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PZT Sensor Array for Local and Distributed Measurements of Localized Cracking in Concrete

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Abstract

An application is developed with surface mounted Lead Zirconate Titanate (PZT) patches for sensing damage in the form of a stress-induced crack in a concrete substrate. A localized crack is introduced in a controlled manner using a fracture test. Full-field displacements obtained using digital image correlation are used for crack penetration and crack width measurements. Electrical impedance (EI) measurements are obtained from the individual PZT patches, which are attached at different locations relative to the crack. Stress wave transmission measurements are performed using the PZT patches as actuator-receiver (AR) pairs. The EI measurements indicate that small, quantifiable changes in the mechanical impedance of the substrate are experienced by the PZT patch in the vicinity of the localized crack, which sensitively detect crack initiation. The stress wave-based measurements are very sensitive to the presence of physical discontinuity created by a localized crack in the stress wave path. A measure of stress wave attenuation, the attenuation factor is developed, to quantify the measured changes in the stress wave produced by the physical discontinuity in concrete upon

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22 unloading a stress-induced crack. The physical discontinuity due to a stress-induced crack
23 opening on the order of $10\mu\text{m}$ can be detected from the measured changes in the attenuation
24 factor. The physical discontinuity in the concrete associated with a stress-induced crack
25 opening on the order of $100\ \mu\text{m}$ produces a complete attenuation of the stress wave of $120\ \text{kHz}$.
26 The combined use of PZT patches in the EI and the AR modes can be used to detect local
27 changes close to a PZT patch and it allows distributed sensing over the entire volume of a
28 structural element.

29

30 **1. Introduction**

31 PZT is a piezoelectric material, which is being used for developing economical methods
32 for continuous damage assessment in structures. PZT exhibits a coupled electromechanical
33 (EM) response; surface charges are produced when mechanical strain is induced and strain
34 when electrical potential is applied. PZT-based sensors offer a significant potential for
35 continuously monitoring the development and progression of internal damage in structures.
36 Several damage detection strategies have been developed using PZT patches attached to a
37 substrate [Song et al. (2008), Zhu and He (2011), Lim et al (2012), Lu et al. (2013), Rucka and
38 Wilde (2013), Divsholi and Yang (2014), Narayanan and Subramaniam (2016a, b), Liang et
39 al. (2016), Huo et al. (2017), Ai et al. (2017)]. The use of PZT patches has been primarily
40 focused on metallic and composite structures with very limited application to concrete. The
41 use of PZT patches in concrete structures is still evolving.

42 The electrical impedance (EI) obtained from the measured electrical response of a PZT
43 patch at multiple frequencies depends on the electromechanical (EM) response of the PZT
44 material, the geometry of the patch and the boundary conditions. The electrical impedance
45 measurements from a PZT patch bonded to a substrate depend on the EM response of the

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3 46 coupled system. When a PZT patch is attached to a substrate, the dynamic motion of the PZT
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5 47 patch in response to an applied electrical potential depends on the dynamic mechanical
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7 48 impedance to its motion provided by the substrate, the mechanical impedance [Liang et al.
8
9 49 (1994), Giurgiutiu et al. (1999), S. Park et al. (2006), Na and Lee (2012), Narayanan et al.
10
11 50 (2017)]. The use of a PZT patch to infer about the level of damage in the substrate requires
12
13 51 interpreting the coupled EM response of the PZT patch attached to the substrate.
14
15 52 Understanding the response of PZT patch attached to a concrete substrate is still evolving.
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17 53 Changes are registered in EI measurements due to formation of cracks well in advance of
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19 54 failure [Park et al. (2000)]. The EM impedance (EMI) derived from the electrical
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21 55 measurements on PZT patches attached to a concrete substrate sensitively detect changes in
22
23 56 the local material compliance produced by distributed damage in the vicinity of the sensor
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25 57 [Narayanan and Subramaniam (2016a, b)]. For a PZT patch attached to a concrete substrate,
26
27 58 its motion at a given frequency is directly influenced by a zone of influence, which represents
28
29 59 the finite volume of material. The EMI measurements from a concrete substrate are shown to
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31 60 be sensitive to incipient distributed damage in the material within the zone of influence
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33 61 [Narayanan et al. (2018)]. A smaller zone of influence and higher sensitivity to local changes
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35 62 increases at higher frequencies. The EI measurements therefore provide a local measure of
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37 63 damage in the vicinity of the sensor.
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45 64 The coupled constitutive electro-mechanical response of piezoelectric material allows a
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47 65 PZT patch to be used as an actuator for generating stress waves in the substrate material and
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49 66 as a receiver for sensing stress waves. The PZT patches are used as actuator/receiver (AR)
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51 67 pairs for generating and receiving stress waves. In the distributed sensing mode, damage in the
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53 68 material is inferred through changes in the elastic waves which propagate through the bulk
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55 69 material [Jung et al. (2002), Aggelis and Shiotani (2007), Marani et al. (2014)]. Presence of
56
57 70 cracks in the wave propagation has been shown to significantly alter the wave characteristics
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3 71 [Lu et al. (2013), Watanabe et al. (2014), Kee and Nam (2015), Luo et al. (2016)]. Most of the
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5 72 studies of PZT-based distributed monitoring were reported on metallic structures. The
6
7 73 condition monitoring of concrete infill in fiber reinforced polymer tubes and failure in concrete
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9 74 and composite structures has been monitored using PZT sensor arrays [Xu et al. (2017),
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11 75 Memmolo et al. (2016), Divsholi and Yang (2014), Lu et al. (2013)]. Most of the researchers
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13 76 used time of flight and decrease in wave energy to assess changes in the material
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15 77 characteristics.

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19 78 In concrete, damage initiation takes place in the form of distributed micro cracks, which
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21 79 eventually coalesce to form localized cracks. Cracks in concrete are associated with cohesive
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23 80 crack bridging stresses. There may be significant degradation of the capacity of the structure
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25 81 by the time of appearance of visible cracking on the surface of a concrete structure. Initiation
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27 82 of early intervention measures, which can effectively increase the service life of the structure
28
29 83 require early detection of damage. Methods to detect incipient damage in the form of micro
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31 84 cracks are required to provide effective methods of monitoring structural health and service
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33 85 life performance of structures. Procedures for locating cracks in concrete and for assessing the
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35 86 depth of opening of these cracks is critical for evaluating the degradation of concrete structures.

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41 87 Localized sensing methodology based on EI technique provides information about
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43 88 changes in the local material, which produce changes in its compliance in the vicinity of PZT
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45 89 patch. Any damage located away from the sensing range of a PZT patch would not be detected
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47 90 in its EM signature. In concrete structures where large volume of material has to be monitored
48
49 91 a large number of PZTs is required for local sensing. Sensing methodology using pairs of PZT
50
51 92 patches for monitoring changes in the stress wave can be used for distributed sensing over a
52
53 93 larger region. Local sensing technique (EI measurements) can be employed to detect the
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55 94 damage in the vicinity of the PZT patches while distributed sensing using PZT sensor arrays
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57 95 can be used to monitor the location and the magnitude of damage in a region. The concept of
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3 96 array of sensors which combines both local and distributed sensing using minimum number of
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5 97 sensors provides detailed interpretation about the damage.
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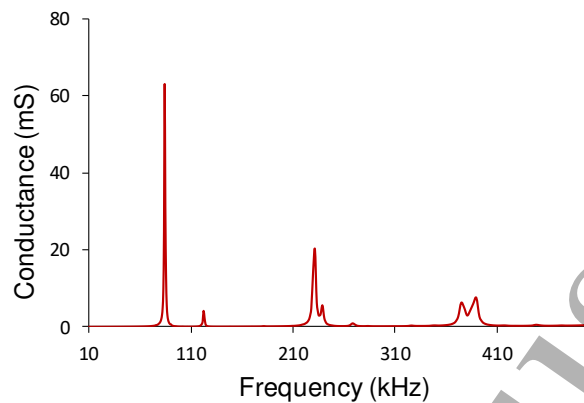
8 98 A sensing scheme using an array of PZT sensors for combined local and distributed
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10 99 damage monitoring is developed. Surface mounted PZT patches are used for continuous local
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12 100 monitoring of concrete and obtaining the information related to damage in the vicinity of the
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14 101 patch. Additionally, the PZT sensor array is used for monitoring damage in the actuator-
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16 102 receiver (AR) mode. The results of an experimental evaluation involving the use of a fracture
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18 103 test specimen are presented and issues related to the development of proposed system are
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20 104 evaluated for the case of localized damage in the form of a crack in concrete. The sensitivity
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22 105 of the EM impedance-based local measurements and the through-transmission measurements
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24 106 to a localized crack in concrete is evaluated.
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32 108 **2. Background**

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35 109 PZT patches are made of piezoceramic materials, which have high electro-mechanical
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37 110 coupling properties. The electrical impedance (inverse of admittance) signature of the PZT
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39 111 patch can be measured when it is excited with an alternating electrical potential. The electrical
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41 112 impedance is a complex number consisting of real and imaginary parts, and is determined as
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43 113 the ratio of the current to the applied voltage. The electrical conductance response (real part of
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45 114 electrical admittance) of a PZT patch (20 mm x 20 mm x 1 mm size) when an alternating
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47 115 potential excitation of 1 V amplitude over a range of frequencies between 10 kHz and 500 kHz,
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49 116 is shown in **Figure 1**. The peaks in the conductance response can be identified with the
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51 117 resonant modes of the PZT patch [Liang et al. (1994), Xu and Liu (2002)]. The mechanical and
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53 118 the electromechanical resonances happen at the same frequency in a piezoelectric material
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55 119 because of the electro-mechanical coupling. The electro-mechanical resonance frequencies of
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3 120 the PZT patch depends on the mechanical resonances which in turn depends on geometry of
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5 121 the patch [Giurgiutiu (2001)].
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124 **Figure 1.** Electrical conductance spectrum of a free PZT patch (patch size: 20 mm x 20 mm
125 x 1 mm)
126

127 The EI response of a PZT patch attached to the substrate subjected to an applied electrical
128 potential depends on the dynamic impedance to its motion from the substrate. The resistance
129 to the motion of a PZT patch from the surrounding elastic medium is expressed as the
130 mechanical impedance. Most approaches for modeling the PZT patch-structure interaction
131 have varied in the degree of sophistication in representing the motion of the PZT patch and the
132 structure. The first systematic attempt to model the PZT patch-structure interaction was
133 presented by Liang et al. (1994) using a PZT actuator driven one-degree-of-freedom spring-
134 mass-damper system. Subsequently, for a PZT patch, an effective 1-D approach was found to
135 give a better representation of the dynamic response of the PZT considering in-plane motion of
136 the PZT coupled to an elastic substrate [Bhalla and Soh (2004)]. The frequency dependent
137 complex admittance response of the PZT patch, \bar{Y} is given as
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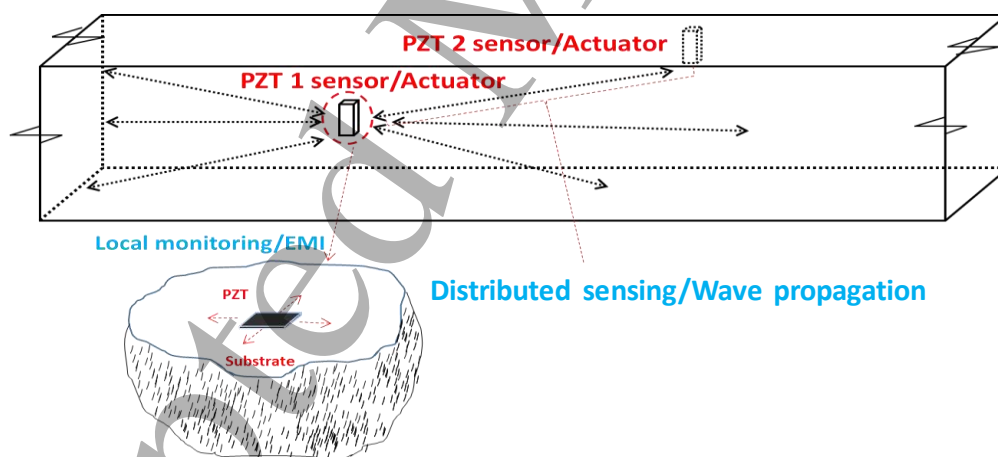
$$\bar{Y} = \frac{4\omega il^2}{h} \left[\frac{\bar{\epsilon}_{33}^T}{(1-\nu)} - \frac{2d_{31}^2 \bar{Y}^E}{(1-\nu)} + \frac{2d_{31}^2 \bar{Y}^E Z_{a,eff}}{(1-\nu)(Z_{s,eff} + Z_{a,eff})} \left(\frac{\tan \kappa l}{\kappa l} \right) \right] \quad (1)$$

139 where $Z_{a,eff}$ and $Z_{s,eff}$ are the mechanical impedances of the PZT and the substrate,
 140 respectively; l and h are the half-length and the thickness of the PZT patch, respectively; ν is
 141 the Poisson's ratio of the piezoelectric material; $\bar{\epsilon}_{33}^T$ is complex dielectric constant; $\bar{\epsilon}_{33}^T =$
 142 $\epsilon_{33}^T (1 - \delta i)$; δ =dielectric loss factor; \bar{Y}^E is the complex modulus of PZT given as $\bar{Y}^E =$
 143 $Y^E (1 + i\eta)$; η is the mechanical loss factor; d_{31} is the piezoelectric strain constant; k is the
 144 wave number which is calculated as $k = \omega \sqrt{\frac{\rho(1-\nu^2)}{Y^E}}$; ρ is the density of the PZT material; E is
 145 the electric field applied for actuation with circular frequency ω and i is $\sqrt{-1}$.

146 A change in the mechanical impedance of the surrounding medium changes the EI
 147 response of the PZT patch. For a concrete substrate, the effective dynamic response of the PZT
 148 patch was shown to be influenced by the damping and the stress in the substrate [Narayanan
 149 and Subramaniam (2016b)]. Considering the high material damping of concrete, the dynamic
 150 response of a PZT patch attached to a concrete substrate exhibits a frequency dependence. The
 151 vibratory motion of the PZT patch is influenced by the mechanical impedance derived from a
 152 zone of finite size. For a PZT patch attached to the concrete substrate, the dynamic response,
 153 which consists of distinct modes of vibration of the PZT patch is significantly influenced by
 154 the compliance of the material within a zone of influence. The zone of influence for the
 155 vibratory motion of a bonded PZT patch depends on the frequency of vibration; the zone of
 156 influence is smaller for higher frequencies [Park et al. (2000), Zagrai and Giurgiutiu (2001),
 157 Narayanan et al. (2018)]. Any changes in the material compliance within the zone of influence,
 158 influences the vibratory motion of the PZT patch. Distributed damage produces an increase in
 159 the compliance and the level of damping of the material. Both these effects are known to

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3 160 produce a downward shift in frequency and decrease in amplitude of the resonant mode in the
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5 161 EI spectrum.
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8 162 In this study, an array of surface mounted PZT patches are used for combined EI and AR
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10 163 measurements. As shown in **Figure 2**, an array of PZT patch sensors is deployed in a structural
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12 164 element, where the EI measurement from the PZT patch is used for local monitoring while the
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14 165 through-transmission measurements are used for distributed sensing. Each PZT patch is used
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16 166 as an actuator and a sensor for through-transmission measurements in the AR mode. A
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18 167 schematic representation of the methodology is given in **Figure 2**. A received signal undergoes
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20 168 the losses due to signal propagation path and in epoxy at the concrete-beam interfaces.
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22 169 Measures for quantifying changes in the EMI and the received waves due to damage in the
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24 170 form of a localized crack are developed for the level of material discontinuity produced by a
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26 171 stress-induced crack of a given opening.
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50 174 **Figure 2.** Schematic representation of local-distributed monitoring system using surface
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52 175 mounted PZT patches.
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58 177 **3. Materials and Methods**
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3 178 The details of the concrete used in this study is given in **Table 1**. Coarse aggregate
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5 179 consisted of 20 mm and 10 mm crushed gravel in a 1:1 proportion and river sand was used as
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7 180 fine aggregate. Cement conforming to the requirements of OPC grade 53 as per the Indian code
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9 181 of practice, IS 12269:2013 was used. The 28-day compressive strength and modulus of rupture
10
11 182 obtained by testing standard 150 mm cubes and 500 mm x 150 mm x 150 mm sized beams.
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14 183 The properties of the concrete are given in **Table 1**.

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16
17 184 The experimental program consisted of using PZT patches in the distributed (AR) mode
18
19 185 and for local EI-based measurements on beams where the damage is induced in the form of a
20
21 186 localized crack. A fracture beam was used to produce a crack under flexural loading. The
22
23 187 experiments were conducted using notched concrete beams of size 500 mm (length)
24
25 188 x 150 mm (height) x 150 mm (width), made with plain cement concrete. A notch, 25 mm in
26
27 189 depth was introduced in the middle and fracture tests were performed using a computer-
28
29 190 controlled, servo-hydraulic testing machine. The test setup consisted of third point loading as
30
31 191 per the requirements of UNI 11039-2:2003 standard. The flexure test was conducted with a
32
33 192 span equal to 450 mm in four-point bending configuration. The fracture test was conducted in
34
35 193 crack mouth opening displacement (CMOD) control. The CMOD was increased at rate of
36
37 194 30 $\mu\text{m}/\text{minute}$. During the test, the crack tip opening displacement (CTOD) was also measured
38
39 195 using a clip gauge mounted at the tip of the notch. Six square 20 mm PZT patches of 1 mm
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41 196 thickness were attached to each beam. Properties of the PZT is given in **Table 2**. Two PZT
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43 197 patches were bonded on front face and two on back face, remaining two were attached to the
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45 198 soffit of the beam. The PZT patches labelled PZT5 and PZT6 were positioned at the bottom of
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47 199 the beam, 50 mm away from the notch. The other PZT patches were bonded at mid-height of
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49 200 the beam. The PZT patches labelled PZT2 and PZT4 were attached on opposite faces and were
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51 201 located at a distance of 50 mm from the center of the beam. The PZT patches labelled PZT1
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53 202 and PZT3 were attached on opposite faces of the beam at a distance 50 mm away from the end
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of the beam. All the PZT patches were bonded to concrete using a two component epoxy. The properties of the epoxy are given in **Table 3**. The complete test set up showing the locations of the gauges and the PZT sensors is shown in **Figure 3a**.

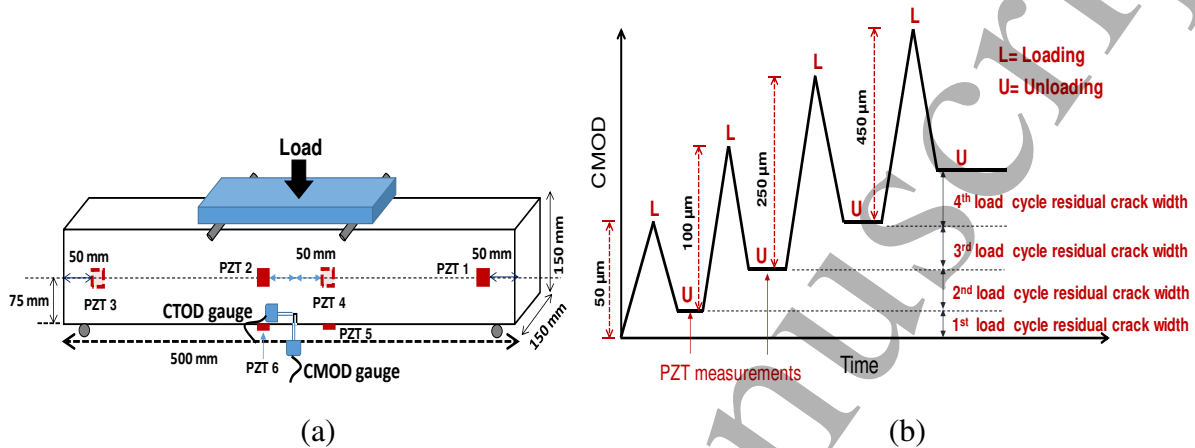


Figure 3. (a) Test set up for fracture tests with configuration of PZT patches (b) Cyclic loading showing the progressive increase in CMOD.

The test program consisted of cyclic, incremental loading to a larger crack opening in every subsequent gauge; the beam was progressively loaded to predefined values of CMOD. The loading program is shown schematically in **Figure 3b**. Initially, the beam was loaded up to a CMOD equal to 50 μm and unloaded. In the subsequent load cycle, the specimen was loaded to a CMOD value equal to 100 μm relative to the CMOD in the unloaded configuration. In subsequent load cycles, the CMOD was increased to values equal to 250 μm and 450 μm with respect to the residual crack openings at the end of second and third cycles, respectively. In the text, the first, the second, the third and the fourth load cycles are referred to by the maximum relative CMOD values equal to 50 μm , 100 μm , 250 μm and 450 μm , respectively.

222 **Table 1. Properties of the concrete**

Mix proportion (cement: water: fine aggregate: coarse aggregate)	Density (kg/m ³)	Compressive strength (MPa)	Young's modulus (GPa)	Modulus of Rupture (MPa)
1:0.45: 1.85: 2.89	2320	50	33	3.6

224 **Table 2. Properties of the PZT material**

Properties	Values
Elasticity matrix	$C_E = \begin{bmatrix} 1.20 \times 10^{11} & 7.51 \times 10^{10} & 7.50 \times 10^{10} & 0 & 0 & 0 \\ 7.51 \times 10^{10} & 1.20 \times 10^{11} & 7.50 \times 10^{10} & 0 & 0 & 0 \\ 7.50 \times 10^{10} & 7.50 \times 10^{10} & 1.10 \times 10^{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.10 \times 10^{10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.10 \times 10^{10} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.25 \times 10^{10} \end{bmatrix} Pa$
Piezoelectric Constants	$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 5.84 \times 10^{-10} & 0 \\ 0 & 0 & 0 & 5.84 \times 10^{-10} & 0 & 0 \\ -1.71 \times 10^{-10} & -1.71 \times 10^{-10} & 3.74 \times 10^{-10} & 0 & 0 & 0 \end{bmatrix} C/N$
Relative permittivity	$e = \begin{bmatrix} 1730 & 0 & 0 \\ 0 & 1730 & 0 \\ 0 & 0 & 1700 \end{bmatrix}$

Poisson's ratio, ν	Density, ρ (kg/m ³)	Dielectric loss factor, δ	Damping ratio, ζ	Mechanical quality factor, Q_m
0.35	7700	0.02	0.006	75

227 **Table 3. Properties of the Epoxy**

Young's modulus (GPa)	Poisson's ratio	Density (kg/m ³)
2	0.36	1300

229 The EI measurements were performed on all the PZTs before attaching to the beam. The
 230 EI measurements were performed at an applied voltage of 1 V over 800 discrete frequencies
 231 ranging between 10 kHz and 500 kHz. A 6500B series impedance analyzer of Wayne Kerr
 232 make was used for the electrical measurements. The measurements from the PZT patches after
 233 attaching to the concrete beam consisted of EI measurements from the individual PZT patches

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3 234 and through transmission measurements from pairs of PZT patches in the AR mode. A
4
5 235 schematic sketch of the test setup used for measurements from the PZT patches is shown in
6
7 236 **Figure 4**. The impedance and the wave propagation measurements were taken after unloading
8
9 237 from the predetermined value of CMOD. The experimental set up for the EI and the AR
10 238 measurements consisted of an impedance analyzer, a function generator, an amplifier, a digital
11 239 storage oscilloscope and a computer. In the AR mode, the waveform generated by the function
12 240 generator was amplified and sent to the actuator PZT. Then, the response signal of the
13 241 remaining five PZTs were logged by the computer, which was interfaced with the digital
14 242 storage oscilloscope. After acquiring the wave propagation data from all the PZTs, the actuator
15 243 PZT was switched to the impedance analyzer through the switching unit and the EI
16 244 measurements were recorded. A typical conductance (real part of admittance) signature of the
17 245 a PZT patch bonded to beam is shown in **Figure 4**. This measurement procedure was followed
18 246 when the specimen is in unloaded state after each load cycle (unloading from CMOD openings
19 247 equal to 50 μm , 100 μm , 250 μm and 450 μm , relative to the previous unloaded configuration).
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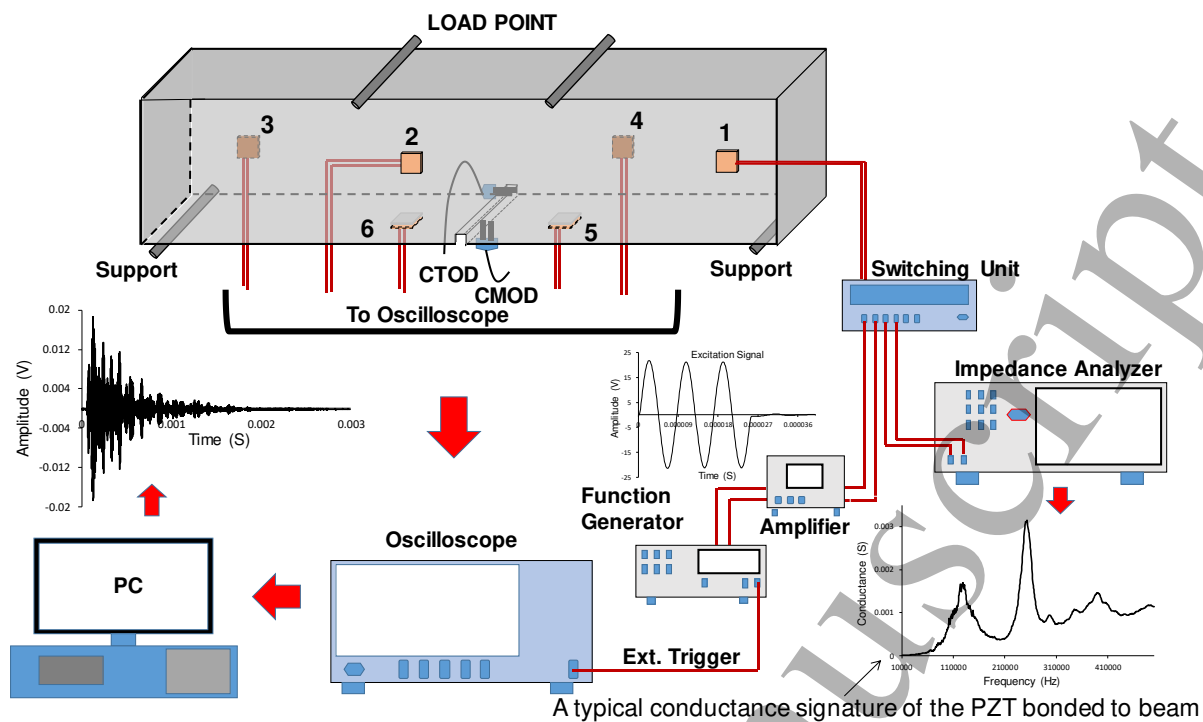


Figure 4. Experimental setups for EI measurements from individual PZT patches and through transmission measurements from pairs of PZT patches in the AR mode.

In the AR mode, the excitation applied to the PZT patches consisted of a 3-cycle tone burst sine signal with center frequency of 120 kHz with a 45 V peak-to-peak voltage at a pulse repeating frequency equal to 100 Hz (**Figure 5a**). The center frequency of 120 kHz was selected to match with the center frequency of the first resonance peak of the bonded PZT to provide higher input and higher sensitivity to received wave. The first resonance peak of the bonded PZT occurs at a low frequency and has the highest energy when compared to other resonance frequencies, which results in lower attenuation of the transmitted waves and a larger received signal. A typical received signal at PZT2 when PZT 1 was actuated (A_1R_2) is shown in **Figure 5b**. All the six PZT patches were individually excited and the response from the all other PZT patches were collected at a sampling frequency of 6.25 MHz.

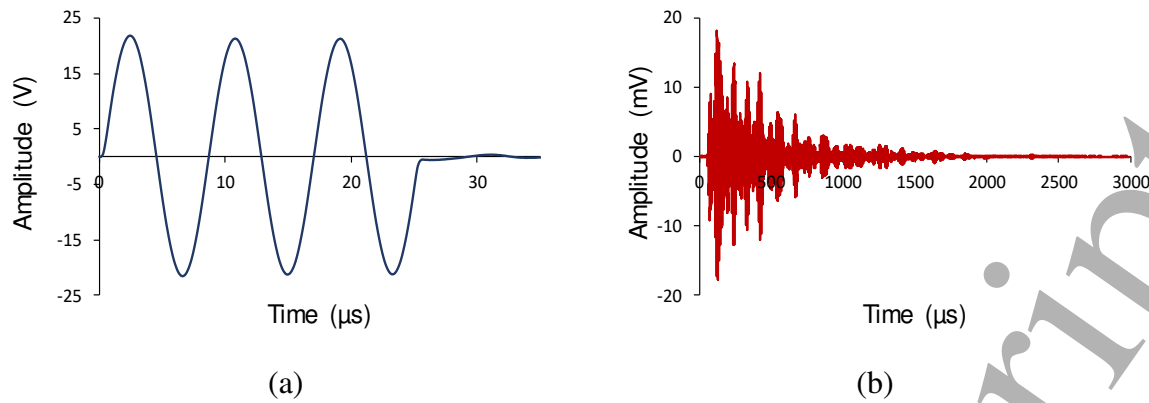
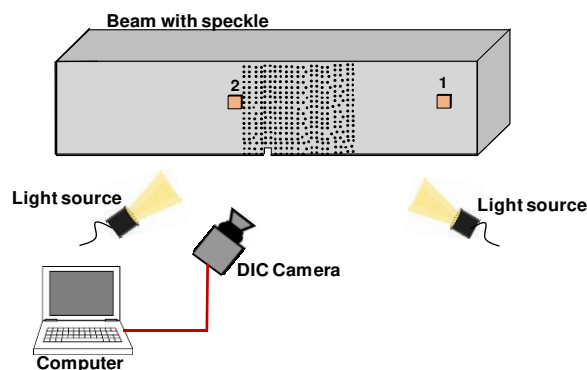


Figure 5. Signals from a through-transmission measurement in the AR mode: (a) The excitation signal applied to the actuator (b) The received signal at PZT2 when actuating PZT1 (A₁R₂)

During the loading cycles, full-field surface displacements from the beam were obtained using digital image correlation (DIC). DIC measurements were performed on notched specimens to monitor the localization of damage and the subsequent propagation of a crack. DIC relies on correlation between images of specimens in the deformed and the reference unstressed state. A spray painted speckle pattern was created on the surface of the beam. The front face of the beam was initially painted white to create a uniform background. A random pattern was created with a mist of black paint, which was sprayed on the white background. After seating the specimen in the loading setup, the front face of the specimen was uniformly lit with white light. During the flexure test, digital images of the specimen were captured using a camera which was fitted with a 50 mm lens and was placed at a distance of 1 m from the specimen surface. A schematic representation of the DIC setup is shown in **Figure 6**. A digital image of the specimen, referred to as the reference image was captured prior to initiation of loading. Images of the specimen were captured during the loading program. Each image was 5 mega pixels and physical calibration was established to be in the range of 12-14 pixels per mm.

285



286

287 **Figure 6.** Schematic representation of the DIC setup.

288

289 Spatially continuous surface displacements are obtained from correlation between of the
290 random speckle pattern in the deformed and the reference images of the specimen. Analysis
291 for correlations and pattern identification was performed within small neighborhoods called
292 subsets [Bruck et al. (1989), Schreier and Sutton (2002)]. Within each subset, a unique pattern
293 of grey level distribution is formed because of the random sprayed-on pattern. The grey-level
294 pattern in each subset differs from other subsets. The correspondence between matching
295 subsets in images of the specimen in the reference and the deformed states was established
296 using spatial domain cross-correlation. The mapping of positions within the reference image
297 to positions in the deformed images was performed using second-order, two-dimensional shape
298 functions. Sub-pixel level accuracy was obtained using the Quintic B-spline interpolation of
299 the gray values. The cross correlation analysis of the digital images was performed using the
300 VIC-2D™ software. Strains were calculated from the displacement gradients at each loading
301 stage, by evaluating the shape functions and their partial derivatives at the center of the subset.
302 In the analysis, a subset of size 29 pixels x 29 pixels was used. For the setup used in this study,
303 the random error in the measured displacement was in the range of 0.002 pixels and the
304 resolution accuracy of strain was determined to be 1 μm .

4. Experimental Results

The load-CMOD responses of three beam specimens are shown in **Figure 7a** and the load-CMOD response of one beam is shown in **Figure 7b** for clarity. The beam was tested in four stages. In each stage, the beam was loaded in CMOD control to a predetermined crack opening relative to the beginning of load cycle and then unloaded to zero load. The EI and wave propagation measurements were taken in the unloaded configuration. The quasi-static load response can be readily identified with the load envelope obtained from the load cycles. The peak load of the envelope load response is attained in the first load cycle. CMOD equal to 50 μm is in the post-peak part of the softening load response. There is a continuous increase in the residual CMOD on unloading after each loading cycle. There is also correspondingly a decrease in the stiffness of the load-CMOD response. With every subsequent load cycle, the peak load attained is also smaller.

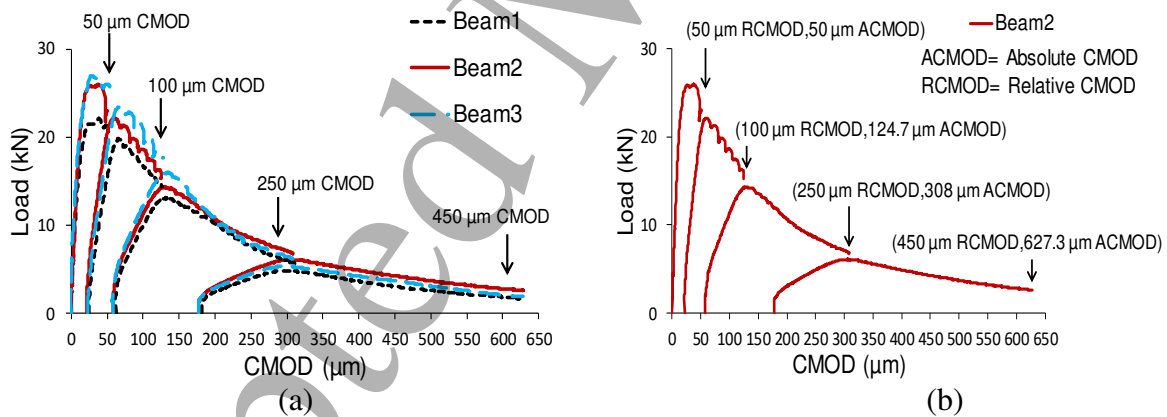
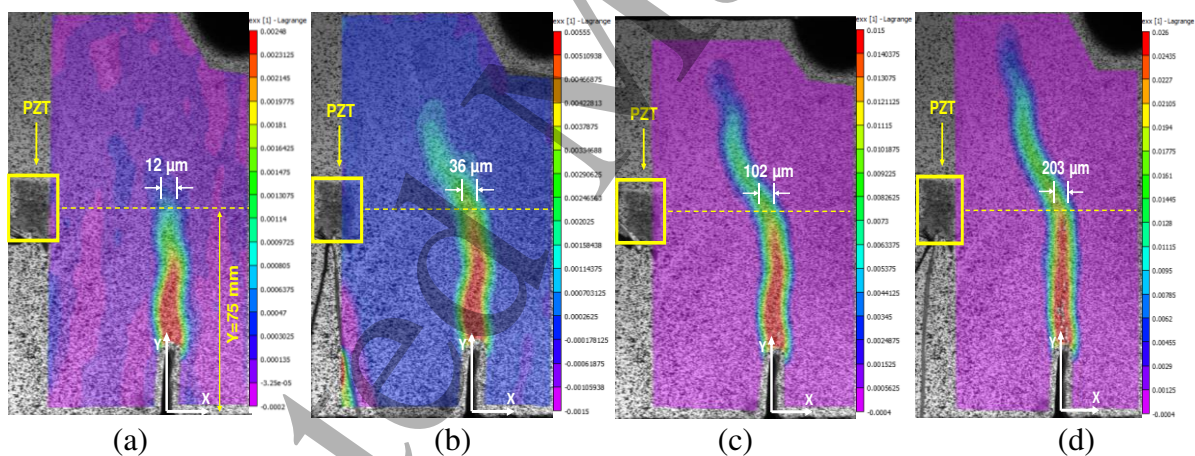


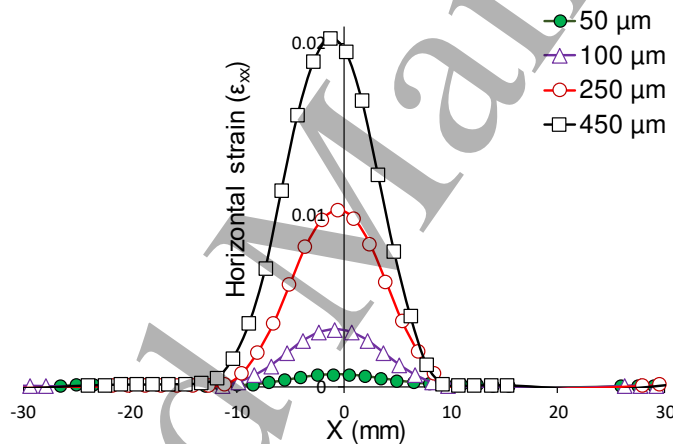
Figure 7. (a) Load-CMOD responses of beams; (b) Load-CMOD of Specimen Beam 2. The CMOD relative to the residual CMOD for each cycle are shown. The absolute value of CMOD at the end of each cycle is also indicated in the bracket.

324 Contours of horizontal strain (ϵ_{xx}) from the beam specimen 2 at different CMOD values
 325 obtained using DIC are plotted in **Figure 8**. The contours of strain are plotted at the top of the
 326 load cycle, just prior to unloading. Localization of the strain can be identified in all the contour
 327 plots. The location of the crack can be clearly identified even at a small CMOD equal to 50 μm .
 328 The localized zone propagates along the depth of the beam with increasing CMOD. While the
 329 crack could be identified in the contours of ϵ_{xx} even at a small CMOD of 50 μm , the crack
 330 could not be delineated visually up to a CMOD of 124 μm . There is a sharp gradient in strain
 331 within a small region centered on the crack. In the region in the immediate vicinity of the PZT
 332 patch, the magnitude of strain is very small and there is no visible damage which produces
 333 variation in the measured strain. There is also no visible damage in the form of micro cracking
 334 in the region away from the crack.



336
 337
 338 **Figure 8.** Strain contour (ϵ_{xx}) at different CMOD levels (a) 50 μm (b) 100 μm relative to
 339 unloading after first load cycle (up to an absolute CMOD equal to 124.7 μm) (d) 250 μm
 340 relative to unloading after second load cycle (up to an absolute CMOD equal to 308 μm) (e)
 341 450 μm relative to unloading after third load cycle (up to an absolute CMOD equal to
 342 627 μm)

344 The horizontal strain (ϵ_{xx}) along length of the beam at the mid-height location along a line
 345 with Y coordinate fixed at 75 mm above the bottom face and 50 mm above the notch for
 346 various CMOD levels are shown in **Figure 9**. The variation of ϵ_{xx} along the length shows a
 347 sharp increase in the magnitude of strain indicating localization of strain within a small region
 348 centered on the notch. It is observed that the width of the localization remains relatively
 349 constant with increasing crack opening. With increasing crack opening at the soffit of the beam
 350 given by the CMOD, there is an increase in the magnitude of maximum strain. There is also
 351 correspondingly a sharper strain gradient within the region of localization with increasing
 352 CMOD.

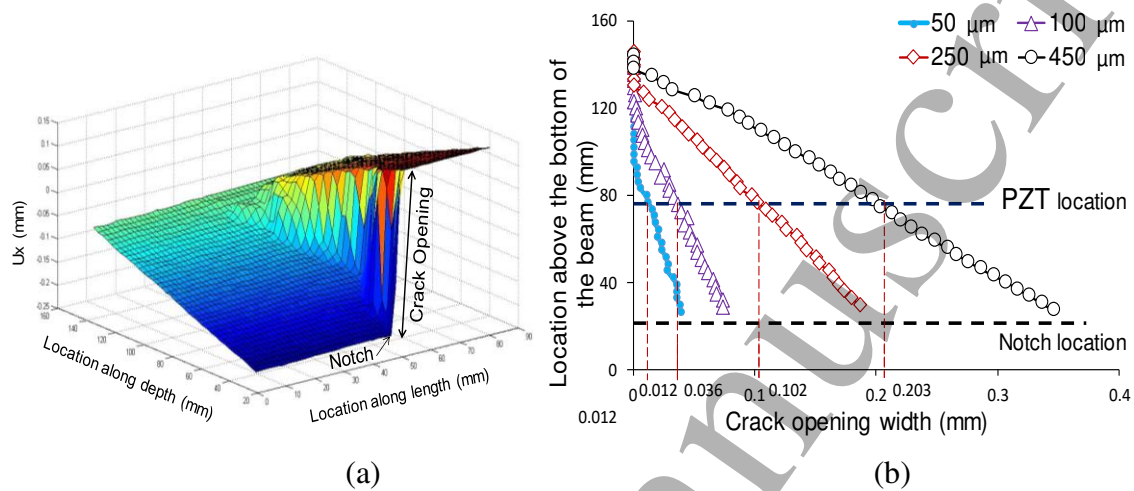


354
 355 **Figure 9.** Variation in the horizontal strain (ϵ_{xx}) with X coordinate for a line located at
 356 Y = 75 mm from the bottom of the beam at different values of relative CMOD after each
 357 unloading.

359 The 3D contours of horizontal displacement (U_x) obtained at the end of the last load cycle
 360 when the CMOD was increased to 450 μm from the unloaded configuration, is shown in
 361 **Figure 10a**. The crack in the medium is identified by the displacement discontinuity emanating
 362 from the notch. The profile of the crack is identified by the sudden increase in the U_x over a

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3 363 small region. The discontinuity in U_x introduced by the crack emanating from the notch is
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5 364 evident in the jump in the U_x . The presence of the crack and the associated physical opening
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7 365 within a subset resulted in a loss of correlation within the subsets in which the crack was
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9 366 present. The loss of correlation and the finite size of the pixel resulted in smearing of the
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11 367 displacement gradient within a region of size equal to the subset size close to the crack. The
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13 368 actual width of the region of localization produced by the crack is therefore smaller than the
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15 369 width of the zone with high strains indicated in **Figure 9**. A procedure for obtaining the crack
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17 370 opening precisely, free from the error introduced by the finite subset size was developed using
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19 371 the asymptote matching procedure [Reddy and Subramaniam (2017), Gali and Subramaniam
20
21 372 (2018)]. The crack opening widths along the depth of the beam at different values of CMOD
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23 373 obtained using the asymptote matching procedure and are shown in **Figure 10b** for beam
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25 374 specimen 2. The CMOD corresponds to the displacement measured across the notch at $Y=0$,
26
27 375 using the CMOD gauge located at the bottom of the beam. The CMOD is also shown marked
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29 376 in the figure at the location corresponding to $Y=0$. The crack opening widths were determined
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31 377 from the U_x measured using DIC. Corresponding to the CMOD measured on the soffit of the
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33 378 beam, there is a decrease in the crack opening width with increasing Y coordinate above the
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35 379 notch. The zero crack opening along the depth of the beam gives the physical location of the
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37 380 tip of the propagating crack. The observed crack opening as a function of depth for different
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39 381 values of CMOD indicates that the crack tip progresses along the depth of the beam with
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41 382 increasing CMOD. For a CMOD of $50\mu\text{m}$, the crack has propagated along the depth and the
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43 383 tip of the crack can be identified at 86 mm from bottom of the beam and the corresponding
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45 384 crack opening at the mid-height location is $12\mu\text{m}$. At a CMOD equal to $100\mu\text{m}$ relative to
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47 385 unloaded configuration at the end of the first load cycle (absolute CMOD equal to $124.7\mu\text{m}$),
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49 386 the tip of the crack is located at $Y= 119\text{ mm}$ and the crack opening at the mid-height location
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51 387 is $36\mu\text{m}$. In the subsequent load cycles when the CMOD is increased to $250\mu\text{m}$ and $450\mu\text{m}$
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388 relative to the unloaded CMOD from the previous cycles, the crack advances to a depth of
 389 124 mm and 135 mm, respectively. The corresponding crack openings at the mid-height are
 390 102 μm and 203 μm , respectively.



394 **Figure 10.** (a) Contour showing crack opening displacement at the relative value of CMOD
 395 = 450 μm after the third cycle; (b) Crack opening width as a function of depth of the beam at
 396 different crack mouth opening displacements.

398 4.1 Measurements from PZT patches

399 The stress wave attenuation measurements were performed in the unloaded state, where
 400 the removal of the load results in closing of the crack. The measured changes recorded by the
 401 PZT patches therefore correspond to the physical discontinuity in the medium produced by the
 402 stress-induced crack. Each PZT patch was individually actuated (**Figure 11b**) and the
 403 responses were recorded at all the other PZT patches. This measurement procedure was
 404 repeated when the specimen was in the unloaded state after pre-determined crack opening
 405 indicated by different relative values of CMOD (50 μm , 100 μm , 250 μm and 450 μm). The
 406 level of noise obtained from the standard deviation of the initial part of the signal was on the

order of 0.1 mV. All the received signals were conditioned with a linear phase, band-pass filter.

A comparison of actual received signal and filtered received signal is shown in **Figure 11a**.

Figure 11b shows a typical signal received by PZT2 using PZT1 as the actuator (A_1R_2) at the seating load, prior to initiation of the first cycle of loading. The received signal is significantly smaller in magnitude when compared with the excitation. The decrease in the magnitude of the received signal is attributed to losses in the path of the wave produced by the geometric spreading of the wave and the material attenuation in the wave path in the epoxy and in the concrete. There is also a significant increase in the length of the received wave when compared with the excitation applied, which is due to several effects such as, the ringing of the PZT patch, geometric spreading and multiple reflections, mode conversions and from inhomogeneity of the beam specimen [Aggelis and Shiotani (2007)].

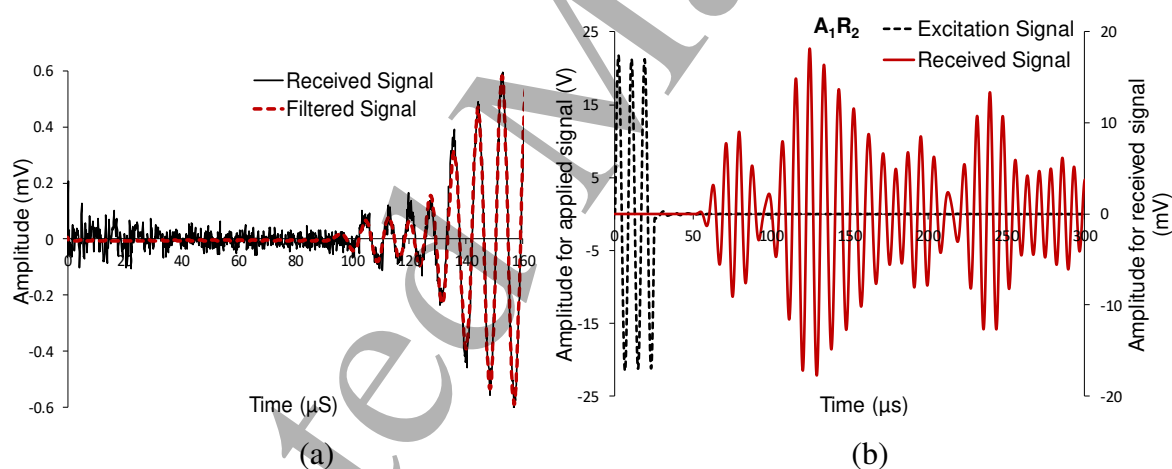
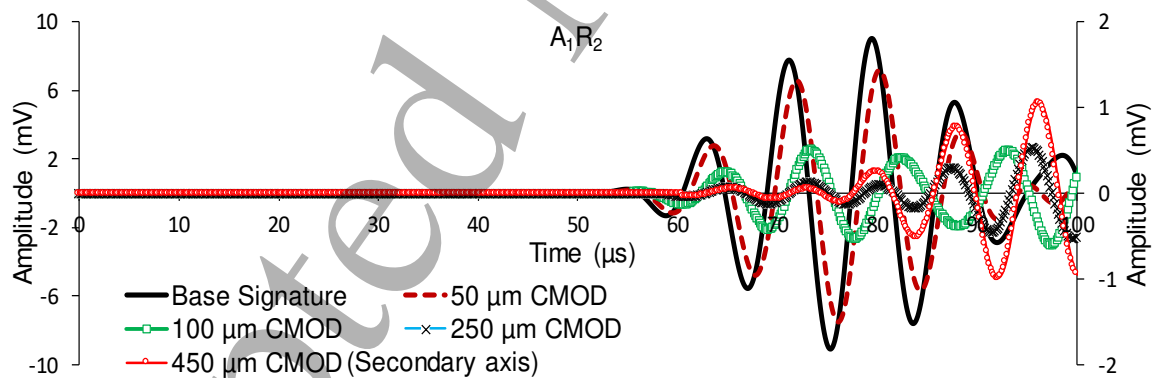


Figure 11. (a) Comparison of the actual received and the filtered received signal (b)

Comparison of the actuating signal with sensor signal prior to loading and the received signal after filtering.

425 **Figure 12** shows the signals recorded from different PZT sensors (PZT2, PZT4, PZT6)
 426 when PZT1 was actuated. The received signals at PZT6 have a smaller amplitude when
 427 compared with the signals recorded by PZT2 and by PZT4 even in the pristine stage. The
 428 amplitude of the signal is influenced by the material and geometric attenuation in path of the
 429 transmission. Each subfigure in **Figure 12** shows the variation in the received signal in the
 430 unloaded state after each cycle. The changes recorded at the different PZT patches however
 431 vary depending on the positions of the PZT patches relative to the notch. With increasing
 432 CMOD, there was a decrease in the amplitude and an increase in the time of arrival of the stress
 433 waves received at PZT2 and PZT6 when compared with the corresponding baseline signatures.
 434 The changes in the received waves are produced by the presence of the crack in the path of
 435 stress wave propagation. The received signals of PZT4 are not significantly altered since the
 436 wave path does not intersect the crack. The received signals at PZT4 exhibit a small change
 437 which may be attributed to stress wave reflection from the crack surface.



(a)

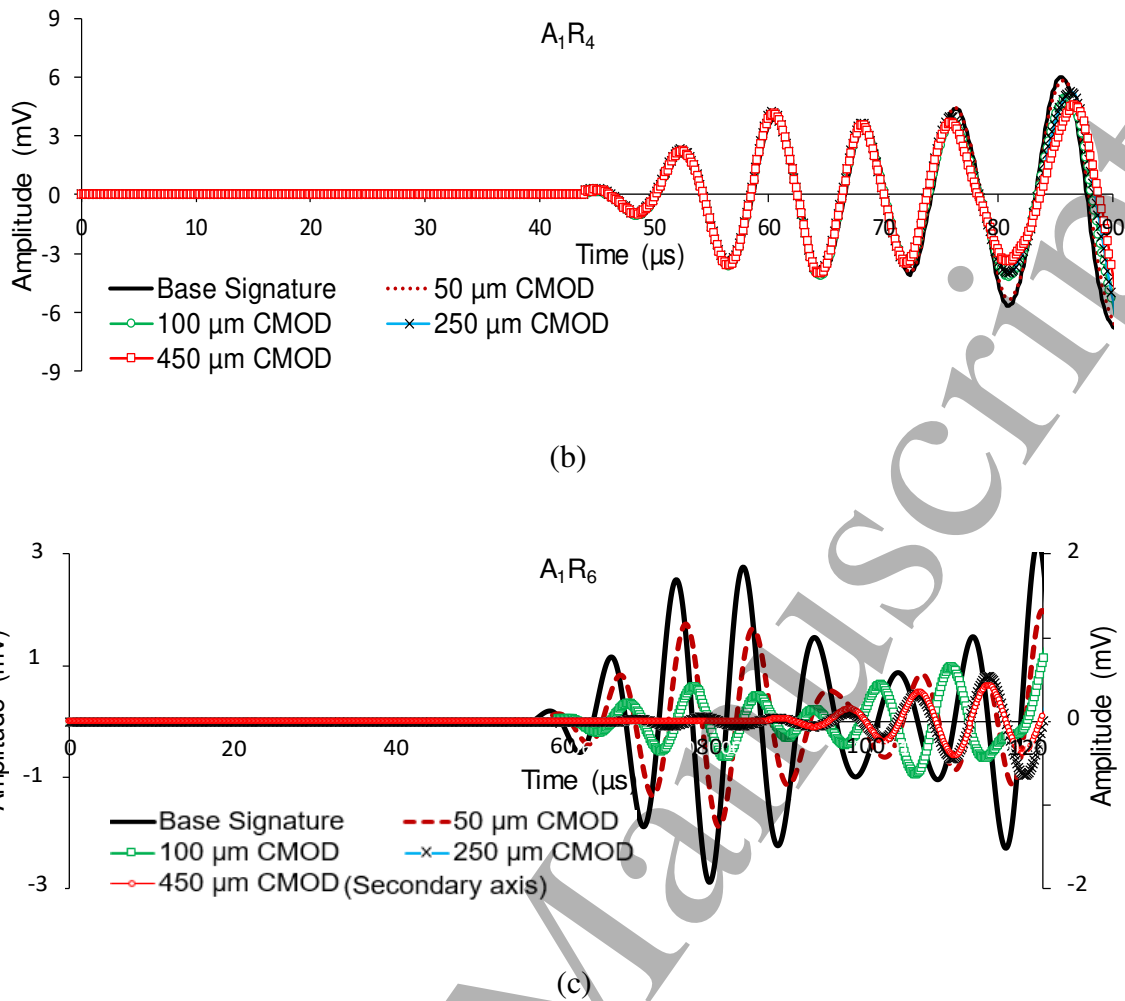


Figure 12. The received signals when PZT1 is actuated for different crack opening displacements: (a) received at PZT2 (b) received at PZT4 (c) received at PZT6.

When PZT1 is actuated, the stress wave signals received at the other PZT patches depend on the stress wave transmission path. Any changes in the received signal characteristics are produced by changes in the stress wave transmission path. When comparing the sensor signals after each load cycle with base line signature, the signals received at PZT 2 and PZT6 undergo changes in the time of arrival and the energy content. The contours of ϵ_{xx} shown in **Figure 9** also show that there was ϵ_{xx} concentration beyond the mid height of the beam in the A_1R_2 transmission path for all four CMOD levels. There is an increasing level of material discontinuity in the propagation path produced by the crack after each load cycle.

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3 457 Correspondingly, there is a larger decrease in the amplitude and a larger increase in the arrival
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5 458 time in the received signals. After the first load cycle, the crack was not visually apparent and
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7 459 was only detected from the displacement discontinuity recorded using DIC. From the crack
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9 460 opening width as a function of height shown in **Figure 10b**, for a CMOD equal to 50 μm , the
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11 461 crack propagating depth was 86 mm from bottom of the beam and the crack opening
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13 462 displacement at the mid-height in the loaded configuration was 12 μm . The crack propagated
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15 463 beyond the direct wave path of A_1R_2 (actuating PZT1 and receiving PZT2) even at the CMOD
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17 464 equal to 50 μm .

21
22 465 Typical electrical conductance spectra recorded from EI measurements from the six PZT
23
24 466 patches attached at different locations on the beam specimen 2 are shown in **Figure 13**. Distinct
25
26 467 resonance modes are clearly identified with peaks in the spectra. The relative locations and
27
28 468 amplitudes of the peaks in the conductance spectra are relatively constant. The variations in
29
30 469 the absolute values of amplitudes and the center frequencies of the individual peaks are due to
31
32 470 variations in the properties of the individual PZT patches and the thickness of the epoxy used
33
34 471 for bonding the PZT patch to the concrete substrate. The first and the second resonance peaks
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36 472 are centered on 120 kHz and 250 kHz, respectively. The peaks of resonance have previously
37
38 473 been shown to be sensitive to changes in substrate compliance within their respective zones of
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40 474 influence [Narayanan and Subramaniam (2016a, b)]. The zones of influence for the first and
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42 475 the second resonant peaks for 1 mm thick, 20 mm square patches have been shown to be
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44 476 150 mm and 100 mm, respectively. The local peaks on the first resonant peak are identified
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46 477 with the influence of the boundary of the specimen, which is within its zone of influence
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48 478 [Narayanan et al. (2018)]. The presence of distributed damage, which influences the
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50 479 mechanical impedance of the substrate in the zone of influence has been shown to produce
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52 480 changes in the amplitude and center frequency of the resonant peak.
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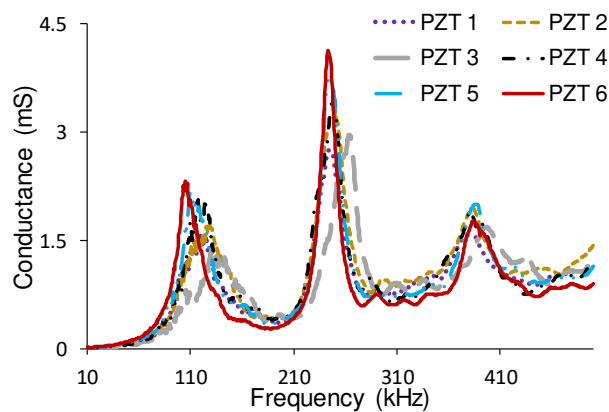


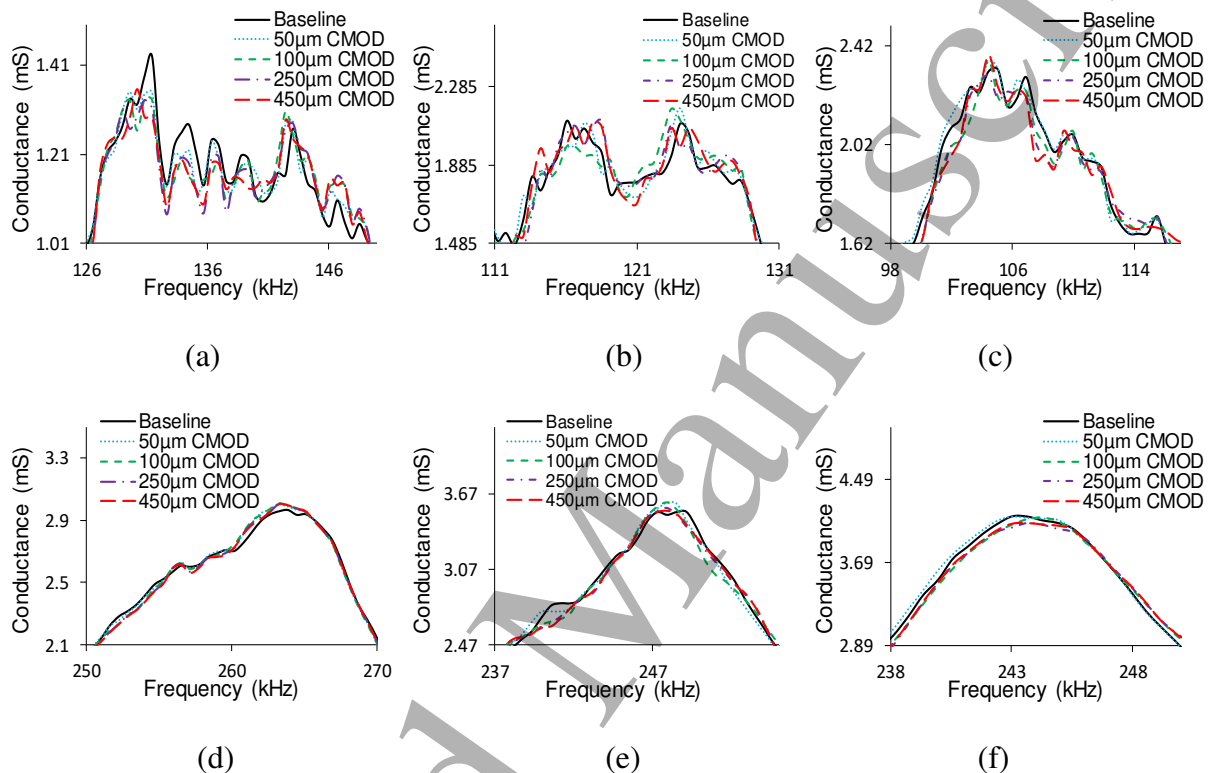
Figure 13. The electrical conductance spectra recorded from the PZT patches

The EI measurements were recorded from the PZT patches in the unloaded state. The conductance spectra over frequencies centered on the first and second peaks for PZT2 and PZT5 (50mm away from notch) and PZT3 (180mm away from notch) are shown in **Figure 14**. The electrical conductance obtained from the PZTs centered on the first resonant peak are shown in **Figures 14 a, b, c**. A change is noticed in the EI response of all the PZTs. As the crack is located away from the zone of influence of first peak for PZT 3, the changes are minimal. For PZT 2 and PZT5, there are irregular changes identified in the local peaks due to the presence of the material discontinuity within the zone of influence of the first peak of the PZTs.

The electrical conductance obtained from the PZTs centered on the second peak are shown in **Figures 14 d, e, f**. There were no changes in the second peak of EM response of PZT 3 since the crack lies outside its zone of influence [Narayanan et al. (2018)]. There are small changes in conductance signatures centered on the second resonant peak for PZT2 and PZT5 at the different levels of CMOD as the crack passes through the zones of influence. The measurements from DIC indicated that the crack was very localized while the material away from the localized zone had no damage. Considering no visible distributed damage, the

501 presence of localized damage within the zone of influence does not appear to significantly
 502 influence the mechanical impedance offered by the concrete medium to the motion of the PZT
 503 in the second resonant mode. The second resonant mode is therefore not sensitive to the
 504 presence of a localized material discontinuity produced by a stress-induced crack in concrete.

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510 **Figure 14.** Electrical conductance spectra close to first peak at different CMOD levels of (a)
 511 PZT 3 (b) PZT 2 (c) PZT 5. Conductance spectra close to second peak at different CMOD
 512 levels of (d) PZT 3 (e) PZT 2 (f) PZT 5.

513

514 5. Analysis of Results

515 The experimental studies conducted on the beam at different levels of CMOD indicate that
 516 there is a consistent change in the recorded parameters induced by the localized crack. The
 517 stress-induced crack in concrete is associated with a physical opening under applied loading

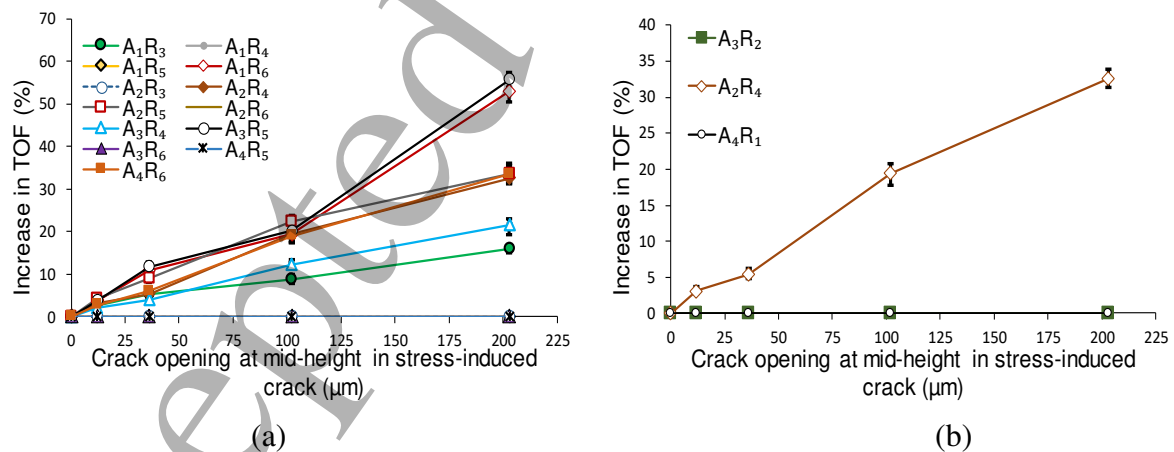
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3 518 and it produces a discrete discontinuity in the material in the unloaded state. The discrete crack
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5 519 present in the concrete is also very localized and does not produce any additional strain or
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7 520 damage in the bulk of the medium. From the DIC measurements it was established that even
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9 521 at a CMOD equal to $50\ \mu\text{m}$, the crack had propagated to a depth of 86 mm above the notch.
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11 522 The physical opening at the mid-height was determined to be $12\ \mu\text{m}$ in the loaded state when
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13 523 the CMOD was $50\ \mu\text{m}$. With an increase in the CMOD there was an increase in the physical
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15 524 crack opening along the depth of the crack. The opening displacement produced by a stress
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17 525 induced crack creates a physical discontinuity in the material medium. The measurements from
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19 526 the PZT patches were performed in the unloaded state, and these correspond to the material
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21 527 discontinuity produced by the stress-induced crack.
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27 528 A quantification of the observed changes is performed to identify the changes in the wave
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29 529 characteristics and the EI measurements produced by the presence of the localized crack in the
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31 530 medium. In the AR measurements, the changes are observed in the time of flight of stress wave
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33 531 arrival and in the amplitude of stress wave. Percentage changes in the time of flight (TOF) and
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35 532 the attenuation factor ($A(f)$) were used to quantify the changes in the received signal in the AR
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37 533 mode. Changes in the conductance signature at the resonance peaks of the EI response were
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39 534 quantified using the root mean square deviation (RMSD).
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44 535 The changes in propagation path of stress wave due to material discontinuity produce changes
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46 536 in the time of flight (TOF) of the received signal. The percentage (%) change in the TOF at
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48 537 each level of CMOD was calculated using Equation (2), where $(TOF)_a$ is the TOF at different
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50 538 CMOD and $(TOF)_0$ is the TOF at zero CMOD. Time of flight of the signals were calculated
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52 539 using voltage thresholding technique where a threshold value ($5\ \mu\text{V}$) was set for the signal and
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54 540 the time at which the received signal crosses threshold is taken as TOF. The threshold voltage
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56 541 was set based on maximum noise level present in the signal.
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$$\Delta TOF(\%) = \frac{[(TOF)_d - (TOF)_0]}{(TOF)_0} * 100 \quad (2)$$

The $\Delta TOF(\%)$ for the different AR pairs are plotted as a function of the different stress-induced crack opening at the mid-height of the beam in **Figure 15**. The physical crack opening at the mid-height location of the beam determined using DIC are used for the plot. The values corresponding to reverse excitation of PZTs are not plotted since these values were nominally identical. After the first cycle of loading, there is an increase in the $\Delta TOF(\%)$ in the received signals at the different PZTs. In the AR pairs, where the wave path did not intersect the crack, there was no change in the $\Delta TOF(\%)$. In the subsequent load cycles when the relative value of CMOD was equal to 100 μm , 250 μm and 450 μm there is a further increase in the $\Delta TOF(\%)$ for in the AR pairs with signal path crossing the crack (A_6R_5 , A_1R_3 , A_3R_4 , A_4R_6 , A_3R_5 and A_1R_6). The measurements in $\Delta TOF\%$ progressively increase with an increase in the physical discontinuity in the concrete produced by the stress-induced crack associated with the measured opening.



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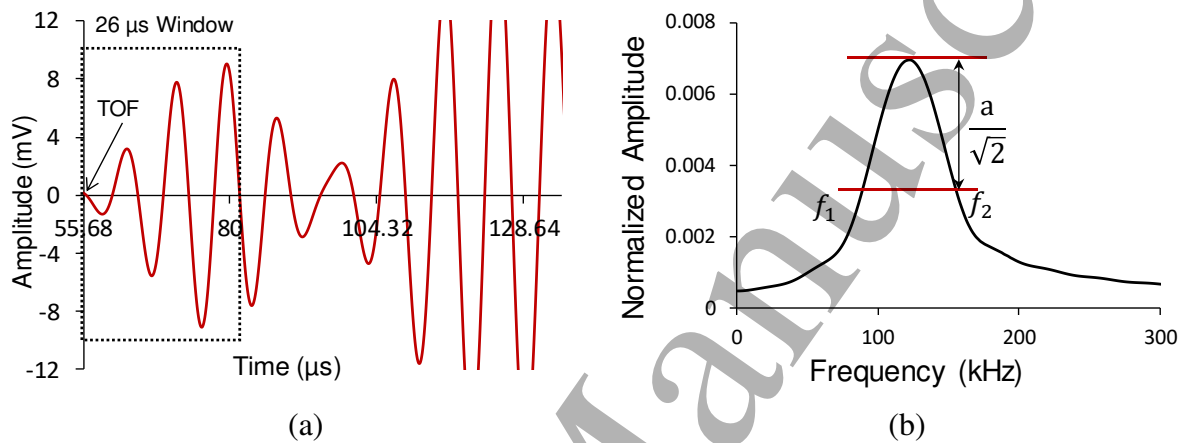
Figure 15. (a) $\Delta TOF(\%)$ at different CMOD values. b) $\Delta TOF(\%)$ for transmission paths

A_3R_2 , A_2R_4 and A_4R_1

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3 560 The $\Delta\text{TOF}(\%)$ for transmission paths A_3R_2 - A_2R_4 - A_4R_1 , which connect PZTs located at mid-
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6 561 height, are plotted as a function of stress-induced crack opening in the stress wave path in
7
8 562 **Figure 15b**. There is no change on the $\Delta\text{TOF}(\%)$ measured in the signal path A_3R_2 , A_4R_1 . In
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10 563 the path A_2R_4 there is consistent increase in $\Delta\text{TOF}(\%)$ with an increase in the stress induced
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13 564 crack opening. Changes in the time of flight of the received signal are attributed to the presence
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15 565 of the material discontinuity in the stress wave path. The $\Delta\text{TOF}(\%)$ therefore provides a
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18 566 reliable parameter for detecting changes in the transmission of the stress wave due to the
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20 567 discontinuity in the material medium produced by a localized stress-induced crack in concrete.

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23 568 A comparison between the actuated signal and the received signal prior to initiation
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25 569 of loading indicates that there is significant attenuation in the path of wave. When one
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27 570 PZT pair is used in the AR mode it is of interest to determine the additional attenuation
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30 571 produced by the material damage. The influence of attenuation in the stress wave path
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32 572 produced by the materials, concrete and epoxy, have to be separated to determine the
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34 573 additional attenuation produced by the crack. The changes in the received signals due to
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36
37 574 the propagation of crack depend on the distance between actuator and sensor, depth and
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39 575 width of crack. In an array of sensors where comparison among different transmission
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41 576 paths are necessary to identify the location and the severity of the crack, a new damage
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43 577 index known as Attenuation factor ($A(f)$) is introduced in the analysis for compensating
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45 578 the intervening effects such as properties of PZTs, amplitude of the resonance frequencies
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47 579 of PZTs, epoxy concrete interface losses and length of direct propagation path. The
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50 580 procedure is similar to the self-calibrating technique where the signal processing in the
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52
53 581 AR mode consisted of normalizing signals in the frequency domain [Achenbach et al.
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55 582 (1992), Wang and Subramaniam (2011)]. The received signal in time domain signal was
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58 583 transformed to the frequency domain using the FFT algorithm. The direct stress
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60 584 transmission in an AR pair is the stress wave in the early part of the received signal. The

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3 585 signal received subsequently contains reflections from the boundaries and edges. The initial
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5 586 26 μs (length of actuating signal) signal starting from time of flight of the received signal was
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7 587 taken as the direct stress wave (non-reflected signal) as shown in the **Figure 16a**. The FFT of
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9 588 non-reflected time domain signal with the corresponding half power bandwidth was shown in
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11 589 **Figure 16b**.



593 **Figure 16.** (a) Non-reflected signal (26 μs) (b) FFT of the received non-reflected time
594 domain signal (26 μs)

596 The received signal in a through transmission measurement in time domain contains influences
597 of losses due to propagation media and can be expressed as,

$$598 \quad r_s = a_s * l_{ea} * l_{sp} * l_{es} \quad (3)$$

601 where r_s is the received signal, a_s is the actuating signal, l_{ea} , l_{es} are the signal losses in the
602 layer of epoxy present at the actuator and sensor, respectively, l_{sp} is the due to propagation

through concrete, and '*' is the convolution operator. The received signals at zero CMOD ($r_s(f)_0$) and at different CMOD levels ($r_s(f)_d$) can be expressed as,

$$r_s(f)_0 = a_s(f) \cdot l_{ea}(f) \cdot l_{sp}(f) \cdot l_{es}(f) \quad (4)$$

$$r_s(f)_d = a_s(f) \cdot l_{ea}(f) \cdot l_{sp}(f) \cdot l_{es}(f) \cdot L_d(f) \quad (5)$$

where $r_s(f)_0$, $r_s(f)_d$ are the magnitudes of FFT at zero and CMOD equal to d , $L_d(f)$ is signal loss due to crack. $L_d(f)$ is calculated from equation (4) and (5) as,

$$L_d(f) = \left(\frac{r_s(f)_d}{r_s(f)_0} \right) \quad (6)$$

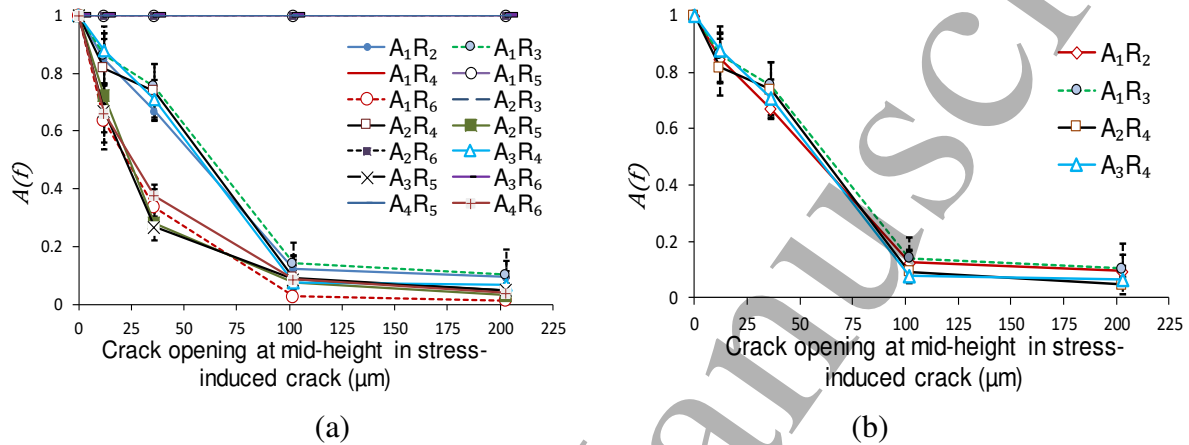
The attenuation factor, $A(f)$ was determined as the average of $L_d(f)$ at the bandwidth

$$A(f) = Avg. (L_d(f))_{f_1, f_2} \quad (7)$$

where the magnitudes of FFT corresponding to a frequency f_1 to f_2 at amplitude equal to $\frac{1}{\sqrt{2}}$ of peak amplitude in the FFT (**Figure 16b**).

Attenuation factor ($A(f)$) was calculated for all the received signals using Equation (7) and is shown in **Figure 17a**. There is no change in the attenuation factor even at very large crack openings for the transmission paths which do not encounter crack. There is a considerable decrease in the $A(f)$ for the transmission paths which encounters the crack, even at the stress-induced physical opening of 12 μm at the mid-height of the beam. The decrease in the attenuation factor values were high for signals received from PZTs placed at the soffit of the beam when compared with values of the signals received at the PZTs place at the mid-height of the beam. This is can be explained considering the crack opening in the direct stress wave path between an AR pair. The crack width opening along the depth of a specimen at different values of CMOD are shown in **Figure 10b**. The signals received at the PZTs placed at the soffit of the beam experienced a higher attenuation because of a larger physical opening in the

625 direct path connecting the actuator to the receiver. Upon unloading, the physical discontinuity
 626 is larger in the stress wave path connecting PZT patches located on the beam soffit from
 627 actuators located across the crack. There is a complete attenuation of direct stress wave when
 628 the stress induced crack opening reaches a value of 100 μm .



630
631

632 **Figure 17.** Attenuation factor ($A(f)$) as a function of crack opening at mid-height in the
 633 stress induced crack (a) all AR pairs; (b) For AR pairs placed at the mid-height of the beam.

634

635 The changes in attenuation factor corresponding to the transmission paths which encounter a
 636 physical opening produced by a stress-induced crack and pass through center line of beam
 637 (actuator and receiver located in the mid-height of the beam) are shown in **Figure 17b**. For the
 638 PZTs mounted at the mid-height, the $A(f)$ is identical for the stress wave paths linking the AR
 639 pair which cross the crack plane. It can therefore be concluded that the observed $A(f)$ in these
 640 cases is only due to the magnitude of the physical discontinuity produced by the crack. The
 641 changes in $A(f)$ are only due to the changes in characteristics of discrete crack such as depth
 642 and width of crack, irrespective of length of signal transmission path. The similarity in the
 643 trends of changes in attenuation factor irrespective of length of signal transmission path also

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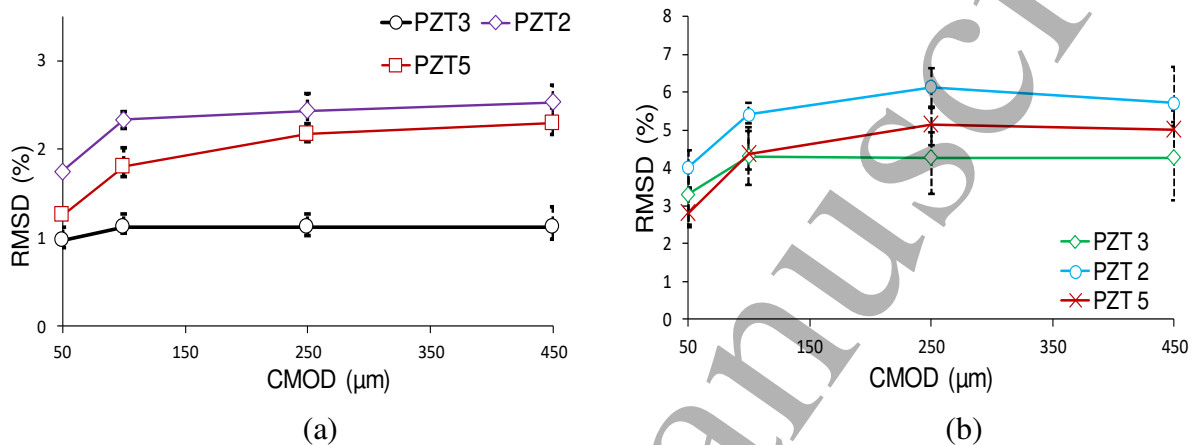
644 suggests that the attenuation factor only depends on the severity of crack irrespective of all
 645 other intervening effects. The $A(f)$, therefore provides an effective way to analyze the received
 646 signals to detect changes introduced by material discontinuity in the stress wave path. The
 647 $A(f)$ is sensitive to a physical discontinuity in the concrete medium even in the unloaded state
 648 associated with a stress induced crack opening on the order of $10\mu\text{m}$. The physical
 649 discontinuity in the concrete associated with a stress-induced crack opening on the order of
 650 $100\ \mu\text{m}$ produces a complete attenuation of the stress wave. This indicates that there is no
 651 direct transmission of direct stress waves centered on $120\ \text{KHz}$ across a physical discontinuity
 652 in concrete resulting from a stress-induced opening between the crack faces on the order of
 653 $0.1\ \text{mm}$.

654 A damage index derived from the RMSD is used to calculate the difference between the
 655 conductance signatures recorded for different crack openings. The RMSD with respect to the
 656 baseline measurement (zero CMOD) were calculated in the frequency range of the bandwidth
 657 for first and second resonant peaks using Equation (8), where, x_i and y_i are the values of
 658 baseline conductance and conductance at different CMOD levels and N is total number of
 659 frequencies in the bandwidth of the corresponding peak.

$$660 \quad \text{RMSD} = \sqrt{\frac{\sum_{i=1}^N (y_i - x_i)^2}{\sum_{i=1}^N (x_i)^2}} \quad (8)$$

661 Damage index based on RMSD for PZTs of different positions are is shown in **Figure 18a**.
 662 The damage index was calculated using the frequency range of the bandwidth for second
 663 resonant peak. PZT3, which located $180\ \text{mm}$ from the crack location registered a small change
 664 in the RMSD with increasing crack opening. PZT2 and PZT5, which are attached on the face
 665 and the soffit, respectively at the distances of $50\ \text{mm}$ from the beam centerline show an
 666 increase in the RMSD with increasing CMOD. **Figure 18b** shows the RMSD calculated using
 667 first resonance peak in the frequency range of bandwidth. PZT3 is showing same RMSD trend

668 as for second peak. There is a larger increase in value for RMSD at all CMOD values for PZT2
 669 and PZT5 when comparing with RMSD of the second peak. The scatter in the RMSD values
 670 may be attributed to the irregular trend in the local peaks present on first resonance peak of the
 671 PZT.



673
 674
 675 **Figure 18.** RMSD (%) (a) Second resonance peak (b) First resonance peak

676
 677 The measured RMSD detects changes in the first cycle while the changes in the subsequent
 678 load cycles are not significant. The RMSD measurements are indicative of changes in the
 679 material medium within the zone of influence produced by the discontinuity introduced by the
 680 crack. The discontinuity in the unloaded state represents the physical separation introduced in
 681 the material due to the stress-induced crack opening. The RMSD values indicate that the EI
 682 measurement is very sensitive in detecting the discontinuity more than the magnitude of the
 683 discontinuity. EI measurement would therefore provide a very sensitive measure of crack
 684 initiation in concrete in the vicinity of the PZT patch.

686 6. Summary and Findings

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2
3 687 A combined local and distributed monitoring system for concrete structures using an array
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5 688 of surface mounted PZT patches is presented. EI impedance measurements from individual
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7 689 PZT patches are used for local monitoring while the through-transmission stress wave
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9
10 690 propagation technique is used for distributed sensing. Progression of discrete crack in concrete
11
12 691 was evaluated using a full-field displacements measured on the surface of the beam obtained
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14 692 with the use digital image correlation and was correlated with measurements obtained from the
15
16 693 PZT patches. The crack opening is mapped from a very small value on the order to 10 μm to
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18 694 100 μm . The material away from the localized discontinuity produced by the crack is shown
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21
22 695 to relatively free from any damage.

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24 696 Both the EI and the stress-wave propagation techniques are shown to be influenced by
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26 697 discontinuity in the concrete substrate produced by a stress-induced crack. The EI
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28 698 measurement is sensitive to the formation of localized damage in the form of a load induced
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30 699 crack in the vicinity of the PZT patch. A new damage index known as attenuation factor is
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32 700 introduced for the wave propagation technique. The attenuation factor is shown to be an
33
34 701 effective damage index for detecting the severity of discontinuity produced by a crack. The
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36 702 attenuation factor is shown to determine attenuation of the wave produced by the discontinuity
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38 703 encountered by the direct stress wave, independent of the length of propagation. The
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40 704 attenuation measurements were performed in the unloaded state, where the removal of the load
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42 705 results in closing of the crack. The through transmission of direct stress wave through the
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44 706 medium is very sensitive to the presence of a discontinuity left in the medium resulting from a
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46 707 stress-induced crack in its path. There is an attenuation of the wave even for a physical
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48 708 discontinuity in the concrete in the stress free state associated with a small stress-induced crack
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50 709 opening on the order of 10 μm . There is a complete attenuation of the direct stress wave
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52 710 transmission at 120 kHz for physical discontinuity in the concrete associated with a stress-
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55 711 induced crack opening on the order of 100 μm .

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3 712 The measurements from the PZT patches indicate that the localized discontinuity in
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5 713 concrete produced by a stress induced crack is easily detected using the attenuation factor from
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7 714 the direct stress wave transmission path. The stress-induced crack has considerable crack
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9 715 closing stresses provided by aggregates bridging the crack. The discontinuity in the unloaded
10
11 716 state represents the physical separation introduced in the material due to the stress-induced
12
13 717 crack opening. The cracks which would have propagated due to overloads, but are closed due
14
15 718 to removal of the loads can therefore be easily be detected using attenuation factor
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17 719 measurements. This provides a very convenient measure for monitoring increment of damage
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19 720 due in the material. Further, crack opening on the order of 200 μm under service loads is often
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21 721 stipulated for durable design [ACI 224R-01 (2001), IS-456 (2000)]. The attenuation factor
22
23 722 from distributed sensing provides for monitoring discontinuity in the material medium even in
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25 723 the unloaded state, when the crack is not visually detectable. The initiation of the discontinuity
26
27 724 would be reflected in the EI signature if the discontinuity lies within its zone of influence.
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29 725 Service load condition of the concrete structure can therefore be monitored conveniently using
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31 726 combined EI and AR modes of an array of PZT patches.
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