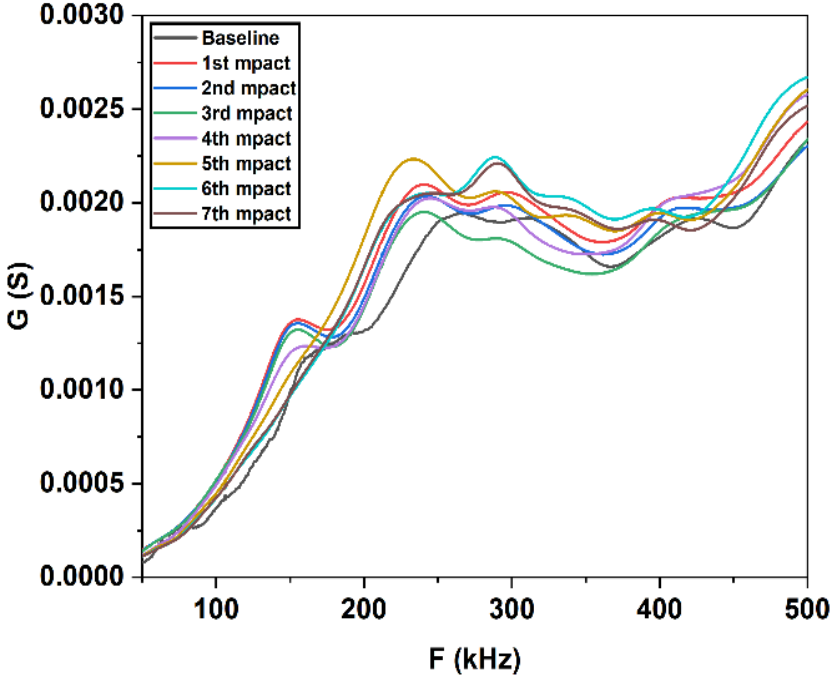
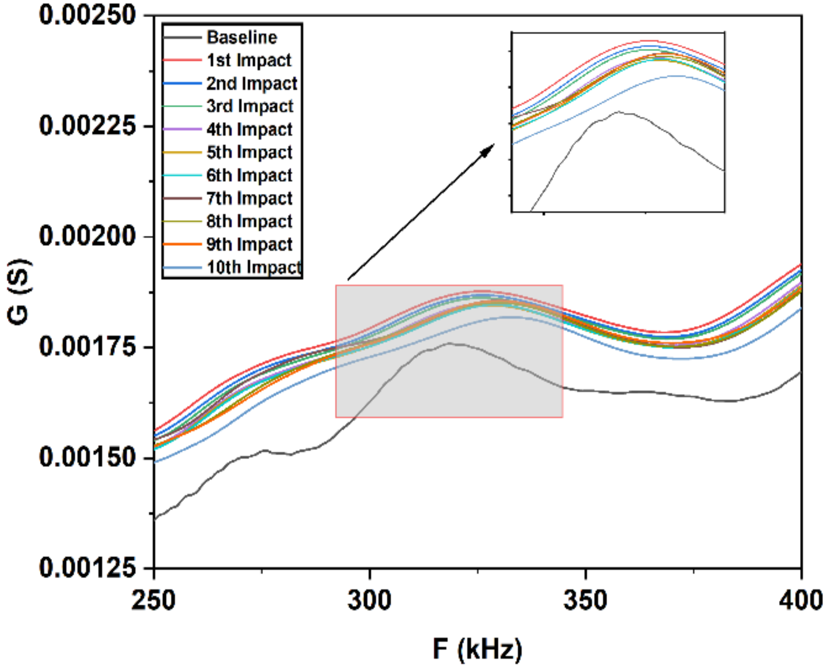
Pre-heated at 50ºC , 100ºC and 150ºC and then subjected to impact loading



JKTPS at 50ºC



JKTPS at 100ºC



JKTPS at 150ºC

As compared to the baseline, conductance signature shifts in the upward direction for the 1st impact and then shift in the downward direction for the further impact load. Shifting of the signature in the upward direction from the baseline to the 1st impact is due to the temperature sensitivity behaviour of sensors

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NUMERICAL INDICES

RMSD	MAPD
Root mean square deviation	Mean absolute percentage deviation
Root mean square deviation (RMSD) is **used for measuring the difference between the signatures of piezo sensors from its initial (baseline) structural conformation to its final position**.	The mean absolute percentage error (MAPE), also known as mean absolute percentage deviation (MAPD), is **a measure of prediction accuracy of a forecasting method in statistics**
$RMSD = \left(\frac{\sum_{k=1}^{N} \left[Re(Z_k)_j - Re(Z_k)_i \right]^2}{\sum_{k=1}^{N} [Re(Z_k)_i]^2} \right)^{\frac{1}{2}}$	$MAPD = \frac{1}{N} \sum_{k=1}^{N} \left| \left[Re(Z_k)_j - Re(Z_k)_i \right] / Re(Z_k)_i \right|$

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RMSD VARIATION FOR JKTPS AND SBPS

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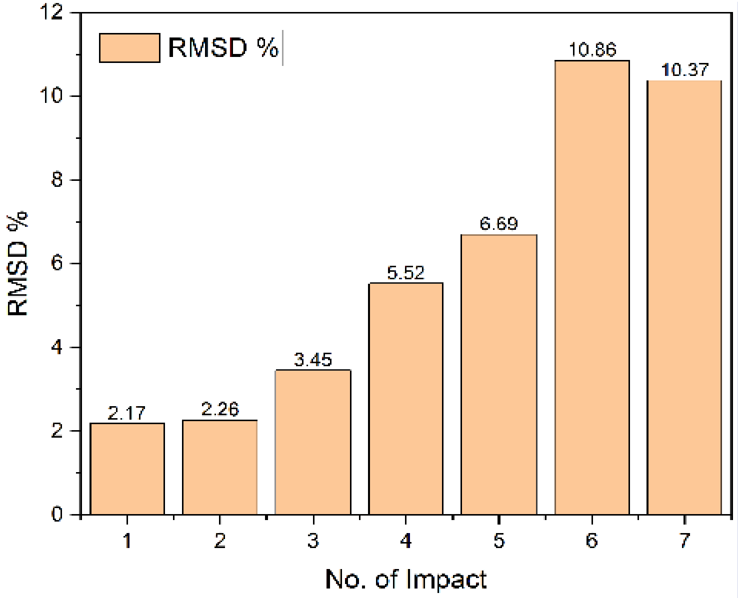
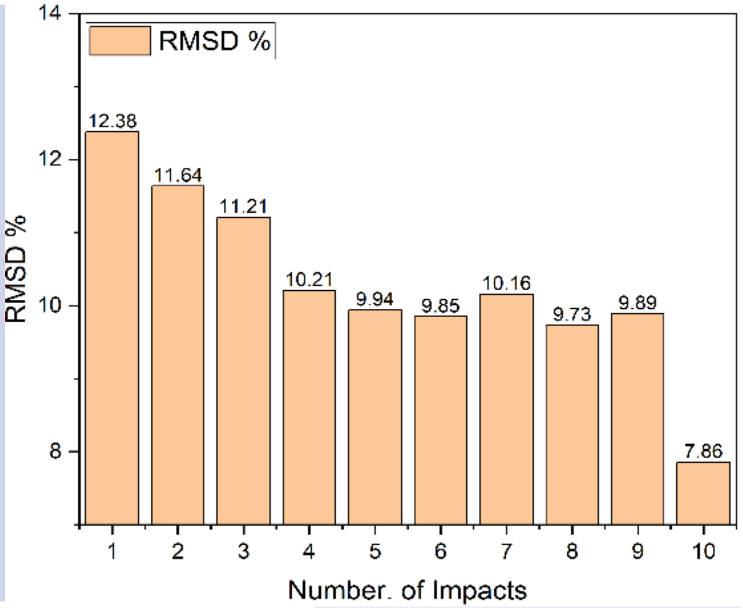
At Ambient Temperature	At 150 ºC Temperature

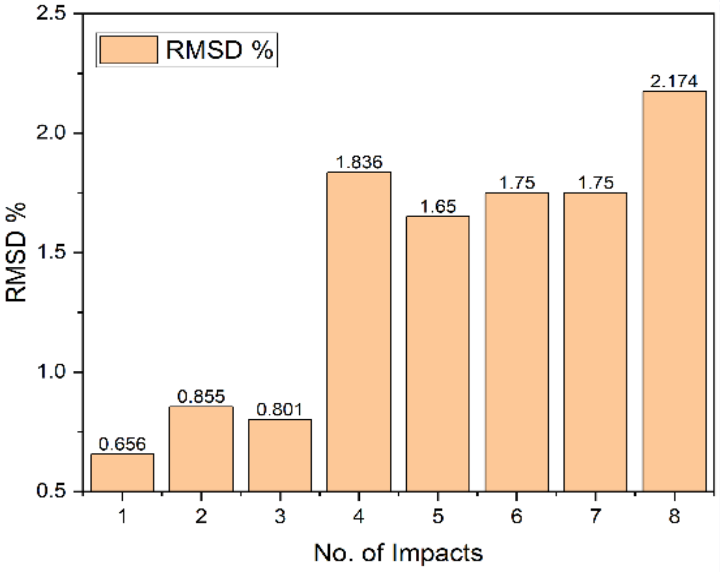


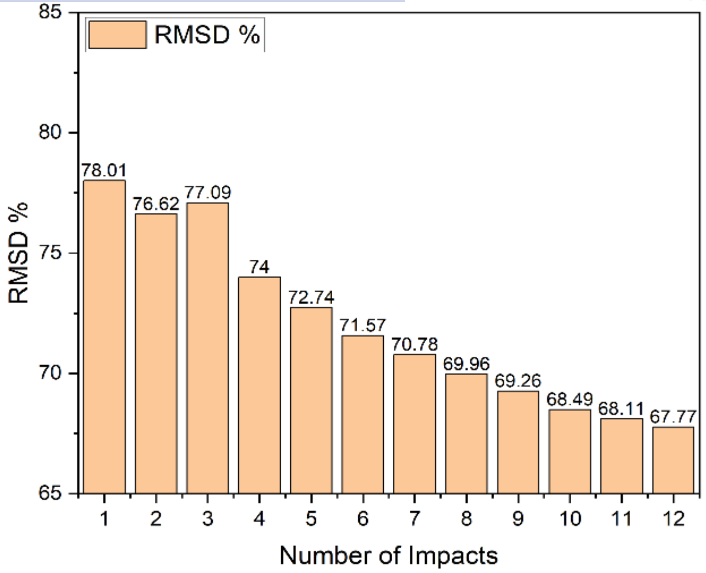
JKTPS

JKTPS



SBPS





SBPS

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MAPD VARIATION FOR JKTPS AND SBPS

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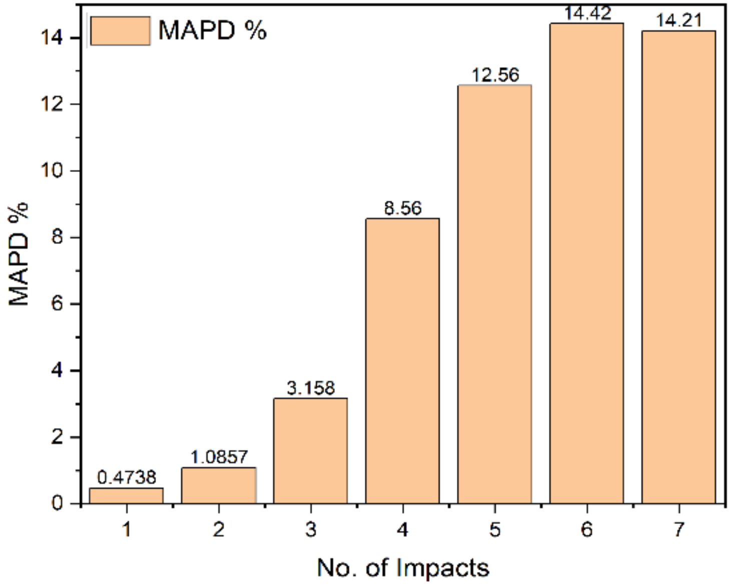
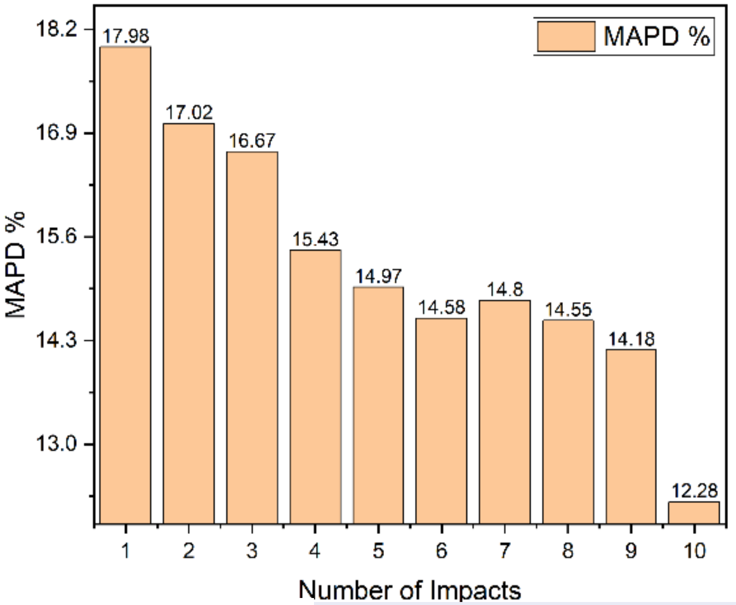
At Ambient Temperature	At 150 ºC Temperature

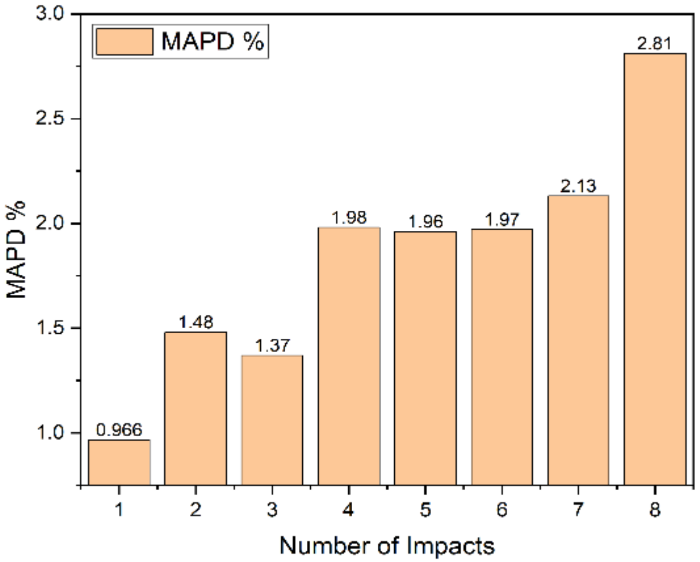


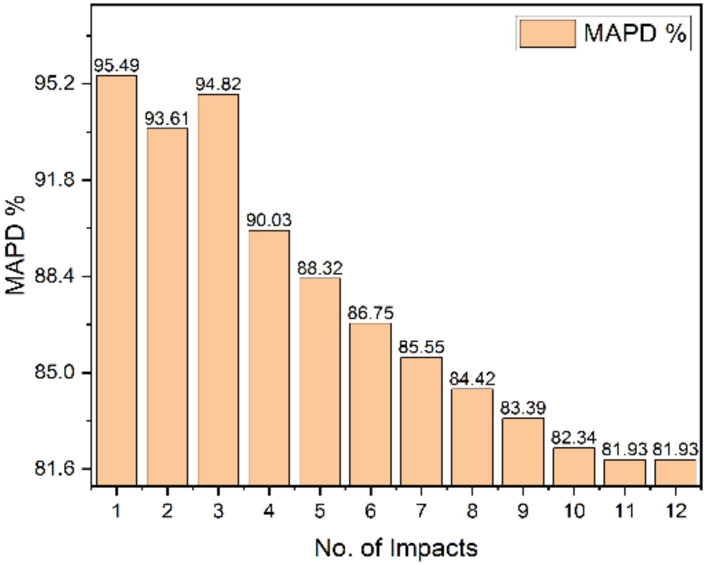
JKTPS

JKTPS



SBPS





SBPS

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ANALYSIS BASED ON THE MECHANICAL IMPEDANCE PARAMETER

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Equivalent stiffness variation for different sensors configuration under 3 m height of impact at 150 ^{o}C

Number of Impact	Healthy State	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	% Variation
Equivalent stiffness for JKTPS (10^4 N/m)	4.50	4.16	4.146	4.127	4.115	4.072	4.069	4.061	4.059	4.041	4.031	**10.42 % Loss of Stiffness**
Equivalent stiffness for SBPS (10^4 N/m)	4.51	4.34	4.32	4.29	4.28	4.24	4.23	4.21	4.20	4.18	4.17	**7.53 % Loss of Stiffness**
Equivalent stiffness for NBPS (10^4 N/m)	4.51	4.41	4.37	4.32	4.31	4.27	4.25	4.20				**6.87 % Loss of Stiffness**

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Remaining life estimation using equivalent structural parameters

$\Delta s = \left|\frac{\Delta k}{k}\right|$

- Δs - Changes in the stiffness caused by incremental damage
- Δk - Change in equivalent stiffness compared to k
- k - Original equivalent stiffness in pristine stage

$L = 1 - \frac{N}{N_0}$

- L - A non-dimensional parameter (represents the remaining life of structure)
- N_0 - Signifies the total number of impacts applied till failure
- N - Denotes the number of impacts applied until a specific stage

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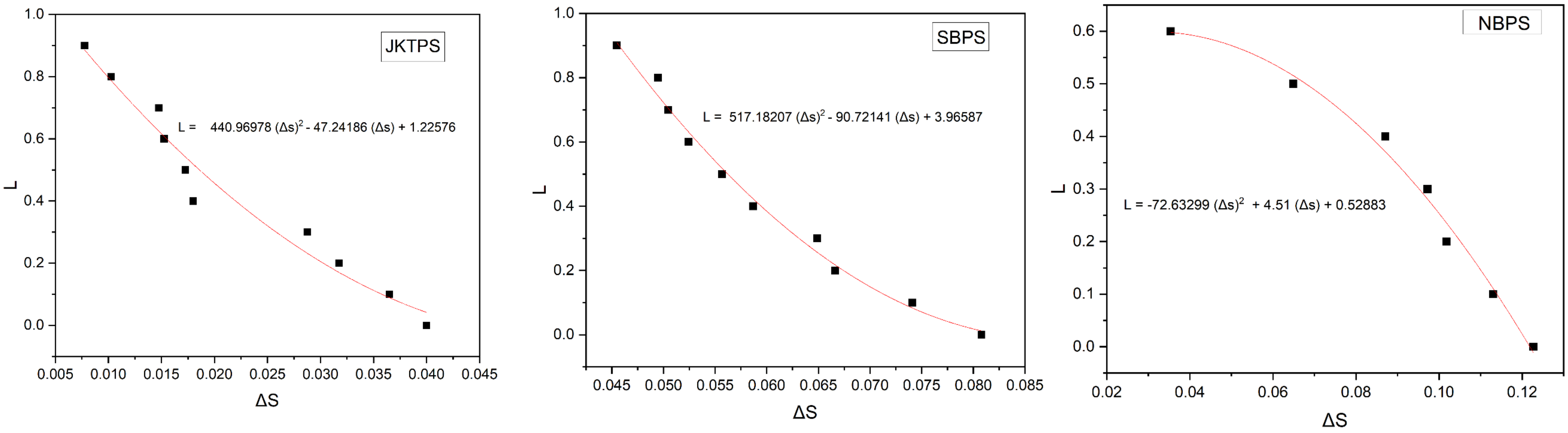
Remaining life estimation using equivalent structural parameters



Variation of *L vs ΔS* for different sensors configurations

Increase in the value of Δ*s*, remaining life of structure reduces

CONCLUSIONS

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- On the basis of statistical tools such as RMSD and MAPD value, both are the reliable tools for calculating the incipient and progressive damage in concrete under the effect of impact loading at varying temperature.
- Due to its lack of direct contact with the host structure, the NBPS recorded lower RMSD and MAPD (1.396% to 3.22%) values than the SBPS (78.01–67.77%) and JKTPS (12.38–7.86%)
- Both the RMSD and MAPD indices followed a distinct pattern at higher temperatures of 150 ^{o}C for all sensor configurations that clearly indicate the damage at higher temperatures.
- The extracted equivalent stiffness with increasing impact number clearly indicates damage propagation in concrete sample for different sensor configuration (10.42 % loss for JKTPS) and also showed satisfactory agreement between the experimental and equivalent plot of x and y.
- Equivalent stiffness can be used to successfully develop an empirical model for predicting the remaining life of structures.

DAMAGE ASSESSMENT IN REINFORCED CONCRETE BEAM UNDER IMPACT LOADING AT VARYING TEMPERATURES

Authors – Dr. Shilpa Pal & Indrajeet Singh

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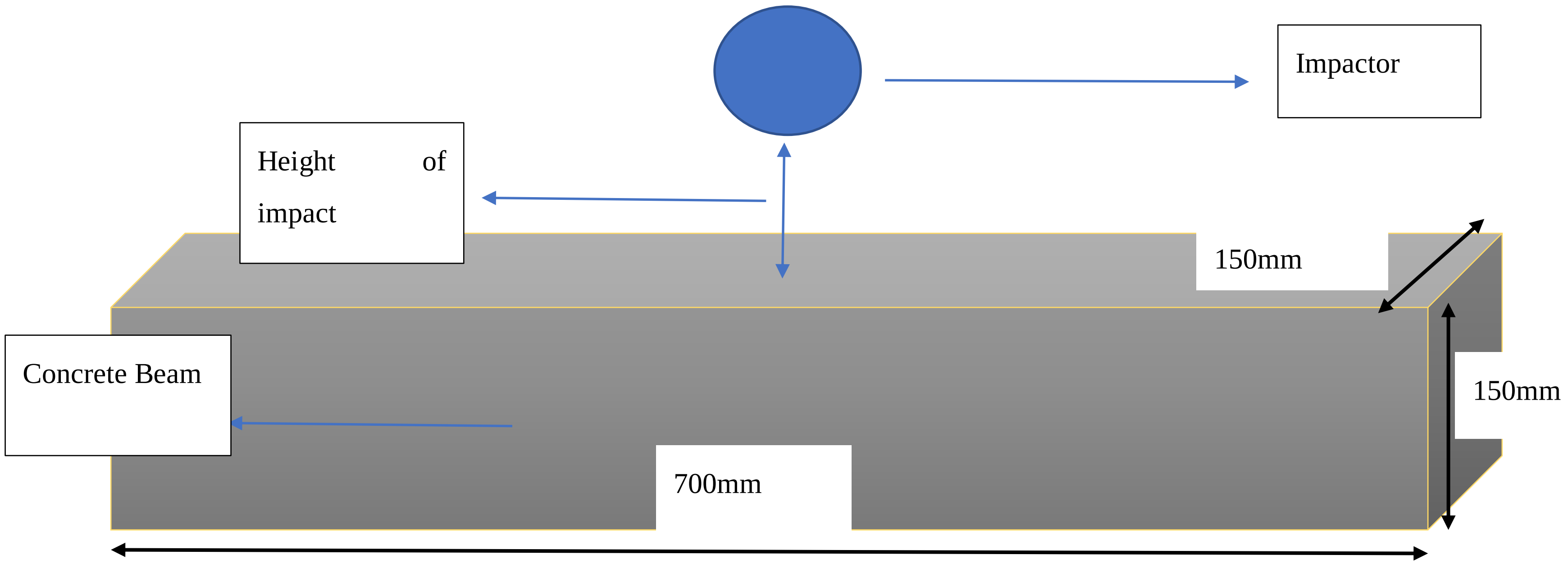
DAMAGE ASSESSMENT IN REINFORCED CONCRETE BEAM UNDER IMPACT LOADING AT VARYING TEMPERATURES

S.No.	Parameter	Description
1	Type of sensors configuration	Embedded
2	Impact height	3 m
3	Impactor size and type	Steel ball with 13 cm diameter
4	Temperature variation	50°C, 100°C and 150°C
5	Boundary condition	Free (Fixed at base)
6	Instruments	LCR meter, oscilloscope, guided pipe
7	Grade of concrete	M30



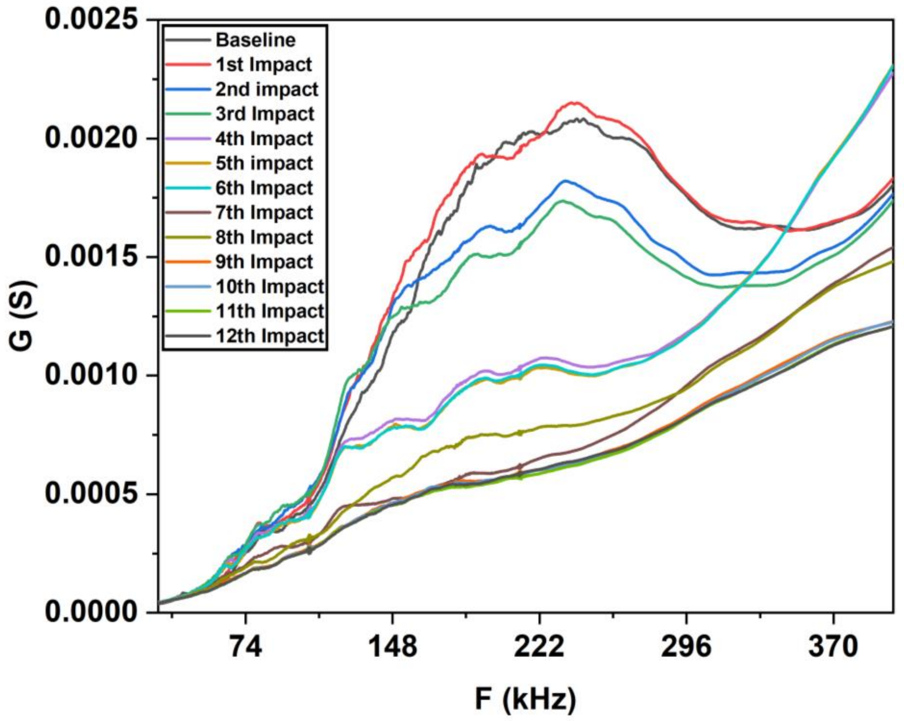
Block Diagram of the test frame

1st impact

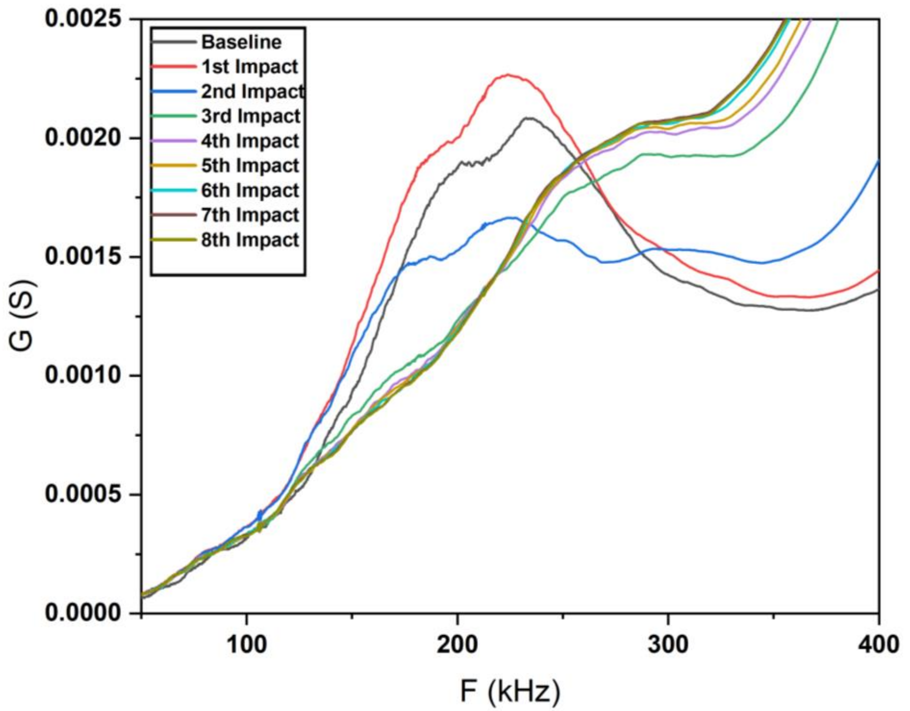
5th impact

10th impact

15th impact

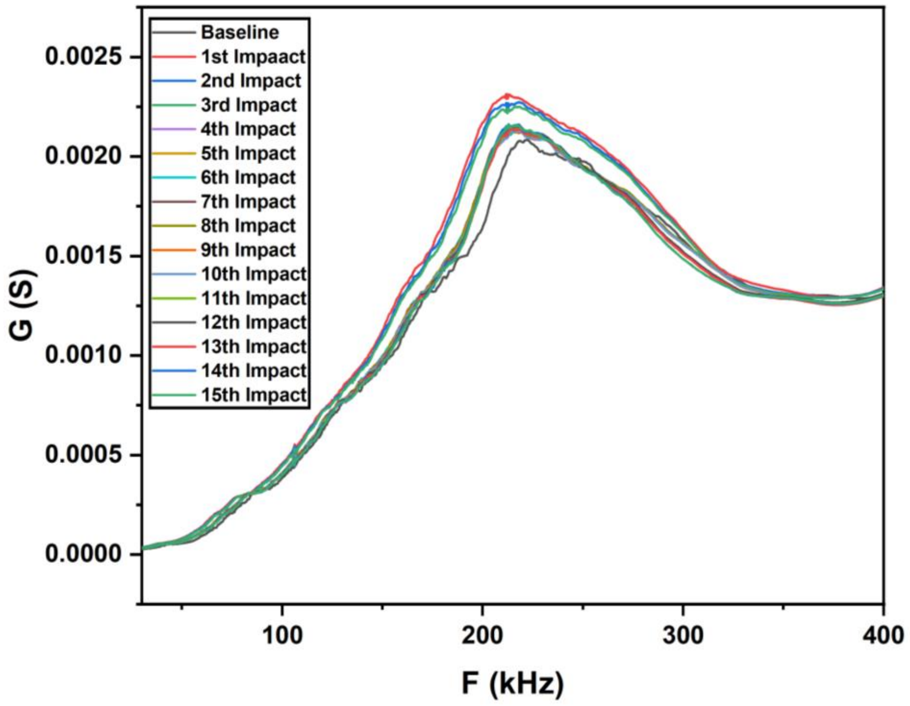


At ambient temperature

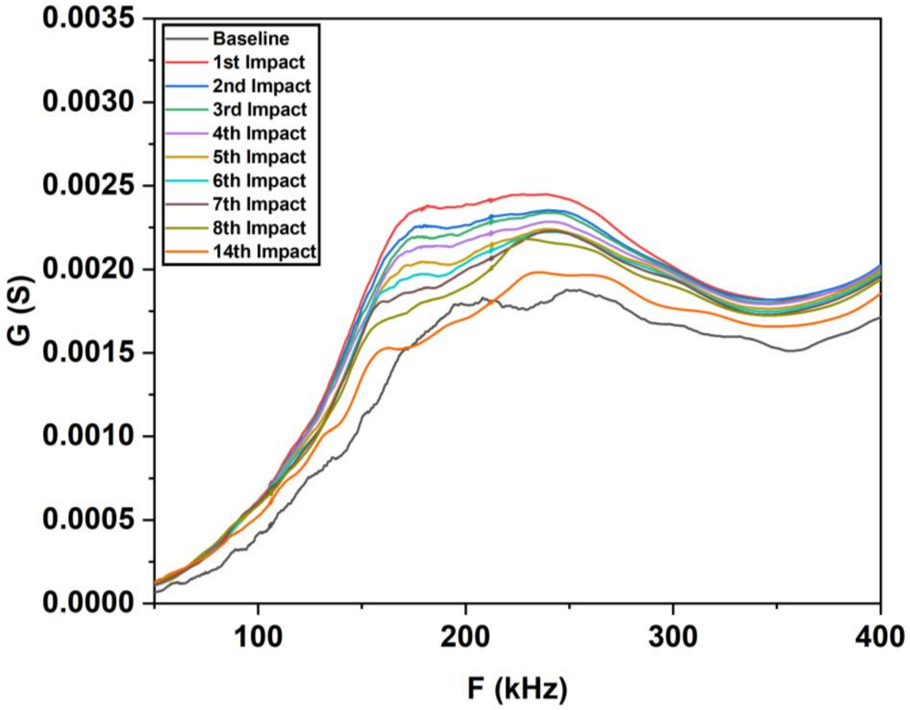


At 50^{o}C

With the increase in number of impacts, the conductance signature shifts in the downward directions that clearly indicate the damage in the concrete.



For 100 ^{o}C



For 150 ^{o}C

- As compared to the baseline, conductance signature shifts in the upward direction for the 1st impact and then shift in the downward direction for the further impact load.
- Shifting of the signature in the upward direction from the baseline to the 1st impact is due to the temperature sensitivity behaviour of sensors.

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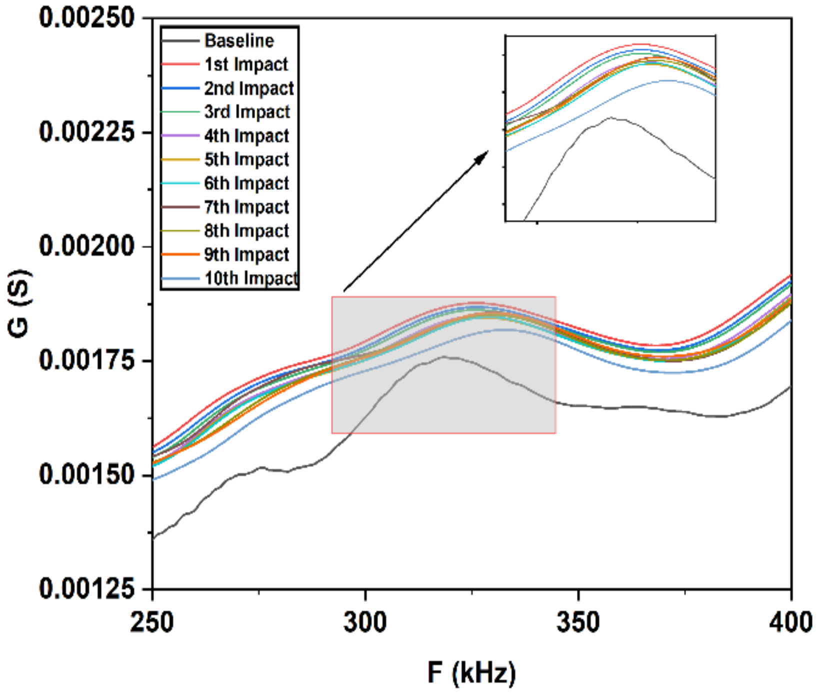
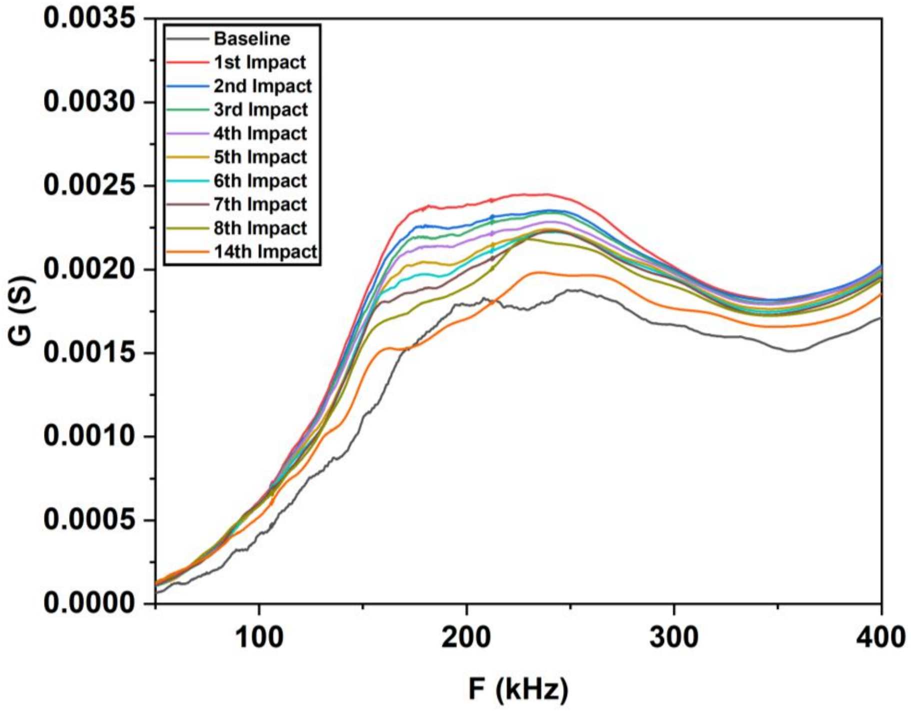
- Both the signatures is following the same pattern.
- Its shows that the same work in the cube can be replicates in the beam



Conductance signature for cube at 150 ºC for JKTPS



Conductance signature for beam at 150 ºC for JKTPS

Authors – Dr. Shilpa Pal & Indrajeet Singh

CONCLUSIONS

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- The results clearly demonstrate that JKTPS Piezo clearly detect damage in the beam for very initial stages.
- The PZT patches could be extremely beneficial not only for detecting beginning damage but also for predicting material breakdown.
- The conductance signature followed a distinct pattern for ambient and higher temperature condition that clearly indicate the damage condition of the structural element
- The extracted equivalent stiffness with increasing impact number followed a distinct decreasing pattern (stiffness loss up to 15%) that clearly indicates damage propagation in concrete beam.

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- The EMI technique is capable in detecting the damage in the concrete structural element under the combined effect of impact and temperatures.

- JKTPS sensors are the best suitable sensors among all the different sensors configuration for detecting the damage in the concrete under the combined effect of impact and temperatures.

- Therefore, it has significant potential in the field of Non-destructive SHM.

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For more information, kindly refer to this published paper

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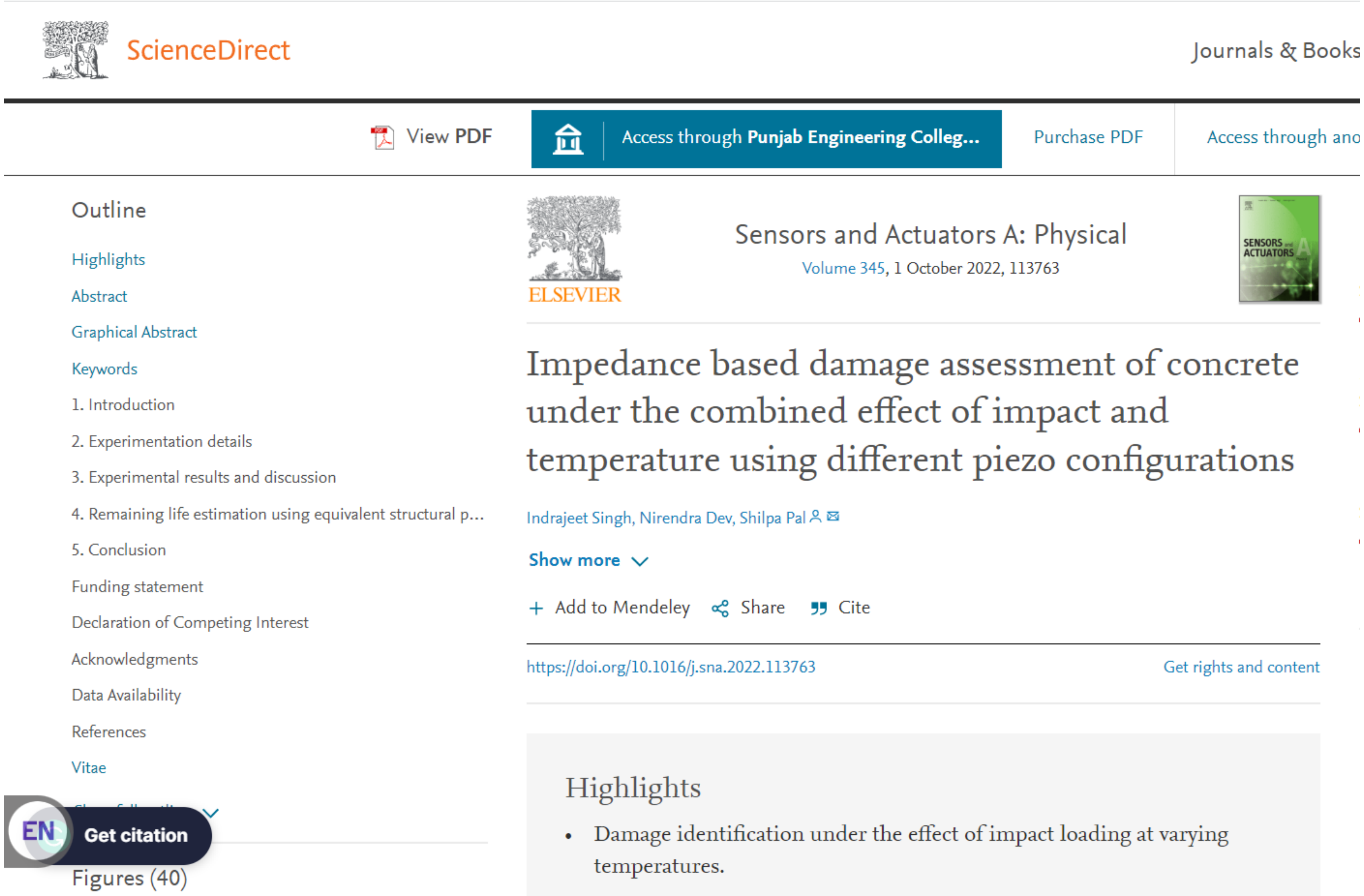

Thank You