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1 **Characterizing Concrete Surface Notch using Rayleigh Wave Phase Velocity and**
2 **Wavelet Parametric Analyses**

3

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8

9 **Abstract:** A multichannel Rayleigh wave (R-wave) measurement technique is proposed for
10 evaluating concrete surface notches with different orientations. In this study, numerical
11 simulations were first conducted to examine the propagation of R-waves in steel-reinforced
12 concrete comprising of surface notch inclining at 30°, 90° and 150° against the horizontal
13 plane. The change of R-wave amplitude was obtained through analysis by wavelet transform
14 (WT) and fast Fourier transform (FFT) for determining their correlations with the notch
15 depth-to-wavelength ratio. Experimental measurements on concrete samples were then
16 carried out to validate the proposed technique and its performance, particularly for cases
17 where notch depth is greater than R-wave wavelength. Good agreement was found between
18 the experimental results and the numerical calculations, offering good possibility for using R-
19 waves to assess vertical and inclined surface notches in reinforced concrete with the proposed
20 technique for R-waves acquisition and analysis.

21

22 **Keywords:** reinforced-concrete; surface notch; Rayleigh wave; wavelet transform; phase
23 velocity; excitation frequency

24

25

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1 **1. Introduction**

2 Concrete structures deteriorate over time as a consequence of pro-longed exposure to
3 various environmental factors for instance the mechanical loading, extreme weather and other
4 forces of nature. Surface cracking is one of the most common defects found in concrete
5 structures. It is the result of the combined effect of drying shrinkage, thermal variation,
6 restraint (external or internal) to shortening, subgrade settlement or mechanical actions like
7 fatigue and overloading [1, 2]. Strategic monitoring and assessment on the condition and
8 health of these structures are needed to prevent further deterioration in the structures which
9 will lead to fracture or even collapse due to the loss of structural integrity. Non-destructive
10 testing (NDT) is a wide group of non-invasive analysis methods which is able to provide
11 information about the internal condition of concrete. Elastic waves methods are amongst
12 some of the popular NDT techniques used for detecting defects and damages in concrete
13 structures. Surface Rayleigh wave (R-wave) that propagates along the surface of the structure
14 had been used in the study and evaluation of the integrity of concrete structures. For example,
15 strength gain evaluation of early-age concrete exposed to different curing conditions [3];
16 investigation of the relationship between R-wave velocity and porosity in dry and fully
17 saturated mortar and porosity estimation in concrete cover from ultrasonic measurements [4];
18 aggregate segregation detection in asphaltic concrete based on the phase velocity and
19 attenuation of R-wave by wedge generation technique along with an air-coupled receiving
20 transducer with a finite-size aperture [5]; examination of concrete blocks, including
21 subsurface cracks with different depths by ultrasound method [6]; honeycomb inspection in
22 early-age concrete by ultrasonic surface wave [7]; application of Second Harmonic
23 Generation (SHG) in R-waves to quantify microstructural changes and microcracks in mortar
24 and concrete [8]; feasibility study of defects detection inside reinforced concrete (RC)

1 structures by using elastic-wave based multi-directional Synthetic Aperture Focusing
2 Technique (SAFT) [9].

3

4 Many efforts make use of characteristics of R-waves such as scattering and
5 attenuation in the application of surface cracks detection and estimation. For example, non-
6 contact, air-coupled surface wave transmission and the effects of sensor locations were
7 investigated for partially or fully closed surface breaking crack by [10-14]. In addition, a two
8 sensor-array methodology was implemented by [15] for effective in-place crack depth
9 estimation based on the study of concrete specimens with vertical slits of different depths.
10 Apart from that, Rayleigh wave dispersion and energy dissipation were analyzed to determine
11 the locations and the depths of surface cracks in concrete beams [16]. Besides, surface crack
12 depth estimation and the evaluation of repair effect for deteriorated concrete piers were
13 analytically and experimentally investigated using Rayleigh waves by [17-20]. Despite these,
14 most of the studies have been associated with estimating concrete cracks that are relatively
15 shallow in depth and the propagation of R-waves in concrete containing an inclined crack has
16 not been investigated in detail to the author's best knowledge. In a most recent effort, we
17 performed multi-channel measurements of R-waves on concrete specimens with surface
18 defects [21, 22]. With the previous numerical and experimental findings serving as the
19 fundamental and knowing the potential of R-waves as an effective means for assessing
20 concrete cracks [23, 24], the aim of this study is to establish an in-depth understanding and
21 quantitative relations useful for characterizing the surface notch, e.g. depth and degree of
22 inclination. A series of simulations for wave motions to examine the behavior of R-waves of
23 varying excitation frequencies towards different depths and degree of inclinations of surface
24 notch were carried out. The outcome of this study is considered to provide further insights on
25 identifying the critical parameters (WT and phase velocity) for quantification of correlations

1 that lead towards establishing a reliable assessment method for concrete structures with
2 similar defective conditions. The simulated R-waves results for different notch depths and
3 inclination angles were then verified through experimental measurements.

4

5 **2. Numerical Simulations**

6 The simulations were conducted by employing commercial software [25] that solves
7 two dimensional (2D) elastic wave propagation problems by temporal acoustic interrogations
8 based on the finite difference method in the plain strain case. The fundamental equation
9 governing the two-dimensional propagation of stress waves in a perfectly elastic medium,
10 ignoring viscous losses is as follows [25]:

$$\rho \frac{\partial^2 u}{\partial t^2} = \mu \nabla^2 u + (\lambda + \mu) \nabla(\nabla \cdot u) \quad (1)$$

11 where $u = u(x, y, t)$ is the time-varying displacement vector, ρ is material density, λ is first
12 Lamé constant, μ is second Lamé constant, ∇ is the gradient of operator, $\nabla \cdot$ is the divergence
13 operator, ∂ is the partial differential operator, t is the time. Eq. (1) is solved at discrete points
14 with respect to the boundary conditions of the model, which include the input source that has
15 predefined time-dependent displacements at a given location and a set of initial conditions,
16 while wave propagation in each distinct homogeneous phase is solved according to Eq. (1) as
17 well [26, 27].

18

19 A two dimensional steel reinforced concrete model with a dimension of 500 mm
20 (width) \times 300 mm (depth) was proposed (see Figure 1). All materials were considered elastic
21 without viscosity components. The mechanical properties of the concrete and steel
22 reinforcement were configured as uniform throughout the whole study and produced
23 longitudinal wave velocities of approximately 4300 m/s and 6099 m/s, for concrete and steel
24 reinforcement, respectively. The source of wave was configured as excitations by impacts

1 (point source), which was located on the top surface and produced a full cycle elastic wave
 2 with different range of frequencies in order to estimate the effect of the different
 3 wavelengths. In the simulation, three sensors were placed on the left and right side of the
 4 inclined surface notch, respectively with spacing of 40 mm. The distance between the source
 5 and nearest sensor S1 was set to 170 mm to avoid significant the near and far field effects.
 6 From the simulation, the influence of notch on waveform distortion, reduction of amplitude
 7 and pulse velocity was assessed. For time sampling, the step was $0.0962 \mu s$ while the basic
 8 period of the highest frequency (150 kHz) was $6.67 \mu s$, implying that a typical cycle was
 9 represented by almost 70 points, more than 10–20 points which are considered adequate.
 10 Table 1 tabulates the elastic properties of simulation model, which were obtained and
 11 calculated from laboratory testing and wave measurement of concrete specimen. The material
 12 and geometry of concrete medium set as uniform throughout the simulation work. In
 13 addition, the parameters of investigation such as angle of inclination, vertical depth, and
 14 frequency of excitation are provided in Table 2.

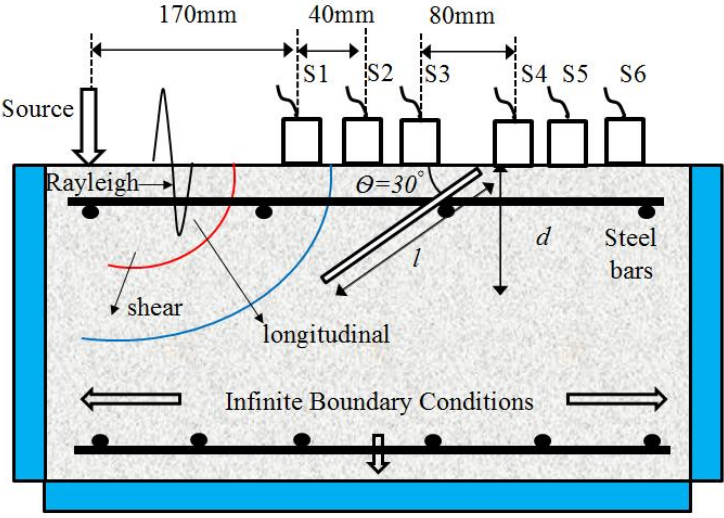


Figure 1. Wave motion simulation model.

1

Table 1. Properties of steel reinforced concrete model

PARAMETER	Concrete Model	Reinforcing Steel
Lambda, λ_m	15457 MPa	12482 MPa
Mu, μ_m	14600 MPa	83590 MPa
Density, ρ_m	2313 kg/m ³	7850 kg/m ³
P-wave velocity, V_P	4394.92 m/s	6099.28 m/s
R-wave velocity, V_R	2311.96 m/s	3219.95 m/s
Wavelength of R-wave, λ_R	2.31 mm	3.22 mm

2

3

Table 2. Characteristics of simulated notches

Types of defect	Depth, d (mm)	Length, l (mm)	Degree of inclination θ, (°) to the horizontal plane	Frequency of wave, f (kHz)
Surface notch	15, 30, 45, 60, 75, 90, 120, 150	30 to 150 at 30 mm increment	30, 90, 150	10, 20, 30, 40, 50, 60, 80, 100, 150

4

5

6 **3. Signal Processing and Waveform Analysis**

7 In this study, matched filtering of center of energy (MFCE) technique was employed
8 in raw data signal processing. It is understood that R-wave carries a higher amount of energy
9 than body waves. The developed MFCE technique is useful for extracting R-wave component
10 from the recorded waveforms, based on identification of wave amplitudes corresponding to
11 R-waves. The MFCE technique could identify the location of the center of energy for R-wave
12 and "zero pad" the amplitudes of other waves while keeping the one related to the arrival of
13 R-wave, which was usually signified by a large increase in both the positive and negative
14 phase in the waveform. After that, matched filtering on each processed signal was executed
15 with respect to the processed signal obtained from the first sensor. The details of the

1 technique can be found in [23]. The windowed signals (R-waves) after the MFCE process
 2 were further analyzed by WT and FFT techniques. FFT was performed on the processed data
 3 and from the resulting frequency response, phase difference between first sensor and
 4 following sensors was calculated. Phase velocity component of R-waves for a particular
 5 frequency was the obtained using the following equation [28, 29]:

$$V_p = \lambda f = \frac{2\pi f \Delta x}{\Delta \phi} \quad (2)$$

6 where V_p is phase velocity, π is phi, λ is wavelength, f is corresponding frequency, Δx is the
 7 distance between sensors and $\Delta \phi$ is phase difference which defined as the difference between
 8 unwrapped angle for processed signals detected by each sensor. In addition, the continuous
 9 wavelet transform (CWT) based on the Gabor wavelets, which has been demonstrated to be
 10 very useful as a time-frequency analysis tool of wave signals in SHM [30-34], is used to
 11 calculate a dispersion-invariant maximum point in the processed signal. Theoretically, the
 12 CWT is defined as [35]:

$$F_\psi(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \Psi\left(\frac{t-b}{a}\right) dt \quad (3)$$

13 where $\Psi(t)$ is a mother wavelet with finite energy, a is a scale parameter, $F_\psi(a, b)$ is a
 14 wavelet coefficient for a given time domain signal $f(t)$. Any mother wavelet can be used for a
 15 wavelet transform, which is the major advantage of the wavelet transform. The mother
 16 wavelet used in study was Gabor wavelet based on the Gaussian function and its Fourier
 17 transform are given as [36] due to the similarity in shape to the raw waveforms and could
 18 lead to a more consistent results:

$$\Psi(t) = \frac{1}{\sqrt[4]{\pi}} \sqrt{\frac{\omega_p}{\gamma}} \exp\left[-\frac{t^2}{2} \left(\frac{\omega_p}{\gamma}\right)^2 + i\omega_p t\right] \quad (4)$$

$$\hat{\Psi}(\omega) = \frac{\sqrt{2\pi}}{\sqrt[4]{\pi}} \sqrt{\frac{\omega_p}{\gamma}} \exp\left[-\frac{t^2}{2} \left(\frac{\omega_p}{\gamma}\right)^2 (\omega - \omega_p)^2\right] \quad (5)$$

1 where, ω_p is the center frequency, $\omega = 2\pi$, γ is a constant taken as $\gamma = \pi(2/\ln 2)^{1/2}$. The
2 identified frequency (corresponding to peak coefficient intensity) from sensor S1 was used to
3 correlate with the rest of wavelet transforms. Generally, the information about standard time
4 and frequency content and wavelet transform coefficient can be obtained from the algorithm.
5 Meanwhile, the distribution of wavelet transform coefficient is shown in the form of a
6 contour plot. Since the transform distributes the energy of a wave in time and frequency,
7 hence it is possible to identify the occurrence of particular frequency content at a certain time.

8

9 **4. Materials, sensors and excitation**

10 Four steel reinforced concrete block specimens of $300 \times 300 \times 500$ mm were cast and
11 the experimental set-up as shown in Figure 2. Among the specimens, one served as the
12 control sample, while the rest consisted of an artificial notch inclining at 30° , 90° and 150° . A
13 triangular shaped polystyrene foam board was employed to represent surface notch that has
14 different "notch depths" along the transverse direction of the specimen. For experiment
15 measurement, piezoelectric accelerometers (by ICP[®]) with frequency range of 0.005 kHz to
16 60 kHz were used. As illustrated in Figure 2, six accelerometers were placed on the top
17 surface of the specimen, in an arrangement similar to the one adopted in the simulation.
18 Elastic wave excitations were made by dropping steel balls onto the concrete surface at 170
19 mm away from the trigger sensor S1. Throughout the experiment, steel ball impacts were
20 implemented by the same operator to minimize inconsistencies in the generation of stress
21 waves. Steel balls with different sizes were used for the purpose of generation of R-waves
22 with different dominant frequencies to investigate the relations between wavelength, notch
23 depth, angle of inclination and change in amplitude as well as the velocity. It was known that
24 as the diameter of the steel ball becomes smaller, the corresponding dominant frequency
25 becomes higher [37]. In this study, wave excitations were conducted from both sides for the

1 Control specimen and the one with vertical notch to minimize the geometrical effect. On the
2 other hand, for specimens with 30° and 150° inclined notches, excitation was carried out on
3 concrete surface at both sides of the notch and the waveforms were stacked to enhance signal
4 consistency and the sound-to-noise ratio. To ensure good coupling between sensor and
5 concrete, electron wax was used for mounting the sensors.

6

7 A waveform acquisition system (PXIe-4492 by National Instruments Co.) was used to
8 conduct measurement and record waveform data with an interval of 5 μs for a period of 0.02
9 seconds. The elastic waves consist of longitudinal, shear (spreading into the specimen with a
10 spherical wavefront) and R-waves (confined near the surface (see Figure. 1)). The
11 accelerometers can record the strongest Rayleigh mode and also the initial part of
12 longitudinal wave which is the fastest type and arrives first at detection point.



13

14 **Figure 2.** Photograph of accelerometer sensors arranged on the upper side of concrete
15 specimen.

16

17 **5. Results**

18 *5. Waveforms and Signal Processing*

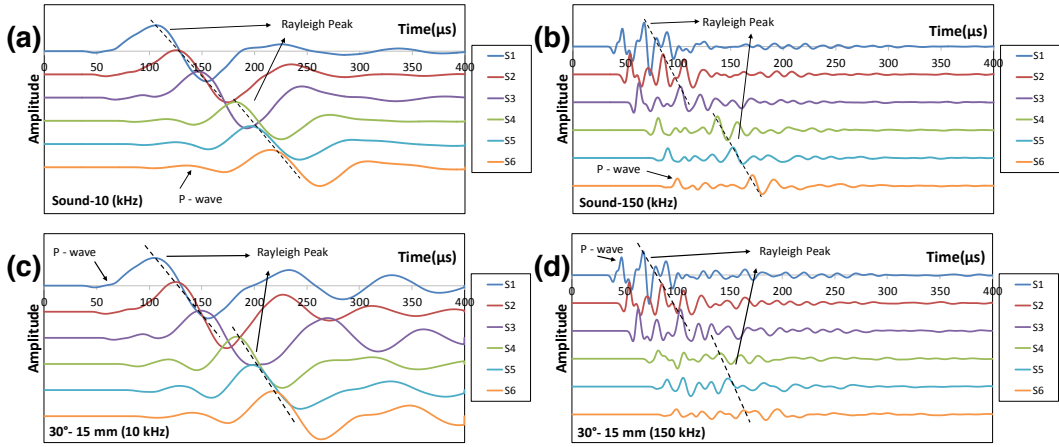
19 Figures 3 (a) and (b) show typical waveforms obtained from simulating models
20 without notch, which were generated by excitation frequencies of 10 and 150 kHz. The strong
21 burst in the waveform belongs to the Rayleigh mode was observed, which follows the weak

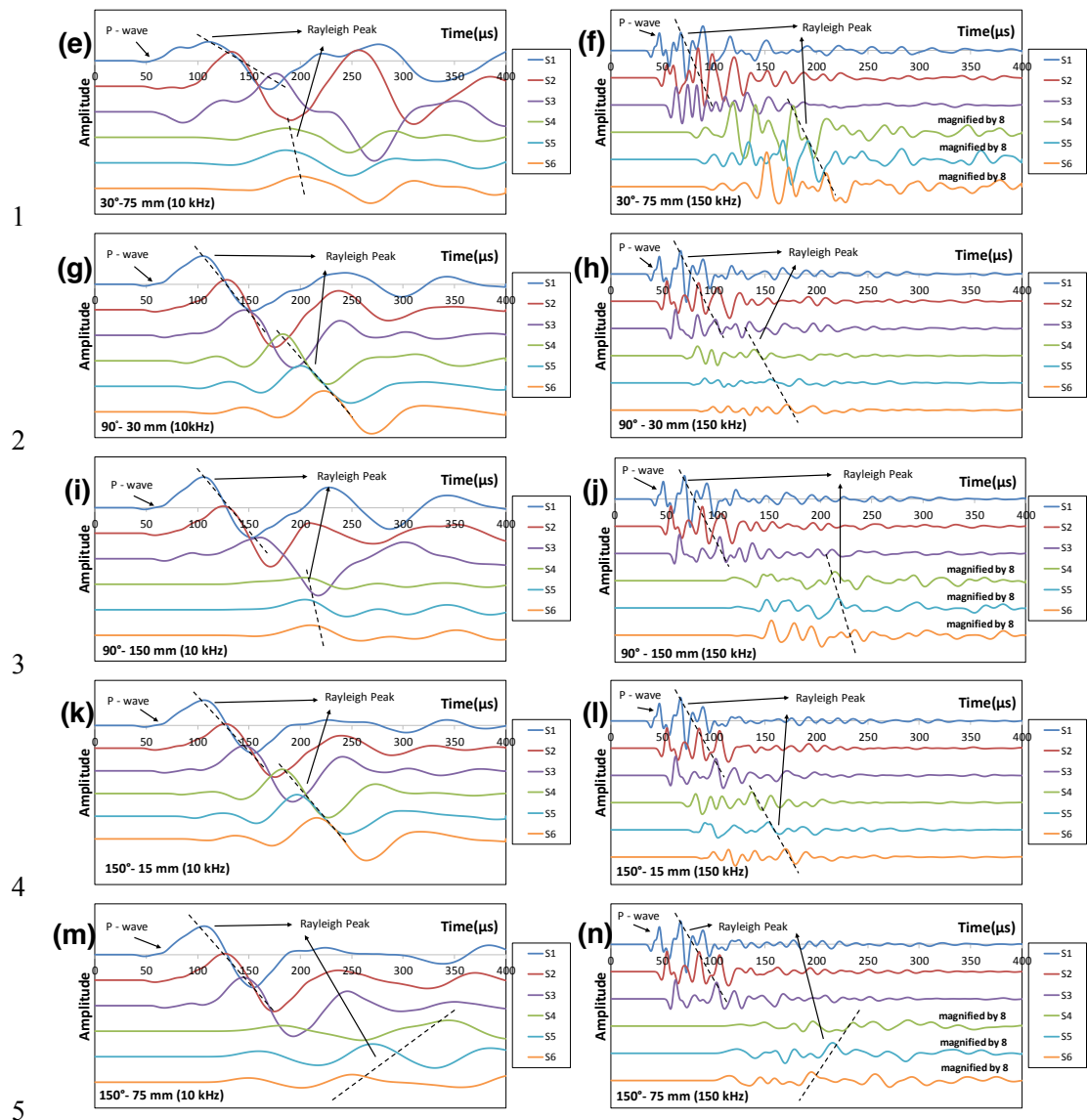
1 initial arrival of the P-wave, especially for higher excitation frequencies due to its lower
 2 velocity and slowest types. Simulated waveforms of various notched concrete models
 3 acquired from same excitation frequencies are also shown in Figures 3 (c) to (n). Distorted
 4 waveforms recorded by sensors S4, S5 and S6, located on the side after the notch indicated an
 5 abrupt decrease in amplitude (waveforms were magnified by a factor of 8 in Figures 3 (f), (j)
 6 and (n)) as compared to those obtained from the sensors of sound concrete model or the ones
 7 located before the notch (S1, S2 and S3), which are visible. A portion of the waves was
 8 reflected back when they impinged on the free surface of a notch, while the other portion
 9 passed through below the notch. The waves were then diffracted and scattered when they
 10 impinged on the tip of the notch [38]. In addition, the arrival of R-waves has obviously been
 11 delayed, especially in the deeper notch cases (150 mm). This reveals that less energy is
 12 transmitted through the notch for a longer pathway before reaching the corresponding
 13 sensors. Clearly, the depth of the notch has tremendous influence on the wave amplitude and
 14 the transit time of the signal as recorded by sensors after the notch.

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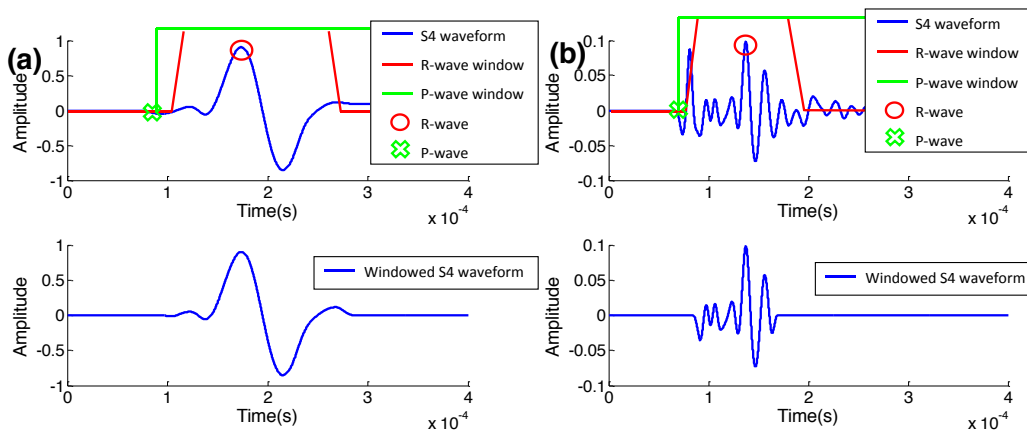
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 8 **Figure 3.** Simulated waveforms collected from steel reinforced concrete model for sound
 9 concrete mode using (a) 10 kHz and (b) 150 kHz excitations; 15 mm 30° inclined notch using
 10 (c) 10 kHz and (d) 150 kHz excitations; for 75 mm 30° inclined notch using (e) 10 kHz and
 11 (f) 150 kHz excitations; for 30 mm 90° vertical notch using (g) 10 kHz and (h) 150 kHz
 12 excitations; for 150 mm 90° vertical notch using (i) 10 kHz and (j) 150 kHz excitations; for
 13 15 mm 150° inclined notch using (k) 10 kHz and (l) 150 kHz excitations; for 75 mm 150°
 14 inclined notch using (m) 10 kHz and (n) 150 kHz excitations

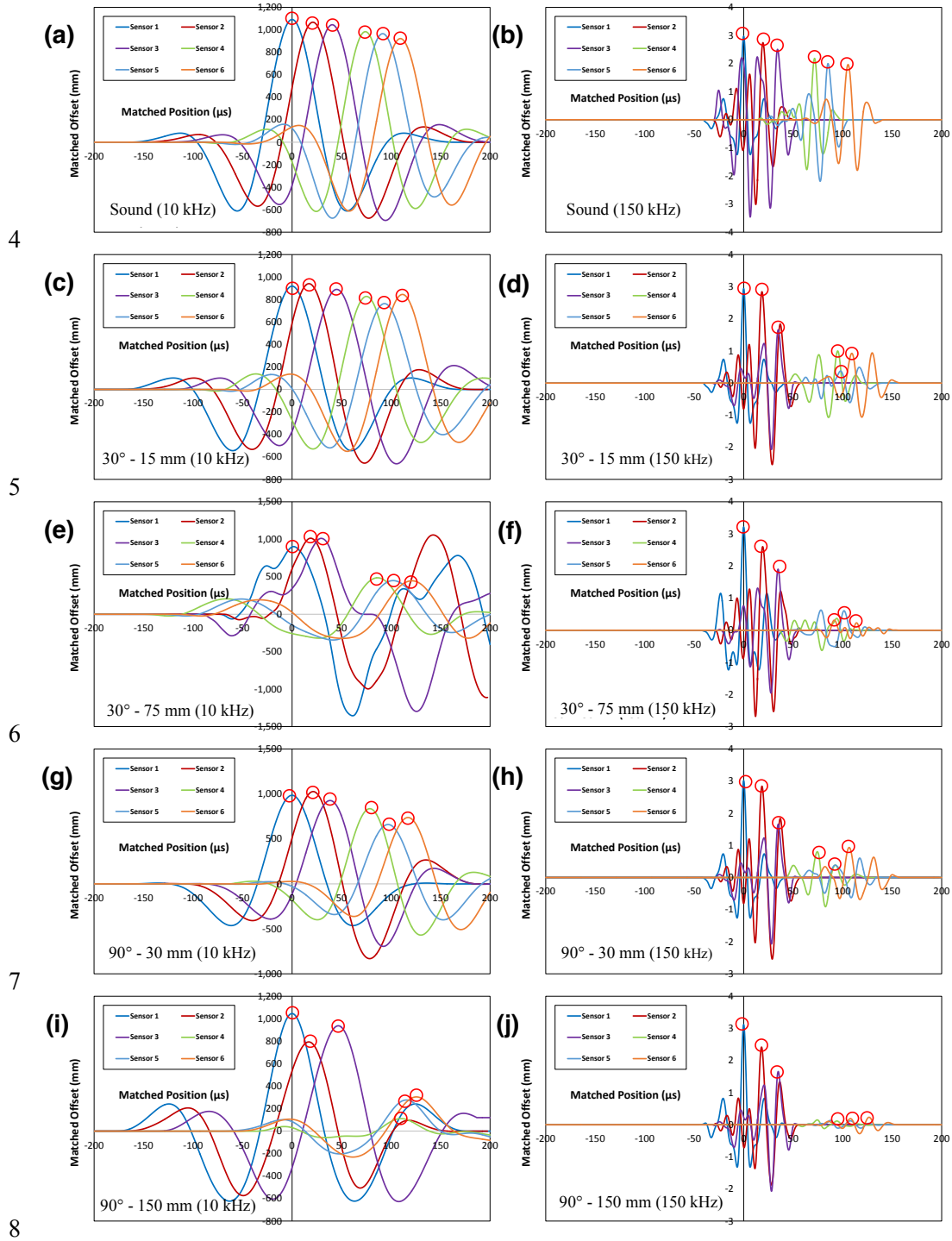
1 Examples of raw and MFCE processed waveforms acquired from sensor S4 were
 2 presented in Figure 4. The R-wave peak is indicated by red circle, while the P-wave is
 3 marked by green cross to distinguish the arrivals of P- and R-waves. The window was applied
 4 around the center of energy of R-wave, while the rest of the waveform was zero-padded as
 5 can be seen in Figure 4. In order to comprise one full cycle of elastic wave components, the
 6 length of windows adopted in this study is set to at least 1.5 times greater than its excitation
 7 wavelength. The processed waveform resulted in a more clear-cut isolated component,
 8 indicating a characteristic peak arrival belonging to the R-wave. Moreover, the processed
 9 waveform was found to yield peak frequency very similar to the frequency of excitation,
 10 indicating that the this frequency could be regarded as the characteristic frequency of the R-
 11 waves generated.
 12

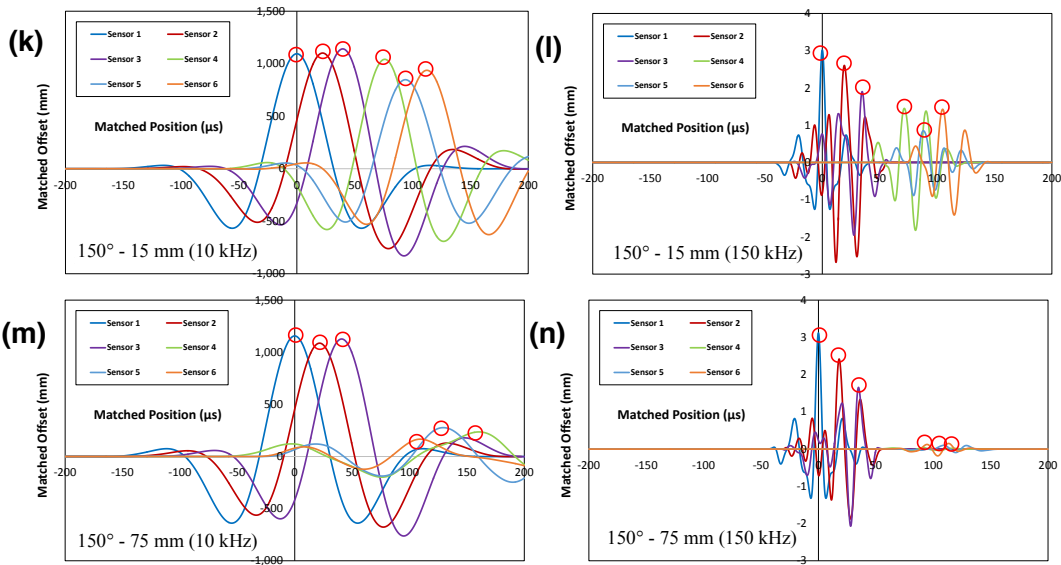


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 14
 15 **Figure 4.** Processing of waveforms using proposed matched filtering algorithm from sensor
 16 S4 for sound steel reinforced concrete model using (a) 10 kHz and (b) 150 kHz excitations
 17

18 Figure 5 shows the processed waveforms and the respective R-wave peak matched
 19 positions based on MFCE technique for sound and various notches concrete models with
 20 excitation frequencies of 10 kHz and 150 kHz, respectively. The variations of amplitude and

1 the delayed of R-wave peaks were almost identical and comparable to the raw data as shown
 2 in Figure 3, showing the performance of the proposed MFCE algorithm in determination and
 3 extraction of R-wave components from raw waveform data.





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4 **Figure 5.** Processed waveforms and the respective final R-wave peak matched positions
 5 based on MFCE method for sound concrete model using (a) 10 kHz and (b) 150 kHz
 6 excitations; for 15 mm 30° inclined notch using (c) 10 kHz and (d) 150 kHz excitations; for
 7 75 mm 30° inclined notch using (e) 10 kHz and (f) 150 kHz excitations; for 30 mm 90°
 8 vertical notch using (g) 10 kHz and (h) 150 kHz excitations; for 150 mm 90° vertical notch
 9 using (i) 10 kHz and (j) 150 kHz excitations; for 15 mm 150° inclined notch using (k) 10
 10 kHz and (l) 150 kHz excitations; for 75 mm 150° inclined notch using (m) 10 kHz and (n)
 11 150 kHz excitations

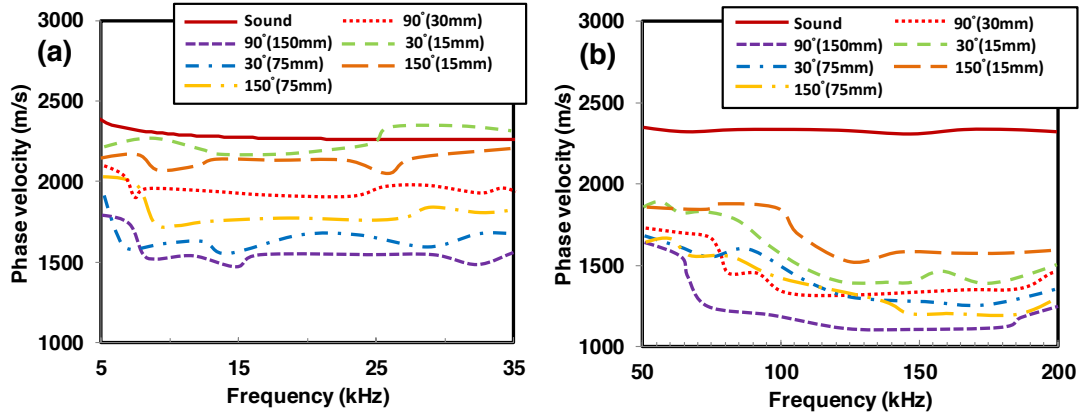
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13 Dispersion curve was utilized to explain the change of phase velocity of R-waves
 14 against the surface notch within the effective frequency bandwidth of excitation. The
 15 effective frequency bandwidth was determined based on the frequency domain function of
 16 the received signals and this bandwidth of frequencies containing most of the signal energy,
 17 which indicating a characteristic peak frequency belonging to the propagating R-waves by
 18 FFT and by Eq.2. Examples of averaged dispersion curve of each sensor (S1)-sensor
 19 combination for sound and various surface notched concrete model cases are depicted in

1 Figure 6 for the data obtained from 10 kHz and 150 kHz excitations, respectively. The
2 dispersion curves for the sound concrete model were almost consistent throughout the
3 bandwidth under consideration, giving an averaged value of 2295 m/s at 10 kHz and 2398
4 m/s at 150 kHz frequencies, which was very close to that calculated by considering the arrival
5 time of Rayleigh peaks. In contrary, the measured averaged phase velocity of model with a
6 surface notch depth of 150 mm was only 1571 m/s at 10 kHz and 1236 m/s at 150 kHz, which
7 were 31.5 % and 48.4 %, respectively, lower than that of the sound concrete model. Further,
8 it can be seen that the respective dispersion curves have been translated to lower values and
9 were less consistent throughout the bandwidth under consideration. The overall calculated
10 dispersion curves are clearly delayed because of the presence of surface notch, and the curve
11 shape was changed for the steel reinforced concrete models. It is worth to note that the
12 frequency at source shows symmetric, Gaussian-like curve but frequency attenuation is likely
13 to happen after propagating concrete. Therefore, the FFT for sensors may no longer be
14 symmetric. The change of "intensity of frequency" (amplitude of each frequency component)
15 across the indicated bandwidth could result in asymmetric distribution of phase velocity. The
16 recorded phase velocities were used to calculate phase velocity index using equation:

$$PVI = \frac{\sum_{j=2}^6 PV_{n,1\sim j} / 6}{\sum_{j=2}^6 PV_{s,1\sim j} / 6} \quad (6)$$

17 where $\sum_{j=2}^6 PV_{n,1\sim j} / 6$ and $\sum_{j=2}^6 PV_{s,1\sim j} / 6$ are average of R-wave phase velocities from
18 Sensor S1 to the other sensors, respectively, for model with notch and the sound model,
19 respectively.

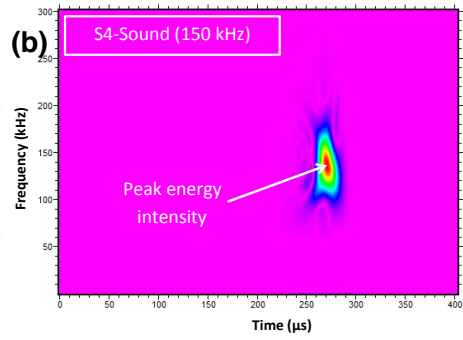
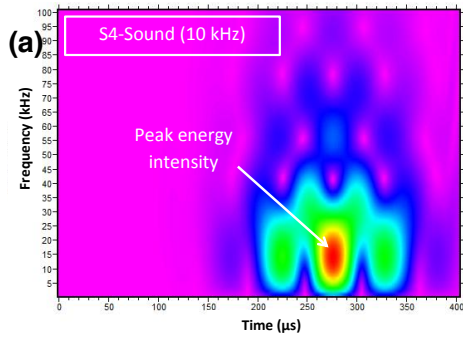


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2 **Figure 6.** Dispersion curve computed for sound and various surface notched concrete models
3 using (a) 10 kHz and (b) 150 kHz excitations

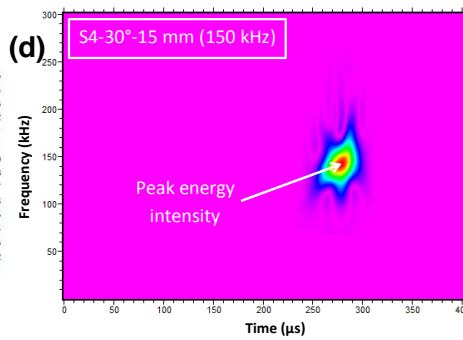
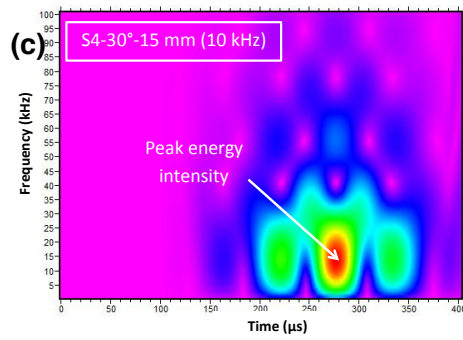
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5 Figure 7 shows the examples of 2D distribution of wavelet transform for 10 kHz and
6 150 kHz excitations as well as for steel reinforced concrete models at sensor S4 (sensor after
7 the surface notch). The wavelet transform diagram shows the magnitudes of wavelet
8 transform auto scaled in rainbow colors, which lower magnitudes correspond to pink while
9 peak magnitudes correspond to red. The peak energy intensity or the arrival of the wave peak
10 at each frequency component can be easily obtained. The identified peak intensity which is
11 corresponding to the respective R-wave amplitude was recorded for further analysis and
12 interpretation using:

$$WTI = \frac{\prod_{j=4}^6 WT_{n,j} / \prod_{i=1}^3 WT_{n,i}}{\prod_{j=4}^6 WT_{s,j} / \prod_{i=1}^3 WT_{s,i}} \quad (7)$$

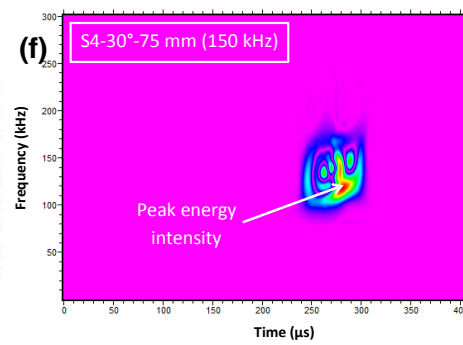
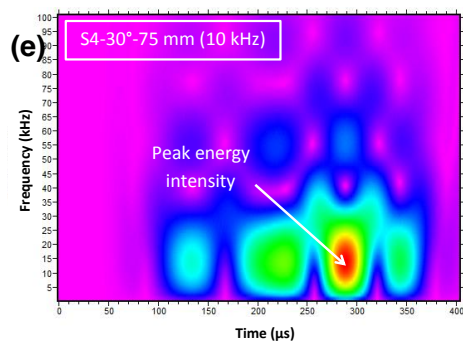
13 where WT_n is R-wave WT coefficient in model with notch, WT_s is R-wave WT coefficient in
14 sound model. The magnitudes of the wavelet transform (peak energy intensity) obtained from
15 sensor S4 were significantly lower for both the 150 mm depth vertical and 75 mm inclined
16 notch cases as compared to the one obtained from the sound reinforced concrete model. In
17 addition, delayed of peak energy intensity was noticed as well, in particular for the deeper
18 notch depth cases.



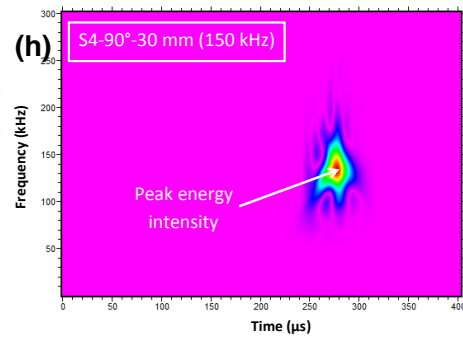
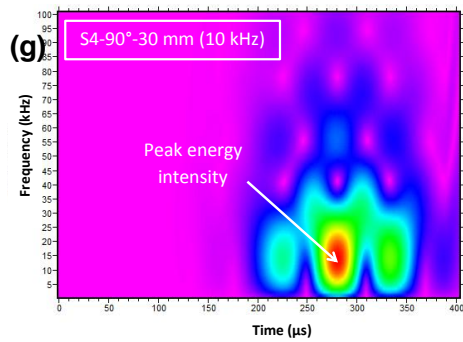
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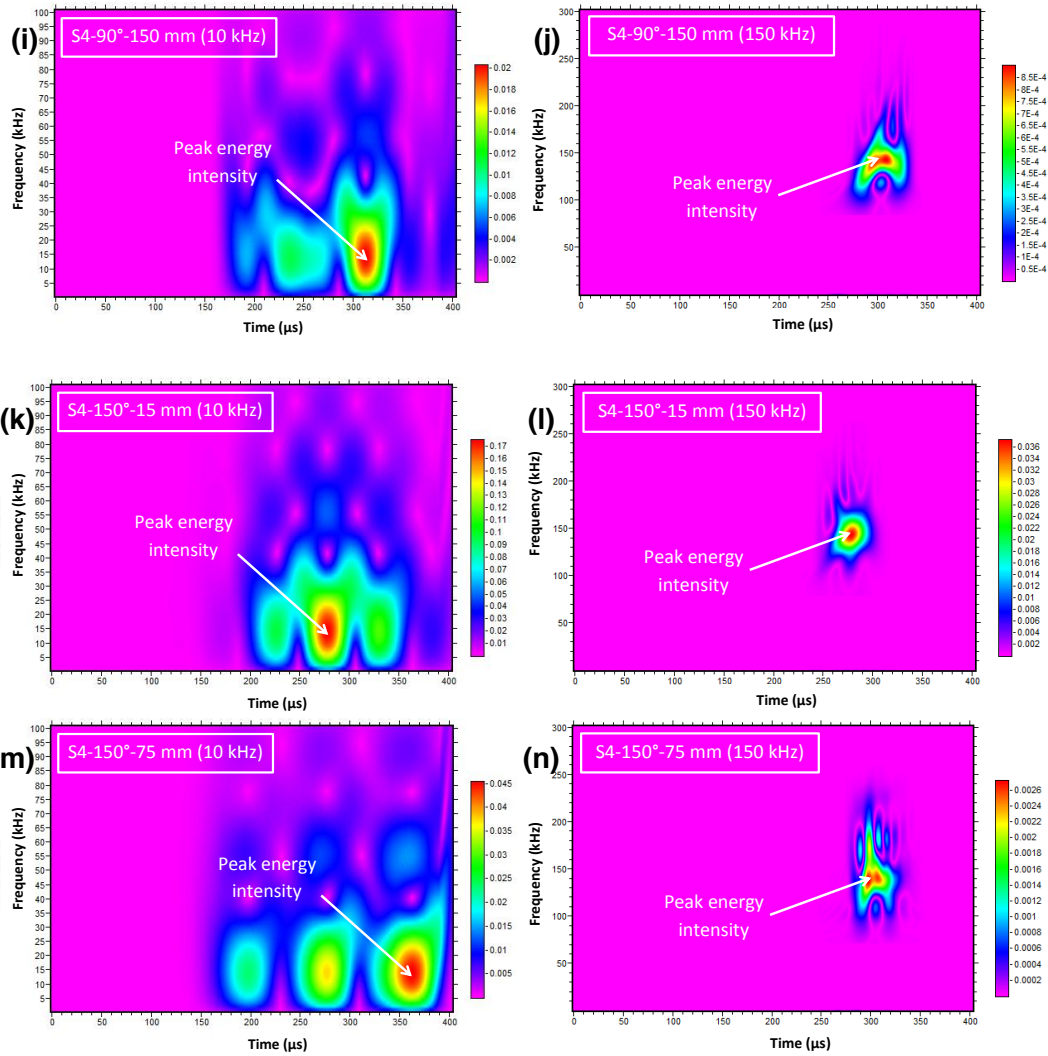
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Figure 7. 2D wavelet transform contour diagram at the fourth sensors (S4) for steel reinforced concrete model using (a) 10 kHz and (b) 150 kHz; for 15 mm 30° inclined notch model using (c) 10 kHz and (d) 150 kHz excitations; for 75 mm 30° inclined notch model using (e) 10 kHz and (f) 150 kHz excitations; or 30 mm 90° vertical notch model using (g) 10 kHz and (h) 150 kHz excitations; for 150 mm 90° vertical notch model using (i) 10 kHz and (j) 150 kHz excitations; or 15 mm 150° inclined notch model using (k) 10 kHz and (l) 150 kHz excitations; or 75 mm inclined 150° inclined notch model using (m) 10 kHz and (n) 150 kHz excitations

1 5.2 *Correlations*

2 The concrete notch depth and degree of inclination were divided by the major
3 wavelength in order to offer a dimensionless relationship and provided a more general form
4 that potentially suit any scale [16, 23, 24, 39-43]. The wavelength can be calculated using the
5 common relation between velocity, wavelength, and dominant frequency. The dominant
6 frequency, f_D for each excitation frequency was computed based on the power spectrum
7 density magnitude plot acquired from the FFT. Table 3 lists the calculated R-waves velocities
8 and these values were used to compute the ratio between notch depth and wavelength, d/λ as
9 well as degree of inclination and wavelength, θ/λ for each excitation frequency.

10 **Table 3.** Velocity of R-waves generated by different excitation frequencies.

Frequency of wave f , (kHz)	R-wave velocity (Steel reinforced concrete model)(m/s)
10	2281.3
20	2361.2
30	2370.1
40	2375.7
50	2378.2
60	2381.3
80	2383.7
100	2390.0
150	2392.6

11

12 The power and logarithmic regressions derived from the plot of R-wave WT and
13 phase velocity indices with respect to the ratio between notch depth and wavelength, d/λ
14 show good correlations, as presented in Figures 8 and 9. It is also found that both the WT and
15 phase velocity indices decreased as the d/λ increased with a slightly lower correlation
16 compared to WT index. Taking WT analysis results of 10 kHz excitation as examples
17 (concrete model with vertical 90° surface notch), the change of WT index with regards to d/λ
18 was noticeable, which changes from 0.54 to 0.016 as d/λ increases from 0.13 to 0.67.

1 However, for d/λ values of greater than 1, the *WT* index change eventually reaches a plateau.
2 From the analyses, it is revealed that higher excitation frequencies result in higher value of
3 velocity or phase velocity. Similar findings were reported in previous studies, pointing that
4 although higher frequency waves suffer from stronger attenuation than the lower frequency
5 ones, their propagation velocity is faster in inhomogeneous media like concrete [44, 45].
6 When the excitation frequency is 10 kHz, 150 mm notch length seems to give the largest drop
7 in R-wave velocity index, which was up to 21.3 %, 14.1 %, 18.4 %, 18.6 % and 15.2 % as
8 compared to the one from sound concrete model for cases with vertical (90°) and inclined
9 notches cases (30° , 60° , 120° and 150°), respectively. On the contrary, the smallest decrease
10 of velocity index which is caused by the notch length of 30 mm, have marked a maximum of
11 8.4 %, 4.3 %, 6.1 %, 5.0 % and 6.4 % dropped for the same cases as mentioned before. It is
12 noteworthy that the velocity index decreases with the increase in notch depth, justifying the
13 fact that the waves have to take longer time or longer path way to reach the other side of
14 notch for deeper notches.

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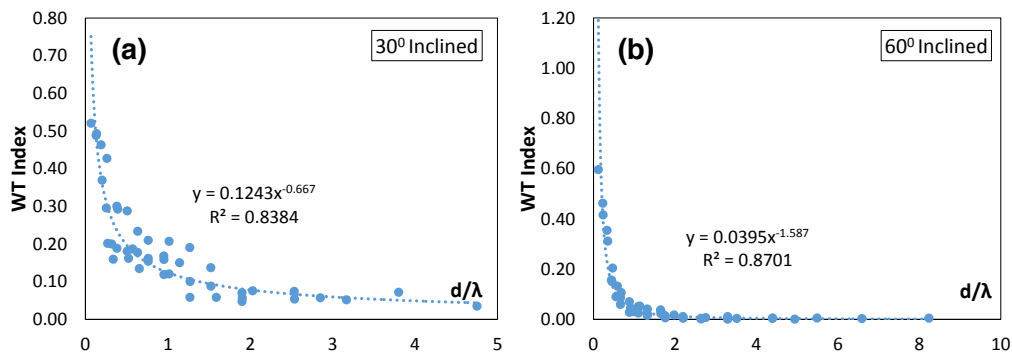
16 The *WT* and phase velocity indices vs. θ/λ data are given in Figures 10 and 11. The
17 *WT* and phase velocity indices exhibit power and logarithmic regressions, respectively, with
18 respect to the ratio between notch angle and wavelength, with moderate correlation
19 coefficients. It is obvious that for higher frequency, the *WT* index becomes lower due to the
20 higher tendency of high frequency components to lose energy through adsorption, scattering
21 and distortion by the notch. Similar findings have been reported previously [18], in which the
22 penetration depth of R-wave is believed to be equivalent to the excitation wavelength. It is
23 assumed that the wave is propagating in a straightforward path below the notch when the
24 wavelength is greater than the notch depth. On the other hand, the other mode of propagation

1 which involves reflection and scattering has occurred when the R-waves wavelength is
2 smaller than the notch depth.

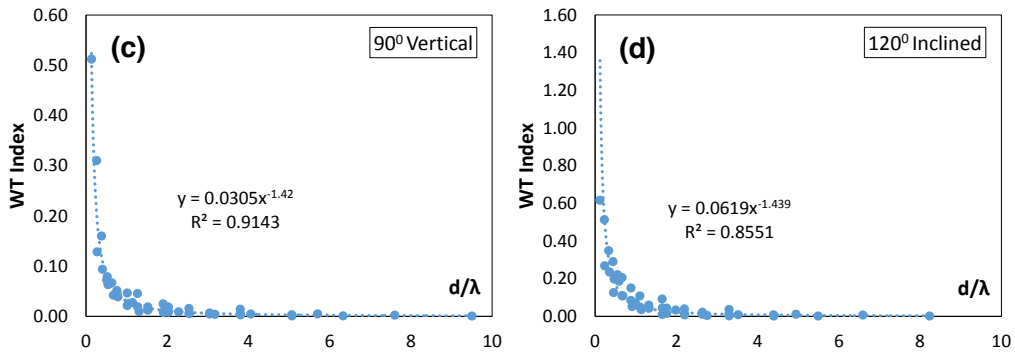
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4 The WT index seems to lose their sensitivity against deeper notch depths. There are
5 few reasons for this behavior. Amongst, the penetration depth of R-wave which is considered
6 as equal to one wavelength. According to Aggelis and Shiotani [18], the amplitude of R-wave
7 at the depth of one wavelength is around 6 % of the surface amplitude for ideal non-
8 attenuative material with mechanical properties similar to concrete. However, the attenuation
9 of concrete certainly has an effect in decreasing the penetration depth, something that is not
10 fully accounted for in the numerical simulation of this study. Besides, the energy of the wave
11 is not proportional to the amplitude but to the square of the amplitude. This implies that the
12 majority of R-wave energy propagates in shallower zone. Hence, despite the fact that the
13 wavelength can be larger than the notch, still the energy passing below the notch is
14 insignificant and therefore, the waveform readings for the larger notches do not show much
15 discrepancy [19].

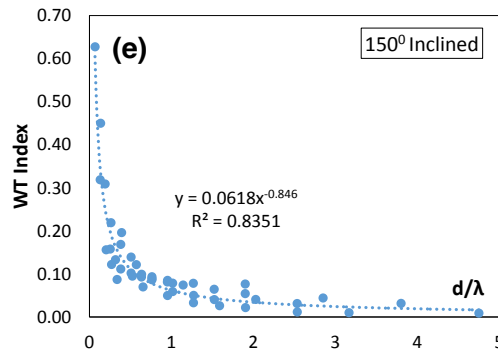
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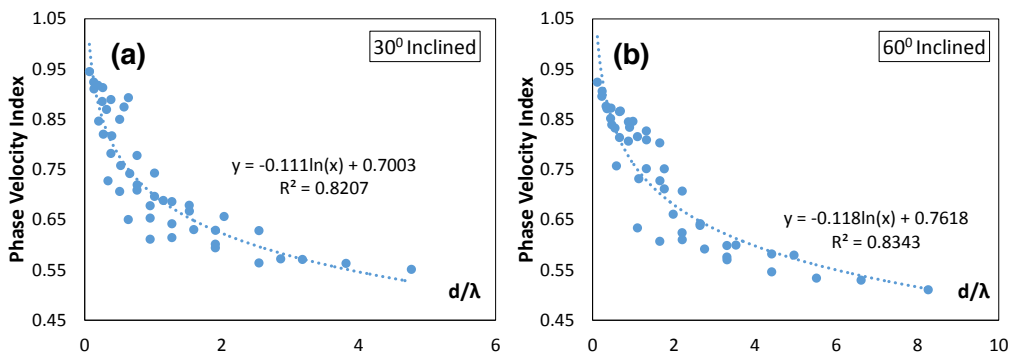
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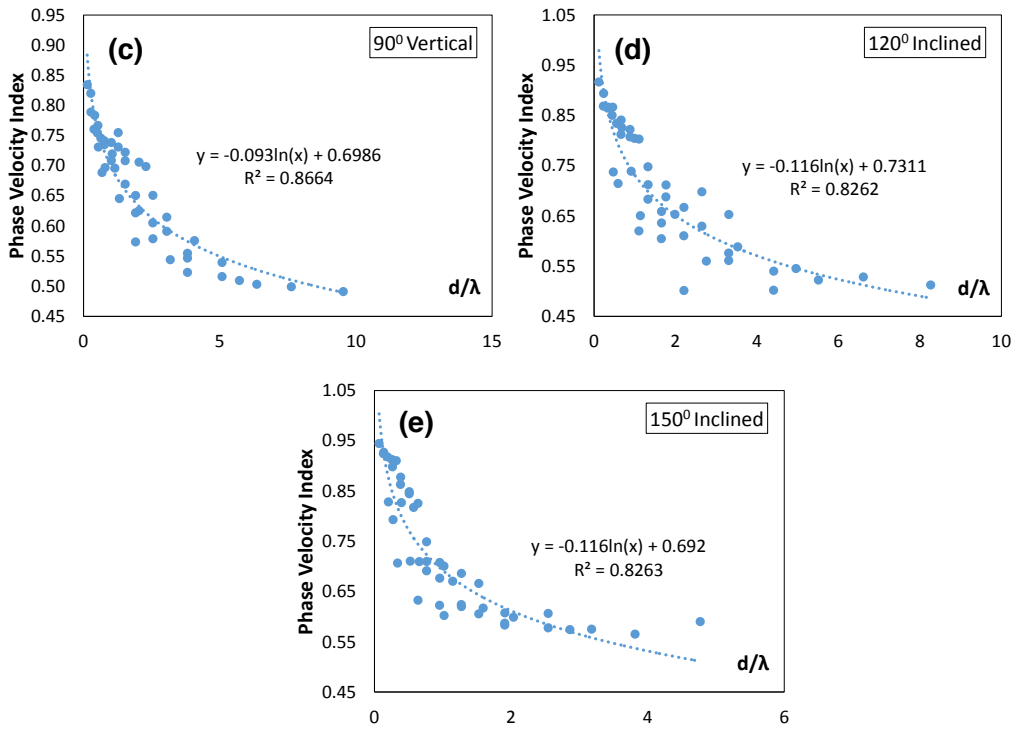
Figure 8. WT index versus d/λ for steel reinforced concrete model with (a) 30° inclined notch cases, (b) 60° inclined notch cases, (c) vertical notch (90°) cases, (d) 120° inclined notch cases and (e) 150° inclined notch cases

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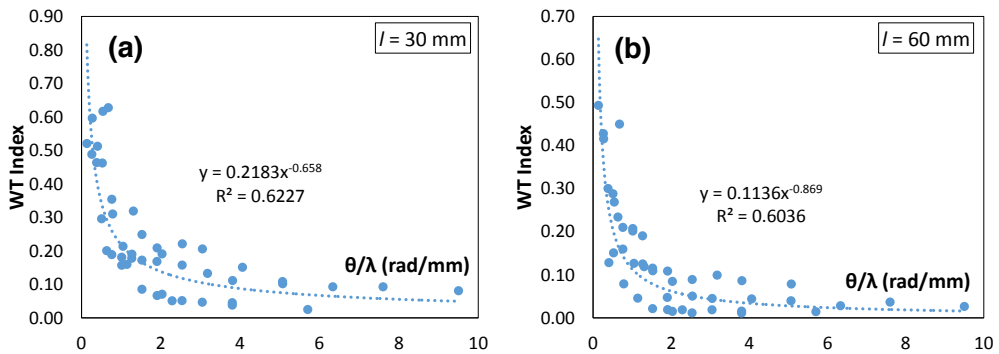
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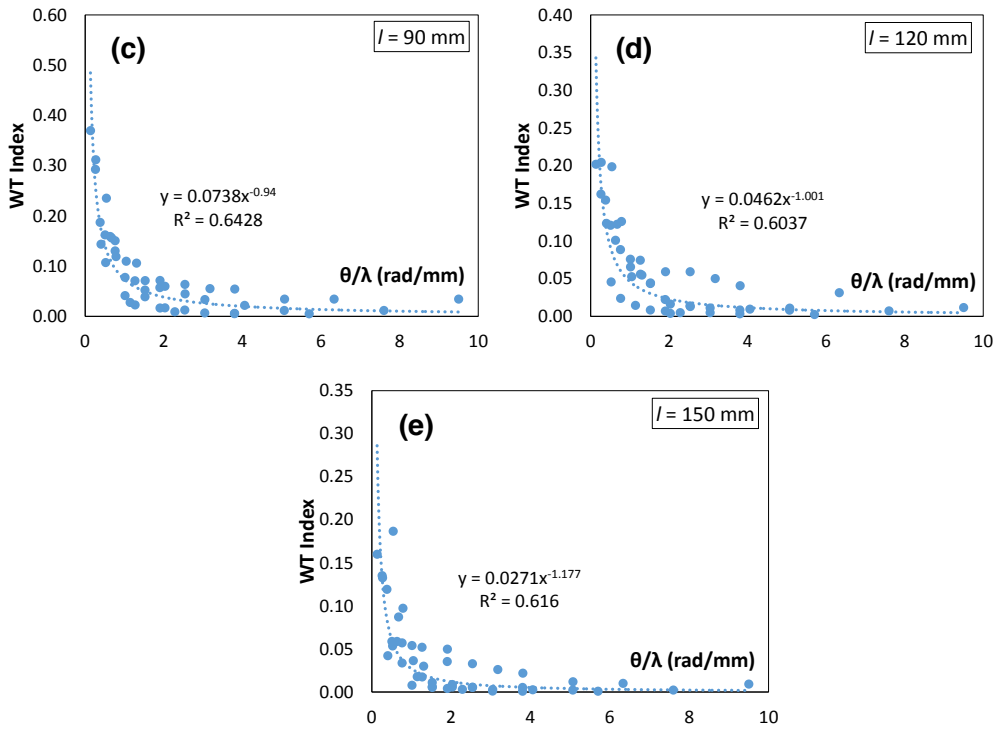
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Figure 9. Phase velocity index versus d/λ for steel reinforced concrete model with (a) 30° inclined notch cases, (b) 60° inclined notch cases, (c) vertical (90°) cases, (d) 120° inclined notch cases and (e) 150° inclined notch cases



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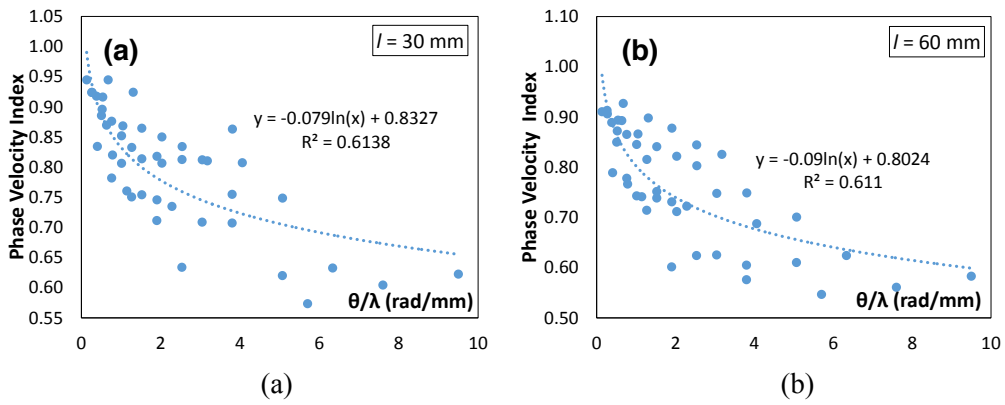
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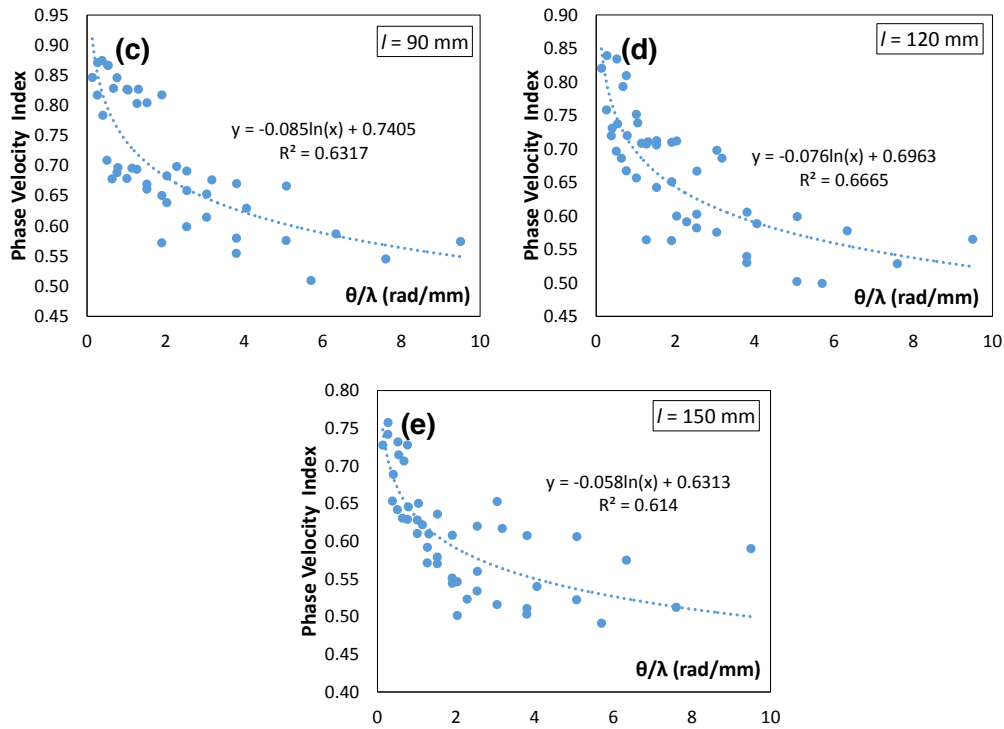
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Figure 10. WT index versus θ/λ for steel reinforced concrete model with (a) 30 mm notch length cases, (b) 60 mm notch length cases, (c) 90 mm notch length cases, (d) 120 mm notch length cases and (e) 150 mm notch length cases



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5.3 Experimental Results

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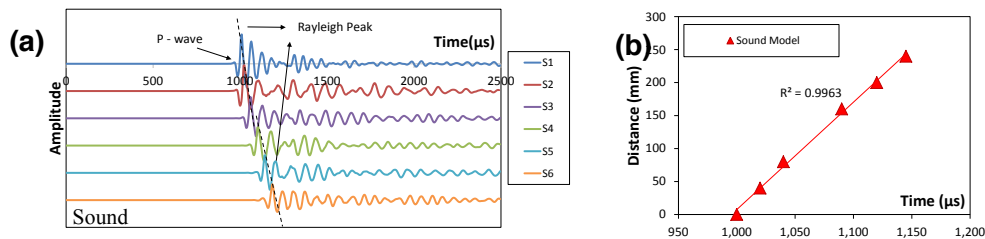
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Figure 11. Phase velocity index versus θ/λ for steel reinforced concrete model with (a) 30 mm notch length cases, (b) 60 mm notch length cases, (c) 90 mm notch length cases, (d) 120 mm notch length cases and (e) 150 mm notch length cases

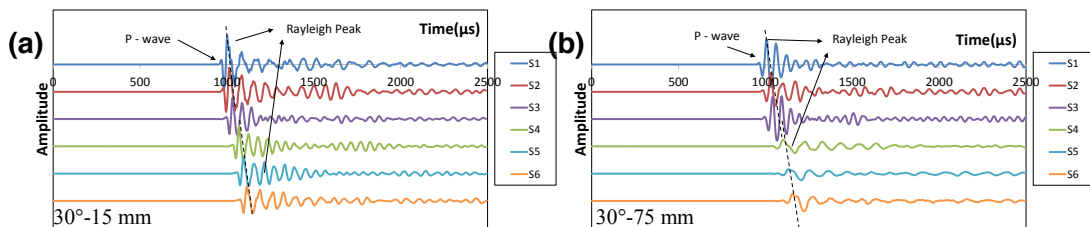
Five different diameters of steel balls (19 mm, 14 mm, 12 mm, 10 mm and 9 mm) were employed as impact sources in the experimental measurements, which exhibit consistent and broad spectral content of forcing function with dominant frequencies of 11.5 kHz, 13.1 kHz, 14.6 kHz, 18.2 kHz and 19.5 kHz, respectively. Examples of waveforms in steel reinforced concrete specimens obtained from tapping a 19 mm steel ball (dominant frequency of 11.7 kHz) against the face of concrete are depicted in Figure 12. Plotting the arrival time of R-wave obtained from each sensor with respect to distance, as seen in Figure 12, yields the propagation velocity which is the slope of the line. The arrival of R-waves

1 arrival time is comparable to the one obtained from simulation. In addition, time domain
 2 traces measured at the same array arrangement for the specimen with inclined 30° (notch
 3 depth of 15 mm and 75 mm), and on vertical notch 90° (notch depth of 30 mm and 150 mm)
 4 as well as on inclined 150° (notch depth of 15 mm and 75 mm) depicted in Figures 13 (a) to
 5 (f) as well. Further, the processed experimental waveforms by MFCE for the same cases are
 6 showed as in Figure 14. As can be seen from the figure, the delay of Rayleigh peaks between
 7 S3 and S4 becomes longer when the depth of surface notch is increased. In addition, major
 8 reduction of amplitude is observable when compared the amplitude recorded from sensors
 9 after the notch to those recorded from sensors before the notch. The propagation of elastic
 10 wave may not be 'straight and direct' underneath the notch along the measurement array but it
 11 might traveled in other shorter paths in concrete medium and been diffracted by the notch tip.

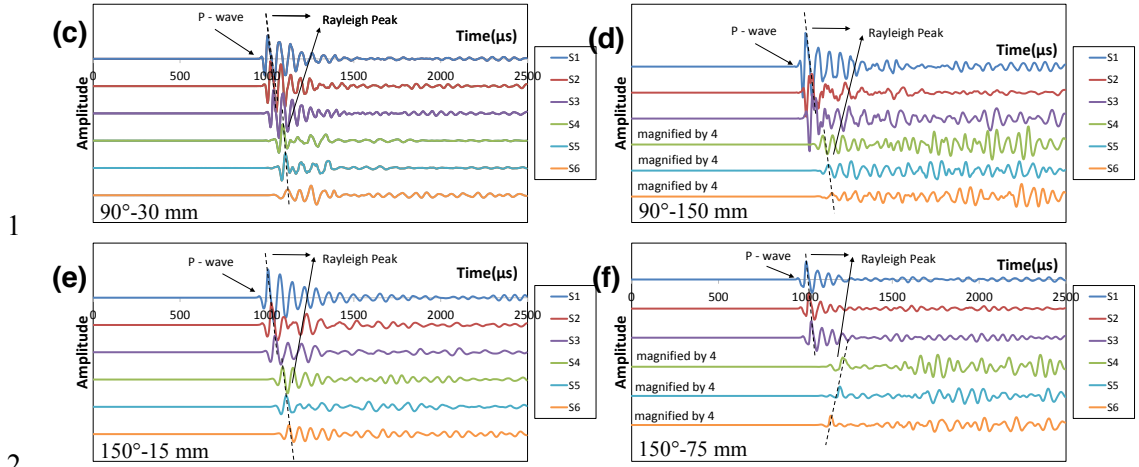


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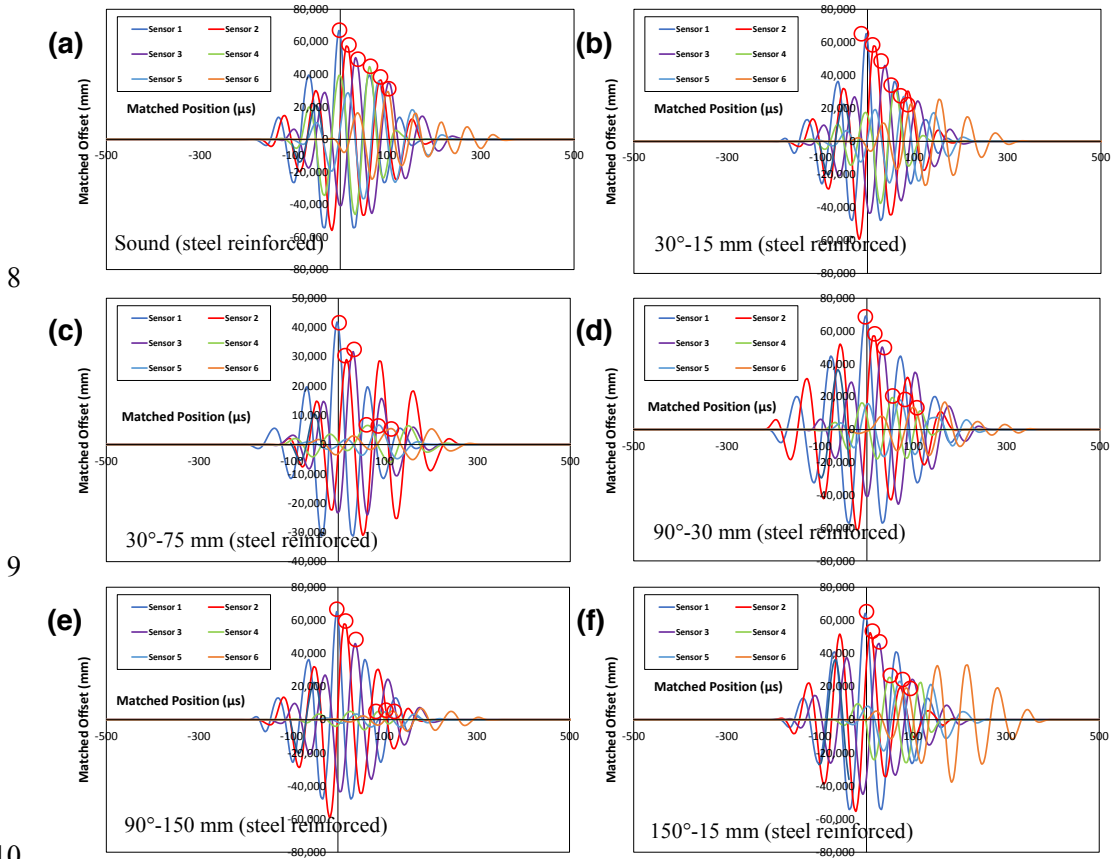
14 **Figure 12.** Experimental waveforms collected for (a) sound concrete specimen and (b) their
 15 corresponding R-waves propagation distance against arrival time. Excitations were done by
 16 19 mm steel ball impact.



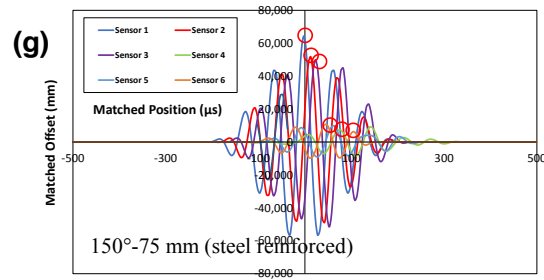
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4 **Figure 13.** Experimental waveforms collected for (a) 15 mm 30° inclined notch, (b) 75 mm
5 30° inclined notch, (c) 30 mm 90° vertical notch, (d) 150 mm 90° vertical notch, (e) 15 mm
6 150° inclined notch and (f) 75 mm 150° inclined notch. Excitations were done by 19 mm
7 steel ball impact.



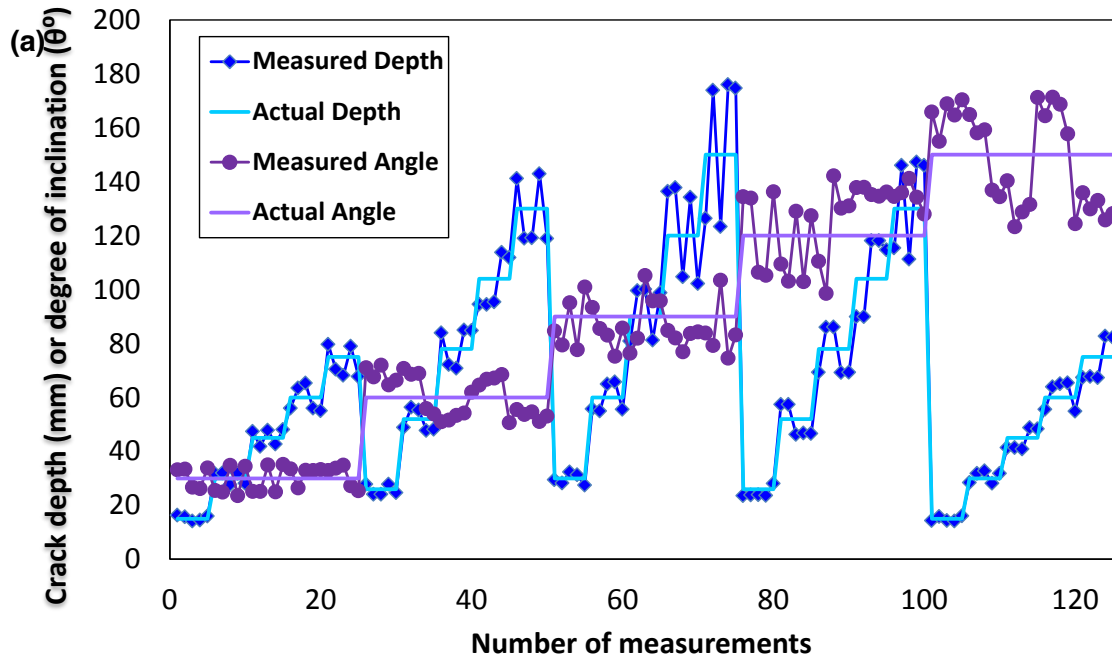
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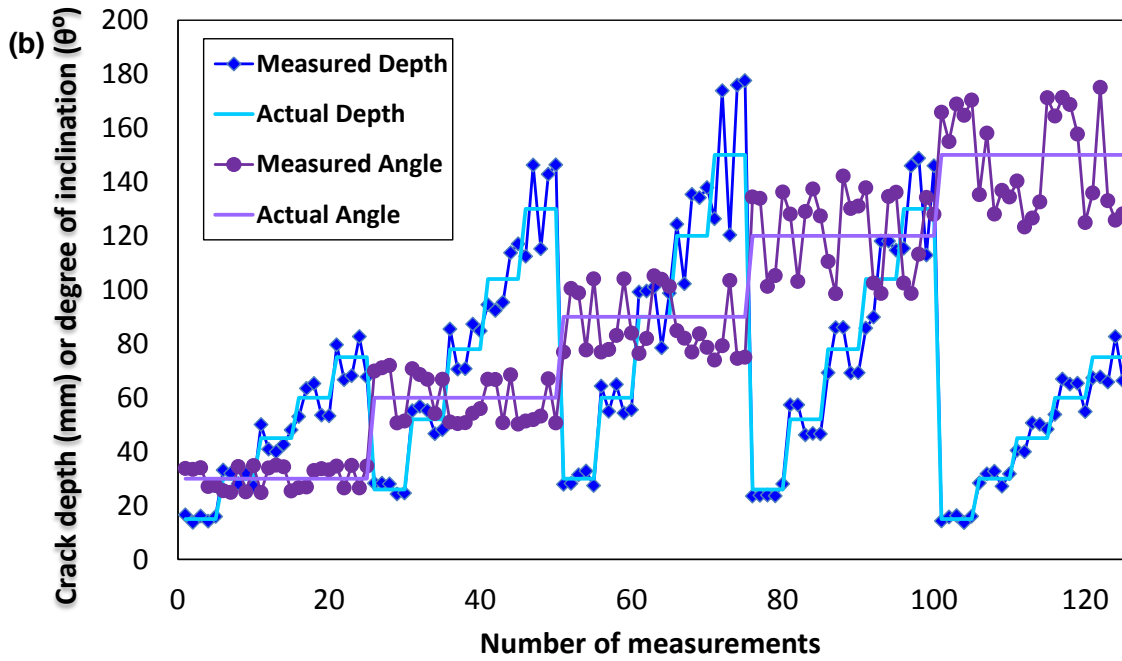
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Figure 14. Processed experimental waveforms and the respective final R-wave peak matched positions based on MFCE method for (a) sound, (b) 15 mm 30° inclined notch, (c) 75 mm 30° inclined notch, (d) 30 mm 90° vertical notch, (e) 150 mm 90° vertical notch, (f) 15 mm 150° inclined notch and (g) 75 mm 150° inclined notch. Excitations were done by 19 mm steel ball impact.

9 The estimation results (based on the correlations established earlier) from experiment
10 measurements were plotted against the actual notch depths and degree of inclinations for
11 comparison, as shown in Figure 15. The actual values are indicated as scatter lines without
12 marker, while the estimation values are represented by scatter lines with marker. The
13 maximum and minimum discrepancies between the actual and estimated values for WT and
14 phase velocity indices were given in Table 4. The notch depth estimation is found to be more
15 accurate than the degree of inclination estimation. Apart from that, the performance of WT
16 index is also more satisfactory than the phase velocity index with lower discrepancies. This
17 can be explained by their higher R^2 values in the correlations established between the indices
18 with the ratio of notch depth-to wavelength as well as with the degree of inclination. From
19 the numerical estimation results, fluctuations were noted especially for the cases of notch
20 depths of 120 mm and 150 mm and degree of inclinations of 120° and 150°.



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3 **Figure 15.** Surface notch depth and degree of inclination estimations based on (a) WT index
 4 (b) phase velocity index.

5

1 **Table 4.** Discrepancy between actual and estimation values for surface notch

Index	Discrepancy between actual and estimated values (%)			
	Depth		Angle	
	Max.	Min.	Max.	Min.
WT	17.8	2.1	21.4	-3.2
Average	8.8		11.7	
Phase velocity	19.8	-3.6	-19.9	-3.3
Average	9.8		12.8	

2 *a negative value indicates over-estimation and vice versa

3

4 **6. Conclusions**

5 In the present work, the behavior of R-waves propagating reinforced concrete with a
6 surface notch is investigated both numerically and experimentally in a more systematic
7 manner. The study is focused on the WT coefficient and phase velocity changes of the R-
8 waves and their dependence on depth and inclination. Multichannel acquisition procedure
9 was developed in the study to record the propagating elastic waves, extract and analyze for
10 the R-wave components. Correlations between the specific R-wave parameters with the ratios
11 of notch depth, degree of inclination and wavelength were established. The accuracy of the
12 correlations was verified through experimental measurements on concrete specimens induced
13 with surface notch. In general measurement results gave satisfactory agreement between the
14 proposed WT and phase velocity indices and notch depth as well as its degree of inclination,
15 making them reliable parameters for quantifying and characterizing concrete surface notch,
16 particularly when the wavelength is greater than the notch depth. The proposed R-wave
17 measurement and assessment methodology can possibly be refined for enhanced reliability
18 and practicality. Its feasibility for in-situ applications could be justified through methods such
19 as coring. Future work will be focused on confirming the addition effect by a real crack as
20 compared to a notch. Additional parameter or factor may be proposed to the correlations to
21 cater for this effect. In addition, a more steady study should also be conducted on developing

1 classification method to characterize surface notch depth and orientation simultaneously,
2 such as the artificial neural network.

3

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10

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Figure
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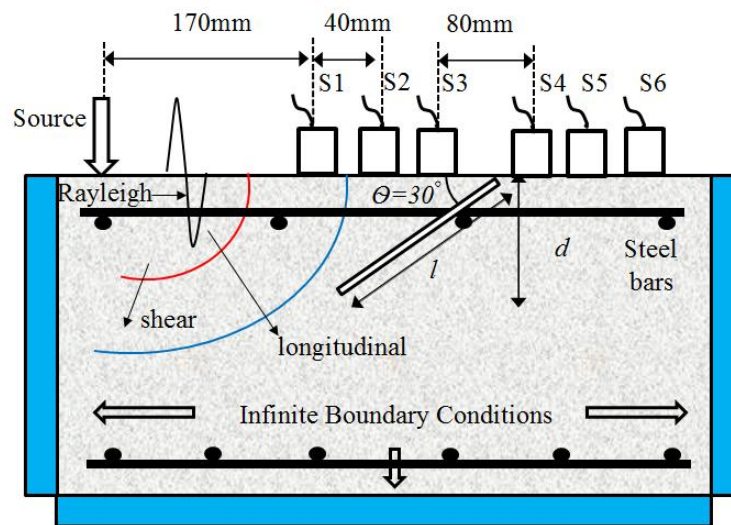


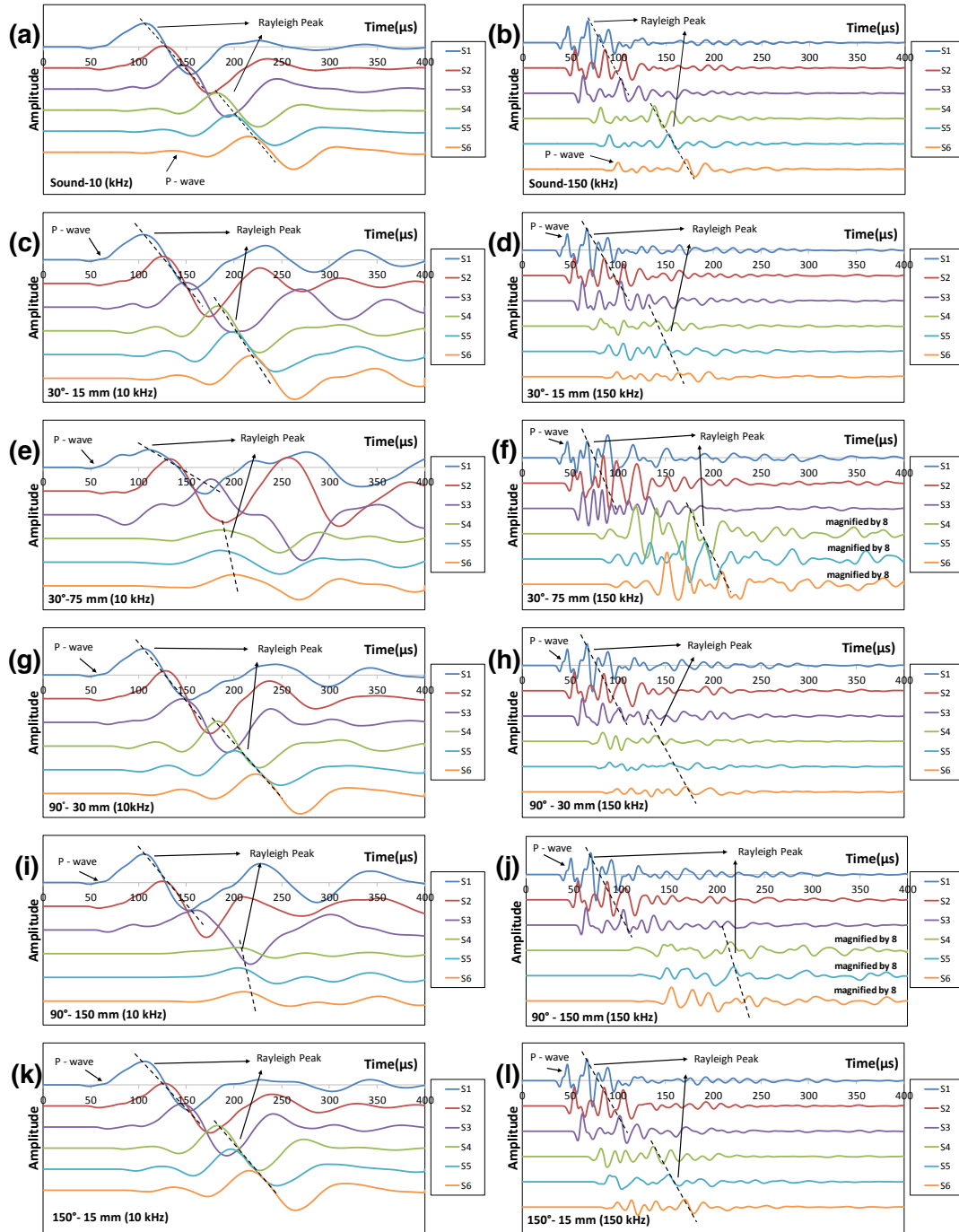
Figure 1. Wave motion simulation model.

Figure
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Figure 2. Photograph of accelerometer sensors arranged on the upper side of concrete specimen.

Figure
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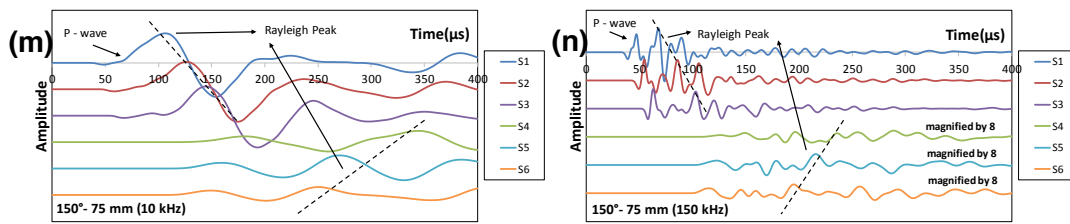


Figure 3. Simulated waveforms collected from steel reinforced concrete model for sound concrete mode using (a) 10 kHz and (b) 150 kHz excitations; 15 mm 30° inclined notch using (c) 10 kHz and (d) 150 kHz excitations; for 75 mm 30° inclined notch using (e) 10 kHz and (f) 150 kHz excitations; for 30 mm 90° vertical notch using (g) 10 kHz and (h) 150 kHz excitations; for 150 mm 90° vertical notch using (i) 10 kHz and (j) 150 kHz excitations; for 15 mm 150° inclined notch using (k) 10 kHz and (l) 150 kHz excitations; for 75 mm 150° inclined notch using (m) 10 kHz and (n) 150 kHz excitations

Figure
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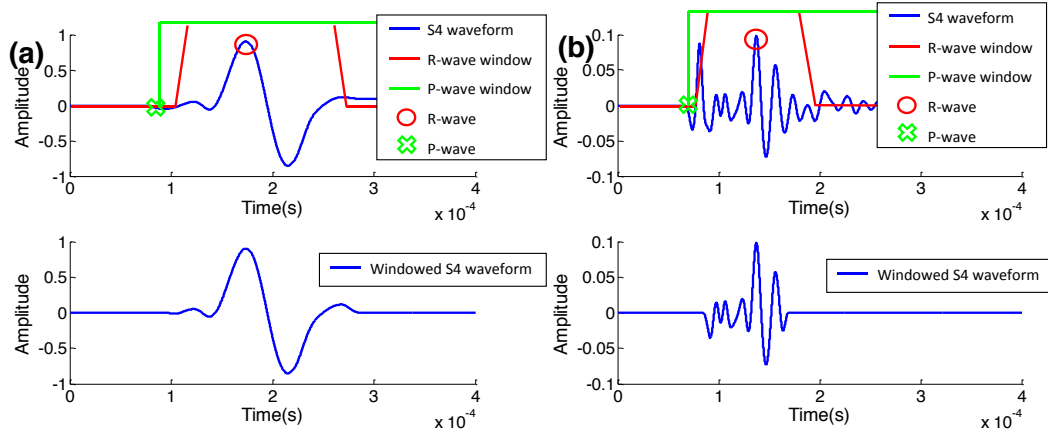
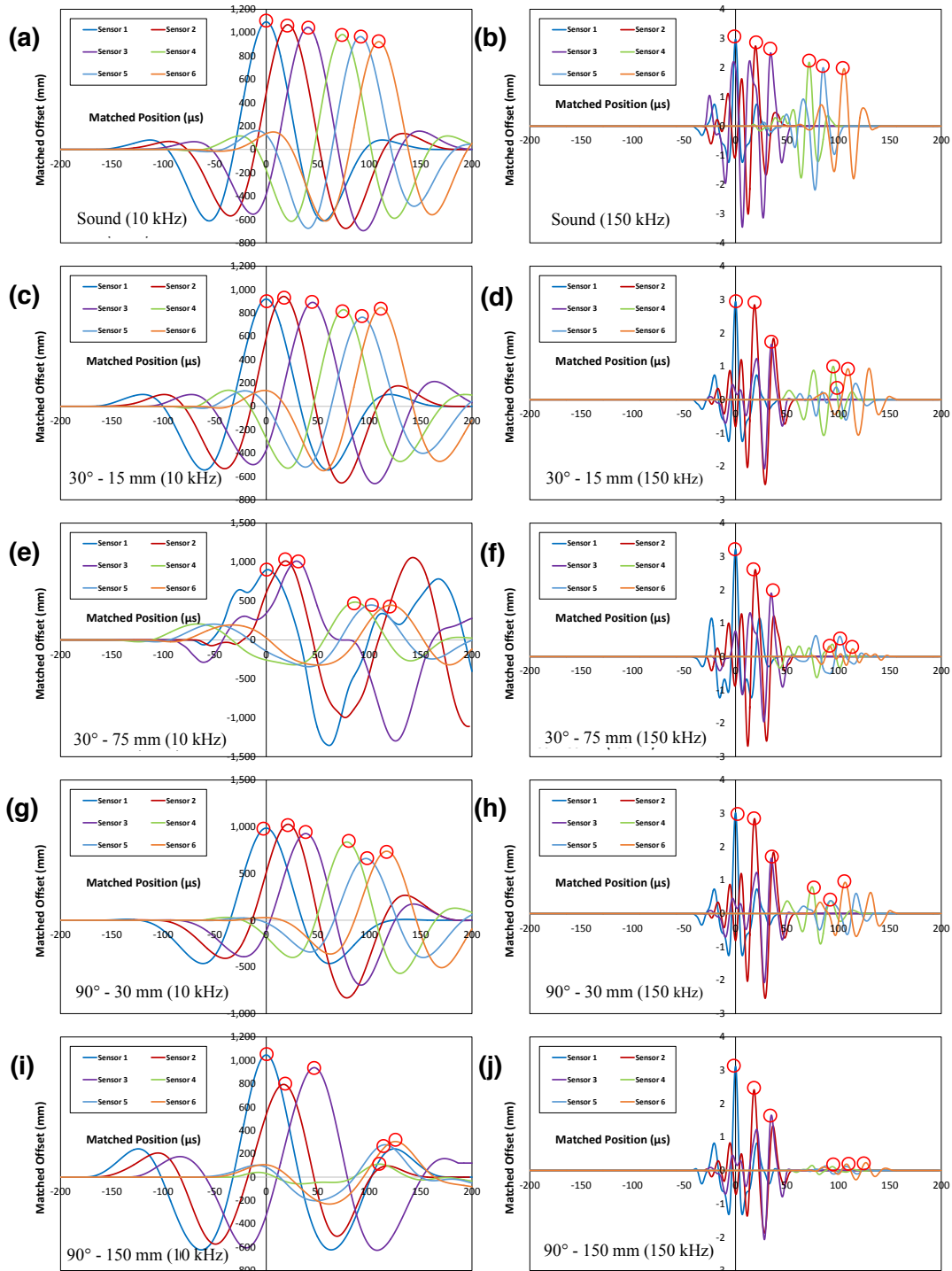


Figure 4. Processing of waveforms using proposed matched filtering algorithm from sensor S4 for sound steel reinforced concrete model using (a) 10 kHz and (b) 150 kHz excitations

Figure
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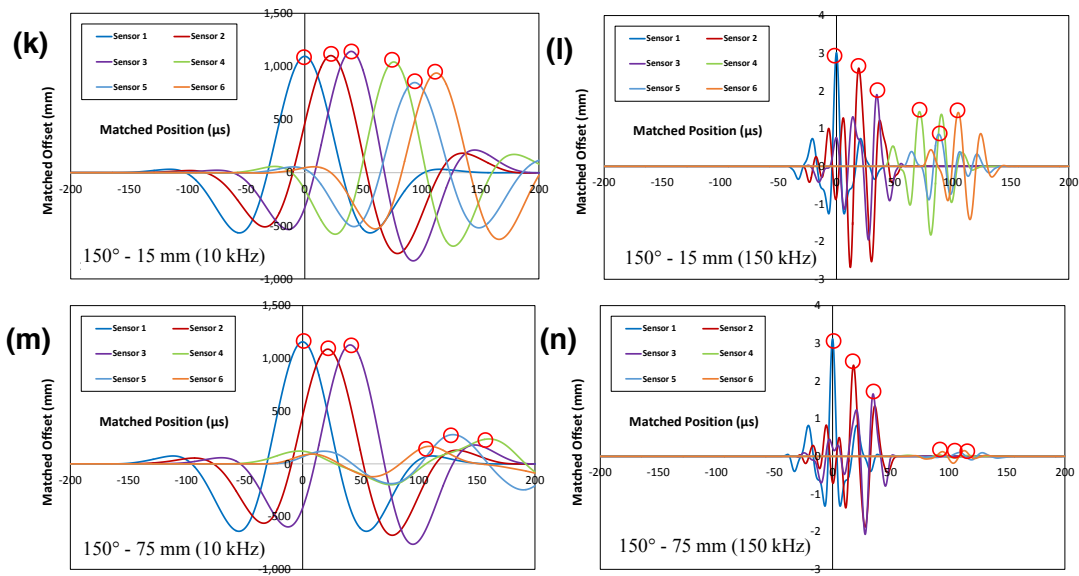


Figure 5. Processed waveforms and the respective final R-wave peak matched positions based on MFCE method for sound concrete model using (a) 10 kHz and (b) 150 kHz excitations; for 15 mm 30° inclined notch using (c) 10 kHz and (d) 150 kHz excitations; for 75 mm 30° inclined notch using (e) 10 kHz and (f) 150 kHz excitations; for 30 mm 90° vertical notch using (g) 10 kHz and (h) 150 kHz excitations; for 150 mm 90° vertical notch using (i) 10 kHz and (j) 150 kHz excitations; for 15 mm 150° inclined notch using (k) 10 kHz and (l) 150 kHz excitations; for 75 mm 150° inclined notch using (m) 10 kHz and (n) 150 kHz excitations

Figure
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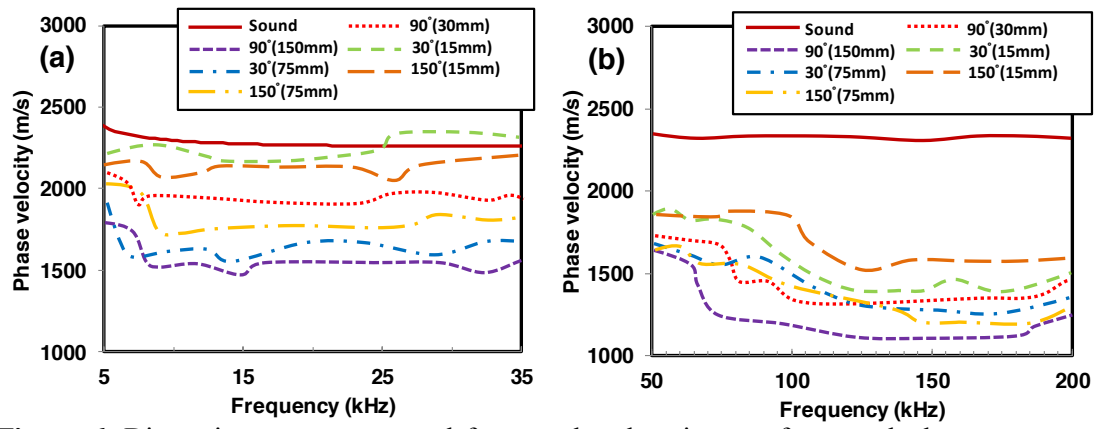
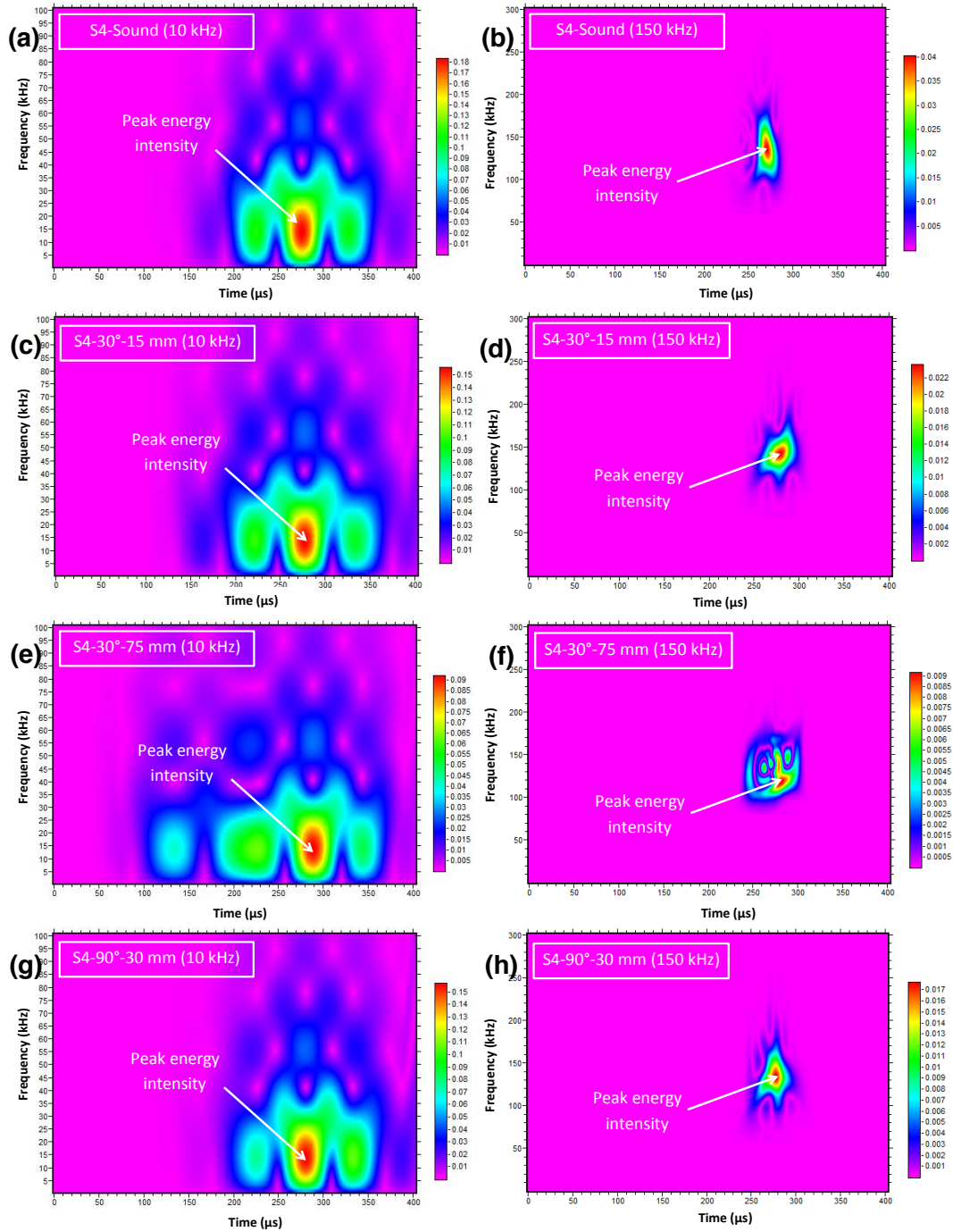


Figure 6. Dispersion curve computed for sound and various surface notched concrete models using (a) 10 kHz and (b) 150 kHz excitations

Figure
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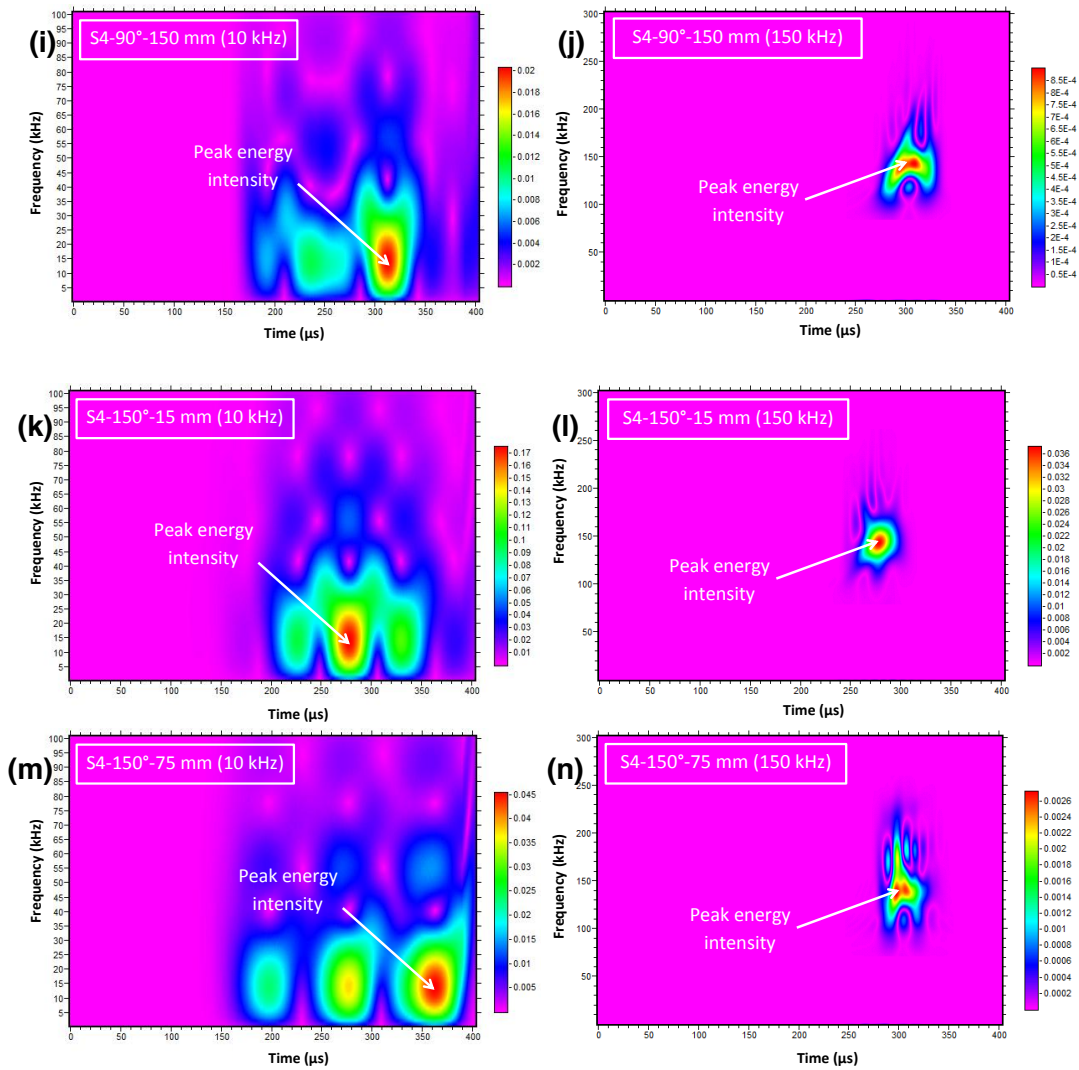


Figure 7. 2D wavelet transform contour diagram at the fourth sensors (S4) for steel reinforced concrete model using (a) 10 kHz and (b) 150 kHz; for 15 mm 30° inclined notch model using (c) 10 kHz and (d) 150 kHz excitations; for 75 mm 30° inclined notch model using (e) 10 kHz and (f) 150 kHz excitations; or 30 mm 90° vertical notch model using (g) 10 kHz and (h) 150 kHz excitations; for 150 mm 90° vertical notch model using (i) 10 kHz and (j) 150 kHz excitations; or 15 mm 150° inclined notch model using (k) 10 kHz and (l) 150 kHz excitations; or 75 mm inclined 150° inclined notch model using (m) 10 kHz and (n) 150 kHz excitations

Figure
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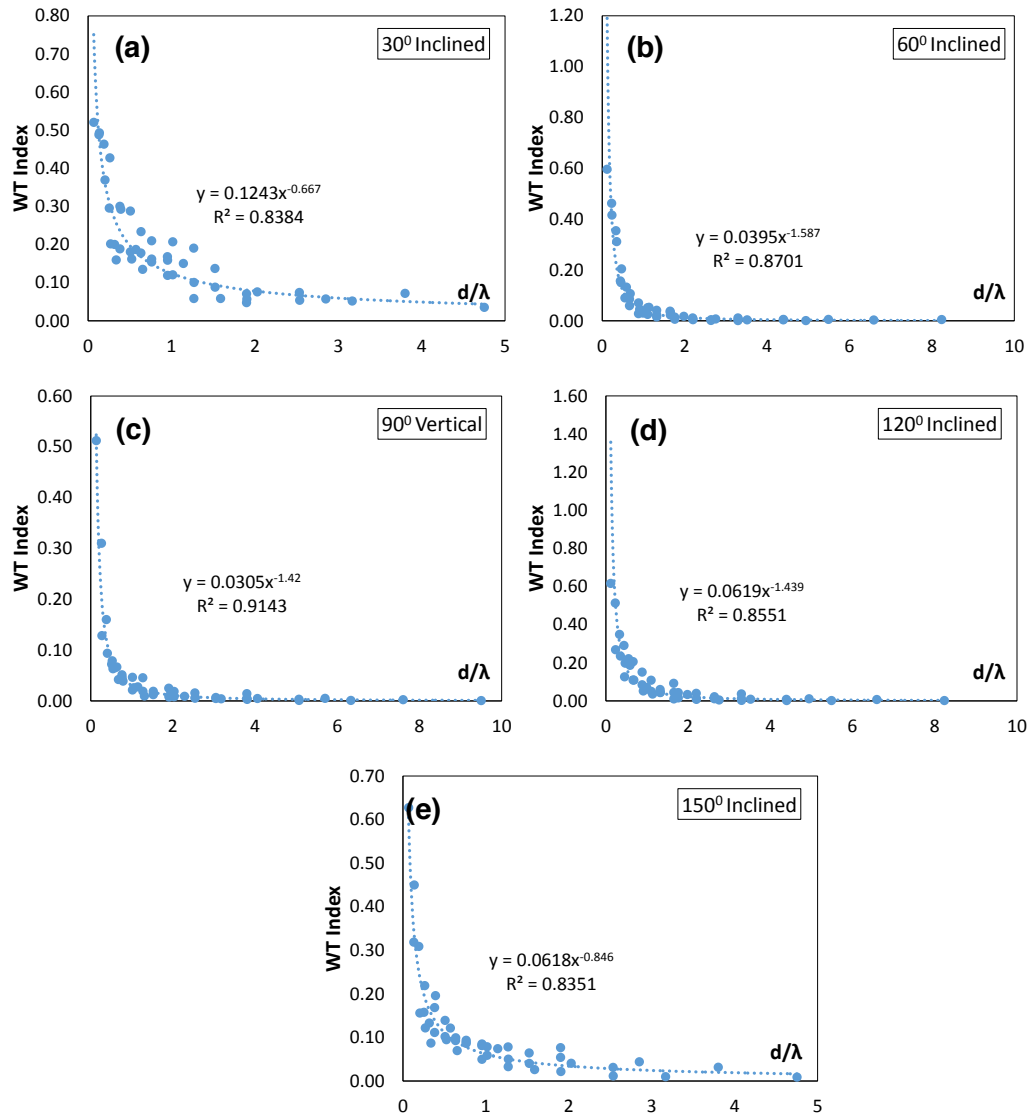


Figure 8. WT index versus d/λ for steel reinforced concrete model with (a) 30° inclined notch cases, (b) 60° inclined notch cases, (c) vertical notch (90°) cases, (d) 120° inclined notch cases and (e) 150° inclined notch cases

Figure
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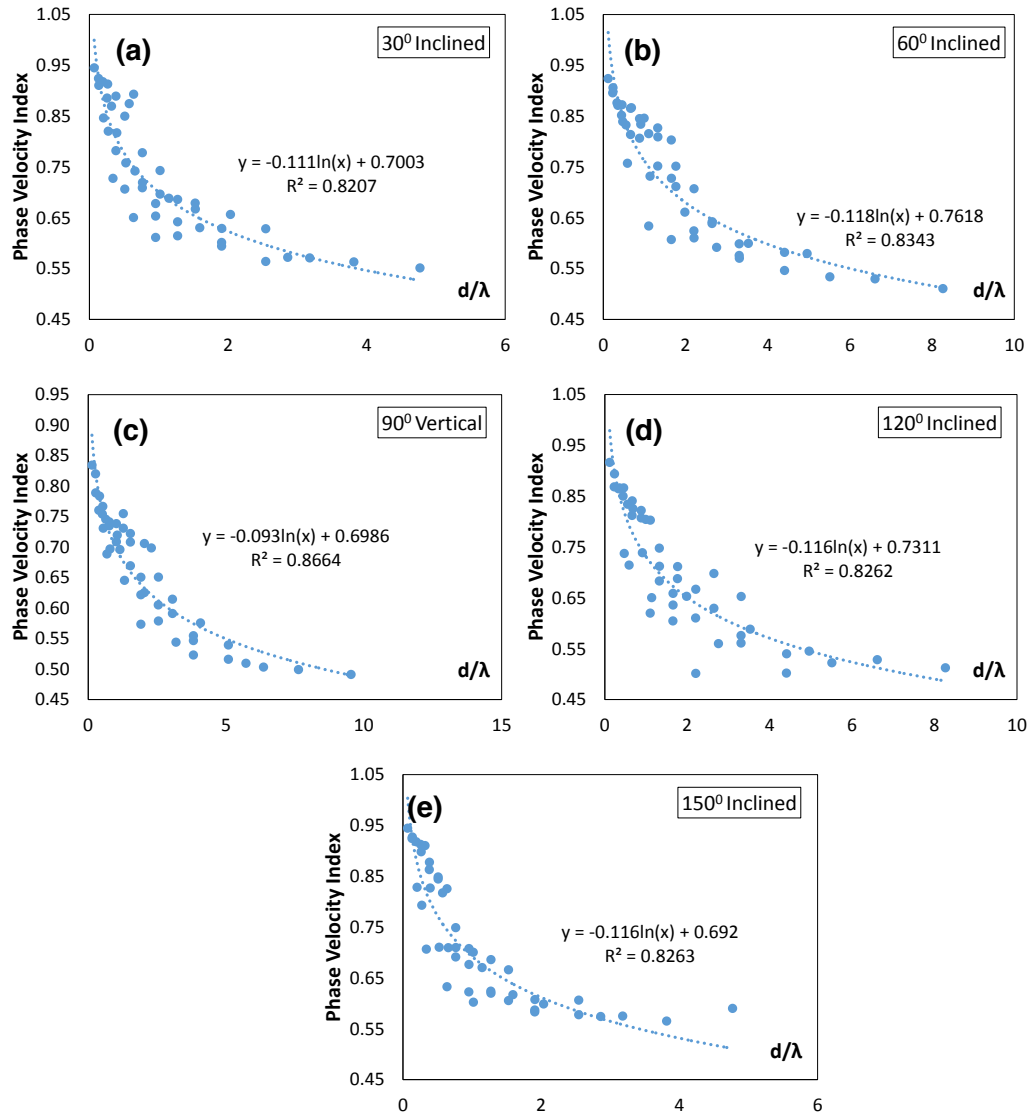


Figure 9. Phase velocity index versus d/λ for steel reinforced concrete model with (a) 30° inclined notch cases, (b) 60° inclined notch cases, (c) vertical (90°) cases, (d) 120° inclined notch cases and (e) 150° inclined notch cases

Figure
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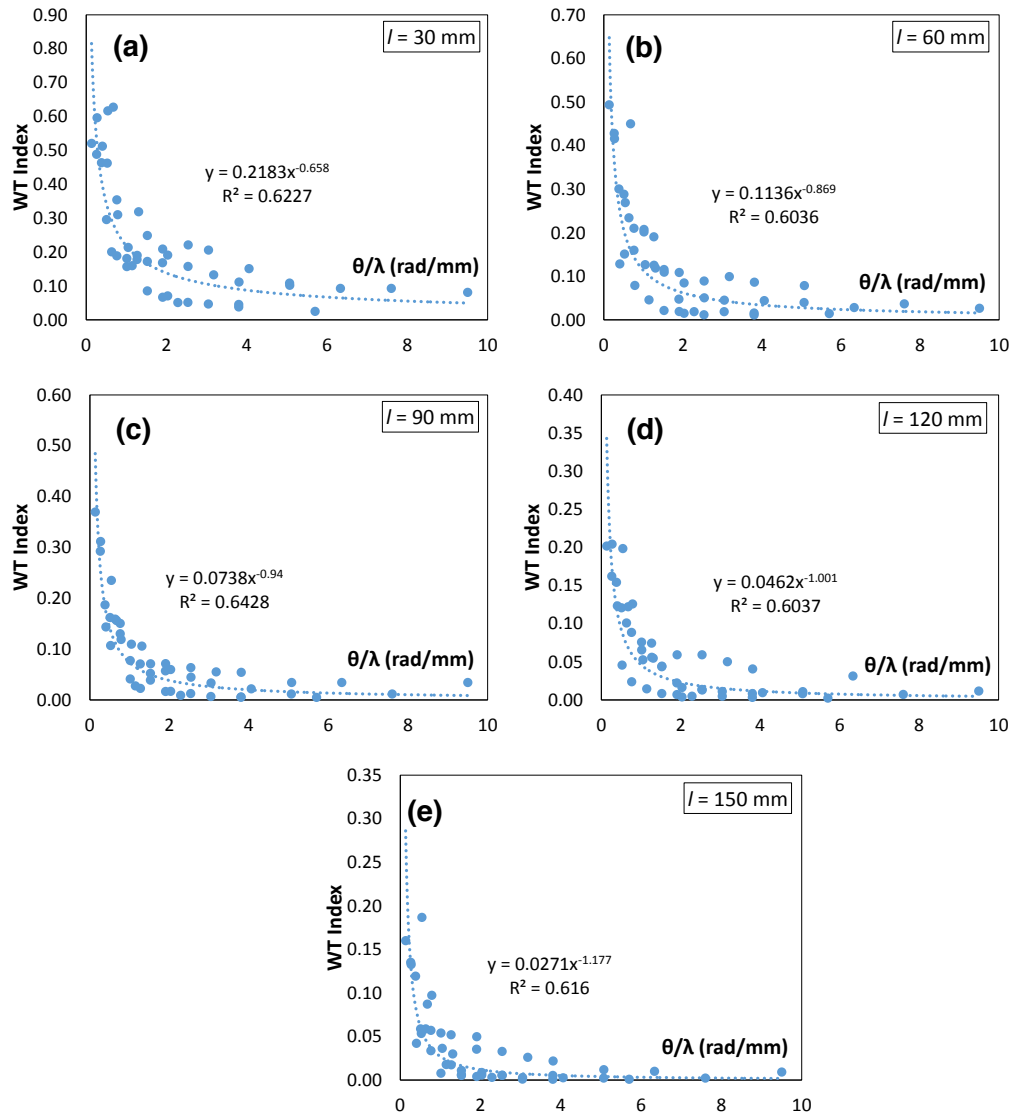


Figure 10. WT index versus θ/λ for steel reinforced concrete model with (a) 30 mm notch length cases, (b) 60 mm notch length cases, (c) 90 mm notch length cases, (d) 120 mm notch length cases and (e) 150 mm notch length cases

Figure
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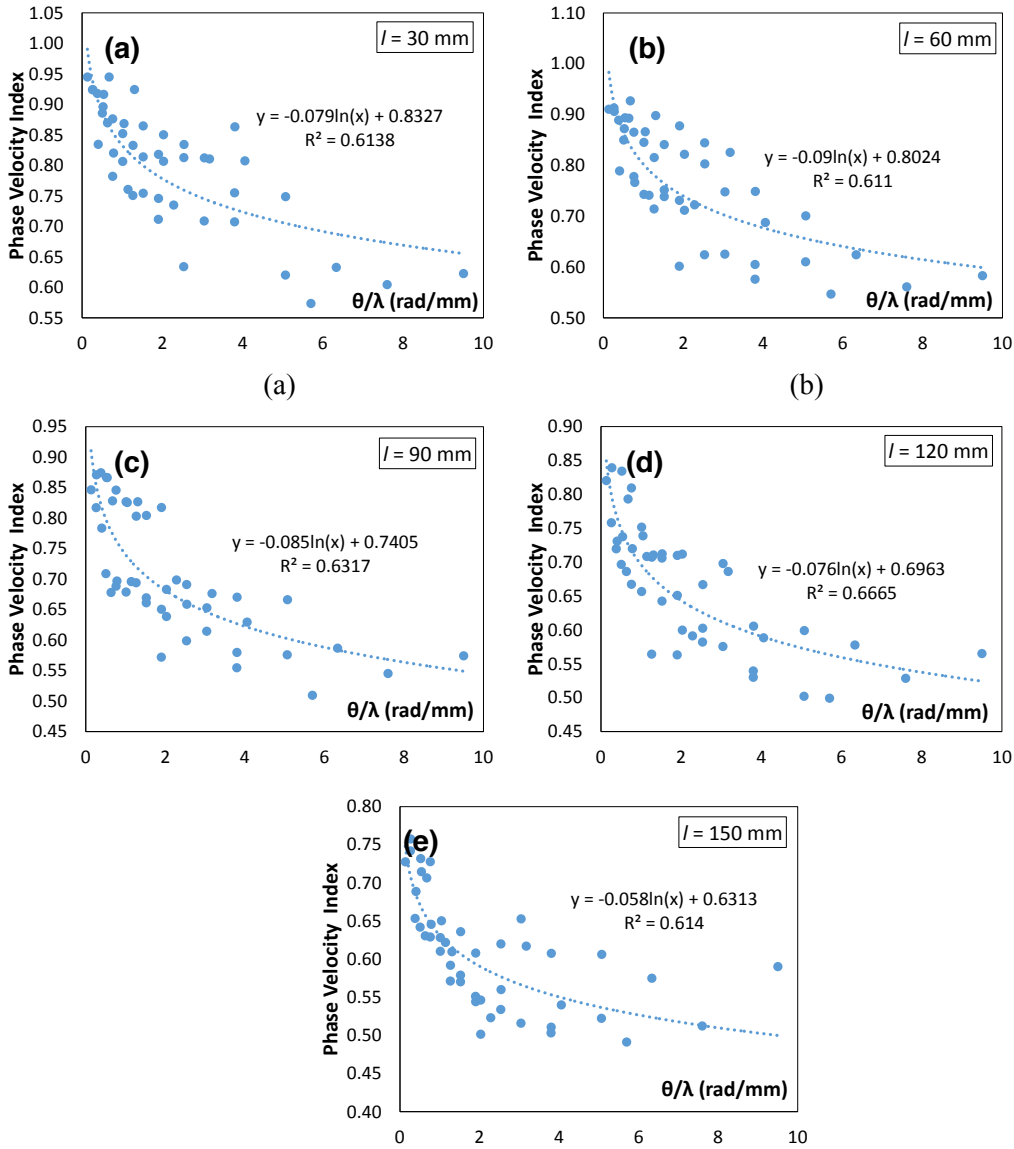


Figure 11. Phase velocity index versus θ/λ for steel reinforced concrete model with (a) 30 mm notch length cases, (b) 60 mm notch length cases, (c) 90 mm notch length cases, (d) 120 mm notch length cases and (e) 150 mm notch length cases

Figure
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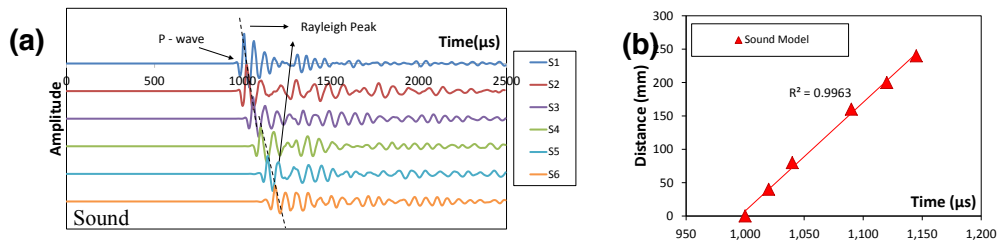


Figure 12. Experimental waveforms collected for (a) sound concrete specimen and (b) their corresponding R-waves propagation distance against arrival time. Excitations were done by 19 mm steel ball impact.

Figure
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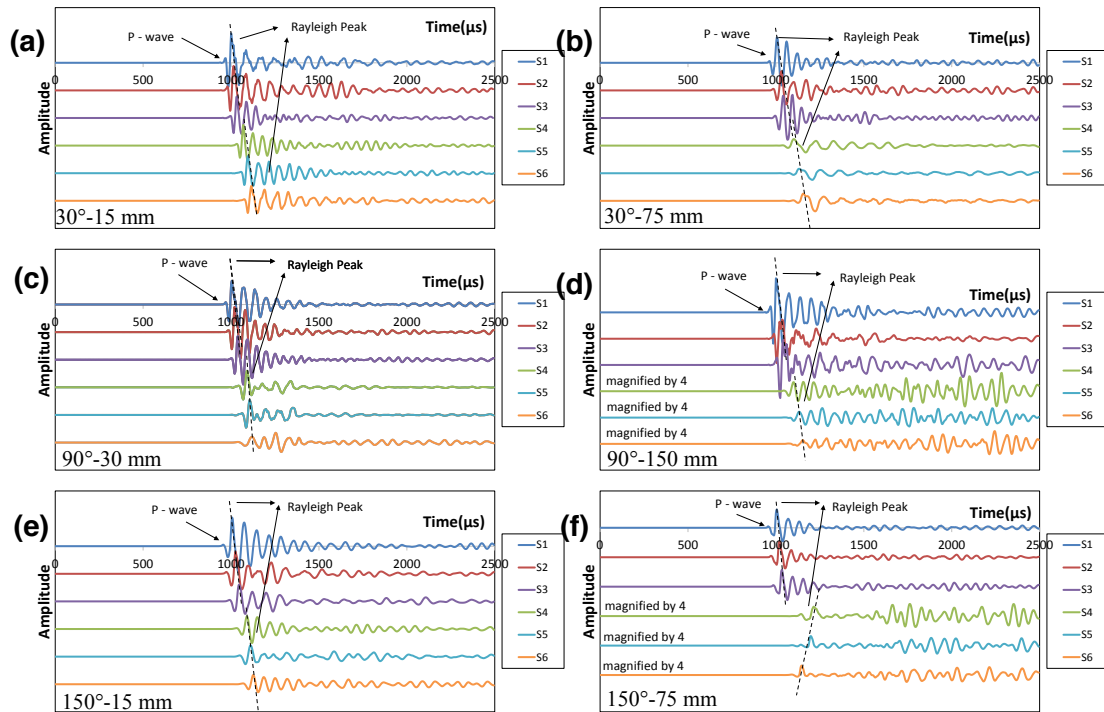


Figure 13. Experimental waveforms collected for (a) 15 mm 30° inclined notch, (b) 75 mm 30° inclined notch, (c) 30 mm 90° vertical notch, (d) 150 mm 90° vertical notch, (e) 15 mm 150° inclined notch and (f) 75 mm 150° inclined notch. Excitations were done by 19 mm steel ball impact.

Figure
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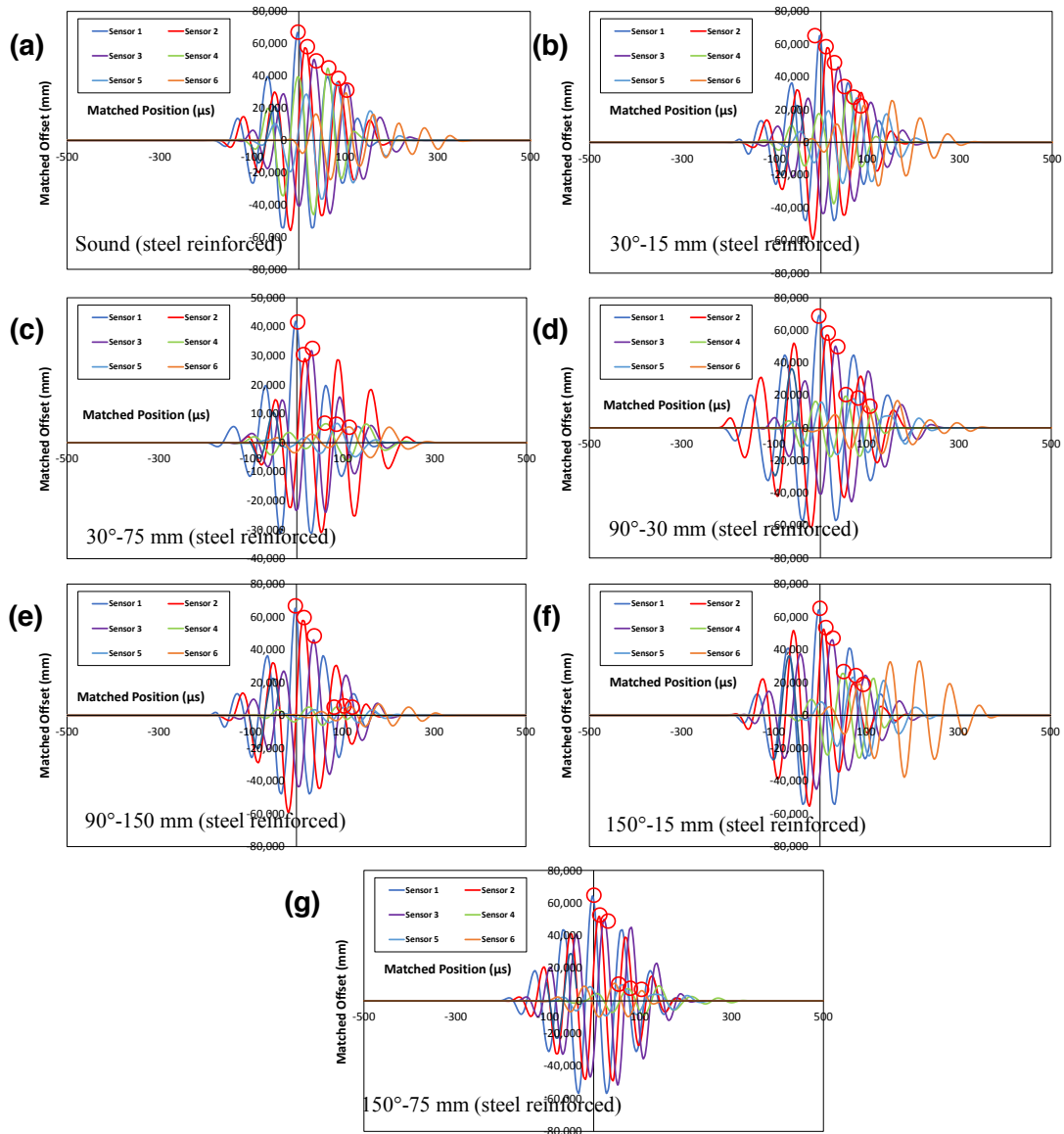


Figure 14. Processed experimental waveforms and the respective final R-wave peak matched positions based on MFCE method for (a) sound, (b) 15 mm 30° inclined notch, (c) 75 mm 30° inclined notch, (d) 30 mm 90° vertical notch, (e) 150 mm 90° vertical notch, (f) 15 mm 150° inclined notch and (g) 75 mm 150° inclined notch. Excitations were done by 19 mm steel ball impact.

Figure
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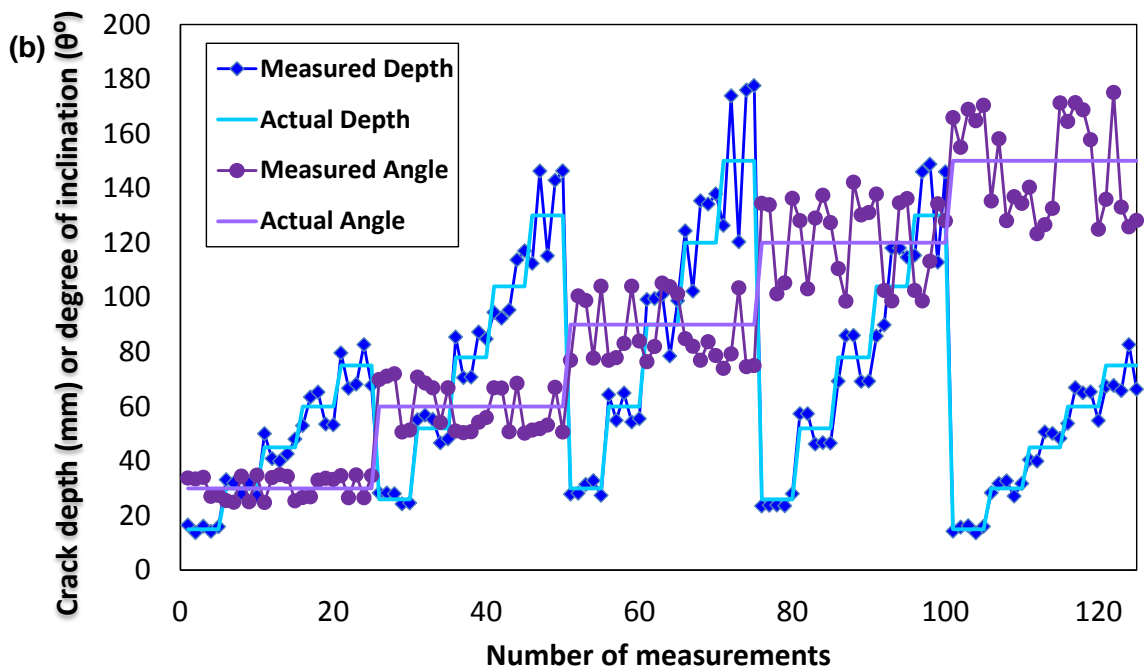
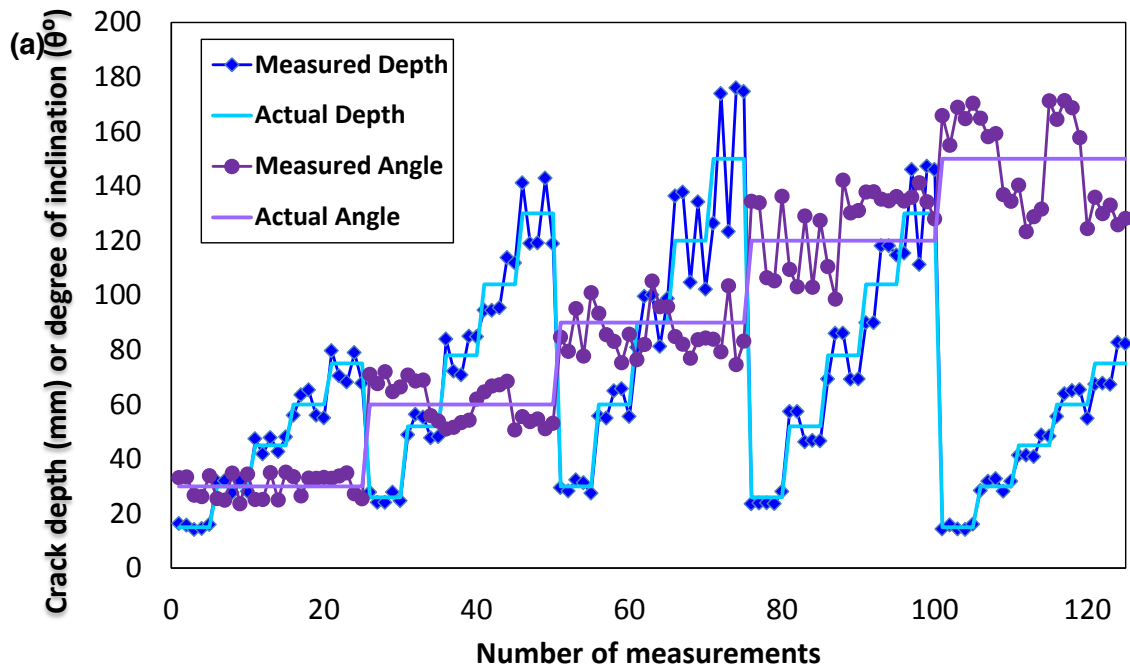


Figure 15. Surface notch depth and degree of inclination estimations based on (a) WT index (b) phase velocity index.