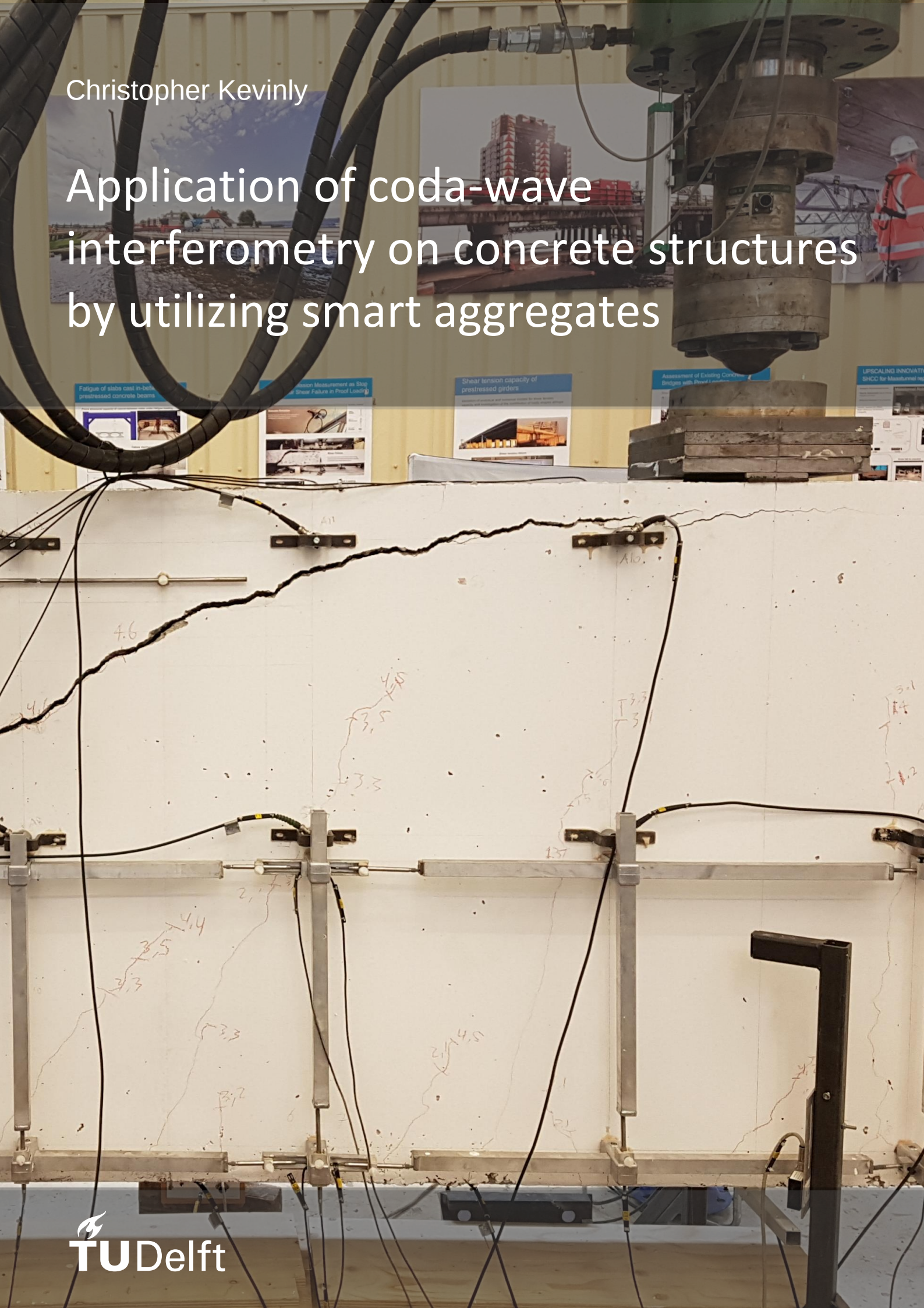


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Application of coda-wave interferometry on concrete structures by utilizing smart aggregates



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By

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“You will seek Me and find Me when you search for Me with all your heart.”

Jeremiah 29:13

Foreword

This thesis is the fruit of my work for the last 12 months of my study in TU Delft. I wish this piece of work will be useful for those interested in structural health monitoring subjects and may one day be used for the greater good of humanities.

First of all, I would like to express my gratitude to Dr. Yang Yuguang, Dr. Deyan Draganov, and Dr. Kees Weemstra, who have guided me throughout the working of this thesis. When I started, I know very little regarding the subject, yet my supervisors constantly encouraged and guided me throughout the process. I am grateful to be guided by such amazing supervisors.

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Ad Miores Dei Gloriam

Christopher Kevinly
Delft, December 2018

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Abstract

Coda wave interferometry is a technique used in the field of seismology, which utilizes the later part of the signal (coda) to detect subtle changes in a medium. In recent years, the application of coda wave interferometry to concrete structure has been assessed for structural health monitoring purposes. Smart aggregate is a sensor which consists of a piezoelectric sheet which is sandwiched between two marble layers which are meant to be used for structural health monitoring purposes by embedding it into concrete. However, its implementation for coda wave interferometry applications had not been attempted previously.

In this research, the application of coda wave interferometry in concrete structures is explored further. The aim of this research is to assess the possibility of implementing coda wave interferometry to monitor the hydration process and the evolution of elasticity-modulus of concrete, as well as to learn how the wavespeed changes in concrete specimens subjected to cyclic loading in compression and bending. Additionally, seismic interferometry is also attempted to retrieve virtual impulse response to be used for coda wave interferometry. All experiments in this research utilize smart aggregates as transducers.

By implementing coda wave interferometry, it is found that wavespeed does increase as concrete ages. This wavespeed increase can be linked to the evolution of elasticity-modulus of concrete, which enables its value to be monitored through the utilization of coda wave interferometry. It is also found that the use of embedded smart aggregate yields excellent reciprocity and stable correlation coefficient throughout the recording, while attached smart aggregates do not perform as well as the embedded ones in terms of reciprocity and correlation coefficient.

Positive linear wavespeed change vs. stress and strain relationships in compressive samples are observed in lower stresses. In higher stresses, both wavespeed change vs. stress and strain display gradient reductions. Under repeated cyclic loadings, the loading phase of the first load cycle tend to have lower initial wavespeed change vs. stress and strain gradients compared to the following load steps, and the wavespeed change vs. stress and strain paths of reloading phases tend to follow the paths of their previous unloading phases. Wavespeed change vs. strain is more representative compared to wavespeed change vs. stress in depicting the compressive specimens' condition due to the occurrence of permanent deformation during loadings.

In a 10m-long beam specimen subjected to bending and shear, coda wave interferometry of later arrivals reveal decrease in wavespeed in the first loading phase of the test, while earlier arrivals show increase in wavespeed in the same phase. Moreover, it is possible to detect major crack formations by utilizing coda wave interferometry, which sensitivity is determined by the location of the cracks relative to the source-receiver sensors' proximity. By assessing earlier arrivals of the signals recorded by smart aggregate implanted in the compression zone, the shift from uncracked to cracked section is observed through changes in wavespeed change vs load gradients.

Seismic interferometry attempt was unsuccessful due to poor repeatability of the hammer hits and insufficient illumination to create diffuse wavefield.

Notations

Mathematical operator

$\times$	Multiplication
$\int$	Integral
$\otimes$	Cross-Correlation
$*$	Convolution

Abbreviations

ASR	Alkali-silica reaction
CC	CC
CSH	Calcium silica hydrate
CH	Calcium hydroxide
CrosCor	Unbiased cross-correlation
CWI	Coda wave interferometry
DIC	Digital image correlation
Disp.	Vertical displacement at loading location
LVDT	Linear variable differential transformer
P-Waves	Pressure wave
SI	Seismic interferometry
S-Waves	Shear wave
dv/v	Relative wavespeed change

Latin upper case

A_{ij}	Acoustoelastic constants of wave propagates in i and polarizes in j . Depends on Lamé's and Murnaghan's constants
----------	---

E_c	Static modulus of elasticity
E_{ci}	Projected static modulus of elasticity
E_d	Dynamic modulus of elasticity
G	Impulse response (Green's function)
T	Cross-correlation length
X	Concrete compression zone height
V_P	Pressure wave velocity
V_S	Shear wave velocity
V_{ij}	Wave velocity propagating in i direction and polarized in j direction
V_{ij}^0	Unloaded wave velocity propagating in i direction and polarized in j direction
V_{ij}^σ	Loaded wave velocity propagating in i direction and polarized in j direction

Latin lower case

f_{ctm}	Concrete mean compressive strength
h	Reference signal
h'	Stretched signal
l, m, n	Second order Murnaghan's coefficients
s	Cement strength coefficient
t	Time, time axis
t'	Stretched time axis

Greek lower case

α	Ratio of steel's elasticity modulus and concrete's elasticity modulus
β_{cc}	Concrete strength projection factor by time
β_E	Concrete modulus of elasticity projection factor by time
ν	Poisson's ratio

σ_{ii}	Axial stress in i direction
P	Reinforcement ratio
ρ	Mass density
λ, μ	Lame's coefficients
τ	Time axis stretching factor to time, $\frac{dt}{t}$
ϵ	Time axis stretching factor to velocity, relative change of wave velocity, $\frac{dV}{V}$

1. Introduction

1.1. Background

As the infrastructures built during the post-world war 2 construction-boom period is reaching their end-of-life phase, there is a growing need to assess and extend the service period of the structures [1]. Therefore, the need for improved structural-assessment methods in existing structures is imminent. Structural-health monitoring (SHM) is a process to identify damage in structures [2], which is essential in assessing the structural capability and its performance state.

Coda-wave interferometry (CWI) is a method developed for geoscience assessments, and in the last several years has been implemented to assess concrete structures [3]–[5]. CWI utilizes the multiple wave scattering through a medium to assess subtle changes of the medium through the alteration of the wave velocity [6], which is possible due to relatively stable scattering property of waves compared to loose atom particle [7].

While it has not been commercially used, CWI implementation in concrete has been successfully demonstrated in detecting temperature change [5], stress change [4], and temperature, mechanical, and alkali-silica reaction (ASR) damages [3]. Despite the possibility, several topics such as CWI implementation in monitoring hydration process and concrete elasticity-modulus' evolution, cyclic compressive loading on concrete, as well as damage assessment of concrete specimen in bending and shear had not been assessed in detail. The use of embedded measurement sensors for CWI applications also had not been attempted before, which will be attempted in this thesis.

This thesis is aimed at conducting CWI to assess the elasticity-modulus evolution of concrete over time, to assess the repeatability of CWI done at different time and specimen shape, and finally to try if the coda wave extracted from seismic interferometry, which is a method to generate virtual impulse responses from a diffuse wavefield, is able to be used for CWI. The possibility of embedded sensors in form of smart aggregate (SA) is also assessed.

1.2. Research objective and questions

The research presented in this thesis investigates the use of CWI to monitor concrete properties change and to detect compressive, bending and shear damage of concrete. In addition, the impulse response is also attempted to be extracted through seismic interferometry to see if it is possible to use the generated impulse response for CWI.

These objectives are fulfilled by finding answers to the following research questions:

- a. Is CWI able to be used for monitoring the hydration process and modulus of elasticity evolution in concrete?
- b. How does the wavespeed changes in concrete specimens subjected to cyclic loading in compression and bending?

While the secondary objective will be assessed by trying to answer the following;

- c. Can we retrieve repeatable coda using seismic interferometry?

1.3. Research methodology

To answer the research questions presented, the research is carried out in several parts. Literature study is done to lay solid foundation of this research, which is done before trying to answer the research question.

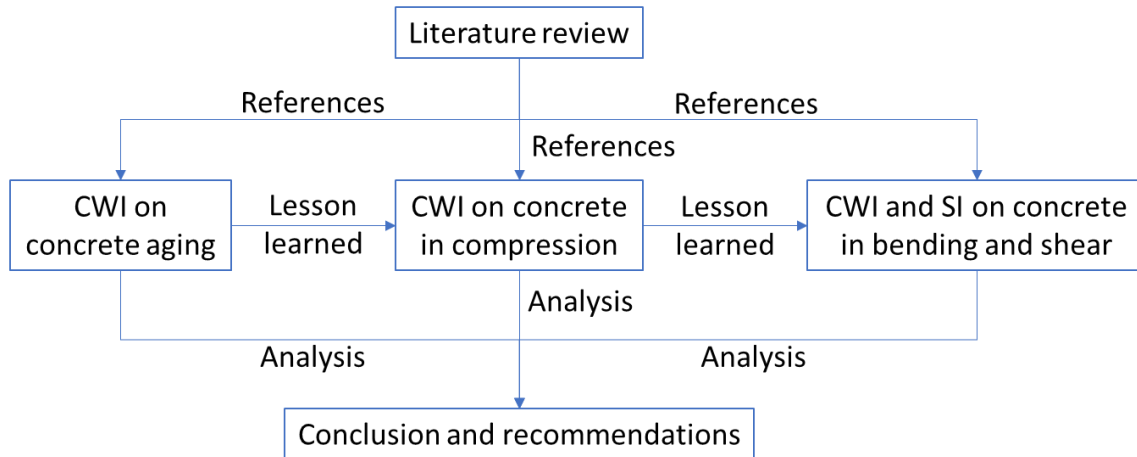


Figure 1.1. Research Workflow.

All parts of this research include experimental testing of concrete samples. The testing consists of signal generation and acquisition throughout sample treatment. The samples are treated based on the aim of a particular test: it could be age, where signal generation and acquisition is done throughout several days as the concrete ages, or load, where signal generation and acquisition is done as the sample is loaded.

1.4. Scope of research

This thesis will be divided into 7 parts.

Chapter 1 provides the general idea, as well as the objective and general methodology of this research. The outline of this thesis is also available in this chapter.

Chapter 2 contains literature assessment of relevant concrete properties, especially regarding wave propagation, scattering, microcracking, and acoustoelastic effect, as well as basic theory regarding CWI and seismic interferometry, and state-of-the-art implementations of CWI in concrete.

Chapter 3 explains the methodology which is used in the research, as well as the equipment which is used and the implementation strategy of both CWI and seismic interferometry when applicable, both in terms of application and processing.

Chapter 4 assesses the change in wavespeed as concrete ages and links it to the elasticity-modulus evolution of concrete. Additionally, the effect of coupling of the sensors is also analysed in the result.

Chapter 5 assesses the effect of cyclic compressive load on the wavespeed in concrete through CWI. Two kinds of samples are tested; cubical specimens and cylindrical specimens. The trend of wavespeed change to stress-induced is assessed.

Chapter 6 explores the usage of CWI in a concrete beam in bending and shear. Structural damage and cracks are attempted to be linked with the CWI result. Additionally, seismic interferometry is also applied to find out if it is possible to retrieve the impulse response between two sensors embedded in the beam specimen and use the retrieved response for CWI.

Chapter 7 concludes the research and summarize the answers of the research questions and provides outlooks for future research and application.

2. Theory

To assess the utilization potential of CWI, it is important to assess how ultrasonic waves propagate and scatter in concrete, as well as their relationship with the physical parameters of concrete such as stress and elasticity-modulus. Moreover, the theory of CWI and its state-of-the-art utilization in concrete structures are also reviewed.

2.1. Body-wave propagation in concrete

The elastic waves travel through concrete in the same way as they propagate through the Earth in Seismology, which means they are partly reflected and partly transmitted at interfaces where mass density and/or stiffness changes [8]. There are two types of body waves; P-waves (longitudinal or compressional wave), which are polarized in the direction of propagation, and S-waves (transverse or shear wave), which are polarized perpendicular to the direction of propagation.

As derived by Bedford [9], the speed of both P and S-waves can be expressed, for uniform and isotropic media, as a function of the elastic modulus, Poisson's ratio and density of the material.

$$V_P = \sqrt{\frac{E_d(1-\nu)}{(1-2\nu)(1+\nu)\rho}} \quad (1)$$

$$V_S = \sqrt{\frac{E_d}{2\rho(1+\nu)}} \quad (2)$$

where V_P and V_S are the P-wave propagation speed and S-wave propagation speed, respectively, E_d is the dynamic modulus of elasticity of the material, ρ is the density of the material, and ν is the Poisson's ratio of the material.

When the waves pass through an interface at which a change of media properties, such as mass density, elasticity-modulus, and/or Poisson's ratio, occurs, reflection and transmission (refraction) will take place. Moreover, mode conversion between P-wave and S-wave may also happen. For simple geometries, the angles of incidence and reflection can be described by Snell's law [10] as shown in Figure 2.1.

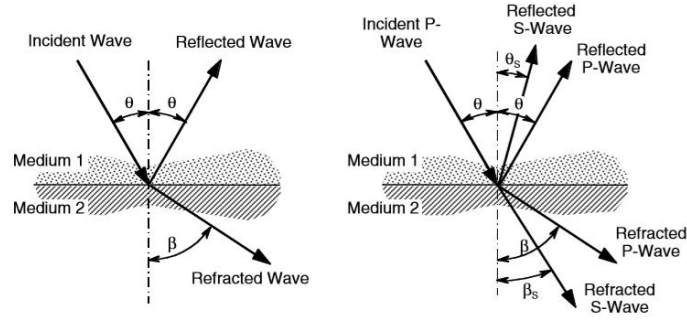


Figure 2.1. Behavior of a P-wave incident on an interface between two different media: reflection and refraction (transmission) (Left) and mode conversion (Right). Adopted from [10].

$$\frac{\sin \theta}{V_1} = \frac{\sin \beta}{V_2} \quad (3)$$

$$\frac{\sin \theta}{V_{P1}} = \frac{\sin \beta}{V_{P2}} = \frac{\sin \theta_s}{V_{S1}} = \frac{\sin \beta_s}{V_{S2}}, \quad (4)$$

where θ is the angle of incidence, β is the angle of refraction, V is the wave velocity, subscript 1 and 2 indicate medium 1 and 2 in Figure 2.1., respectively and subscript P and S correlate to P and S-waves, respectively.

At larger scale, due to the heterogeneous property of concrete, these repeated reflection, transmission, and mode conversion at heterogeneities will result in scattering and attenuation [11]. These heterogeneities include, but are not limited to, aggregates, pores, and cracks.

2.1.1. Ultrasonic wave scattering in concrete

The different sizes of heterogeneities contained in concrete lead to different levels of scattering and attenuation with varying frequency [12]. Therefore, four regimes of scattering in concrete are proposed; modal-analysis regime, simple-scattering regime, multiple-scattering regime, and attenuation regime. The regimes are governed by the wavelength of the signal with respect to the dimension of the heterogeneities, as well as the size of the overall structure.

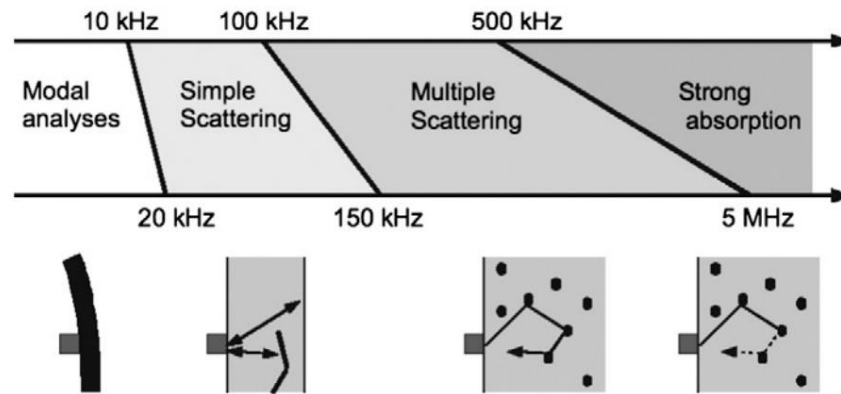


Figure 2.2. Different regimes of signal scattering in concrete. Adopted from [12].

At low frequencies, typically below 20 kHz, with a typical P-wavespeed in concrete of around 4000 m/s, the wavelength of the signal is around 20 cm, which is roughly comparable with the macroscopic dimension of the structure. at such frequencies, the vibrational eigenmode of the structure is excited.

At higher frequencies, where the wavelength is smaller than the structure size, yet still relatively larger than the heterogeneities of the concrete, scattering is expected. The signals are more sensitive to subtle changes of medium as their frequency increases. However, energy absorption will also increase at higher frequencies. Therefore, it is important to choose a signal frequency such that a usable signal-to-noise ratio in the coda can be obtained, while retaining sensitivity to subtle changes in medium.

2.2. Mechanical properties evolution

As cement powders make contact with water, a chain of reaction called the hydration process starts. Such reaction will convert clinkers contained in the cement powder into cement matrix, which consists of calcium silica hydrate (CSH), calcium hydroxide (CH), and gypsum. CSH is the main contributor to cement matrix's strength, while CH mainly contributes to the basic PH of concrete [13]. Immediately after mixing, the concrete will be flowable which will allow it to be cast into forms. Such flowability is maintained before the initial setting of the cement paste, which indicates the start of CSH formation. From this point on, the structural properties of the concrete such as strength and stiffness will start to develop as shown in Figure 2.3.

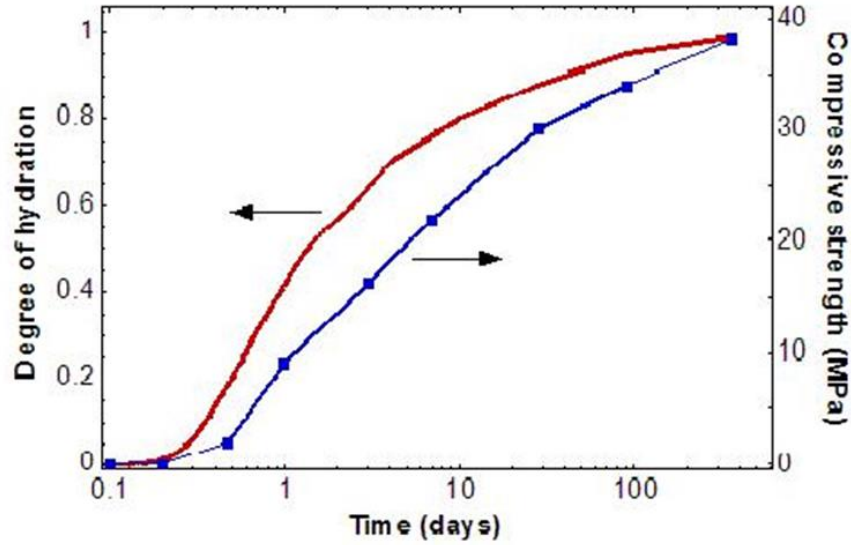


Figure 2.3. Typical development of degree of hydration and compressive strength of a Type I Portland Cement. Adapted from [14].

A way to predict how the strength and stiffness of concrete evolve with time is by referring to the CEB-*fib* Model Code 2010 [15]. This model correlates the compressive strength of concrete at various age to its mean compressive strength at the 28th day and the cement strength class used:

$$f_{ctm}(t) = \beta_{cc}(t) \cdot f_{cm} \quad (5)$$

$$\beta_{cc}(t) = \exp \left\{ s \cdot \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\}, \quad (6)$$

where $\beta_{cc}(t)$ is the concrete strength projection factor, $f_{ctm}(t)$ is the mean compressive strength at age t days, f_{cm} is the mean compressive strength at 28 days, and s is the coefficient which depends on the cement strength class listed in Table 2.1.

Table 2.1. Coefficients to be used for different strength class of cement. Adapted from [15].

Strength class of cement	32.5	32.5R 42.5	42.5R 52.5
s	0.38	0.25	0.2

Similar projection is also utilized to predict the elasticity-modulus at a given time. The projection function to predict the modulus of elasticity (E_c) is related with the one used to predict compressive strength, since the concrete strength is related to the modulus of elasticity. $\beta_E(t)$ in Equation 8 is the projection factor of modulus of elasticity of concrete. The projected modulus of elasticity development is shown in Figure 2.4.

$$E_{ci}(t) = \beta_E(t) \cdot E_{ci} \quad (7)$$

$$\beta_E(t) = [\beta_{cc}(t)]^{0.5}. \quad (8)$$

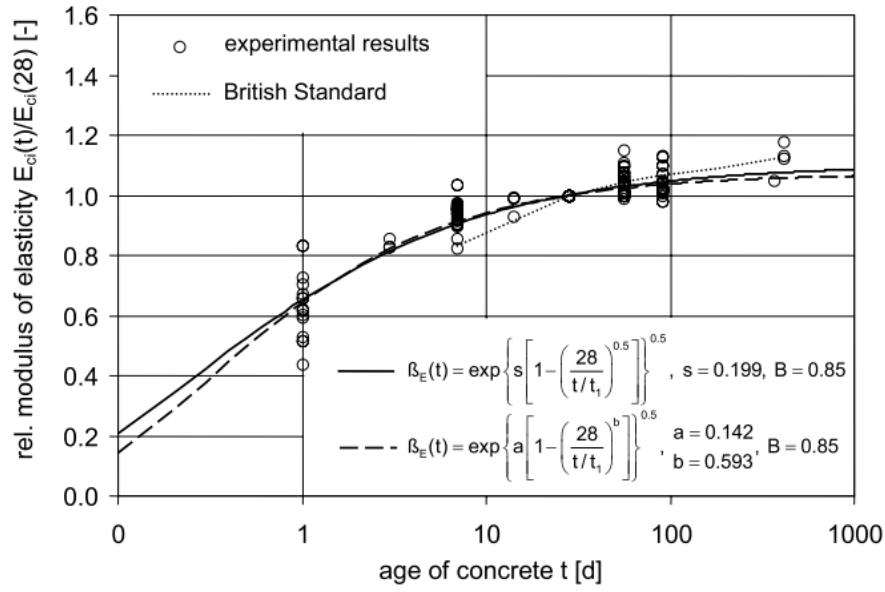


Figure 2.4. Development of the modulus of elasticity with time. Adopted from [15].

As shown previously in Equation 1, the P-wavespeed can be estimated as a function of the elasticity-modulus. Therefore, theoretically, it is possible to assess the increase in the concrete stiffness by assessing the change of the wavespeed. However, the elasticity-modulus predicted by the *fib* Model Code is the static elasticity-modulus, while the one related with the P-wavespeed is the dynamic modulus (E_d). The relation between the static and dynamic elasticity-modulus is established based on the research done by Lydon and Balendran [16]:

$$E_c = 0.83 E_d. \quad (9)$$

2.3. Microcracking mechanism

When microcracking occurs, it may be expected that reduction of wavespeed will happen. Moreover, microcracks may also cause the waveform to change due to attenuation of the wave [17], [18]. Therefore, change in wave velocity and waveform in a specimen with the same loading before and after treatment may be caused by the formation of microcracking.

In sustained continuous compressive load, major visible cracking will occur on the peak of concrete resistance. This case, however, is not the same as the microcracking phenomenon which occurs way before the major cracking occurs. These 'pre-peak' microcracks will be discussed in this section.

At the meso-level, concrete can be modeled as a stack of particles of different sizes bound together by cement paste. As the particles are loaded, compressive and tensile stresses are concentrated at the particles contacts. Those stresses concentrations will cause bonding failure of the cement paste, which would lead to interfacial cracks. The cracks will then proceed to the development of the en-echelon cracks, which borders the triaxially-compressed zone [19]. This mechanism is shown in Figure 2.5.

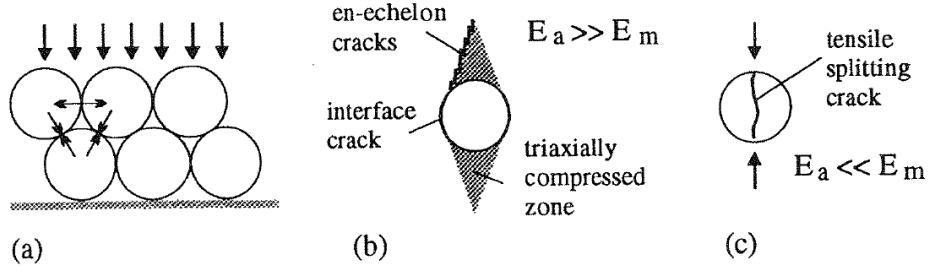


Figure 2.5. Mechanism of micro-crack formation due to matrix-aggregate interaction. (a) stress concentration caused by distributed uniaxial compression. (b) interface cracks and en-echelon cracks occur if the aggregate is stiffer than the matrix. (c) aggregate tensile splitting crack occurs if the aggregate is less stiff than the matrix. Adopted from [19].

For concrete in uniaxial tension, a research by Calixto [20] shows that microcracks are also observed in linear stress vs strain phase. Therefore, both loading in compression and tension may influence the wavespeed and waveform, even at relatively low stress.

2.4. Acoustoelastic effect

When an elastic material is stressed, it is reported that a change in elastic wave velocity will occur, which is referred as acoustoelastic effect. Such phenomenon is beneficial since it allows CWI, which measures wavespeed change in a medium, to be utilized for assessing the stress change in the medium as well. In elastic materials, certain relationships are able to be established to relate wave velocity and stress state, which were derived by Kelly and Hughes [21] using Murnaghan's theory of finite deformation [22].

$$\rho_0 V_{11}^2 = \lambda + 2\mu + \frac{\sigma_{11}}{3K} \left[2l + \lambda + \frac{\lambda + \mu}{\mu} (4m + 4\lambda + 10\mu) \right] \quad (10)$$

$$\rho_0 V_{12}^2 = \rho_0 V_{13}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m + \frac{\lambda n}{4\mu} + 4\lambda + 4\mu \right] \quad (11)$$

$$\rho_0 V_{22}^2 = \rho_0 V_{33}^2 = \lambda + 2\mu + \frac{\sigma_{11}}{3K} \left[2l - \frac{2\lambda}{\mu} (m + \lambda + 2\mu) \right] \quad (12)$$

$$\rho_0 V_{21}^2 = \rho_0 V_{31}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m + \frac{\lambda n}{4\mu} + \lambda + 2\mu \right] \quad (13)$$

$$\rho_0 V_{23}^2 = \rho_0 V_{32}^2 = \mu + \frac{\sigma_{11}}{3K} \left[m - \frac{\lambda + \mu}{2\mu} n - 2\lambda \right], \quad (14)$$

where $V_{i,j}$ is the wave velocity in direction i and polarized in direction j , σ_{11} is the normal stress in direction 1, λ and μ are the first-order Lamé's coefficients, l , m , and n are the second-order Murnaghan's coefficients, and $K = \lambda + \frac{2}{3}\mu$ is the compressibility modulus. Linearization of the system of equations at the first order is shown by Lilliamand [23] as

$$V_{ij}^{\sigma} = V_{ij}^0(1 + A_{ij}\sigma_{11}), \quad (15)$$

where V_{ij}^{σ} is the wave velocity in direction i and polarized in direction j under axial stress σ_{11} , V_{ij}^0 is the unloaded wave velocity in direction i and polarized in direction j , and A_{ij} are the acoustoelastic constants which depends on Lamé's and Murnaghan's coefficients [23].

2.5. Theory of coda-wave interferometry

CWI is a technique which utilizes the later part of a signal (coda) to retrieve information regarding the medium. The coda of the signal often provides more clues regarding what is happening in the medium, since this part of the signal had travelled longer distance compared to the first arrival of the signal [12], [24].

The technique is used to detect changes in the propagation medium by detecting wavespeed change through cross-correlation between two signals where there is virtually no difference in the first arrivals of both. These two signals should propagate through the medium, which one of them had propagated through the reference (untreated) and the other one propagated through treated (temperature changes, moisture-content changes, compressive or tensile stresses) medium. While the treatment will alter the wave propagation and scattering between the two signals, it is worth noting that wave scattering is principally more stable compared to particle scattering [7] as illustrated in Figure 2.6.

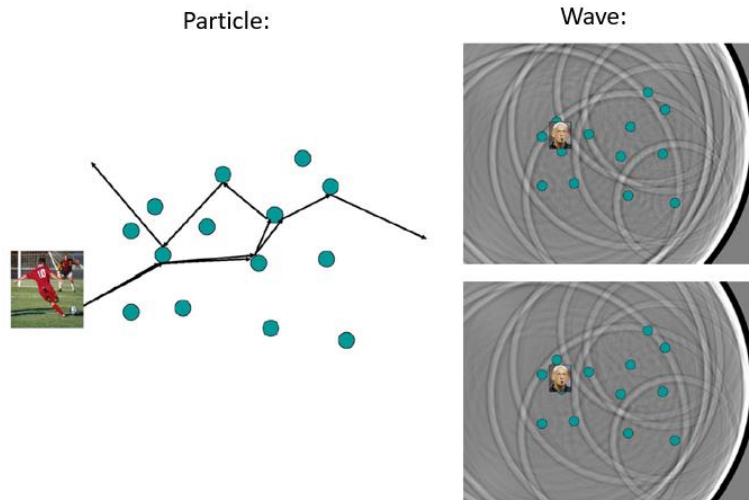


Figure 2.6. While particle will scatter differently due to minor changes in initial conditions, wave propagation is more stable with minor changes in initial conditions. Adopted from [7].

To execute CWI, in principal there are two ways of comparing the coda; by cutting the two signals into several time windows and comparing the signals inside the corresponding windows, extracting the lag to yield the velocity change (Doublet Technique), or stretching the time axis of the whole signal and comparing it with the reference signal, where the velocity change is determined through the amount of stretching done (Stretching Technique). In this research, stretching technique will be utilized.

While CWI is commonly done by using an active source, it may also be beneficial to utilize seismic interferometry to retrieve the impulse response of a virtual source, which will be used

as the signal to be analysed through CWI. Therefore, the basic theory of seismic interferometry is also going to be explained.

2.5.1. Stretching technique

In this method, the difference in wavespeed is determined by comparing a reference signal with the 'stretched' signal by cross-correlating both signals. The time axis of the signal which will be compared with the reference should be stretched to fit the reference signal, which degree of stretching is determined by the velocity change of in the medium with respect to the velocity in the reference medium [24], [25]. The principle of this technique is shown in Figure 2.7.

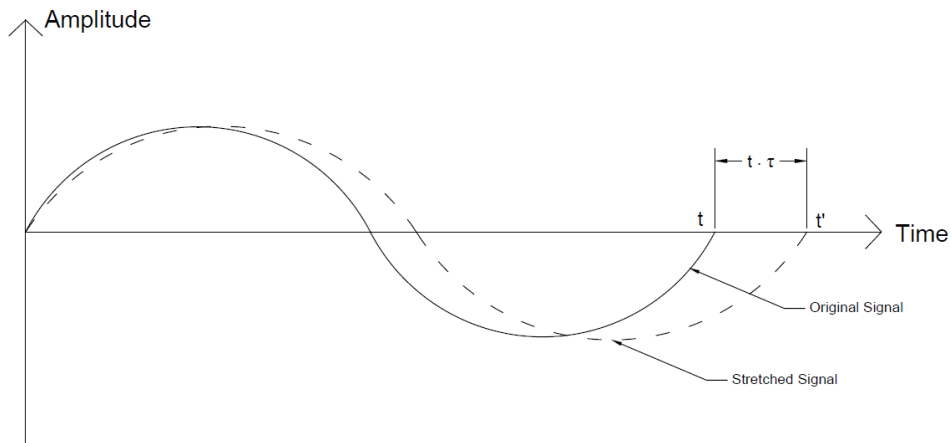


Figure 2.7. Time Stretching Technique.

To stretch the signal, the time axis t should be modified by multiplying it by $(1 + \tau)$, where τ represents how much the time axis is compressed or stretched:

$$t' = t(1 + \tau); \tau = \frac{dt}{t}. \quad (16)$$

Since small stretching of time will mean that there will be a small decrease of wavespeed, a spatial relationship can be made to find the relationship between them. Since both stretched and original signal travelled the same spatial distance, a small increase of travel time translates linearly to a small decrease of wavespeed. Therefore, the relation between the stretching of time and the wavespeed can be established.

$$\frac{dt}{t} = -\frac{dV}{V} \quad (17)$$

$$t' = t(1 - \epsilon); \epsilon = \frac{dV}{V}. \quad (18)$$

After stretching the axis, it is essential to compare the stretched signal with the reference signal so the degree of similarity between them can be known. To compare both signal, cross-

correlation between them are calculated. It is worth noting that the cross-correlation between them should be normalized, which result in a value ranged from -1 to 1.

$$CC = \frac{\int_0^T h'[t']h[t]dt}{\sqrt{\int_0^T h'^2[t']dt \cdot \int_0^T h^2[t]dt}} \quad (19)$$

where h' is the stretched signal, h is the reference signal, and T is the window length. When interpreting the cross-correlation, it is worth noting that $CC=1$ means perfect correlation between two signals, while $CC=-1$ means perfect anti-correlation. In typical cases, the ϵ vs. CC graph resembles the one shown in Figure 2.8. Therefore, the relative wavespeed change ϵ should be picked so the maximum CC is obtained.

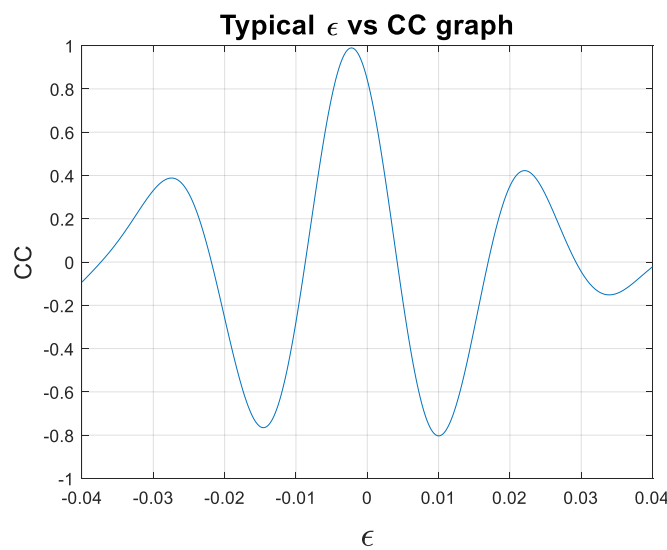


Figure 2.8. Typical ϵ vs. CC graph.

2.5.2. Seismic interferometry

Seismic interferometry exploits existing signals to turn receivers into virtual sources by means of, for example, simple cross-correlations. These signals may come from earthquakes or ambient vibrations, or they can also be actively generated signals. There are two main aims of this method: to study the change in the material in which the wave propagates and to study the wave propagation in the material itself. This method is used widely in geoscience and seismology applications [7], [26], [27].

One of the simplest application of seismic interferometry is the direct-wave retrieval [28]. To illustrate this, two receivers (1 and 2) aligned in one-dimensional line are assumed. One signal source is assumed to be located at one extreme of the imaginary line and emits an impulse along the line to the two receivers. The receivers will receive the impulse at two different times, namely t_1 and t_2 . By cross-correlating the impulse response of both receiver 1 and receiver 2, the result will be the impulse response at receiver 2, as if receiver 1 were acting as the source. The concept is illustrated in Figure 2.9.

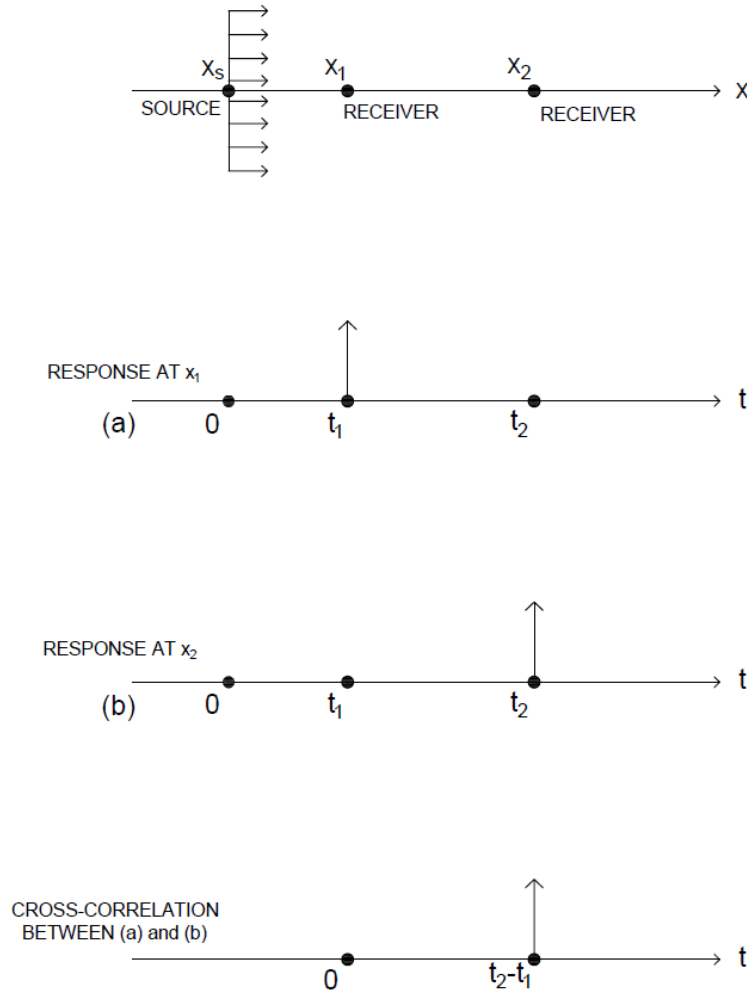


Figure 2.9. Illustration of direct wave interferometry of a pulse. Adopted from [28].

To describe it in mathematical terms, let us state that the impulse response of receiver 1 and 2 due to an impulse from source x_s to be $G(x_1, x_s, t) = \delta(t - t_1)$ and $G(x_2, x_s, t) = \delta(t - t_2)$, respectively. The cross-correlation ($\otimes$) of the impulse responses sensed by receiver 1 and receiver 2 will result in the impulse response of receiver 2 as if receiver 1 were the impulse source, which can be written as

$$G(x_1, x_s, t) \otimes G(x_2, x_s, t) = G(x_2, x_1, t). \quad (20)$$

If the source emits a wavelet signal ($s(t)$) instead of an impulse, the cross-correlation between the signal received by receiver 1 ($u(x_1, x_s, t)$) and receiver 2 ($u(x_2, x_s, t)$) will be the impulse response of receiver 2 as if an impulse were sent from receiver 1, convoluted with the autocorrelation of the incoming wavelet signal ($S_s(t) = s(t) \otimes s(t)$). In mathematical terms, the previous operation can be stated as

$$G(x_2, x_1, t) * S_s(t) = u(x_1, x_s, t) \otimes u(x_2, x_s, t). \quad (21)$$

By doing so, it is possible to determine the time lag between two signals without knowing the source location of the ambient signal. If two similar signals come from both extremes of the time axis, the cross-correlation between the signals received will contain two impulse responses: one at negative times and the other one at positive times. Mathematically, it can be described as

$$\{G(x_2, x_1, t) + G(x_1, x_2, t)\} * S_s(t) = u(x_1, t) \otimes u(x_2, t). \quad (22)$$

In a 2D or 3D situation, the expression above can be used to retrieve the impulse responses between the two sensors by simply summing all the cross-correlation products of signal received from individual external source [29].

2.6. State of the art of coda-wave interferometry on concrete

To give more insight into the experiments which are going to be done, previous works regarding CWI implementation in concrete are studied. So far, CWI had been attempted to detect temperature change [5], damage assessment [24], moisture change [25] and acoustoelastic effect [4], [12].

In the works of Larose et al. [5] and Lin [25], it was observed that temperature change and moisture content does affect wavespeed in concrete. In the works of Larose, it is reported that the wavespeed is higher when the temperature is lower, which in his case, the surrounding temperature difference of 15 centigrade did alter the wavespeed as much as 0.6%. The work of Lin also shows that moisture content does reduce the wave propagation speed. Therefore, the implementation of CWI should be done in controlled environments when possible.

Schurr [24] assessed the damage caused by mechanical loading, alkali-silica reaction, and temperature damage on concrete by using CWI. These damaged samples were then loaded several times in low stresses to assess their dv/v vs stress gradient. In his work, it is shown that in general, the first loading does have lower dv/v vs stress gradient compared to the second and third loading, which gradients are relatively similar afterward. Such trend is also observed in the works of Stahler et al. [4], where the initial dv/v vs stress gradient at low stress is lower in the first load phase compared to the following load phase. These works are referred to confirm the findings gained in the experiments of this thesis.

3. Methodology

3.1. Overview of research methodology

As stated earlier, this research consists of three parts; concrete age analysis through CWI, CWI on concrete in compression, and CWI on concrete in bending and shear. For each part, experimental planning is done to determine specimen schematic, as well as test plans and signal-processing plan. In the tests themselves, the specimens are treated; they can be loaded or aged, in which case CWI is done to monitor specimens' response to the treatment. The signal recordings, as well as the treatment parameters (load, age, displacement) are then processed and analyzed. On the beam specimen used for the bending and shear test in particular, seismic interferometry is done before the loading to attempt to retrieve the impulse response of the beam through two embedded sensors. The schematic of the methodology can be reviewed in Figure 3.1.

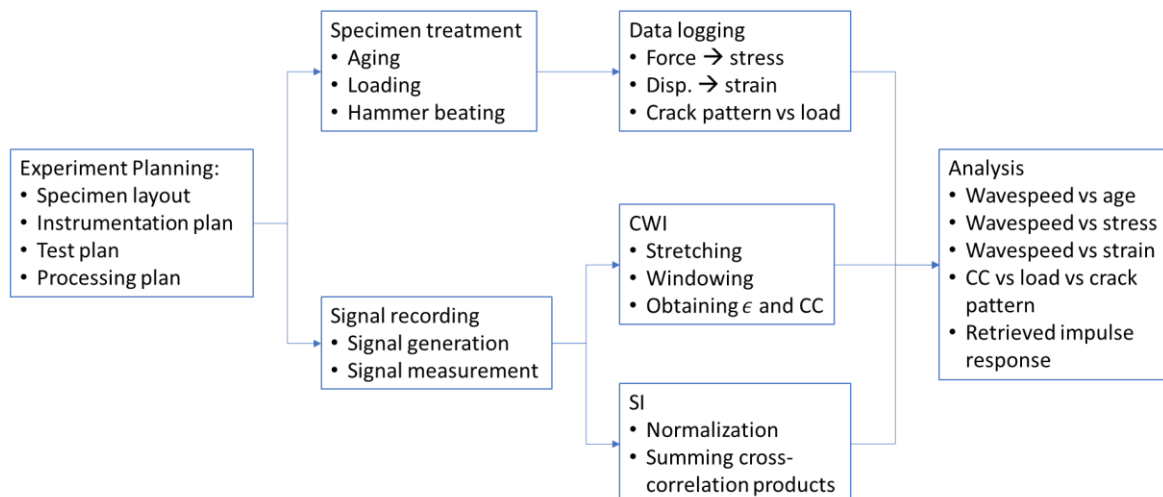


Figure 3.1. Methodology Schematic.

3.2. Loading apparatus and displacement measurement

To apply and control the loading of specimens, as well as to record displacement of specimens, an integrated loading apparatus and displacement-measurement module is used. In general, this module consists of a personal computer which has load-control software as well as displacement- and load-measurement software installed, a hydraulic jack, a loading frame, linear variable differential transformer (LVDTs), and a data-logger set. In the bending and shear experiment, digital image correlation (DIC) measurement is also done to monitor crack propagation.

The data-logging system which is used in this module is designed in-house by Stevin II Laboratory of Civil Engineering and Geoscience Faculty, TU Delft. Loading is controlled by RE1 load control software, which is capable of controlling the hydraulic jack in both load and

displacement control, achieved by utilizing the load cell and LVDT that measures the exerted force and jack displacement relative to the loading frame.

LVDTs are installed on the specimen to measure displacement of desired locations. The information from the LVDTs attached to the sample is then relayed through the in-house data-logging system to the PC, which is then displayed on MP3 software. This software is also developed in-house by Stevin II Laboratory, which is capable of logging and storing LVDTs and load-cell readings.

Depending on the experiment, the loading frame and hydraulic jack vary. For the compressive experiment of Chapter 5, a 3000kN hydraulic jack is used, installed in a compressive loading cage (refer to Figure 3.2.). In the bending and shear test done in Chapter 6, similar hydraulic jack is attached to a loading frame installed on reaction floors, which provides support for both the specimen and the hydraulic jack (refer to Figure 3.3.).



Figure 3.2. Loading apparatus for compression samples.

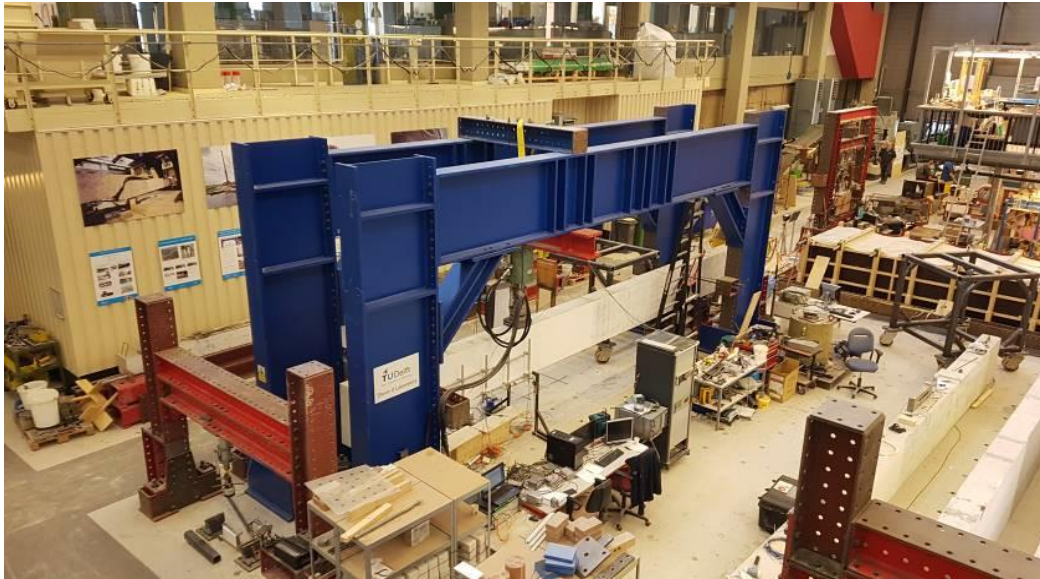


Figure 3.3. Loading apparatus for bending samples.

DIC measurement is done by acquiring images of speckled specimen with a camera, then processing them to acquire the strain and crack width of the specimen. DIC measurement is only done during the bending and shear test of Chapter 6. The apparatus used for DIC measurement consists of a high-resolution camera with wide-angle lens installed, photography light, tripod, and shutter release. The speckle on the specimen is painted by paint roller, which is sized about 1 to 2 millimeters, as shown in Figure 3.4. While DIC measurement results in various results, in this research only the crack pattern is extracted. More detail regarding DIC measurement is contained in the thesis by Garnica G. I Z. [30].

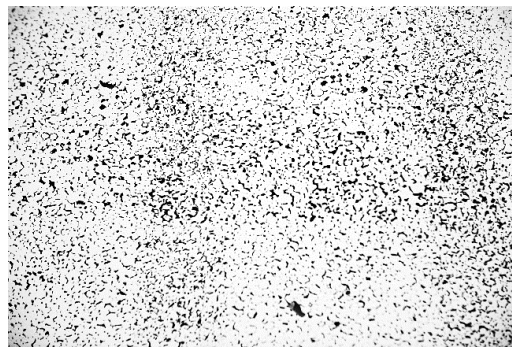


Figure 3.4. Speckle pattern on beam for DIC measurement. Adopted from [30].

3.3. Coda-wave interferometry implementation strategy

CWI is implemented in this research to assess the relative wavespeed change between two signals, either differentiated by time since casting (Chapter 4) or stress state and mechanical damage (Chapter 5 and 6).

3.3.1. Instrumentation

To generate, amplify, transmit, receive, and acquire the signal, an instrumental setup is used which consists of 5 main components: a signal generator, a power amplifier, sensors (in this

case, smart aggregates), an oscilloscope, and a computer on which LabView™ program installed, is used. The schematic of this system is shown in Figure 3.5., while the physical form of the system is shown in Figure 3.6.

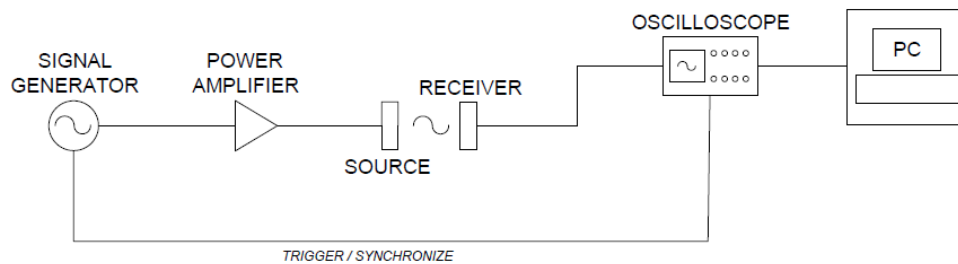


Figure 3.5. Schematic of signal recording setup.

The signal generator being used is an Agilent 33210A, which is capable of generating signals with different waveforms, amplitude, and functions (burst, sweep). In the experiments, a burst of sine waves is generated with an amplitude of 500 mV and a frequency of 88 kHz, which is the resonance frequency of the smart aggregates being used. The output port is connected to the power amplifier which amplifies the signal, while the sync port is connected to the oscilloscope to synchronize measurements with the signal generation.

Signals generated by the signal generator are then amplified by an RF Power Amplifier, whose outputs are fed to the source smart aggregate which is either attached or cast into the sample. The signals are then received by other smart aggregates which act as the signal receivers. The signals from the receivers are then relayed into the oscilloscope, where it is possible to see the received signals in the time domain.

Smart aggregates are utilized to act as both source and receiver. A smart aggregate is a piece of piezoelectric sheet, which is sandwiched by marble layers and sealed from harmful environmental conditions. These sensors are meant to be cast into concrete since they are inexpensive to produce and durable. However, unlike more expensive designated sensors used for structure-health monitoring purposes such as acoustic-emission sensors, smart aggregates are not calibrated and less uniform in their resonance frequency. Therefore, it is best to check each batches resonance frequency by assessing its impulse response. Schematic of a smart aggregate can be seen in Figure 3.7.

The oscilloscope being used is Yokogawa DL9140 series, which is able to accommodate 4 different channels. Depending on the experiment, up to 2 oscilloscopes are used, which allows 8 different channels to be used when necessary. To align the recording time with the signal generation, the main oscilloscope is connected to the 'sync' port of the signal generator.



Figure 3.6. Signal generation and acquisition setup.

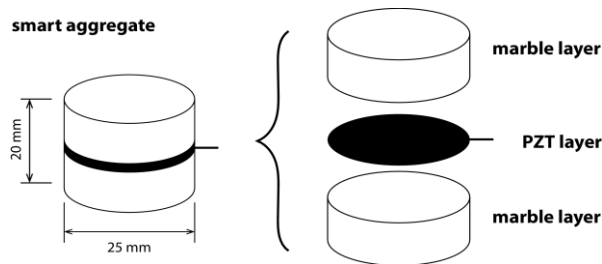


Figure 3.7. Schematic of smart aggregates.

(Courtesy of Yang Yuguang of Civil Engineering and Geoscience Faculty, TU Delft).

3.3.2. Signal generation and sampling

Since CWI does depend on the signals generated and received by the sensors, in this case, smart aggregates, it is important to ensure the quality of these signals. Two measures are taken; to make sure the signals generated to comply with the central frequency of the sensor, and to ensure that the sampling rate exceeds the Nyquist's frequency.

The signals which are fed to the source sensor are single sines, which are used since their frequency can be tuned to control the amount of scattering based on Figure 2.2., and to align the signal frequency with the central frequency of the sensor. In this case, it will be beneficial to have signals which have a frequency leading to either simple scattering or multiple scattering, which correlates to 20 kHz to 500 kHz [12], but not lower than 50 kHz [31]. The smart aggregates which are used in this research have two resonance frequencies: one is between 25 to 95 kHz and the other between 120 kHz to 180 kHz (Figure 3.8). Through trial-

and-error measurements, it is found that the source frequency of 88 kHz is the best compromise between sensitivity and attenuation.

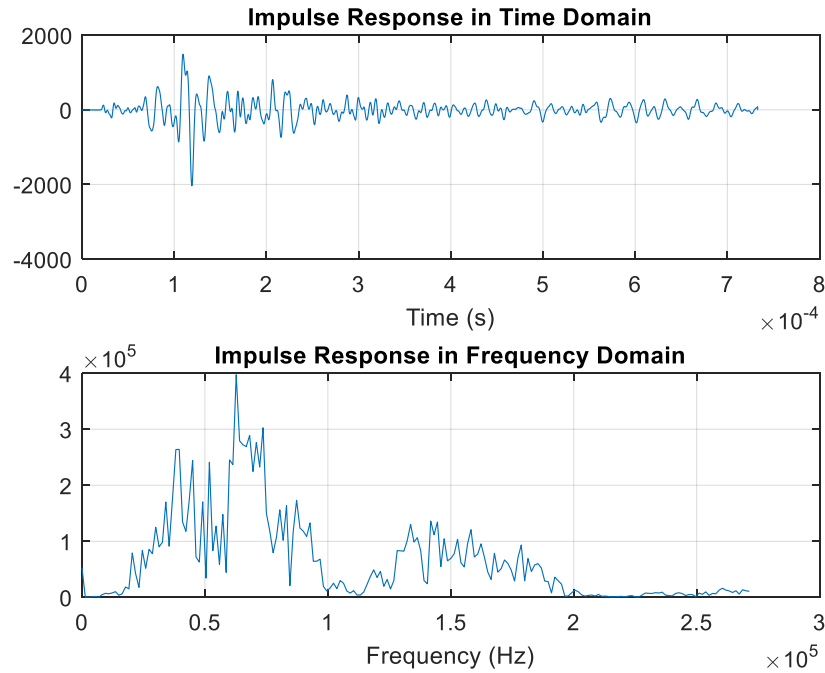


Figure 3.8. Impulse response of the smart aggregates used in this research.

To determine the Nyquist's frequency of the recordings, several recordings with a source frequency of 88 kHz are assessed to check their frequency content, and it is found that the highest frequency contained in the signals received is 2.6×10^5 hertz (Figure 3.9.), making the Nyquist's sampling rate as 5.2×10^5 sample/s. Therefore, the sampling frequency of the recordings should exceed 5.2×10^5 sample/s to prevent aliasing.

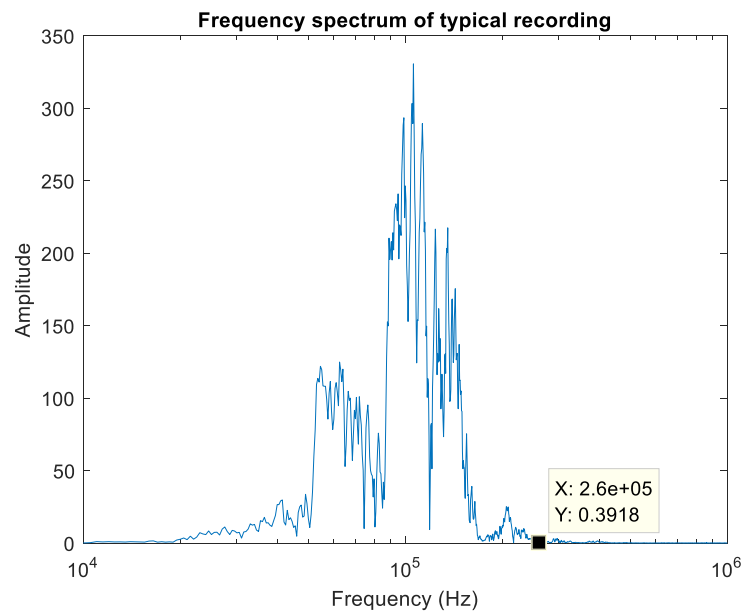


Figure 3.9. Frequency spectrum of a recording taken from the beam test, with a sampling rate of 6.25×10^7 sample/s. marked is the maximum frequency content of this particular recording.

3.3.3. Processing strategy

As seen on Figure 3.10., the waveform of a typical signal acquired in this research is still clear even up to 2ms of propagation, which is roughly equivalent to 9 m of scattering path, assuming wave speed in concrete of 4500 m/s (refer to Part 4.3.3. for estimation of wavespeed).

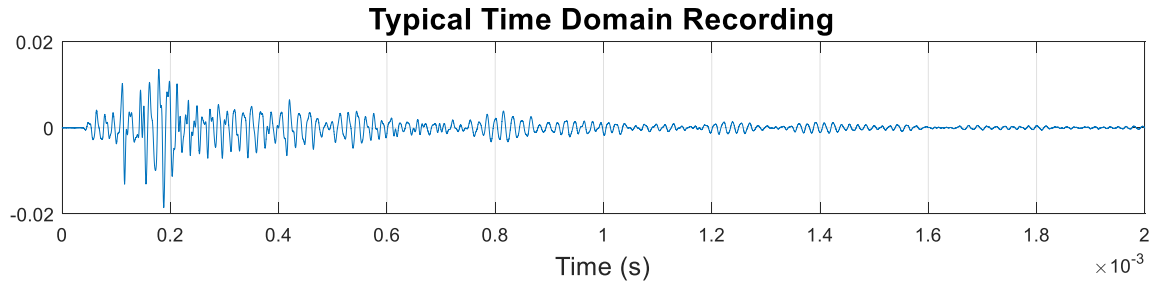


Figure 3.10. Typical received signal in the time domain (this particular recording is taken from a cube specimen).

It is observed that the first arrivals and early coda do have higher amplitude compared to the intermediate and late coda, which may cause the earlier arrivals to be more dominant in the cross-correlation process compared to the later coda. Therefore, windowing is done to ensure that the later coda is well-incorporated in the wavespeed change estimation using the correlation coefficient. In Equation 19, $h[t]$ and $h'[t']$ are windowed reference signal and windowed stretched signal respectively.

$$CC = \frac{\int_0^T h'[t']h[t]dt}{\sqrt{\int_0^T h'^2[t']dt \cdot \int_0^T h^2[t]dt}} \quad (19)$$

The windowing process itself is done by using rectangular window with a length of approximately 8 periods. Rectangular windows are chosen since similar cross-correlation weight throughout the windows are desired and no Fourier transformation is going to be done after windowing, which makes rectangular windows beneficial compared to Hann or Hamming due to preserved signal waveform and less computational demand. Each window overlaps 50% with the adjacent windows to mitigate the case of having an important part of the signal is cut off in one window, and to give uniform weighting in all part of the recording. Choosing less overlapping will cause the un-overlapped part of the recording to be weighted more than the overlapped part. The windowing scheme is shown in Figure 3.11.

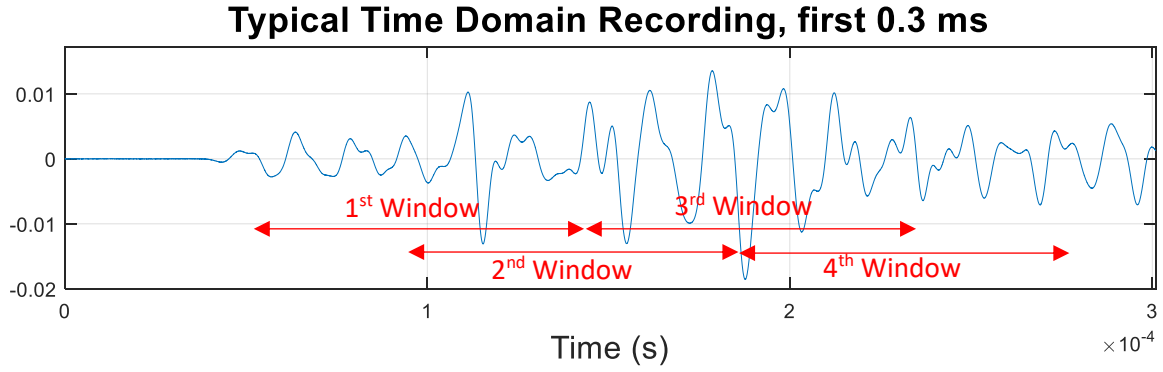


Figure 3.11. Windowing scheme. Only the first 4 windows are shown in this figure.

To determine the relative change of waveform through CWI, the time axis of a signal should be stretched and then cross-correlated with the reference signal. In this case, the whole signal is stretched to fit a certain window, and the process repeats for all windows of the recording. While this process is computationally expensive due to multiple times of stretching for one signal, it provides better accuracy compared to windowing the signal first before stretching it, since stretching windowed signal will not yield good result due to the lack of information in the part where the signal is trimmed.

In processing the signal to conduct CWI, the following processing workflow is followed:

- Importing the binary signal from the data logger into MATLAB.
- Assigning the reference signal and the target signal to be stretched.
- Assigning the range of wavespeed change (epsilon) for assessment.
- Assigning the first arrival of the signal.
- Assigning the center of the window based on the first arrival and recording span.
- Assigning the width of the windows.
- Signal stretching
 - Stretching the signal time axis with respect to epsilon with Equation 18.

$$t' = t(1 - \epsilon); \epsilon = \frac{dV}{V}. \quad (18)$$

- Interpolating the signal into the new stretched time axis by interp1 function in MATLAB.
- For each epsilon value, windowing is done and cross-correlation is done for each window against the reference signal.
- Repeat the process for each epsilon value.
- The epsilon value which yields to the highest correlation coefficient (CC) for each window is taken.
- The epsilon and CC values for each window is stored.
- Displaying the result of the processing depending on how the result should be presented. The way the result is presented may differ in each part of the research.

In aging-analysis part of the research, the CWI results are presented by plotting colour graphs of the relative wavespeed changes and their ϵ value for every window and every time increment. This is done for every pair of sources and receivers. Moreover, in this part of the

research, every CC value of each single epsilon iteration is taken for detecting cycle-skipping phenomenon, which is a phenomenon where the algorithm picks the wrong wavespeed change due to a low correlation coefficient of the recording pair.

In both second and third part of the research, the epsilon ($\frac{dv}{v}$), CC, and signal comparison are aligned so that the $\frac{dv}{v}$ and CC values of a particular window are aligned with the location of the window center of the corresponding signal. For building the $\frac{dv}{v}$ vs stress or strain graph, the $\frac{dv}{v}$ values which are taken are the ones with CC higher than 0.8, except if mentioned otherwise, because windows with lower CC had undergone significant waveform changes and taking $\frac{dv}{v}$ values from these windows may result in misleading interpretation of the recording.

3.4. Seismic-interferometry implementation strategy

3.4.1. Signal generation and instrumentation

To generate required signals, the beam is divided into three zones; Zone 1 is 1.5-meter-long from the left end of the beam (refer to Figure 3.12) and where the support is located, Zone 2 spans for 2 m, and is where the two smart aggregates which are used for seismic interferometry are installed, and Zone 3 spans 1.15 m. Hammer is used to create impulses by striking the beam at specific places (refer to Figure 3.13.). The hitting points are along a predetermined grid with a spacing of 10cm in the crossline direction and 5cm in the inline direction of the beam. The hammer grid points, as well as sensor locations are shown in Figure 3.12. Apart from the grid points, random hammering points are also used in Zone 1 and Zone 3. In these zones, both the sides of the beam and the top are hits 30 times each.

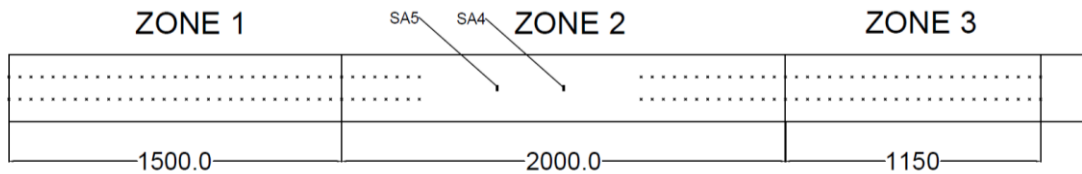


Figure 3.12. Beam layout for seismic interferometry experiment. The dots are predesignated beating points.



Figure 3.13. Hammers used to create impulse.

The sensors which are used in this case are smart aggregates with designation SA4 and SA5, which are separated by 30cm. The same smart aggregates are also used for CWI analysis on concrete in bending and shear. Both are embedded 15cm from the top of the beam. The signals received from these smart aggregates are then transferred to MISTRAS Sensor Highway II system through an in-house made pre-amplifier made by Stevin II Laboratory TU Delft.



Figure 3.14. MISTRAS Sensor Highway II System.

3.4.2. Processing strategy

Each hammer strike will result in two signals, each of them received by one smart aggregate. These two signals are then cross-correlated by using `xcorr` function in MATLAB. Since by default the result of the `xcorr` function does not include any normalization, 'unbiased' normalization is added into the function to prevent misleading tapering of both ends of the cross-correlation results: $CrosCor_{SA4,SA5}(m) = \frac{1}{N-|m|} SA4(t) \otimes SA5(t)$, where $CrosCor_{i,j}(m)$ is the unbiased cross-correlation result between i and j at lag m , $SA4(t)$ and $SA5(t)$ are the discrete digital signals obtained by sensors SA4 and SA5, respectively, N is the size of the array of $SA4(t)$ and $SA5(t)$, and m is the lag between the two signals in the cross-correlation process [32].

The cross-correlation results for the individual hammer strikes are then summed, which results in a retrieved impulse response of the system. The positive time axis is the impulse response with the first entry of `xcorr` function as the virtual receiver and the second entry as the virtual source, while the negative time axis is the other way around.

4. Coda-wave interferometry and concrete aging

4.1. Measuring wavespeed change during hydration process

CWI is used to detect and measure how much the hydration process had occurred, as well as relating the wavespeed change to the modulus of elasticity of the material. In this case, a cylindrical sample with six smart aggregates: two embedded and four attached, are utilized. Since 5 channels are required to log the signals, two oscilloscopes are used in this part of the research. The smart aggregates position is shown on Figure 4.1.

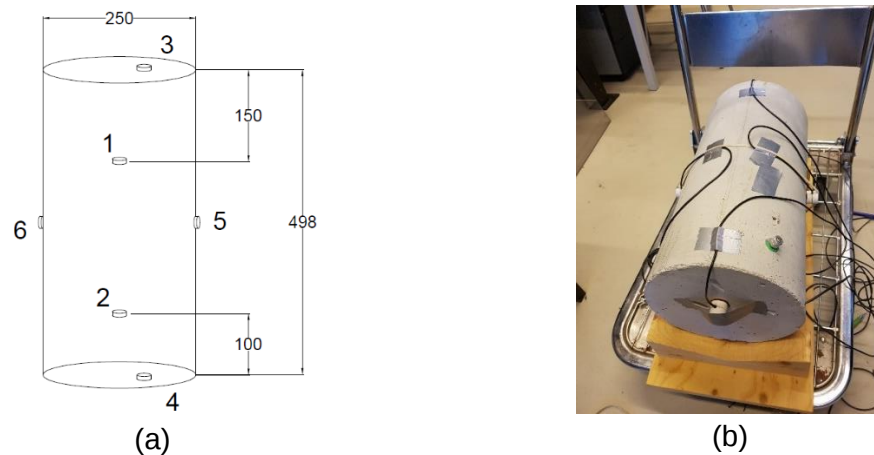


Figure 4.1. Sensor placement schematic (a) and implemented sensor placement (b).

The relation between the hydration process and wave propagation in the cylindrical sample is assessed in the 8th day, 12th day, 15th day, 19th day, 22nd day, 28th day, and 35th day in a controlled environment. In total, 6 sensors are used and each of them was used as source and the rest as receivers, which results in 30 traces for a one-day recording, except for the day-8 test since only two sensors are utilized (Sensor 1 and sensor 2). The traces are marked by using their source and receiver codename, for instance, a trace which results from signal generated from sensor number 1 and received by sensor number 2 will be marked as S1R2.

The signal generated is a single sinusoid with a frequency of 88 kHz, which is in accordance with the resonance frequency of the smart aggregate. In each recording, 25,000 data points are taken during a 1 ms recording.

Time-stretching CWI is performed on traces with the same codename which comes from an adjacent day of testing to determine the velocity change between these two recordings. The traces are divided into 18 windows to be stretched in accordance with part 3.3.3 of this thesis. The CC and the epsilon (velocity change) values of each pair of windows can be determined.

4.2. Experimental result and data processing

As the hydration process goes on, it can be observed that the signals received are more 'compressed' in time during the latter days compared to the earlier one, indicating higher velocity of the wave. It can also be observed that in terms of wave form, the signal comparison between signals recorded in the later days seems to be more stable compared to the ones recorded in the earlier days. A signal pair and the time-stretching result involving the pair can be seen on Figure 4.2 and Figure 4.3.

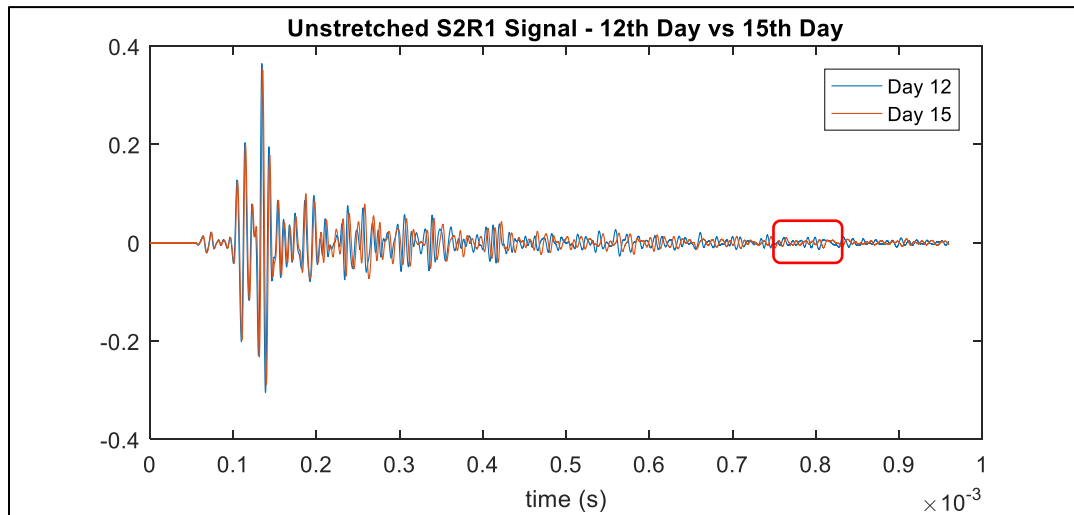


Figure 4.2. Example of time domain recording: comparison between the recording of Source 1 and Receiver 2, Day 12 and 15. 16th window is highlighted.

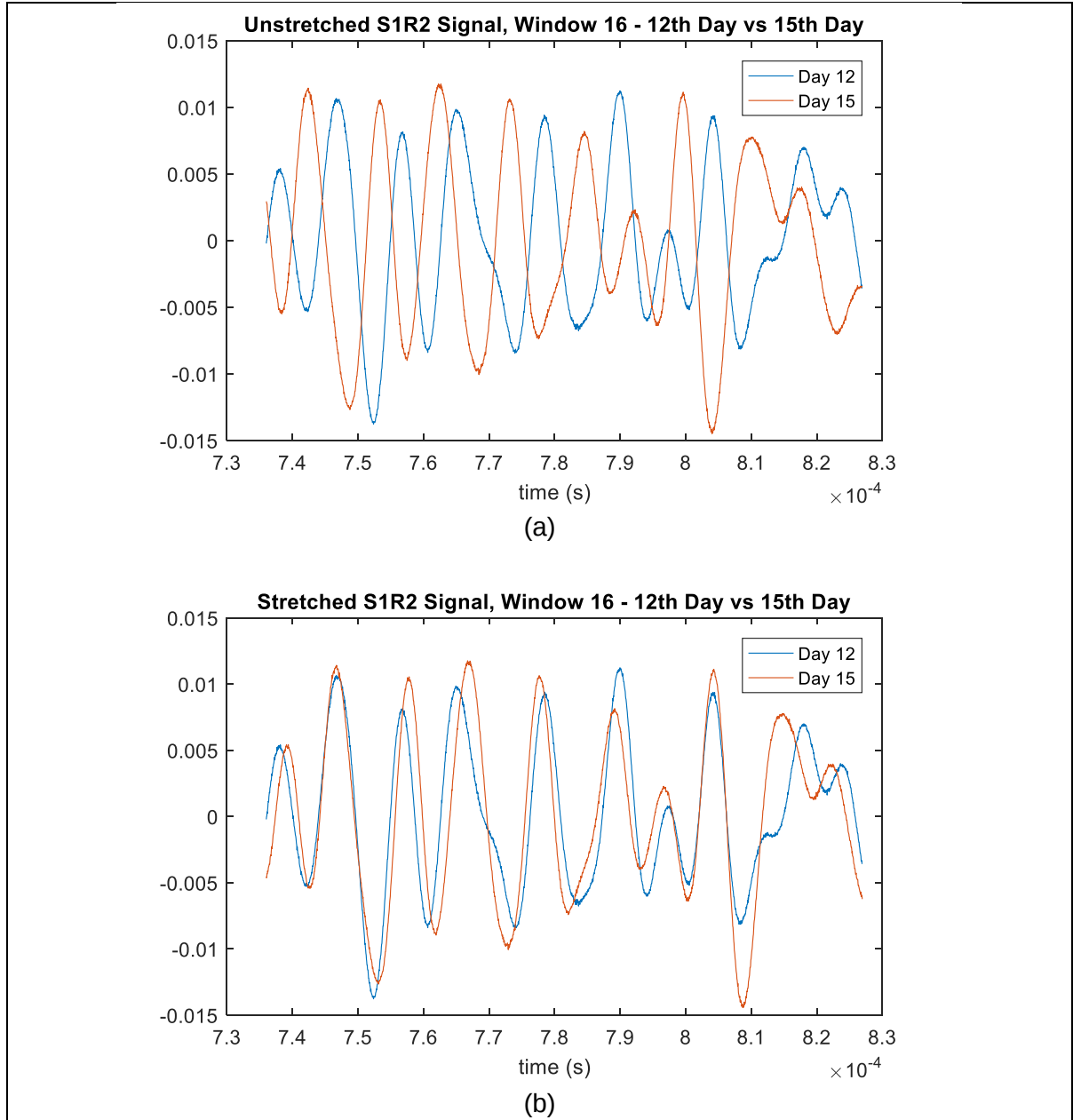


Figure 4.3. Before (a) and after (b) stretching. This recording is extracted from 16th window of the comparison between the 12th and the 15th day signal emitted by source 1 and received from receiver 2. After the stretching process, this pair has a correlation coefficient of 0.8223.

4.2.1. Relative wavespeed change and correlation coefficient

To compare signals in a more comprehensive way, the correlation coefficient vs window number graphs are plotted for all the recording pairs. The same is done for the relative wavespeed change vs window number. Color plots are used since they are able to present the comparison in a more comprehensive manner. Higher CC values indicate higher similarity between the pair of windowed signals, while lower CC values indicate dissimilarity between those two. Positive epsilon values indicate increase of relative velocity; for instance, positive values between day 8 and day 12 recording indicate that the signals recorded in day 12 have higher velocity compared to the ones from day 8.

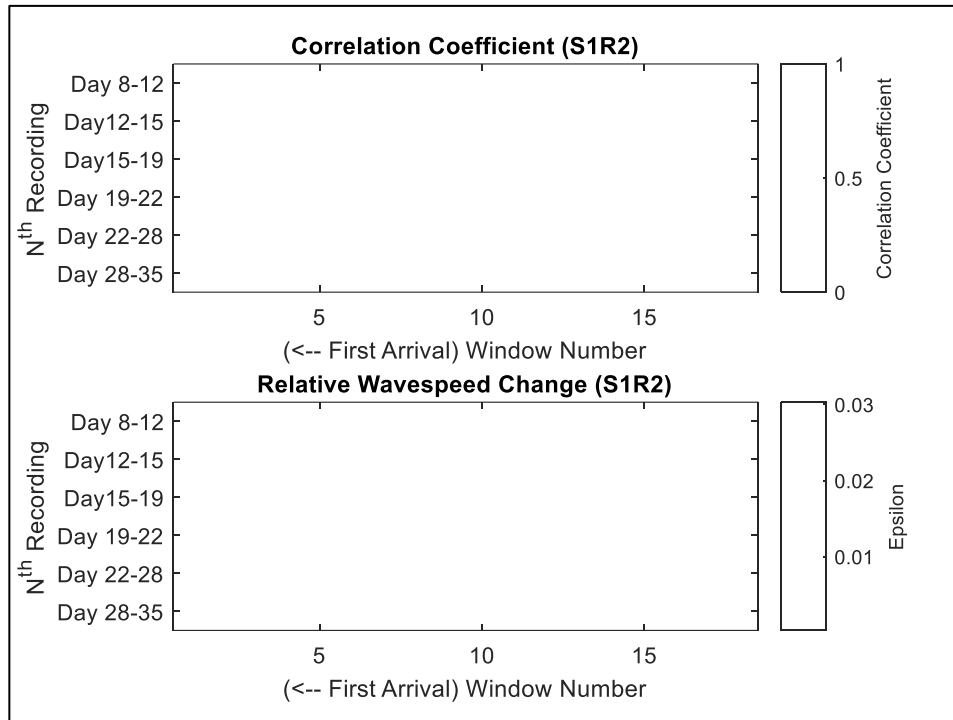


Figure 4.4. Color plot of CC and relative wavespeed change for each windows of all pairs of recordings. Signal source is from sensor 1 and received by sensor 2.

The relative wavespeed change (epsilon) plot of S1R2 recording (Figure 4.4.) shows that the first trace pair (day 8 and day 12) seems to have the most significant change in wavespeed, reaching 2% of change in some windows. As the time goes, the changes in wavespeed subside, where the least change is observed between the 28th day and the 35th day recording. It is also worth noting that the 22nd and 28th day recording comparison have higher epsilon value compared to the 19th and 22nd day recording comparison due to difference in time intervals between the pairs.

It is apparent that the correlation coefficient (CC) values seem to be higher in the earlier part of the recording compared to the later coda. These CC values can be nearly 1 in the first several windows, while in the late windows these values tend to drop. It can also be observed that the later the days of the recording pairs are taken, the higher the overall CCs. Note that in the figure, comparison between day 22 and 28 has lower CC values compared to day 19 and 22 due to larger time gap between recordings. It can be observed that day 28 and day 35 pair also seems to be off the trend, probably due to environmental circumstances.

While the recordings of embedded sensors seem to be reliable, the same could not be said for the result of the attached-embedded (Figure 4.5. and Figure 4.6.) and attached-attached source-receiver pairs (Figure 4.7. and Figure 4.8.). In attached-embedded source-receiver pairs, it is observed that the pairs which attachments are done at flat surfaces (Sensor 3 and 4) does have better correlation and less cycle-skipping compared to the ones which are attached on curved surfaces (Sensor 5 and 6). In attached-attached source-receiver pairs, the correlations seem to be low and many cycle-skipping events are observed. The cycle-skipping phenomenon will be explained later in this chapter.

In attached-attached sensor pairs, the CC tend to be lower compared to the embedded-embedded pairs. Recordings which involve sensor 5 and sensor 6, both are attached on the curved surface of the sample, suffer from generally low correlation coefficient and major cycle-skipping in many of the windows.

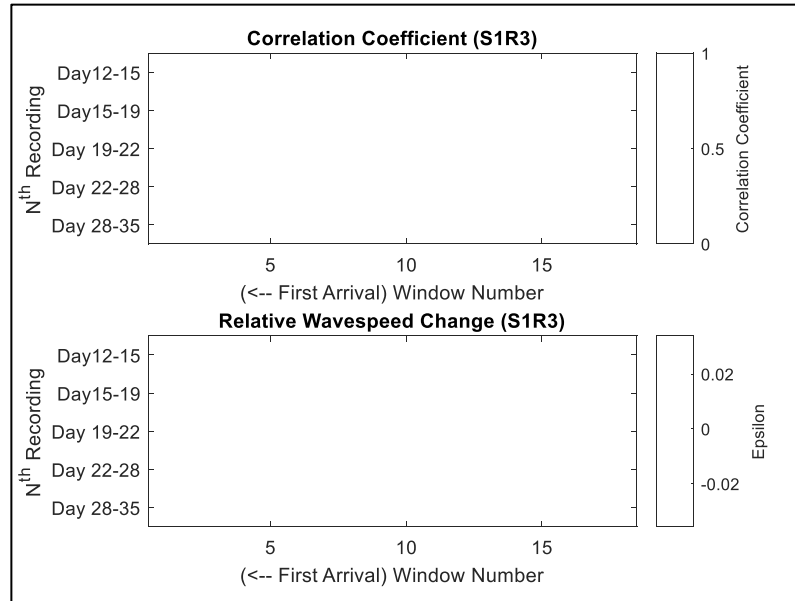


Figure 4.5. Correlation coefficient and relative wavespeed change of signal sent by sensor 1 (embedded) and received by sensor 3 (attached on flat surface of the sample).

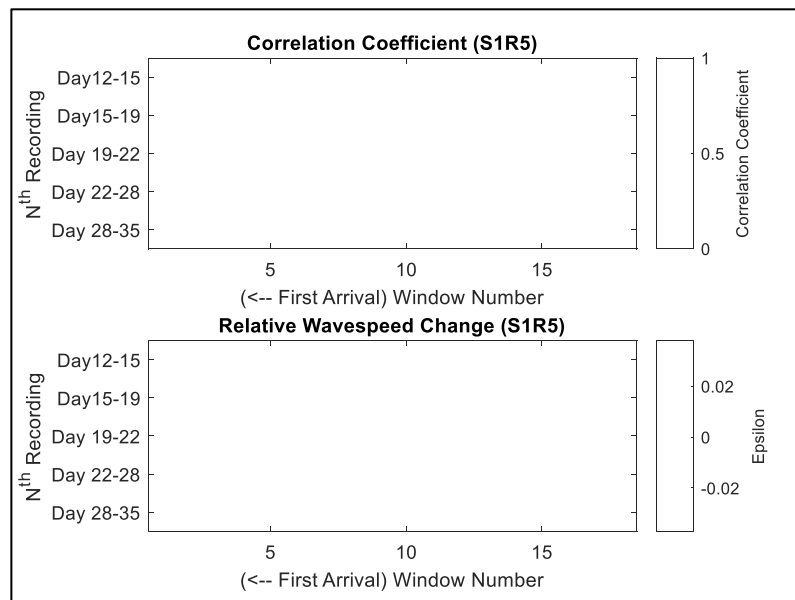


Figure 4.6. Correlation coefficient and relative wavespeed change of signal sent by sensor 1 (embedded) and received by sensor 5 (attached on curved surface of the sample).

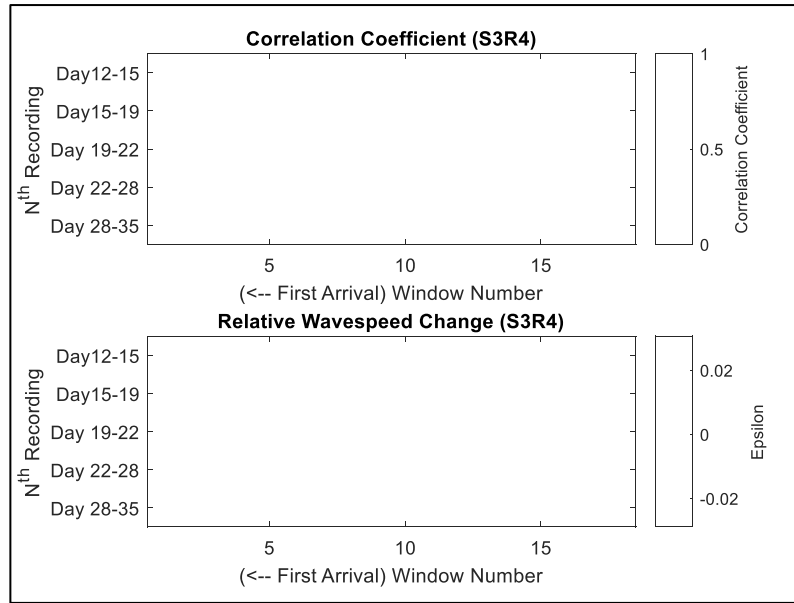


Figure 4.7. Correlation coefficient and relative wavespeed change of signal sent by sensor 3 and received by sensor 4 (both attached on flat surface of the sample).

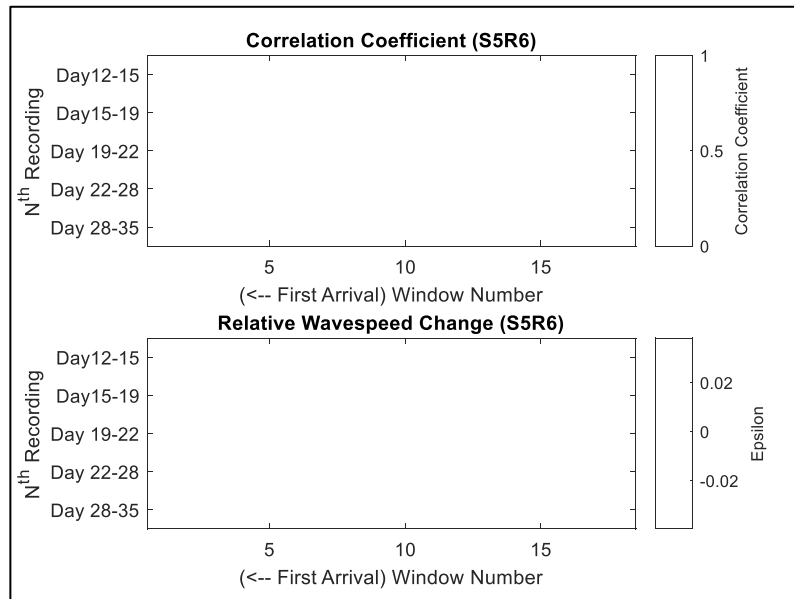


Figure 4.8. Correlation coefficient and relative wavespeed change of signal sent by sensor 5 and received by sensor 6 (both attached on flat surface of the sample).

As the relative wavespeed change for each window of the recording is obtained through stretching, wavespeed change between two days can be made by averaging the wave-speed change of the windows which have a CC exceeding a certain value to avoid cycle-skipping. In all cases, CC threshold is set at 0.8. Since recordings from sensor 3 to 6 are only available from the 12th day, the data is centered at the 12th day for reference.

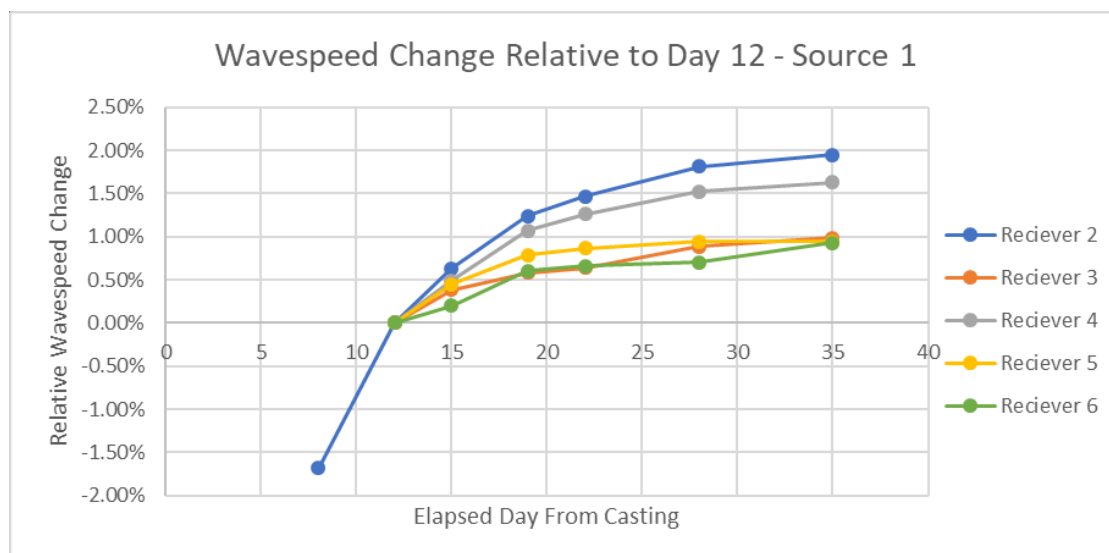


Figure 4.9. Evolution of signal wavespeed emitted from sensor 1.

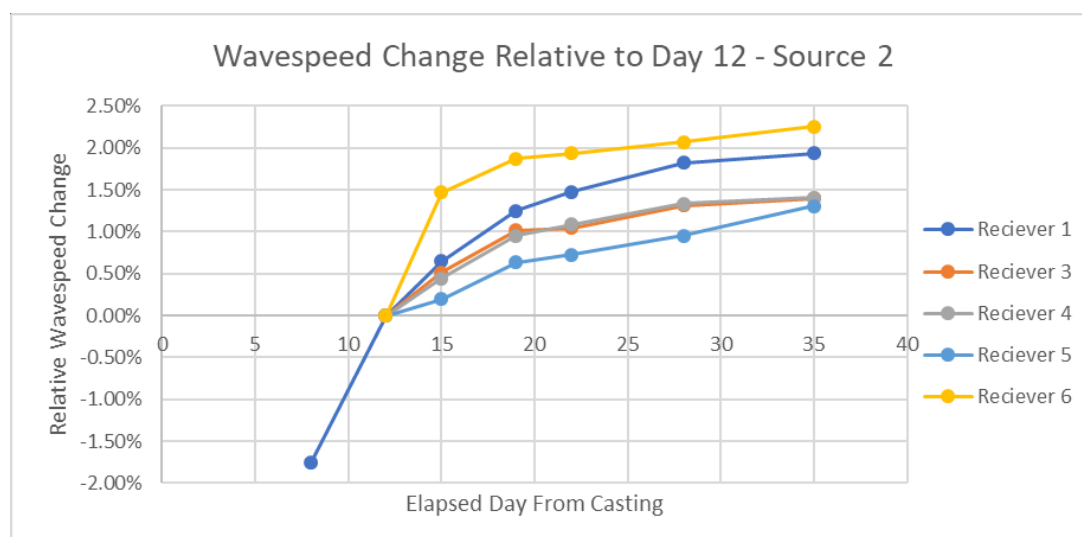


Figure 4.10. Evolution of signal wavespeed emitted from sensor 2.

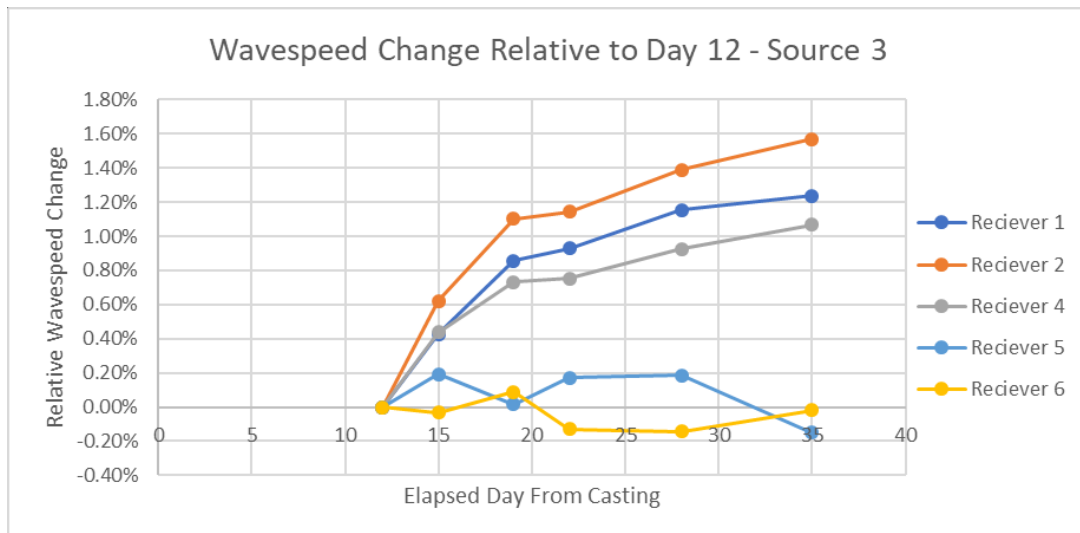


Figure 4.11. Evolution of signal wavespeed emitted from sensor 3.

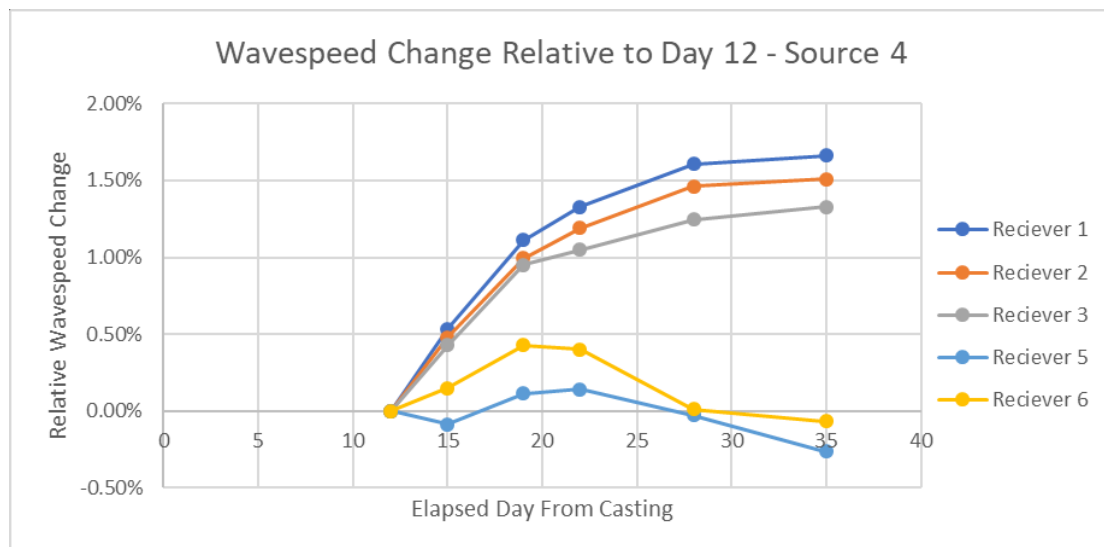


Figure 4.12. Evolution of signal wavespeed emitted from sensor 4.

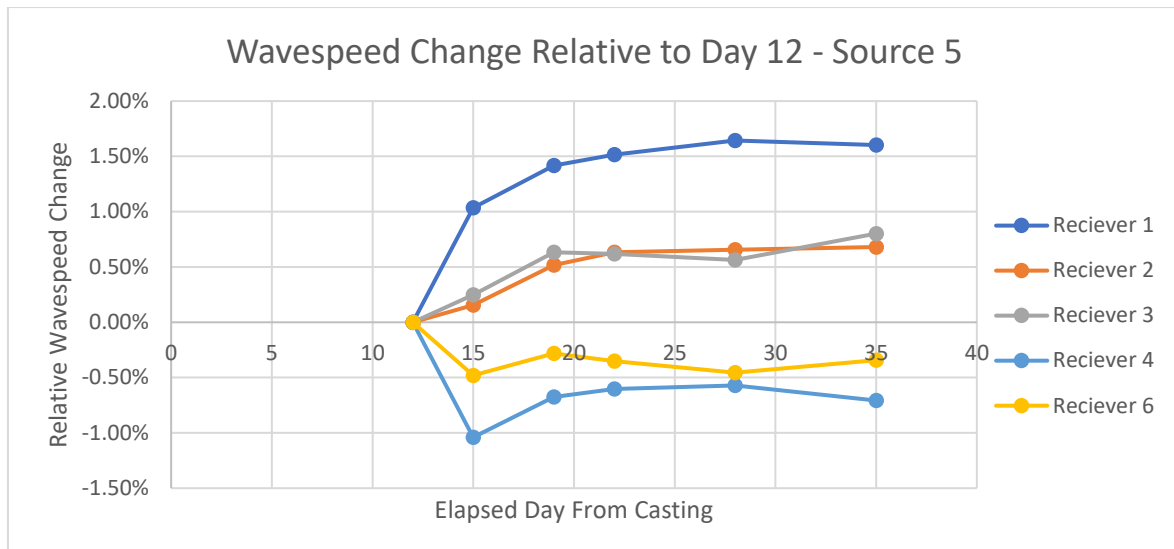


Figure 4.13. Evolution of signal wavespeed emitted from sensor 5.

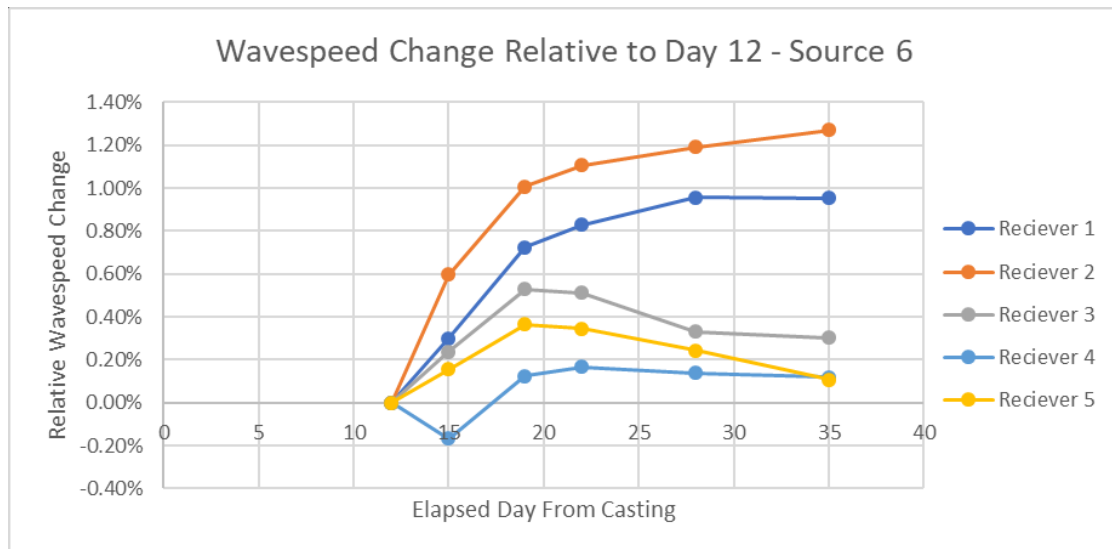


Figure 4.14. Evolution of signal wavespeed emitted from sensor 6.

In every sensor that receives signals from the embedded sensors, it is observed that the wavespeed changes are positively related with time. However, recordings which involve attached sensors as the receivers do have varying wavespeed changes. For instance, it is observed that the wavespeed of S2R6 signal (Figure 4.10) had increased by 2.25% by day 35, while the S1R6 signal (Figure 4.9) has much lower wavespeed increase of only 0.93% at the same time. Such inconsistency occurs in nearly all pairs, except for sensor 1 and sensor 2 pairs.

In recordings of signals emitted from the attached signal, inconsistencies between all recordings are noted. Wavespeed tends to decrease during some period of time in signals emitted from flat surface-attached sensors (sensor 3 and 4) which are received by curved surface-attached sensors (sensor 5 and 6), as seen in Figure 4.11. and Figure 4.12. Such

phenomenon is also observed for the signals emitted from sensor 5 and 6 and received by other attached sensors (Figure 4.13. and Figure 4.14.).

4.2.2. Cycle-skipping phenomenon

While stretching the signal, it is possible that the algorithm miss-picked the wrong epsilon value due to waveform change between recordings, resulting in higher correlation coefficient for an epsilon value which is away from actual epsilon value. This will result in abnormal relative wavespeed change values when compared to other windows of the same signal pair.

To illustrate this phenomenon, S5R3 signal pair from day 15 and day 19 recording are taken as an example. In the relative wavespeed change vs window number (Figure 4.15 a.), it is observed that there are four windows which have wavespeed change values which greatly differs from the values in the other windows. To investigate, a color plot which contains information of wavespeed change, window number and CC are constructed (Figure 4.15 b.).

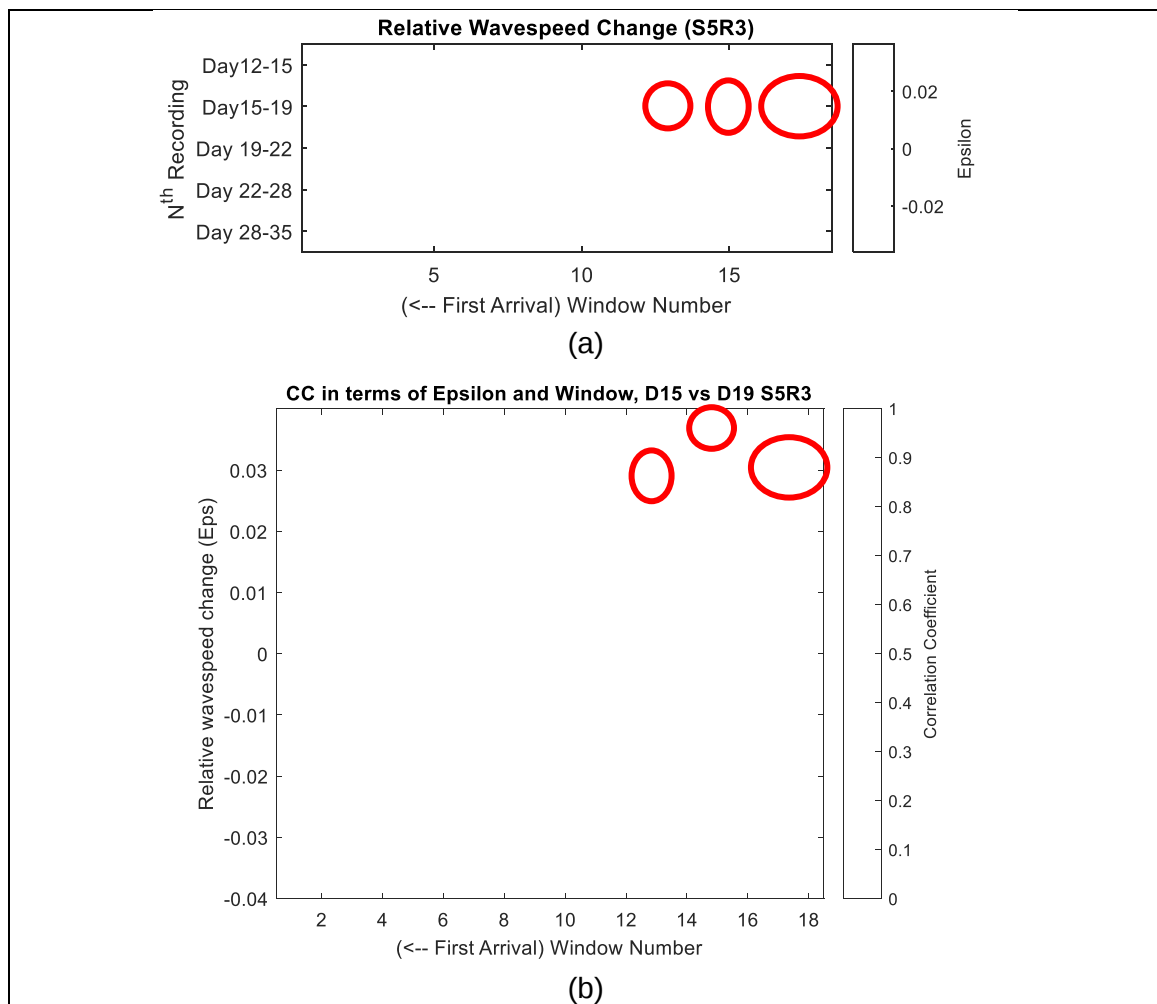


Figure 4.15. Cycle-skipping phenomenon: abnormal epsilon value is taken by the algorithm (a), through check on the recording shows that in these particular windows, the windowed signal seems to have cycle-skipped (marked red).

The color plot presented in Figure 4.15 b. may also be used to qualitatively assess the CWI quality of the signal pairs. For instance, for S1R2 signal comparison between day 19 and day

22 (Figure 4.16), it is observed that the highest correlation coefficient for each window lies approximately along one wavespeed change line for all windows, forming a well-defined line to indicate the 'actual' wavespeed change. While higher correlation coefficient values are also present away from the previously mentioned line, their values are lower compared to the ones in the line.

On the other hand, Figure 4.17 shows a pair of signals from day 15 and day 19 of S5R6 sensor pairs. While it still possesses the trend line of wavespeed change as in Figure 4.16, the trend line fades in the later part of the recording, while even in the earlier part of the recording, the wavespeed change is unstable from one window to another. Cycle-skipping phenomenon is observed here, as the algorithm picks the maximum correlation coefficient values which happen to be away from the main trend line.

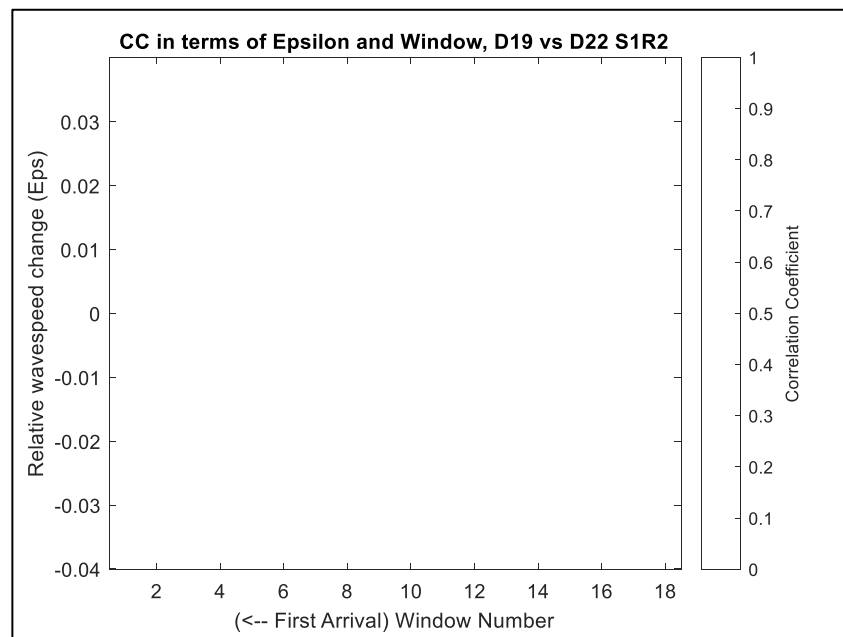


Figure 4.16. Color plot of S1R2 sensor pairs of day 19 and day 22 recordings.

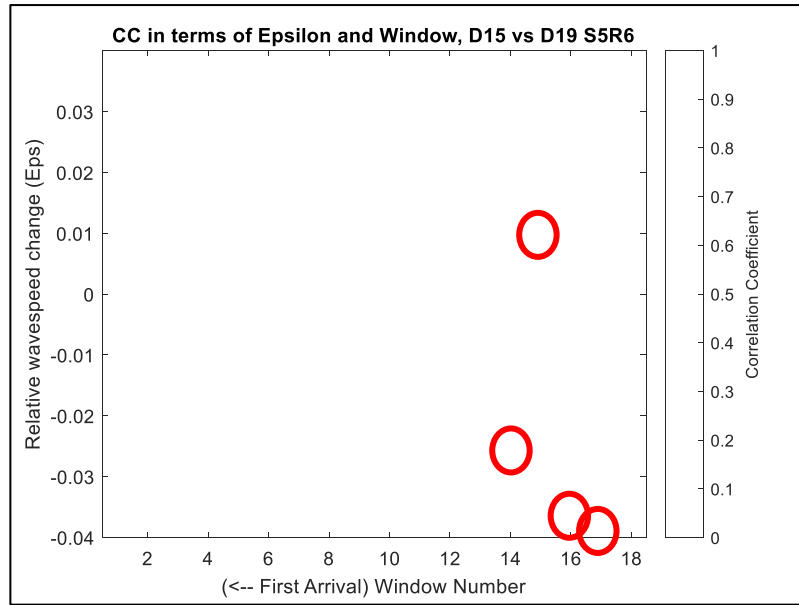


Figure 4.17. Color plot of S5R6 sensor pairs of day 15 and day 19 recordings. Notice the cycle-skipping phenomenon marked in red.

4.2.3. Practical implementation: estimation of Young's modulus through coda-wave interferometry

As CWI can be used to determine the change of wave speed in concrete throughout its aging process, it is beneficial to utilize it for assessing properties evolution of concrete which are related to wave speed. One such property is the modulus of elasticity, which relationship with P-wave speed.

$$V_p = \sqrt{\frac{E_d(1 - \nu)}{(1 - 2\nu)(1 + \nu)\rho}} \quad (1)$$

While CWI is capable in extracting the relative wavespeed change of the signal between days of recordings, it cannot be used for determining the absolute wavespeed of a signal. Therefore, the wavespeed of the medium can be determined by picking the first-arrival time and dividing it by the distance between the source and the receiver (Figure 4.18.). It is worth noting since the smart aggregates used in this experiment emit a combination of S- and P-waves, which means that the first signal received by the receivers is going to be a P-wave due to its higher propagation speed.

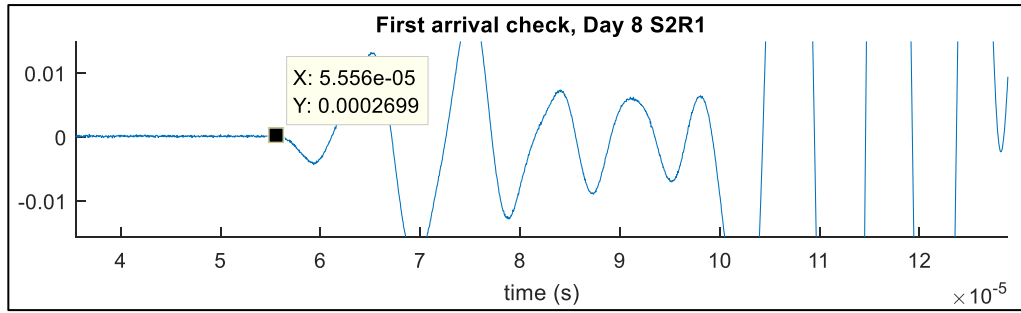


Figure 4.18. Picking the first arrival time of the signal.

By dividing the distance between two sensors (0.25m) by the first-arrival time of the signal in the 8th day recording (0.00005556 s), the P-wave propagation speed of the medium is obtained (4500 m/s). From the obtained wave speed, as well as by assigning the Poisson's ratio of concrete (0.2) and its mass density (2400 kg/m³), the dynamic elasticity modulus can be calculated. The elasticity modulus for the following days can also be calculated using the wavespeed changes obtained through CWI. The static modulus of elasticity is obtained by converting the previously obtained dynamic modulus of elasticity using Equation 9:

$$E_c = 0.83 E_d. \quad (23)$$

For comparison purposes, the result obtained using the above equation is compared with the modulus of elasticity calculated using Equation 7, which is extracted from *fib* Model Code [15] (Figure 4.19.). The complete calculation procedure is shown in Appendix A. By comparing the two, it is seen that the maximum error between the two methods is 4.08% on the 35th day from casting.

Table 4.1. Modulus of Elasticity gained through CWI vs ones gained by *fib* code.

Day	E_{CWI} (MPa)	$E_{Theoretical}$ (MPa)	Error
8	35577.59	36213	1.76%
12	36841.27	37478	1.70%
15	37310.43	38087	2.04%
19	37752.51	38671	2.38%
22	37925.43	39005	2.77%
28	38179.24	39508	3.36%
35	38297.1	39927	4.08%

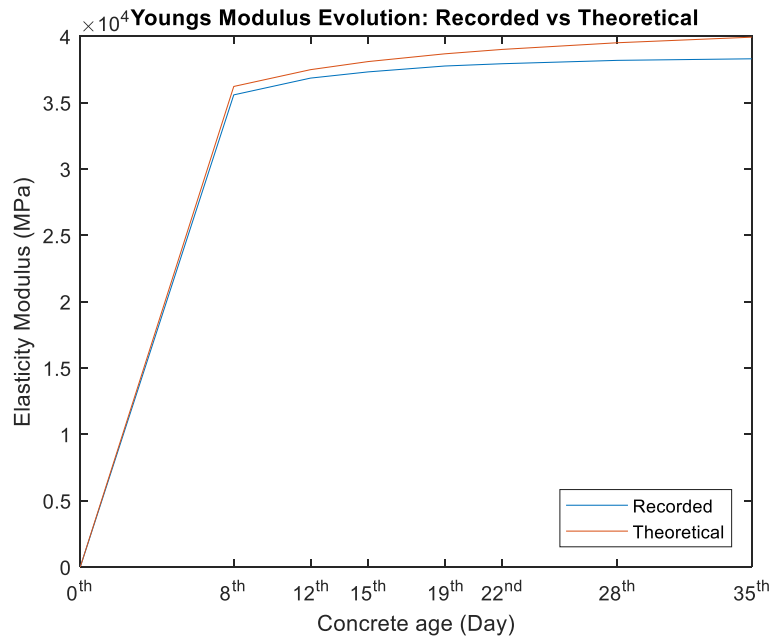


Figure 4.19. Elasticity-modulus evolution estimation from CWI and FIB code (theoretical).

4.3. Discussion

4.3.1. Analysis

For all the recording pairs, the CC tend to be lower for the later coda of the recordings compared to the CCs for in the first arrivals and the early coda. Such phenomenon can be explained by the fact that the later coda is more sensitive to subtle changes in the medium since it had scattered through the medium more than the earlier arrivals. In this case, the hydration process will alter the microstructure of the concrete, resulting in changes in the waveform of the signal over time. The choice of smart aggregates as sensors which has a central frequency of 88 kHz is good, since the frequency is not too high that the signals attenuate heavily, nor too low that the signals are not sensitive to changes occurring during the concrete-aging process.

Throughout the assessment period of 35 days, it is observed that in recordings involving the embedded sensors (sensor 1 and 2) show rise in the wavespeed over time. However, it is also observed in some recordings involving attached sensors (sensor 3, 4, 5, and 6), that decrease in wavespeed occurred. To investigate these conflicting results, reciprocity check is done by comparing the relationship between day of recording and relative wavespeed of the recording pairs. It turns out that the day of recording vs relative wavespeed relationship of S1R2 and S2R1 recordings are almost identical, while for the other pairs are not. The other check is by assessing the CC vs eps vs window colour plots like the one presented in Figure 4.15, in which the colour plots corresponding to sensor pairs containing attached sensors tend to have cycle-skipping in some part of the recordings. Such phenomenon occurs due to the poor coupling in this case between the sensors and the concrete sample, which in case of embedded sensors are not a problem.

As both the S1R2 and S2R1 recordings display increase in wavespeed as the aging process goes on, it is safe to say that the wavespeed indeed increases as the hydration process goes on. Such phenomenon is also expected to be followed by a change in waveform, since the increase of wavespeed is likely to be caused by CSH formations in the cement part of the concrete, as observed in a research by Diamond [33] and Scrivener [34] regarding cement paste microstructure evolution throughout hydration process.

4.3.2. Lesson learned

After conducting the experiment and analyzing the results, several things can be learned:

- The use of acoustic gel to attach smart aggregates is not desirable as the attachment of the sensors is not stable and could slide. Instead, the use of hot-melt adhesive is advised.
- More recordings should have been made earlier during the hydration process since the wavespeed changes more dramatically early in the hydration process.

4.3.3. Remarks and recommendations

From this part of this research, it can be concluded that

- The wavespeed increases as the concrete ages, which correlates with the densening of the cement paste of the concrete matrix as the hydration process goes on.
- Embedded smart aggregates perform significantly better in this case compared to attached smart aggregates, indicated by the lack of cycle-skipping issues and excellent reciprocity of recording couples involving only embedded smart aggregates. Coupling issues between the sensors and the concrete sample in attached smart aggregates seem to be the culprit since in this research the smart aggregates are attached by using acoustic gel couplant, which allows the sensors to be displaced.
- The later coda of the signals is the most sensitive to changes in the medium due to longer scattering path associated with them. Lower CC are expected since the later coda interacts more with the altered medium, which keeps changing due to the continuous hydration process.
- It is possible to use CWI to estimate the modulus of elasticity of concrete by assessing the concrete's wavespeed change as time goes.

Additionally, a few recommendations can be made for the continuation of this research:

- It is preferable that recording can be done daily instead of once in 3 or 4 days.
- The use of embedded smart aggregates is preferable. If attached smart aggregates are to be used, a proper couplant should be used.
- The assessment of different kinds of concrete, such as fiber-reinforced concrete or lightweight concrete is also recommended.
- Verification of the elasticity-modulus is best done with actual tests in addition to model prediction.

5. Coda-wave interferometry on concrete in compression

5.1. Experimental setup

5.1.1. Specimen setup

All the specimens except the second cylindrical specimen were cast on the 15th February 2018. The concrete being used is self-compacting C60/75 concrete, of which mix design is specified in Table 5.1. The second cylindrical sample was cast on the 12th July 2018 with the same concrete mix. Cubical samples were cast with dimensions of 150mm × 150mm × 150mm cubes, while cylindrical samples were cast with a diameter of 250mm and a height of 480mm. The cubes are cured in humid curing room, while the cylinders are cured inside their moulds covered with plastic wrap to prevent moisture from escaping.

Table 5.1. Concrete mix design.

Component	Amount for 40 liters
Sand	33.2 kg
Gravel	29.2 kg
CEM IIIB	11.4 kg
CEM IIIA	11.4 kg
Fillers (Fly Ash)	1.8 kg
Water	7.68 kg
Super Plasticizer	172 grams

LVDTs are attached on the surface of the samples longitudinal to the loading direction and are used to measure displacement between two points of the sample. This data will be used to estimate the longitudinal strain of the sample. All samples except the first cubical sample had two LVDTs attached, while the first cubical sample only had one. For cubical samples, two smart aggregates are installed by using hot-melt adhesive on flat sides facing each other perpendicular to the loading direction. On cylindrical samples, smart aggregates are cast into the sample, with distance between them of 250mm in the loading direction, where the lower smart aggregate is 80mm from the bottom of the cylinder and the top aggregate is 150mm from the top of the cylinder. The schematics of the specimens are displayed in Figure 5.1. for the cubical specimens and Figure 5.2. for the cylindrical specimens.

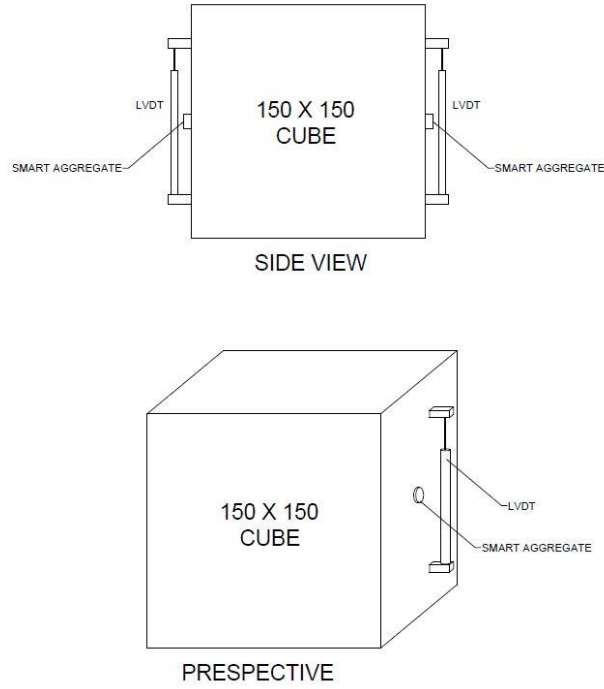


Figure 5.1. Schematic of a cubical specimen.

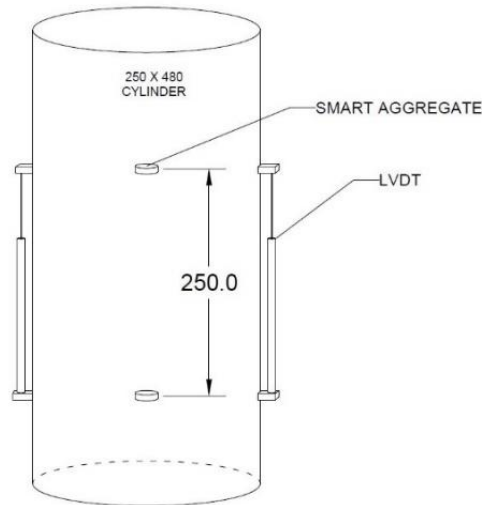


Figure 5.2. Schematic of a cylindrical specimen.

5.1.2. Coda-wave interferometry processing

CWI is done stepwise, which means that the difference in wavespeed is calculated by comparing the signal recorded for a load step to its adjacent two load steps. As stated in Chapter 3 of this thesis, the signal recordings are going to be split into windows of 8 wavelets each, resulting in 41 windows from a 2ms recording. To assess the result of CWI between two single steps, the resulting epsilon ($\frac{dv}{v}$) and correlation coefficient (CC) of all windows are plotted, as well as the two overlaid.

The aim in the CWI analysis of this part is to study the correlation between the stress and strain to the change of speed of the wave propagating through a specimen. Therefore, the relative wavespeed change vs stress and strain will be plotted. Since one pair of signals will result in 41 epsilon (dv/v) values due to the windowing, the average of these epsilon values from the windows having a CC value above a certain threshold are taken. As mentioned in Chapter 3, the threshold value is 0.8, unless mentioned otherwise.

5.2. Cubical specimen tests

5.2.1. Cubical sample tested through multiple time intervals

The first cubical sample was tested through several time gaps. The first test took place on 10th April 2018, followed by the second, third, and the last test which were done on the 18th, 22nd, and 28th May 2018. At the time of the first test, 54 days had passed since the sample was cast. The specimen before prior to loading is shown in Figure 5.3.



Figure 5.3. First cubical specimen before loading.

The loading scheme of the first day, shown in Figure 5.4., consisted of 6 load cycles. The load cycles' peak was increased in every two cycles, resulting in three peak stress levels: 3 MPa, 10 MPa, and 30 MPa, with an unloaded base stress of 1 MPa. After the second peak of each peak stress levels was reached, the sample was unloaded to the base stress without increment. Stress increments of 1 MPa were applied initially, which were increased to 2 MPa load increments for stress levels above 10 MPa. Detailed loading history of the test is shown in Figure 5.4. The loading rate of the sample was 3.48 kN/s, which corresponds to a strain rate of approximately 4.5×10^{-6} /s. The stress vs strain graph of this test is shown in Figure 5.5. Signal recordings were taken at each load increment.

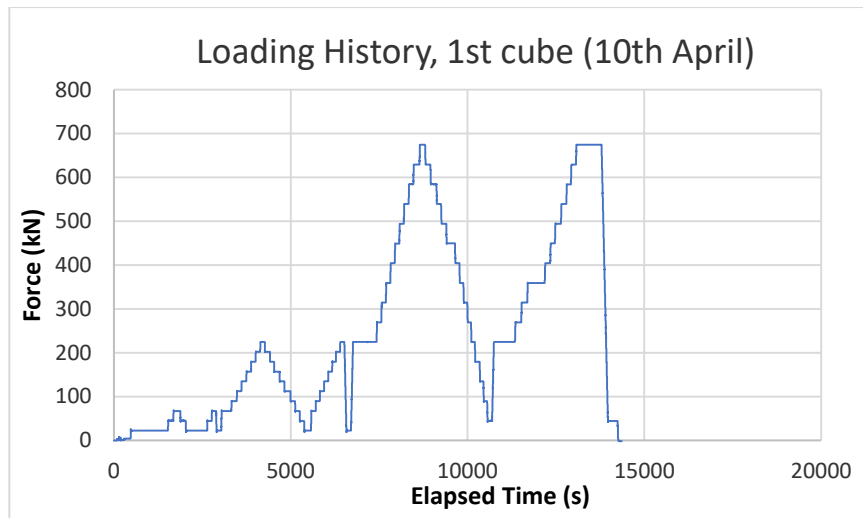


Figure 5.4. Loading history of the test done on the 10th April 2018 on the first cubical specimen.

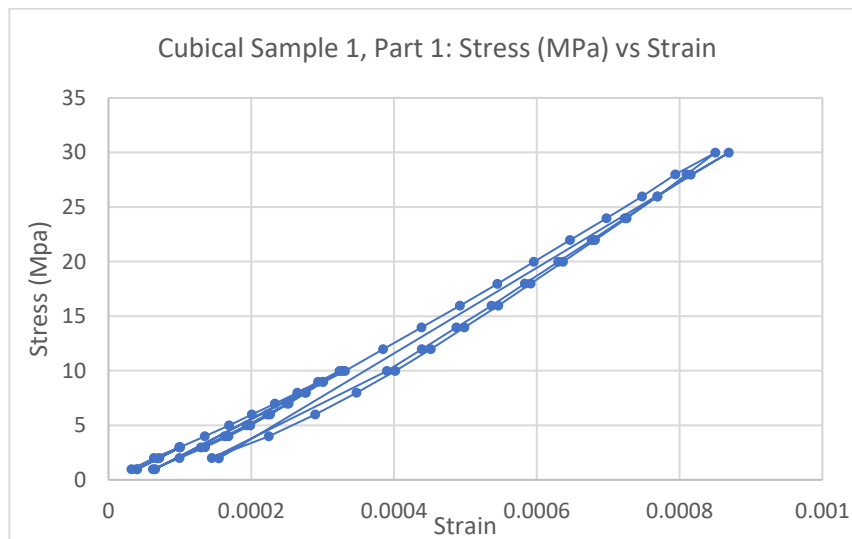


Figure 5.5. Stress vs Strain graph of the test done on 10th April 2018 on the first cubical specimen.

After the test had been done, CWI was conducted, and the relative wavespeed change was calculated. As stated previously, CWI was done stepwise, which means the reference signal of a stretched signal was a signal from the preceding load step, or in case of big steps such as the second unloading step, the reference signal was the signal previously recorded with at same stresses. It was found that recording pairs at lower load levels (Figure 5.6.) tend to have less stable epsilon values and lower CC values between windows compared to recordings taken at higher load levels (Figure 5.7.).

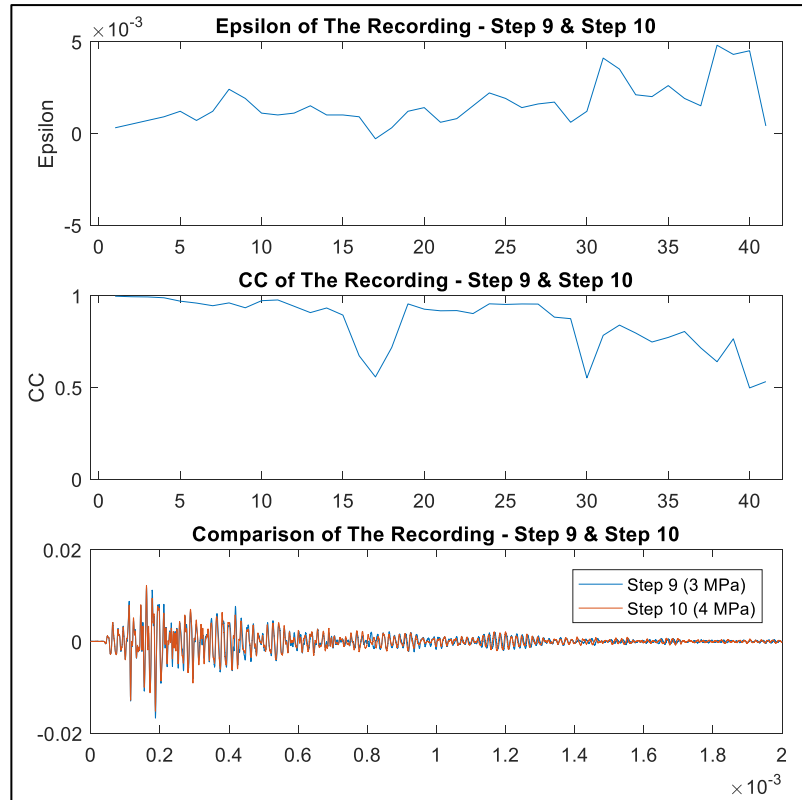


Figure 5.6. CWI result for a pair of recordings at lower load level (3 MPa and 4 MPa).

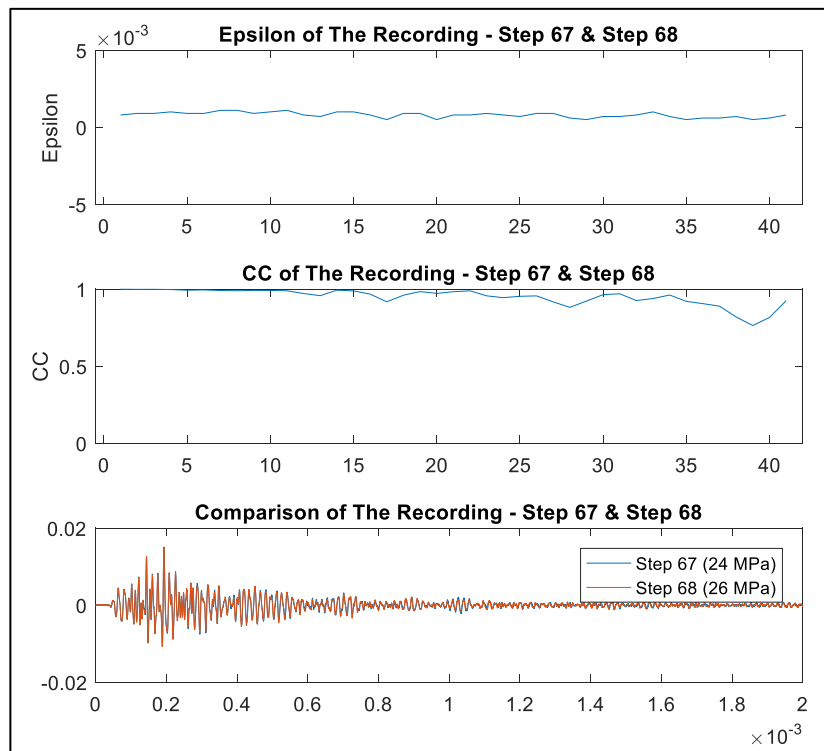


Figure 5.7. CWI result for a pair of recordings at higher load level (24 MPa and 26 MPa).

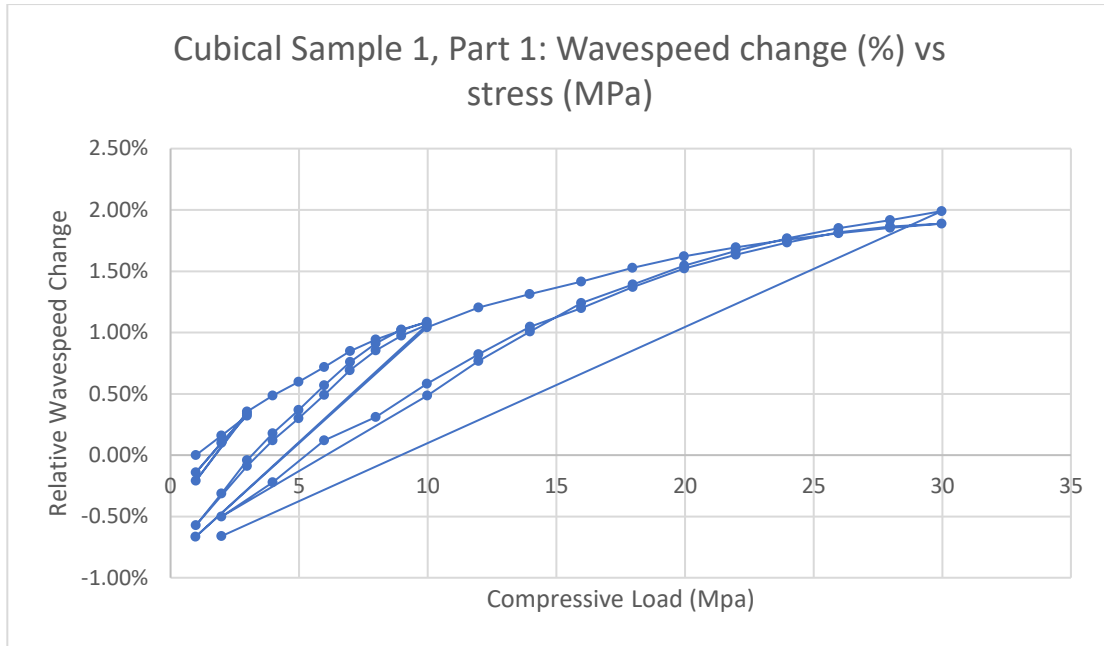


Figure 5.8. $\frac{dv}{v}$ (epsilon) vs stress on the cubical sample tested on the 10th April 2018.

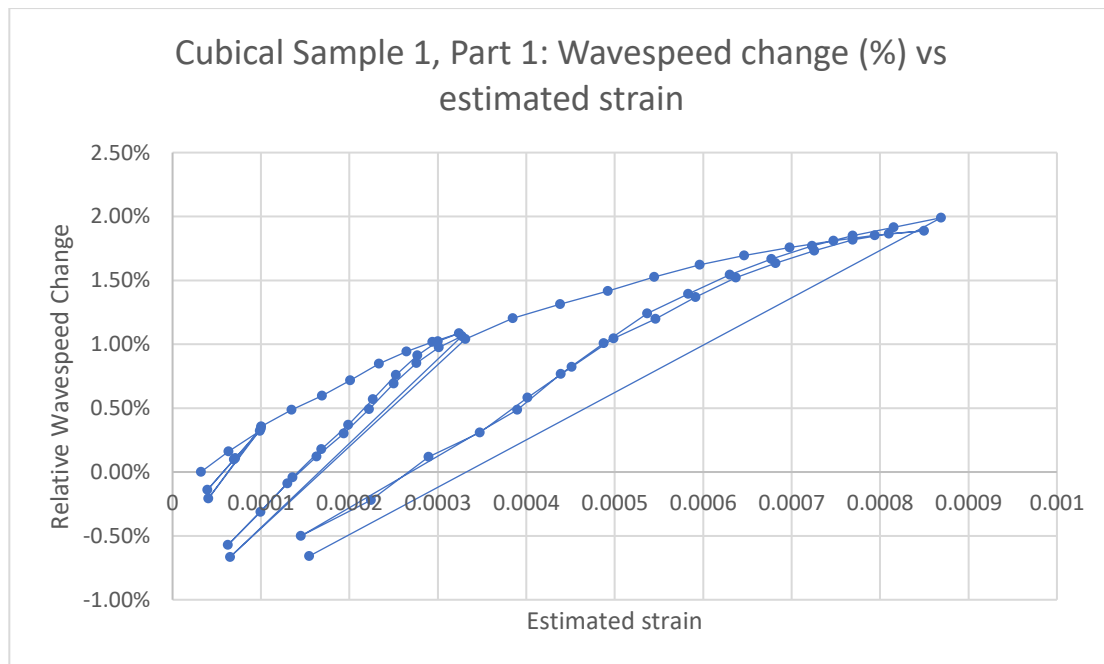


Figure 5.9 $\frac{dv}{v}$ (epsilon) vs estimated strain on the cubical sample tested on 10th April 2018

From the result of the first day test, it can be observed that the initial part of the loading path displays a linear $\frac{dv}{v}$ (epsilon) vs stress (Figure 5.8.) and $\frac{dv}{v}$ vs strain (Figure 5.9.) relationships, before the gradient reduces as the stress and strain increases. Upon unloading, the end values of the wavespeed tend to be lower compared to the ones prior the loading. Another point which is worth mentioning is that upon reloading, epsilon vs stress and strain paths tends to follow their previous unloading paths up to the previous load levels. Upon

reaching the previously reached load level, the $\frac{dv}{v}$ vs stress and $\frac{dv}{v}$ vs strain gradients change, linking with the $\frac{dv}{v}$ vs stress and $\frac{dv}{v}$ vs strain of previous loading phases. Such phenomenon creates an envelope in $\frac{dv}{v}$ vs stress and $\frac{dv}{v}$ vs strain curves.

As seen in Table 5.2., the first cycle had lower $\frac{dv}{v}$ vs stress and strain gradient of 0.0016 and 47.83, respectively, compared to the other cycles. The gradient seems to increase with the load cycle number; however, it was observed that the 4th cycle had lower initial $\frac{dv}{v}$ vs stress and strain gradient compared to the 3rd cycle.

Table 5.2. Wavespeed change vs stress and strain initial gradients – 1st cubical sample, 10th April.

Load Cycle	$\frac{dv}{v}$ σ	$\frac{dv}{v}$ Strain	Previous Maximum Stress (MPa)
1	0.00160435	47.8254728	0
2	0.00240344	79.55844869	3
3	0.0028237	94.02773578	3
4	0.0024136	71.70129151	10

Follow-up tests are done on the 18th May, 22nd May, and 28th May. In these tests, smaller load steps are adopted, especially at lower load phases. In the test conducted on the 18th May, the test is halted for around an hour for lunch break, of which during the break the sample was completely unloaded midway. The loading scheme was rather similar to the preceding test; however, all the unloading phases are incrementally done. The load peak points for the test on the 18th and 22nd of May are 10 MPa, 45 MPa, and 55 MPa. On the 28th May, the sample was loaded until failure. The detailed loading history of the tests are shown in Figure 5.10., Figure 5.11., and Figure 5.12. Additionally, the stress vs strain graph of these tests is shown in Figure 5.13.

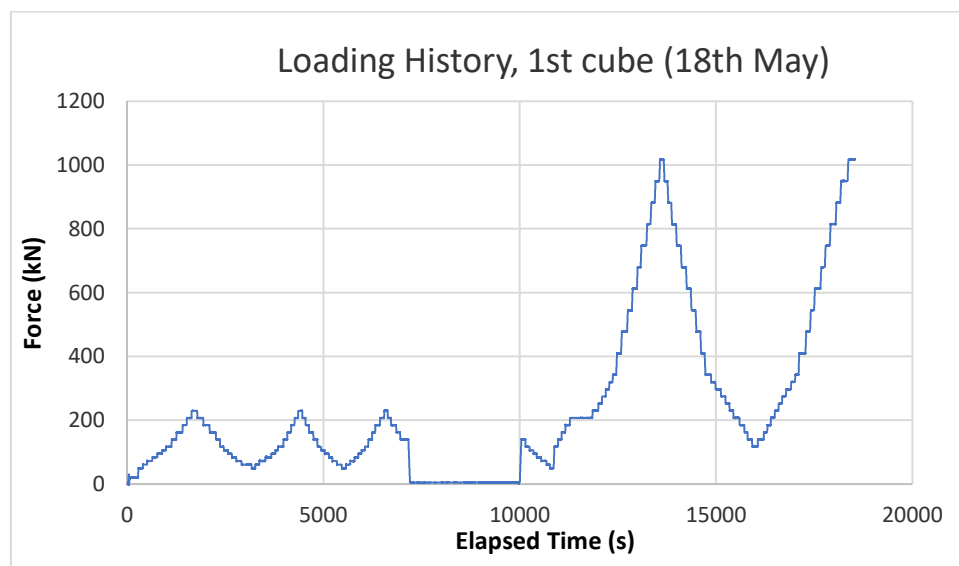


Figure 5.10. Loading history of the test done on the 18th May 2018 on the 1st cubical specimen.

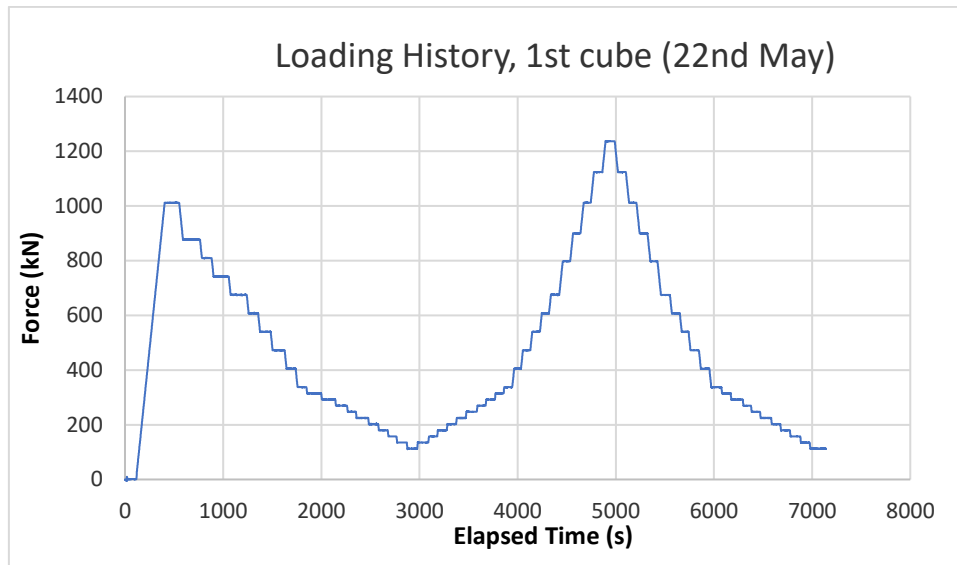


Figure 5.11. Loading history of the test done on the 22nd May 2018 on the 1st cubical specimen.

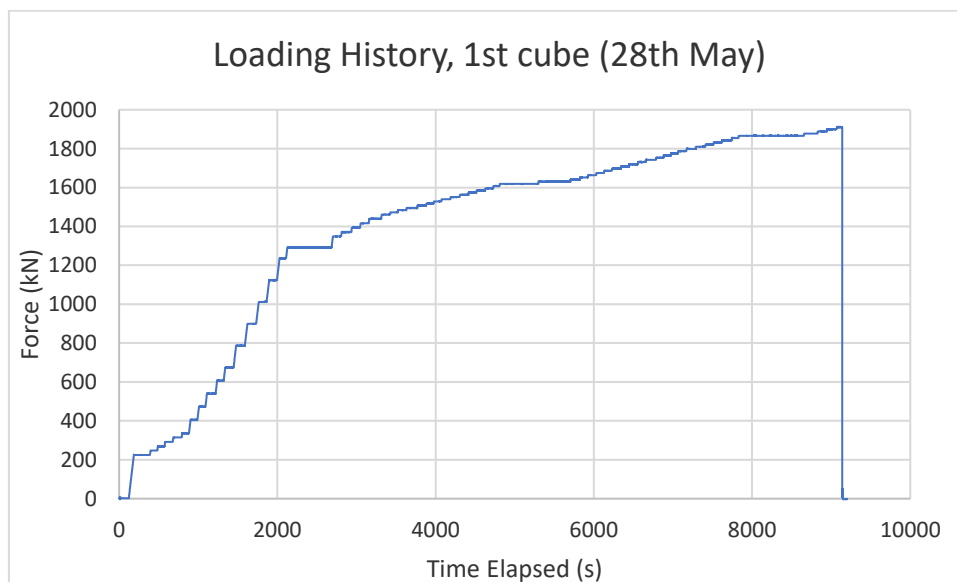


Figure 5.12. Loading history of the test done on the 28th May 2018 on the 1st cubical specimen.

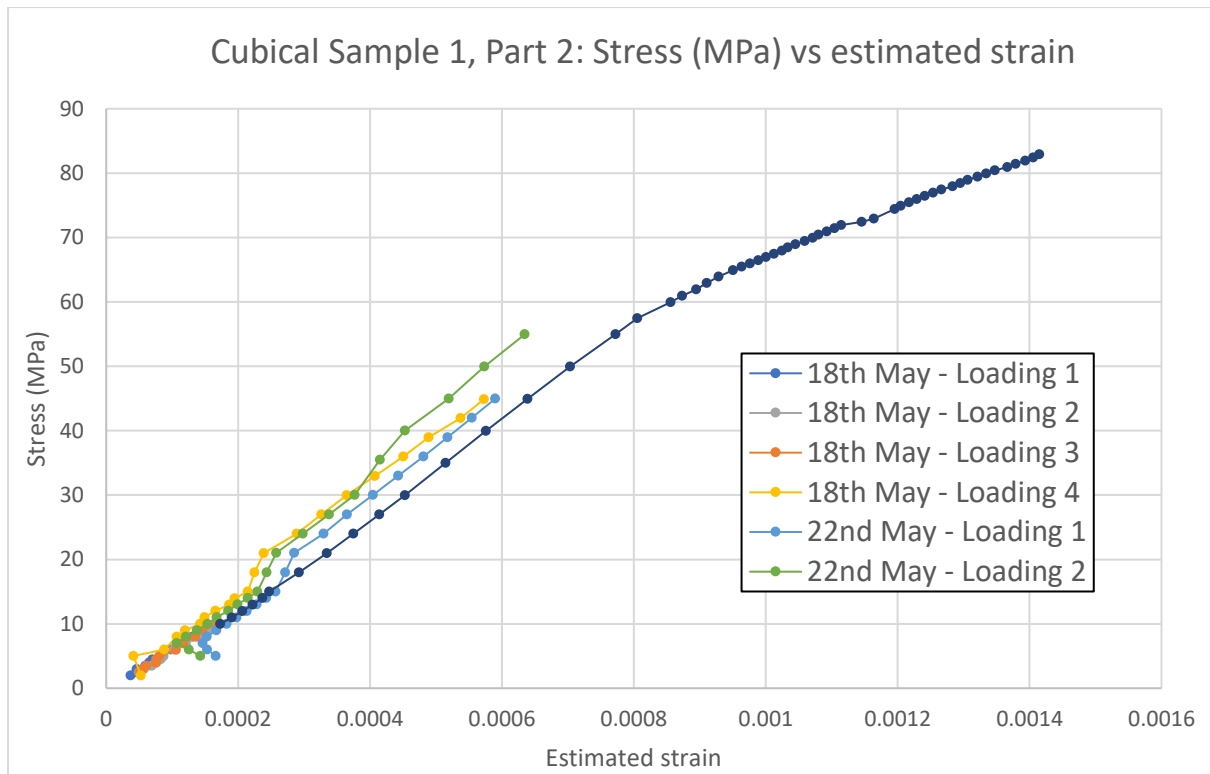


Figure 5.13. Stress vs estimated Strain curve of the second part of the test on the 1st Cubical Specimen.

When processing the data from tests done at three different days, it was noted that while the load level was the same between the final step of the preceding day and the first step of the following day, the waveform between the two was not similar, as seen in Figure 5.14. Therefore, pairs of recordings with the same load were cross-correlated to link the recordings taken at different days; recording at 45 MPa was used to link recordings of the 18th and 22nd May and recording at 30 MPa to link the ones at the 22nd and 28th May. The reference wavespeed of the tests is the load speed at the first load step (2 MPa) of the test done on the 18th May.

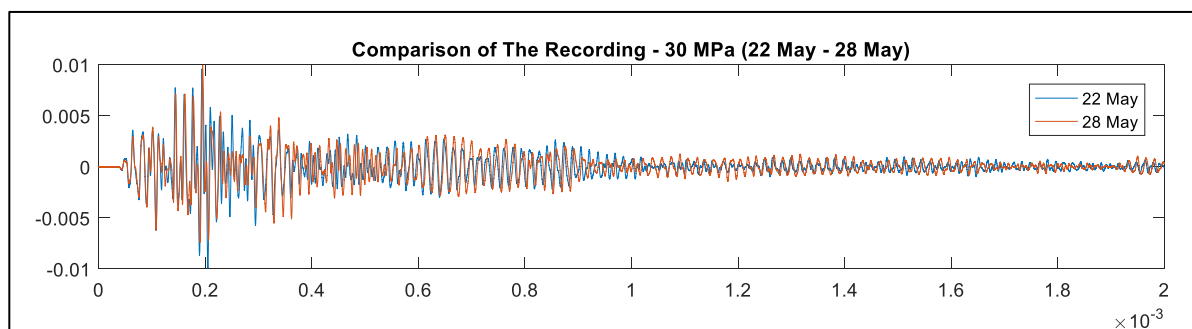


Figure 5.14. Comparison of recordings taken on the 22nd and 28th May at 30 MPa.

Both wavespeed change vs. stress and strain graphs display initial linear trend, before the gradients start to decrease as the loading increases. First unloading phase ends with a lower wavespeed compared to the reference wavespeed (Point A on Figure 5.15. and Figure 5.16.). The two following loading and unloading phases with a repeating peak stress at 10 MPa follow an identical path; at their peak stress level they were characterized by a wavespeed similar to

the one for the first loading phase at 1.5% faster from reference speed (Point B on Figure 5.15. and Figure 5.16.). Similar with the preceding test done on the 10th April, the $\frac{dv}{v}$ decreases as the specimen is loaded further.

The fourth unloading and fifth loading phases are where the wavespeed change vs stress and strain start to differ in trend (Point C on Figure 5.15. and Figure 5.16.). In wavespeed change vs stress graph, the reloading phase diverged from its preceding unloading phase, while the wavespeed change vs strain path of the reloading follows its preceding unloading path more closely. Similar occurrences are also observed at point D, where the first unloading and its following loading phase share the same path in wavespeed change vs. strain graph, while the same cannot be said for the wavespeed change vs. stress graph, where differences in the wavespeed at the same load levels of both phases are observed.

The wavespeed change vs. stress graph in the loading phase of the 28th May test is completely detached from the last unloading phase of the 22nd May, while in the wavespeed change vs. strain graph, the path of this loading phase follows closely the graph of the preceding unloading phase up to 30 MPa load level (Point E on Figure 5.15. and Figure 5.16.). It is also observed that towards the sample failure, the wavespeed change vs stress graph shows rather significant change in gradient, while this change is more gradual in the wavespeed change vs strain graph (Point F on Figure 5.15. and Figure 5.16.).

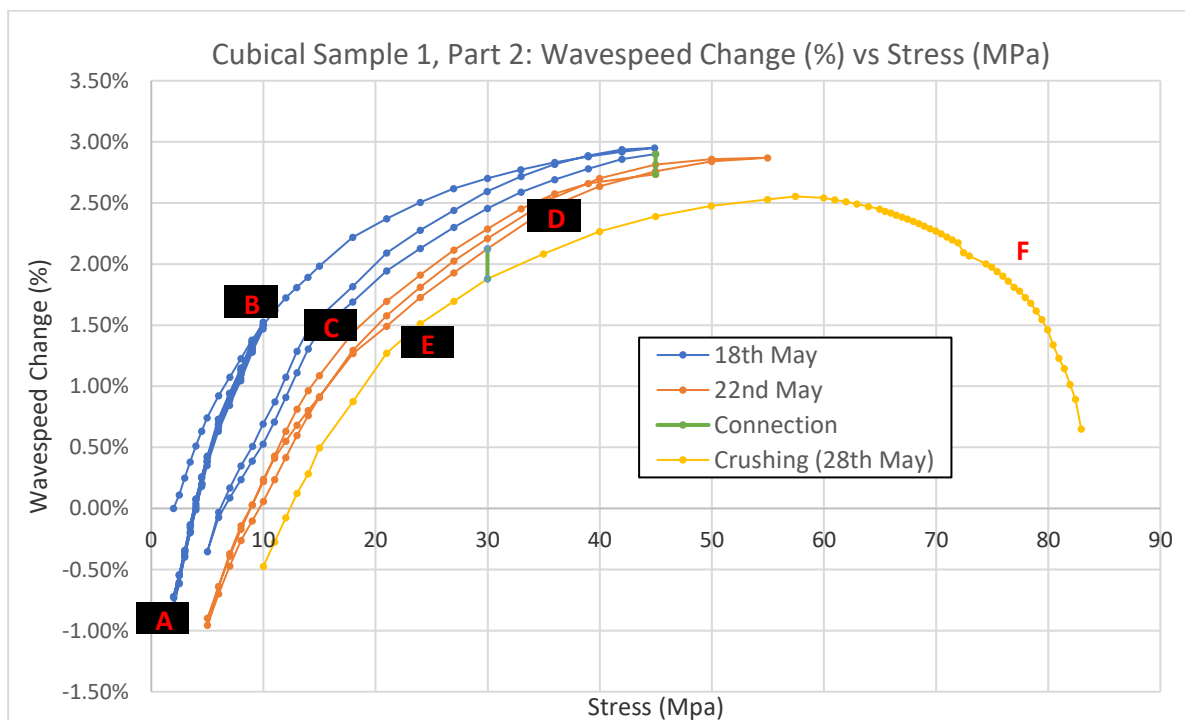


Figure 5.15. $\frac{dv}{v}$ (epsilon) vs load on the cubical sample tested between the 18th to 28th May 2018.

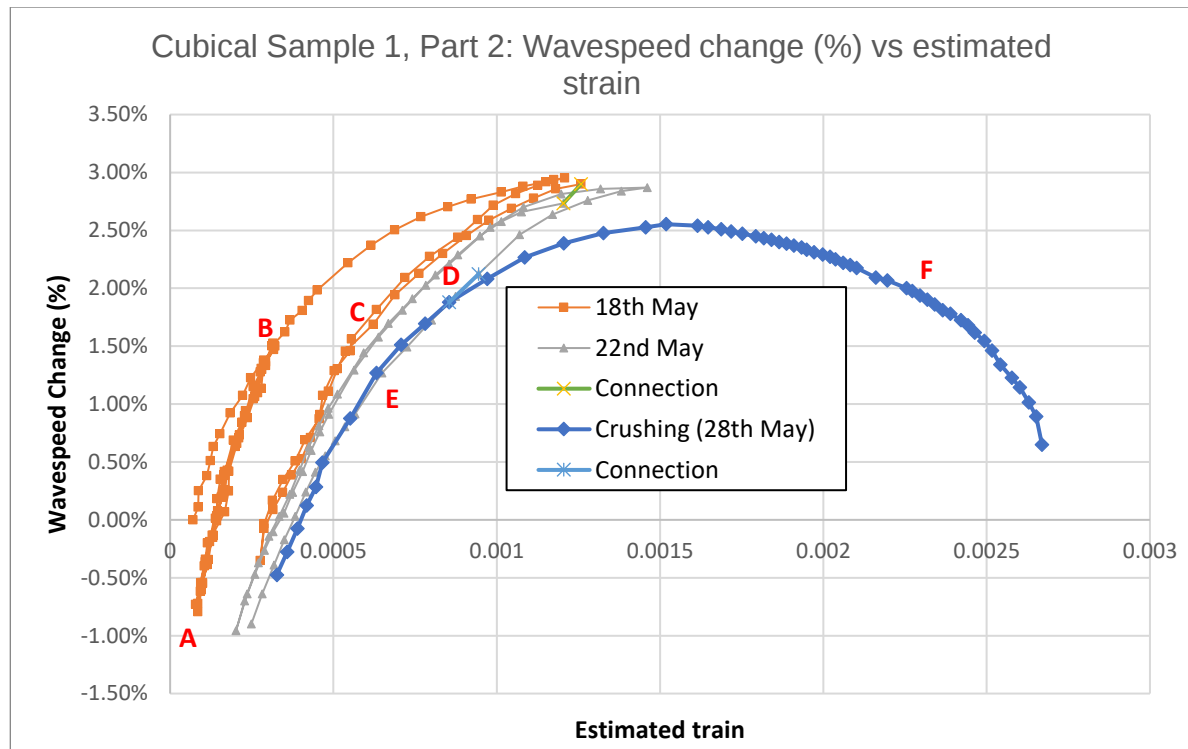


Figure 5.16. $\frac{dv}{v}$ (epsilon) vs estimated strain on the cubical sample tested between the 18th to 28th May 2018.

When compared to the $\frac{dv}{v}$ vs stress and strain gradients of the test conducted on the 10th April, it is observed that both the initial $\frac{dv}{v}$ vs stress and strain gradients of the first cycle are higher on the 18th May test. While in most cases both $\frac{dv}{v}$ vs stress and strain gradients increase in each load step, some exceptions are observed; $\frac{dv}{v}$ vs stress and strain gradients of the 5th cycle are lower than the ones of the 4th cycle, while the $\frac{dv}{v}$ vs strain gradient of the 6th cycle is lower than the one of the 5th cycle. The initial $\frac{dv}{v}$ vs stress and strain gradients of the second phase of the test are listed in Table 5.3.

Table 5.3. Wavespeed change vs stress and strain initial gradients – 1st cubical sample, 18th to 28th May.

Load Cycle	$\frac{dv}{v}$ σ	$\frac{dv}{v}$ Strain	Previous Maximum Stress (MPa)
1	0.0018828	58.79413	30
2	0.002723	95.21558	30
3	0.002745	95.33738	30
4	0.0028694	91.60504	30
5	0.0017544	64.07174	45
6	0.0018272	63.65134	45
7	0.001919	63.93299	55

Prior to failure, the waveform had changed so much that it was impossible to conduct CWI of the signals recorded from the final load steps. Significant reduction in amplitudes is also

observed in the waveform recording of the last load step prior to failure, as seen in Figure 5.17. The failure itself was sudden and explosive, resulting in aftermath shown in Figure 5.18.

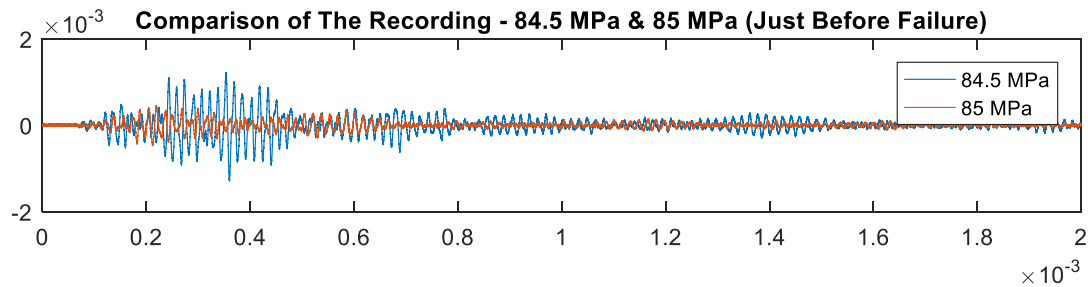


Figure 5.17. Waveform comparison between the last two load steps before failure. CWI cannot be applied in these two signals.

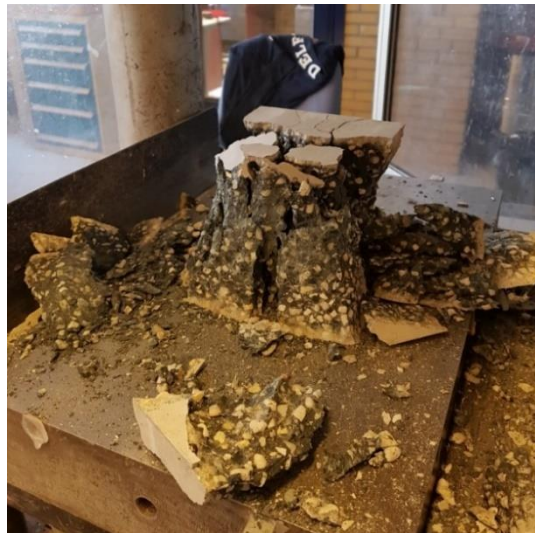


Figure 5.18. First cubical specimen after failure.

5.2.2. Cubical sample tested with early damage occurrence

The second cubical sample underwent early damage in its early loading phase. The test was done on the 5th September 2018, at the time when the concrete had already been 171 days old. The test was split into 3 cycles: the first two were loading cycles consisting of loading and unloading parts which loaded the specimen up to 14 MPa and 34 MPa, respectively, with load steps varying between 1 MPa for load steps with stress level lower than 22 MPa to 2 MPa for load steps with stress level above 22 MPa, while the third cycle was loading the specimen gradually until failure. Detailed loading history of this sample is presented in Figure 5.19., while the stress vs. strain relationship of the test is presented in Figure 5.20. CWI results of the recordings in the first two cycles tend to have lower CC and inconsistent epsilon values within the windows throughout the signal. The crushing part was done with finer load steps (0.5 MPa) throughout the loading process. The sample failed at 77.5 MPa.

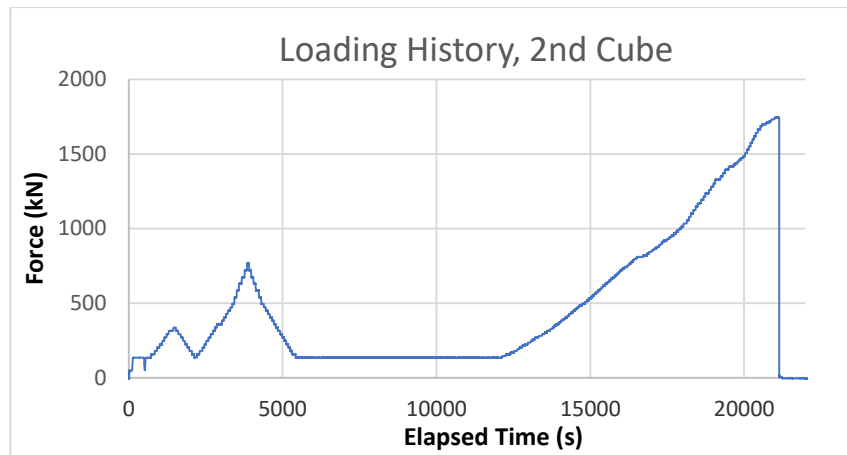


Figure 5.19. Loading history of the 2nd cubical specimen.

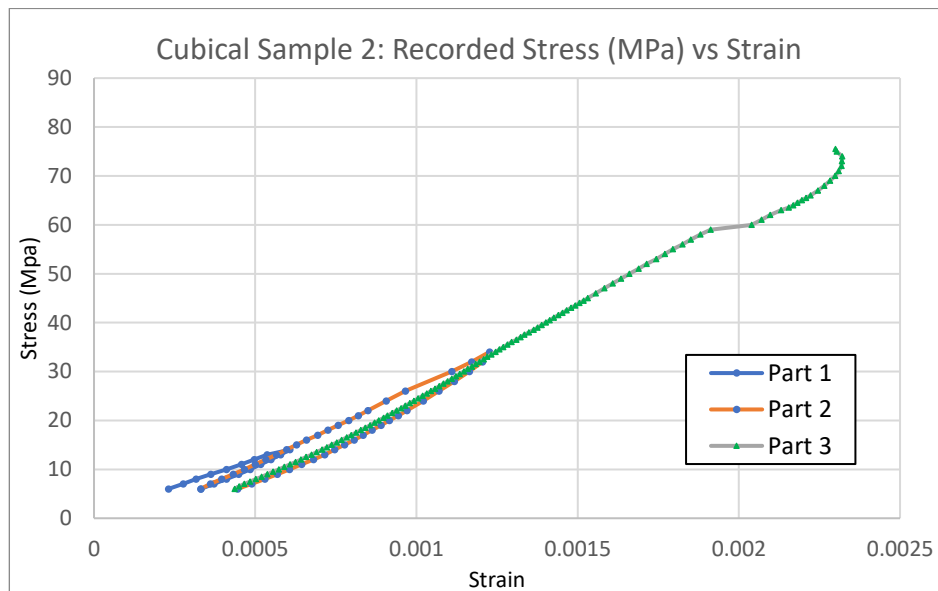


Figure 5.20. Stress vs Strain of the 2nd cubical specimen.

Cracks were observed at the end of the second cycle, as seen in Figure 5.24. These cracks were monitored throughout the third cycle. These cracks seemed to be localized at the edge only, appearing in two facing sides of the cube. As the loading progressed, no other cracks were observed until a moment prior to failure, when small cracks were opening at the corners near the previously created cracks.

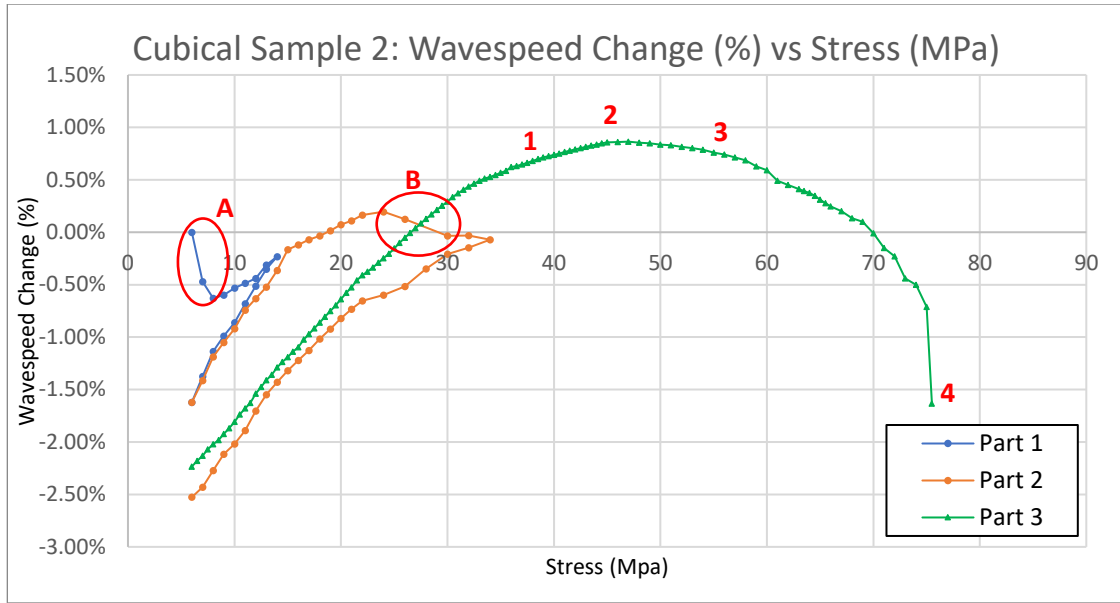


Figure 5.21. $\frac{dv}{v}$ (epsilon) vs load on the second cubical sample.

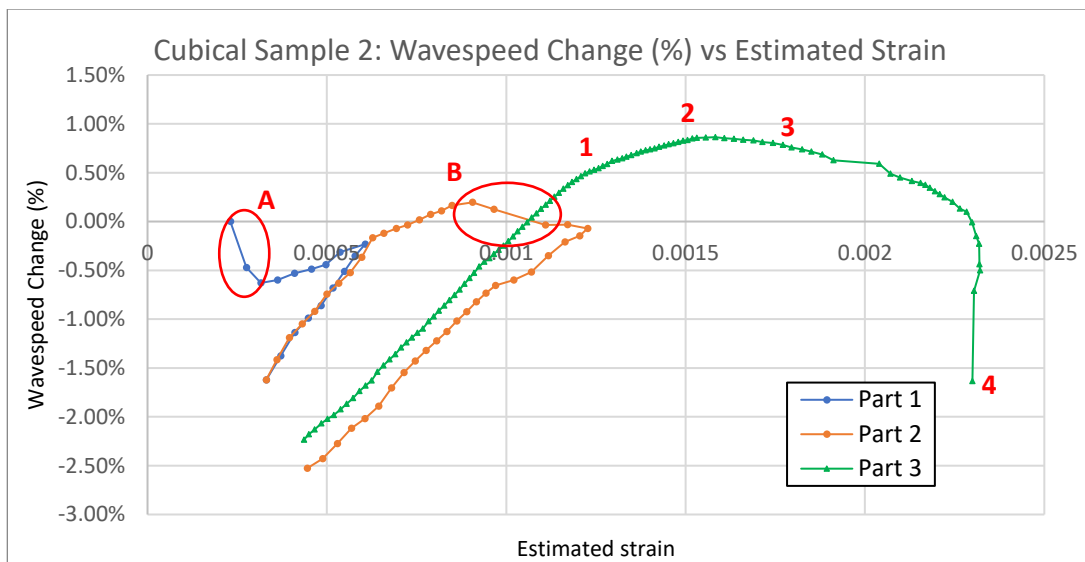


Figure 5.22. $\frac{dv}{v}$ (epsilon) vs strain on the second cubical sample.

In the $\frac{dv}{v}$ vs load (Figure 5.21.) and strain (Figure 5.22.) graphs, negative gradients are observed in the first two load steps on the first cycle (Detail A on Figure 5.21. and Figure 5.22.). While the gradients increase as the loading proceeds, the wavespeed at the peak load of first cycle is 0.23% lower than the reference wavespeed. Unloading to the base stress of 6 MPa led to a drop of wavespeed to -1.62% from the reference wavespeed.

The initial phase of the reloading step of the second cycle follows roughly a linear line from 6 MPa to 14 MPa, with the reloading path following the preceding unloading path more closely in wavespeed change vs strain graph compared to the wavespeed change vs stress graph. Upon reaching the peak stress of the previous load cycle of 14 MPa, both wavespeed vs stress and strain paths resume the loading path of the preceding cycles, creating an envelope.

Another negative gradient is observed starting from 24 MPa load step, which has a relative speed difference of 0.20% from the reference wavespeed (Detail B), before dropping to -0.07% at the peak load of the second cycle (34 MPa). The final wavespeed difference at 6 MPa upon unloading is -2.53% from the reference wavespeed.

Since these two points where negative wavespeed change vs. stress and strain occurred at a stress much lower compared to the expected failure stress of the sample, the detailed CWI results of the two load steps for detail A and detail B are presented in Figure 5.23. In the subfigures, erratic changes in $\frac{dv}{v}$ and CC are observed, with the first load step of detail A displays the most significant changes of $\frac{dv}{v}$ and CC values among the recording windows.

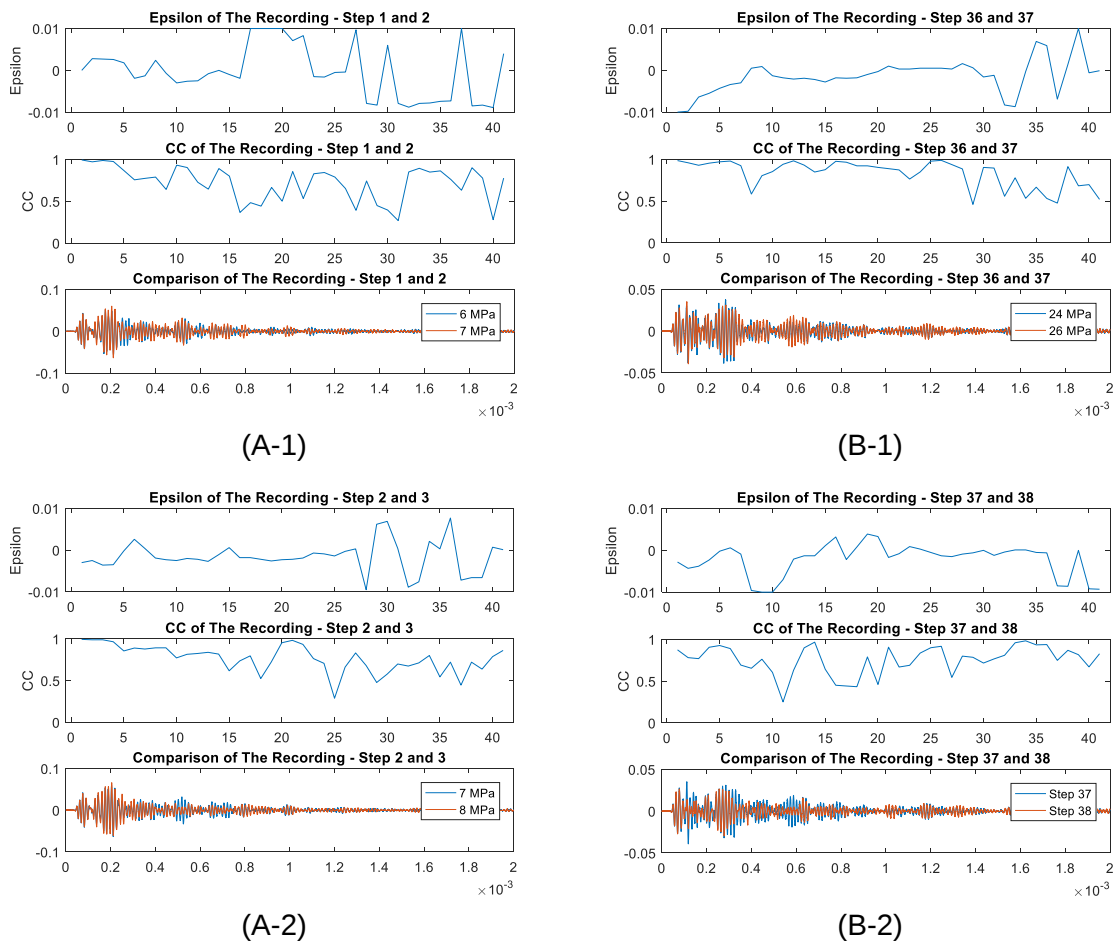


Figure 5.23. Detail of CWI results of detail A and B of Figure 5.21. and Figure 5.22.

The third load cycle was aimed to load the specimen until failure. At the start of the third cycle, an increase in wavespeed from -2.53% to -2.23% from the reference speed after a sustained 90 minutes of loading is observed. Linear $\frac{dv}{v}$ vs stress and strain relationships are observed up to load level 21.5 MPa, where the $\frac{dv}{v}$ vs stress and strain started to level off. The first negative $\frac{dv}{v}$ vs stress and strain is observed at 47 MPa of load, where the relative wavespeed is 0.86% faster than the reference speed. CWI is no longer conductible beyond the load level of 75 MPa due to significant changes in the waveform and reduction in amplitude. Throughout this load cycle, the existing cracks are monitored. Five monitoring points are taken at 37.5 MPa (point 1 in Figure 5.21. and Figure 5.22.), 46 MPa (point 2 in

Figure 5.21. and Figure 5.22.), 55 MPa (point 3 in Figure 5.21. and Figure 5.22.), 75.5 MPa (point 4 in in Figure 5.21. and Figure 5.22.), and 77 MPa (not shown in Figure 5.21. and Figure 5.22.). These monitoring points were decided whenever cracking sound were emitted by the sample. The crack evolution observed in each monitoring points are shown in Figure 5.25.

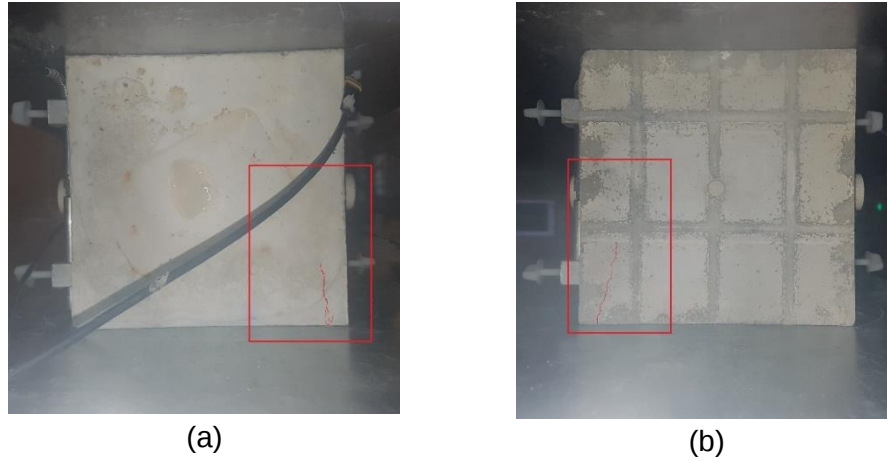


Figure 5.24. Crack as observed at the beginning of load cycle 3. The sides are identified as (a) and (b).

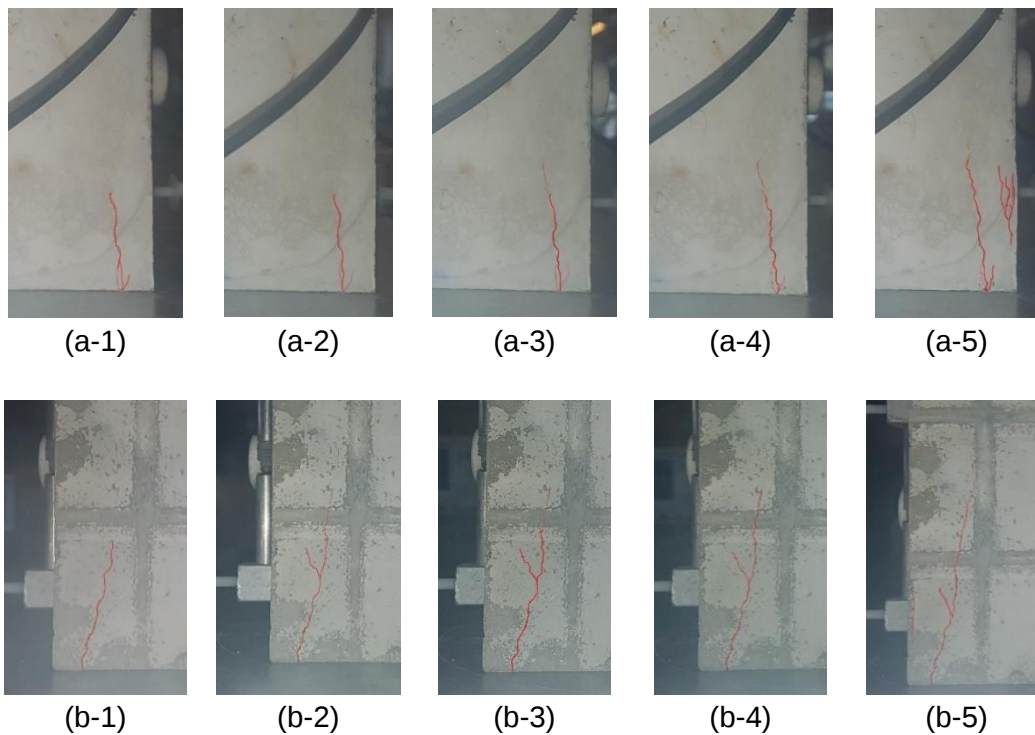


Figure 5.25. Evolution of cracks on both sides. Monitoring point 1 is at 37.5 MPa, 2 is at 46 MPa, 3 is at 55 MPa, 4 is at 75.5 MPa, and 5 is at 77 MPa. Subfigure (a-1) means side a on monitoring point 1.

It is of interest to assess the CWI results to see how crack evolution influences signal waveform and $\frac{dv}{v}$ of the recording. In any given load steps between monitoring point 1 and 3, it can be observed that despite the crack widening is observed visually, the CWI results within these range are stable with near-perfect cross-correlation to one another (Figure 5.26.).

Noticeable change in waveform happened starting from 68 MPa, which is located somewhere between monitoring point 3 and 4. From that point on, the waveform started to change more significantly in each following load step, which was indicated by drop in CCs and great variation of $\frac{dv}{v}$ in between the windows of the recordings (Figure 5.27.). From point 4 to 5, significant change in waveform occurred in each load step, as seen in Figure 5.28., which rendered CWI unusable.

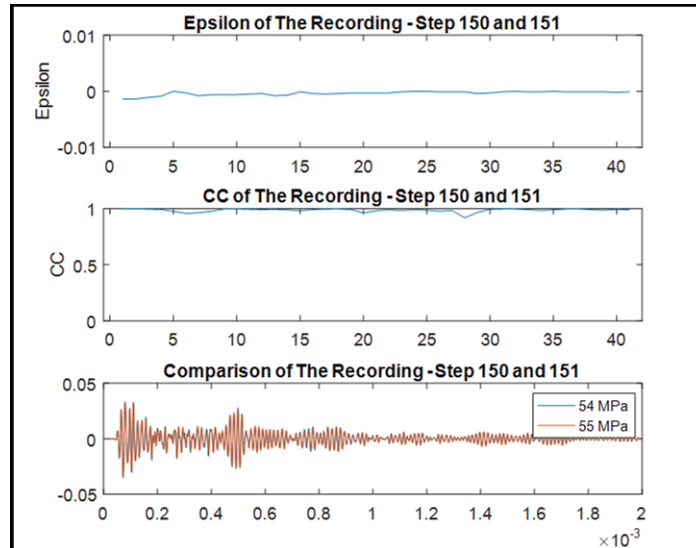


Figure 5.26. Typical CWI result taken between monitoring point 1 and 3. Notice consistent epsilon ($\frac{dv}{v}$) value and near-perfect CC in all windows.

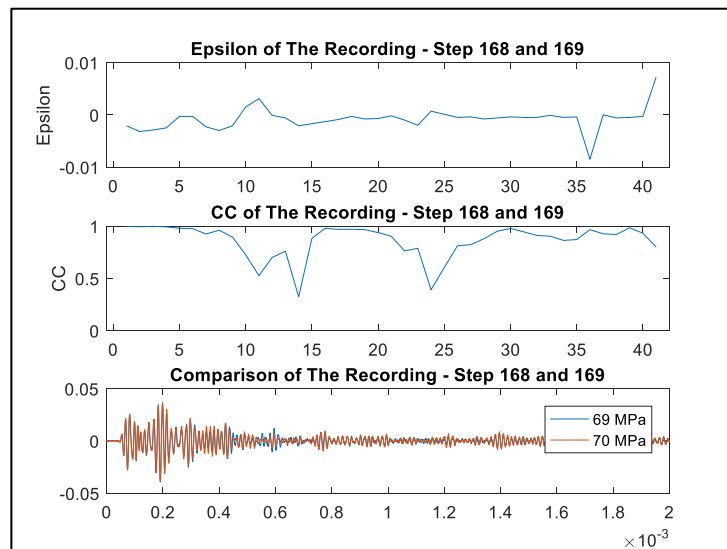


Figure 5.27. A CWI result taken between monitoring point 3 and 4. Notice inconsistent $\frac{dv}{v}$ value and drops in CC in some windows.

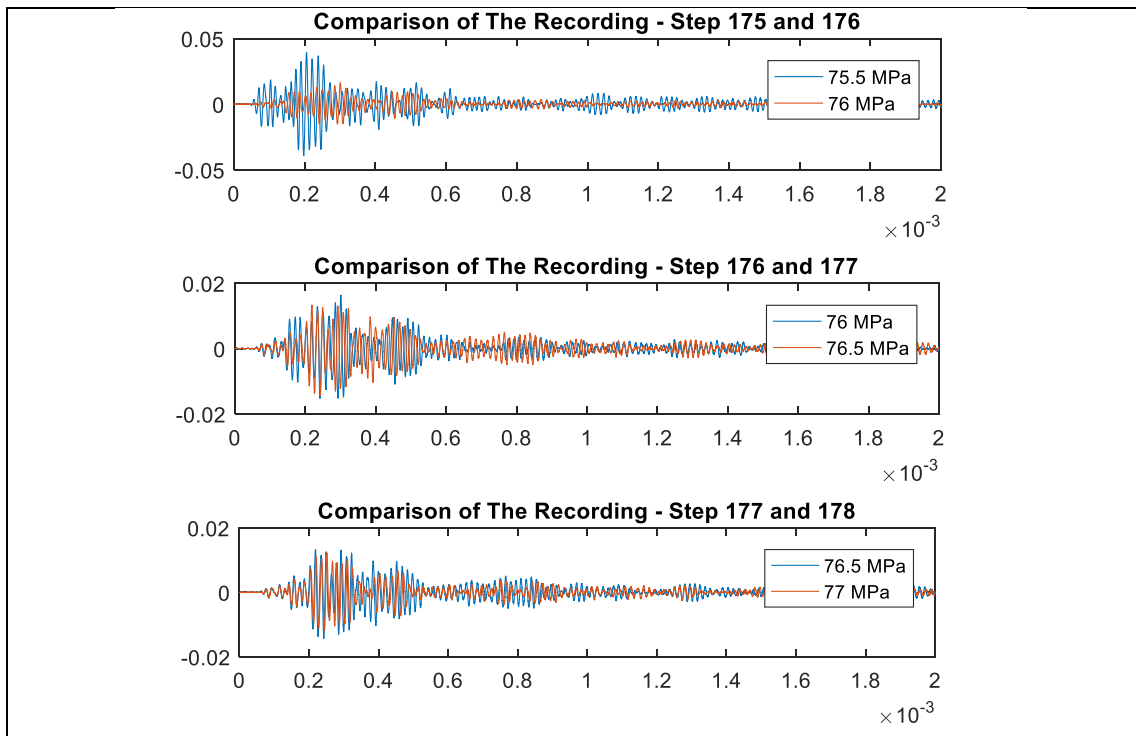


Figure 5.28. Waveform evolution from monitoring point 4 (75.5 MPa) to monitoring point 5 (77 MPa).

The initial wavespeed vs. stress and strain of each cycle is calculated. Since the loading phase of the first cycle started with a negative gradient, the first positive gradient of the cycle was taken instead. Unlike other tests, the wavespeed vs stress and strain initial gradients do not follow a particular trend. However, it is noted from Table 5.4. that wavespeed vs strain initial gradient of the third cycle resembles its predecessor more than the wavespeed vs stress gradient.

Table 5.4. Wavespeed change vs stress initial gradients – 2nd cubical sample.
(*gradient of the first cycle is calculated after the decrease of wavespeed stopped).

Load Cycle	$\frac{dv/v}{\sigma}$	$\frac{dv/v}{\text{Strain}}$	Previous Maximum Stress (MPa)
1	0.00066054*	10.825	0
2	0.0016173	37.346	14
3	0.0011536	36.498	34

The sample failed after sustaining 77.5 MPa of stress for a period of time. The aftermath of the test can be seen in Figure 5.29.



Figure 5.29. Second cubical specimen after failure.

5.3. Cylindrical specimen tests

5.3.1. First cylinder test

The test started on the 4th July and ended on the 5th July 2018, at which time that the specimen was 139 days old. The first day consisted of 5 cycles of loading; the first two cycles had a peak stress of 15 MPa and the next three had a peak stress of 40 MPa. The third cycle did not contain any unloading steps, and there was a time gap between the third and the fourth cycle, during which gap the sample was fully unloaded. The detailed loading history of the first day of the test can be seen in Figure 5.30. Spalling was noticed at the end of the third loading cycle, as seen on Figure 5.31.

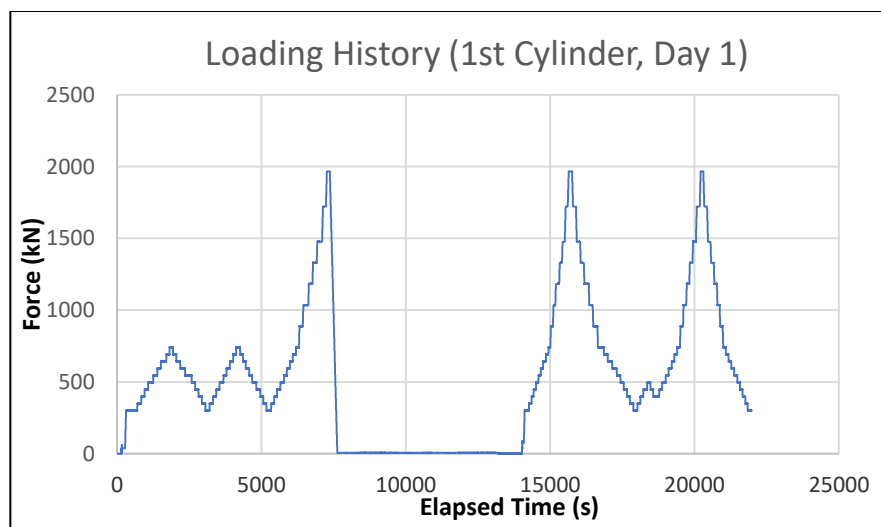


Figure 5.30. Loading history of the first cylindrical specimen, day 1.



Figure 5.31. Spalling at the base of the specimen, noticed after the third loading part of the first day.

The second day of the test only had two load cycles divided into two shifts: a full cycle with maximum load of 50 MPa, and a gradual loading phase which loaded the sample until failure. The failure happened at 50 MPa. In between two shifts, the specimen was left loaded for approximately an hour at 6 MPa of axial load. The detailed loading history of the second day of the test is shown in Figure 5.32., while the stress vs strain relationship of the whole test is displayed in Figure 5.33.

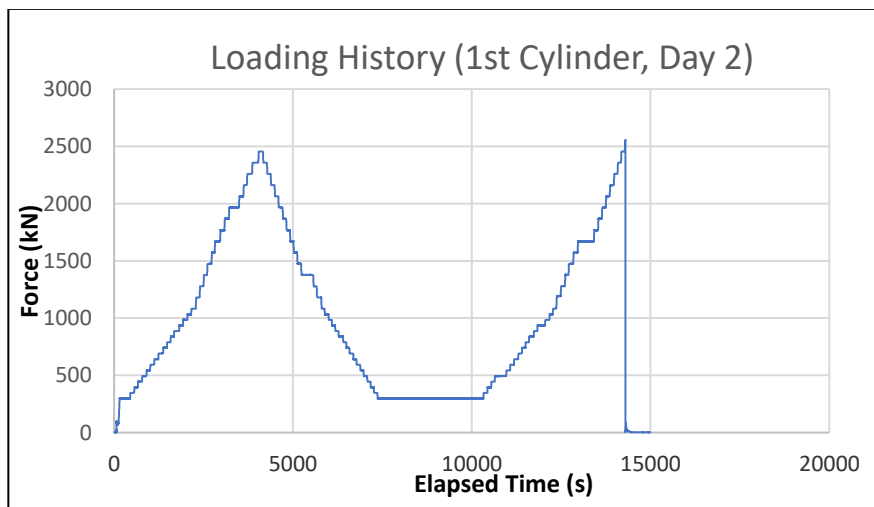


Figure 5.32. Loading history of the first cylindrical specimen, day 2.

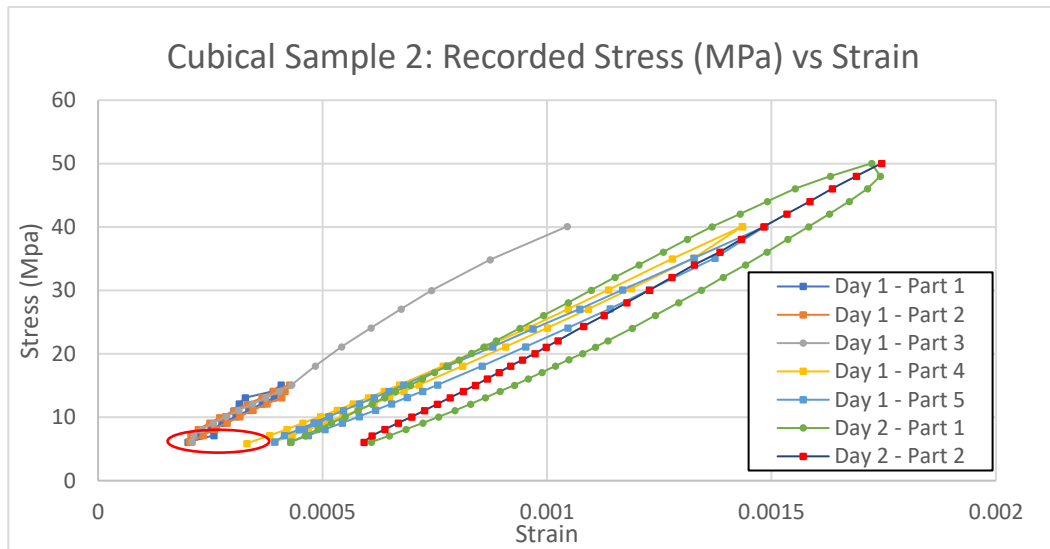


Figure 5.33. Stress vs strain for the first cylindrical specimen. Red mark indicates spalling finding.

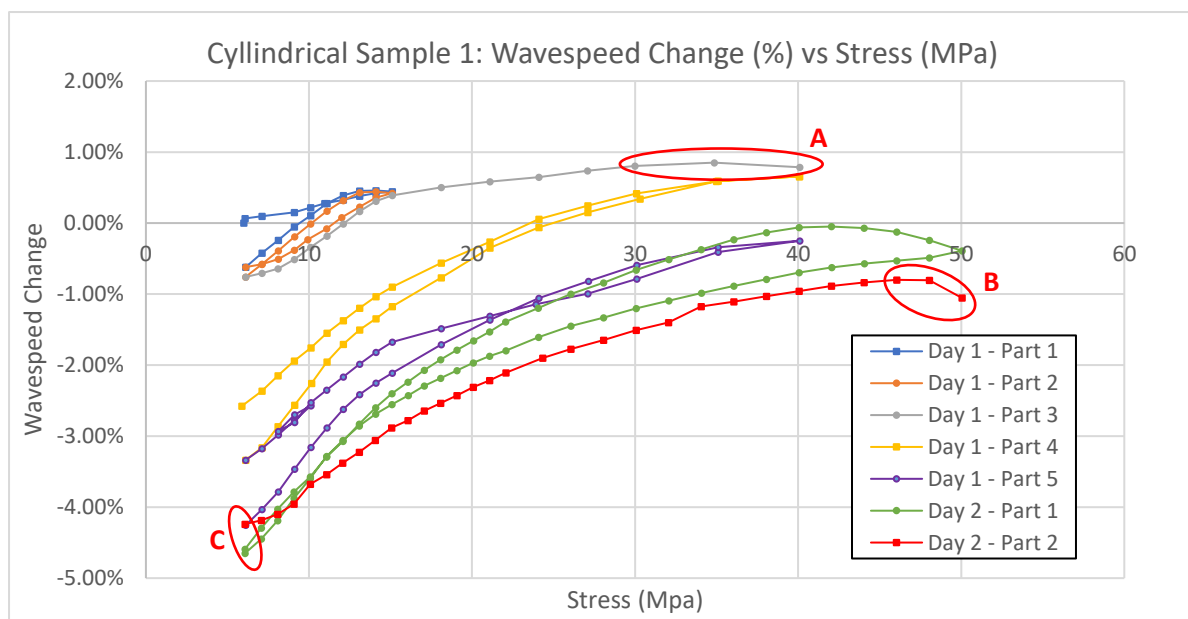


Figure 5.34. $\frac{dv}{v}$ (epsilon) vs stress on the first cylindrical sample.

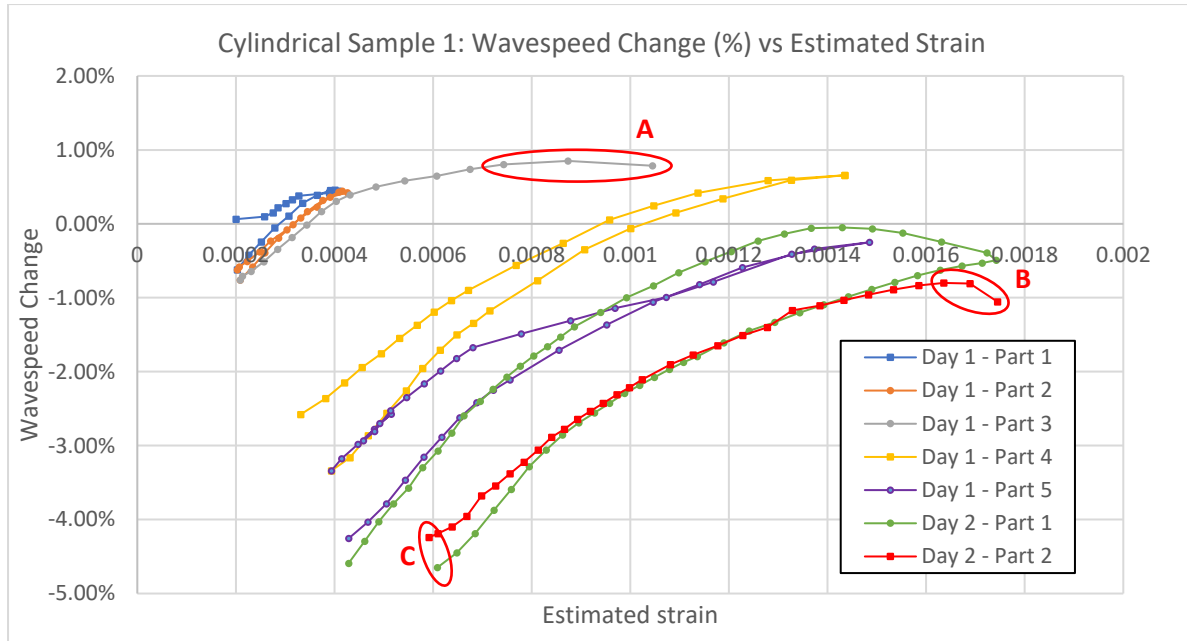


Figure 5.35. $\frac{dv}{v}$ vs strain on the first cylindrical sample.

The trends which are observed in both wavespeed change vs. stress (Figure 5.34.) and strain (Figure 5.35.) graphs comply with the trends observed in the previous tests: initial linear path and decreasing gradient as the loading continues. However, permanent deformations after each loading were prominent, as seen as 'shifts' of the unloaded strain in Figure 5.35. in every loading cycle. An increase of wave speed is observed between the end of the 6th cycle (1st cycle of the second day) and the first load step of the 7th cycle (2nd cycle of the second day) after an hour of sustained low-stress loading (detail C of Figure 5.34. and Figure 5.35.).

When compared to each other, the most noticeable difference between the two is that the reloading paths in wavespeed change vs. strain graph follow more closely to their preceding unloading paths compared to the ones in the wavespeed change vs stress. Other minor differences are that the unloading phase of the first cycle, the second cycle, and the initial part of the loading phase of the third cycle are more linear in the wavespeed vs strain graphs, while they resemble s-curves in the wavespeed vs stress graphs.

The first negative gradient of both wavespeed change vs stress and strain graphs are observed between the last two load steps of the loading path of the third cycle (detail A of Figure 5.34. and Figure 5.35.). Spalling was observed upon unloading, as well as significant decrease in wave speed and significant amount of permanent deformation occurred upon unloading. The next negative gradient of the wavespeed change vs stress and strain graphs are observed in the loading phase of the sixth cycle (first cycle of the second day of the test), and the last negative gradient of both wavespeed change vs stress and strain graphs are seen between the two last load steps of the test, just before failure (detail B of Figure 5.34. and Figure 5.35.). Due to their atypical nature (negative gradient seen in detail A occurred in relatively low stress, and the one in detail B is abrupt compared to its preceding load step), the detailed CWI results of both details are displayed in Figure 5.36. to be compared.

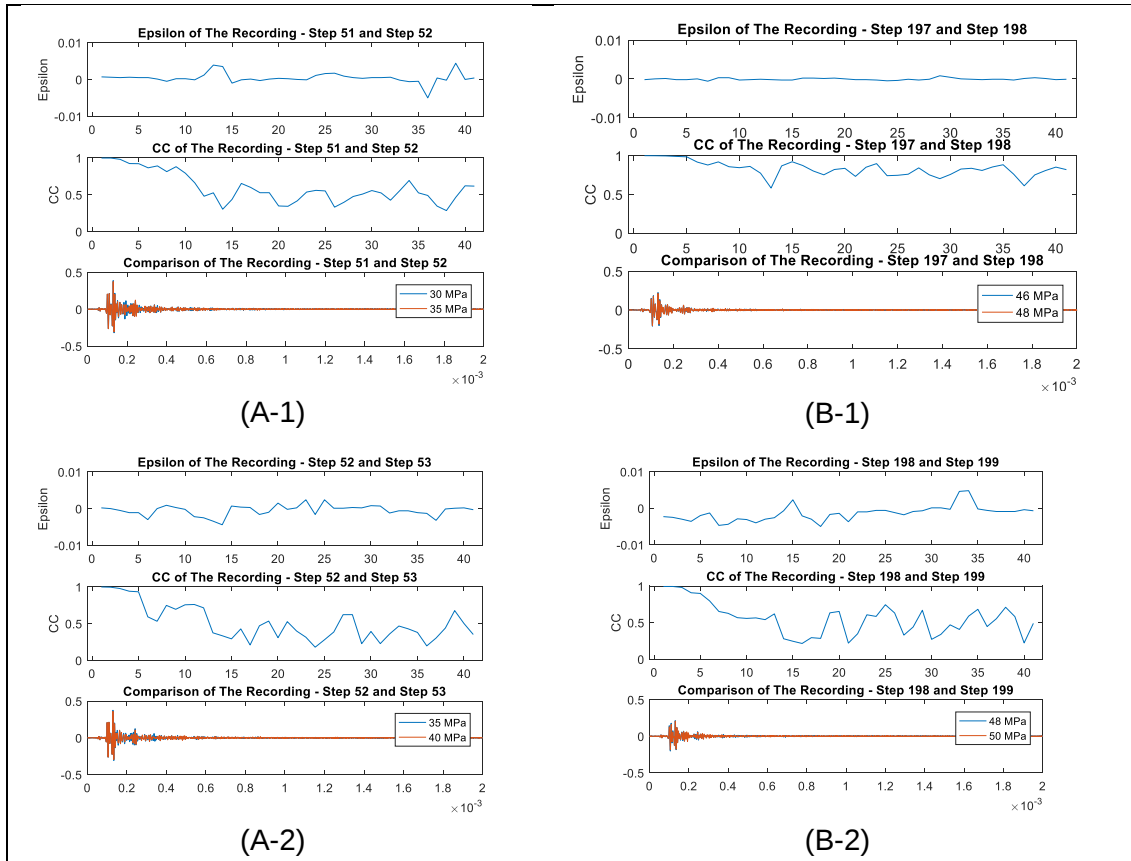


Figure 5.36. Detail of CWI result at A and B of Figure 5.29.

Upon reviewing the CWI results of both detail A and detail B in Figure 5.36., it can be observed that the epsilon values are relatively stable with only some windows being atypical in the first load step of detail A, while in the second step, the epsilon values change from one window to another and CC values are significantly lower compared to the first step throughout the signal. In the first load step of detail B, it can be observed that the epsilon values are stable throughout the signal with high CC values, while significantly lower CC values and erratically changing epsilon values throughout the windows of the signals pair are observed in the second load step of detail B.

The wavespeed vs stress and strain gradients of the linear part of each loading cycles are checked. The wavespeed vs stress and strain gradients of the first cycle are lower compared to the following cycles. In general, the gradients do increase as more loading cycles are done, with a few exceptions observed in the wavespeed vs stress gradients of cycle 5 and 7, as well as the wavespeed vs strain gradients of cycle 4 and 7, which are lower compared to the gradients of their preceding cycle.

Table 5.5. Wavespeed change vs stress initial gradients – 1st cylindrical sample.

Load Cycle	$\frac{dv/v}{\sigma}$	$\frac{dv/v}{\text{Strain}}$	Previous Maximum Stress (MPa)
1	0.000536	25.35832	0
2	0.001472	51.61925	15
3	0.001618	55.88705	15
4	0.001860	50.69142	40
5	0.001767	52.6768	40
6	0.002463	83.60635	40
7	0.001597	56.45522	50

The aftermath of the test can be seen in Figure 5.37. The sample failed when the loading was increased from 50 MPa.



Figure 5.37. First cylindrical specimen after failure.

5.3.2. Second cylinder test

The second cylinder was tested on the 21st to the 22nd of August 2018. This cylinder was tested at the age of 40 days. Three loading cycles were done in the first day with peak loads of 15 MPa, 30 MPa, and 45 MPa. The second day of test was done by gradually loading the sample until it failed. In both days, the load steps varied between 0.5 MPa to 2 MPa, depending on the load level. 0.5 MPa steps were done both for load level below 8 MPa and above 49 MPa, 1 MPa steps were done anywhere between load level 8 MPa and 22 MPa, and 2 MPa steps were done between load level 22 MPa to 48 MPa. Smaller load steps were taken both in the early phase of the test and close to the end since major changes in waveform typically occur at low load levels and at the moment when the specimen is close to failure. The detailed

loading history of the sample can be seen in Figure 5.38. and Figure 5.39., while the stress vs strain relationship of the test can be seen in Figure 5.40.

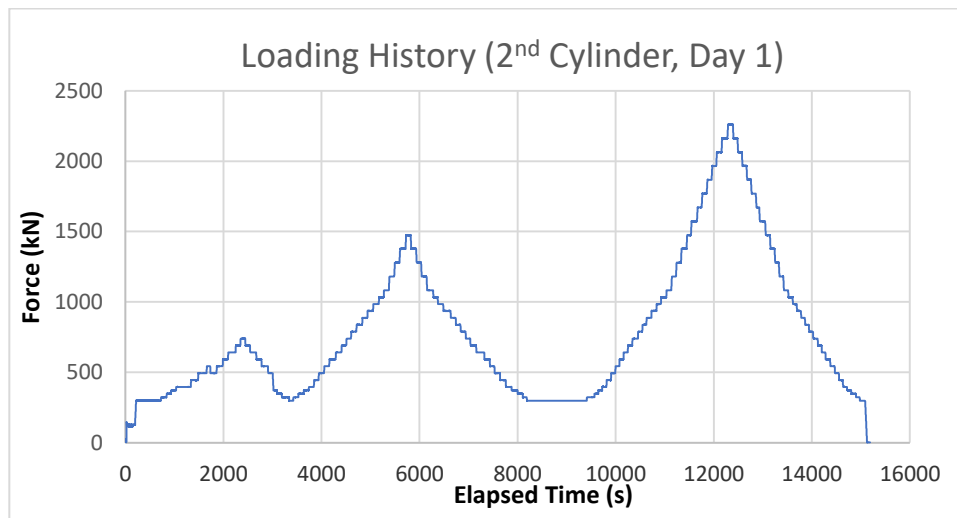


Figure 5.38. Loading history of the second cylindrical specimen, 1st day.

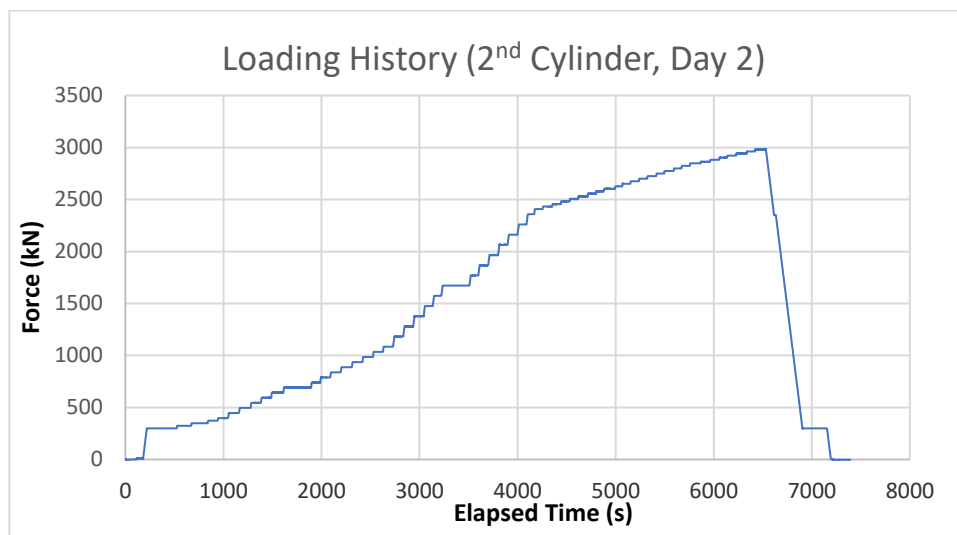


Figure 5.39. Loading history of the second cylindrical specimen, 2nd day.

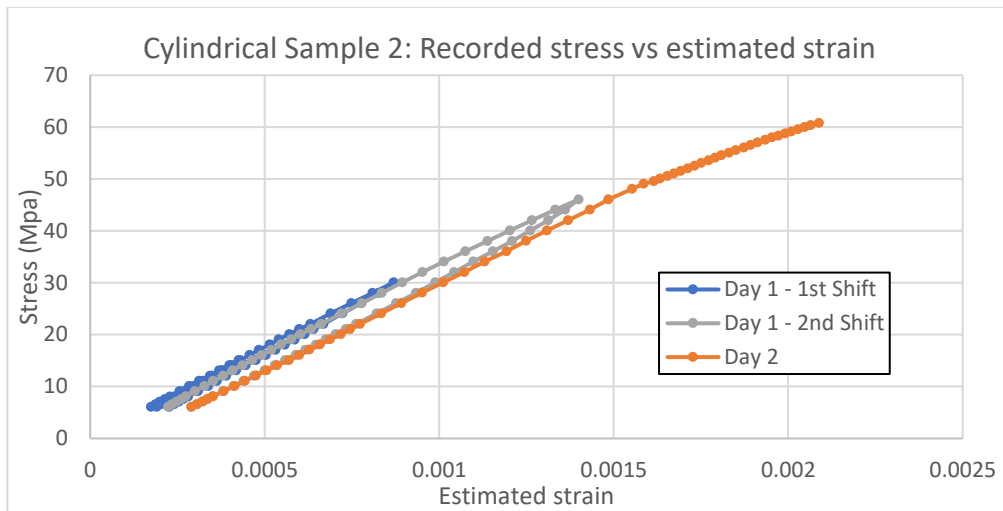


Figure 5.40. Stress vs strain of the second cylindrical specimen.

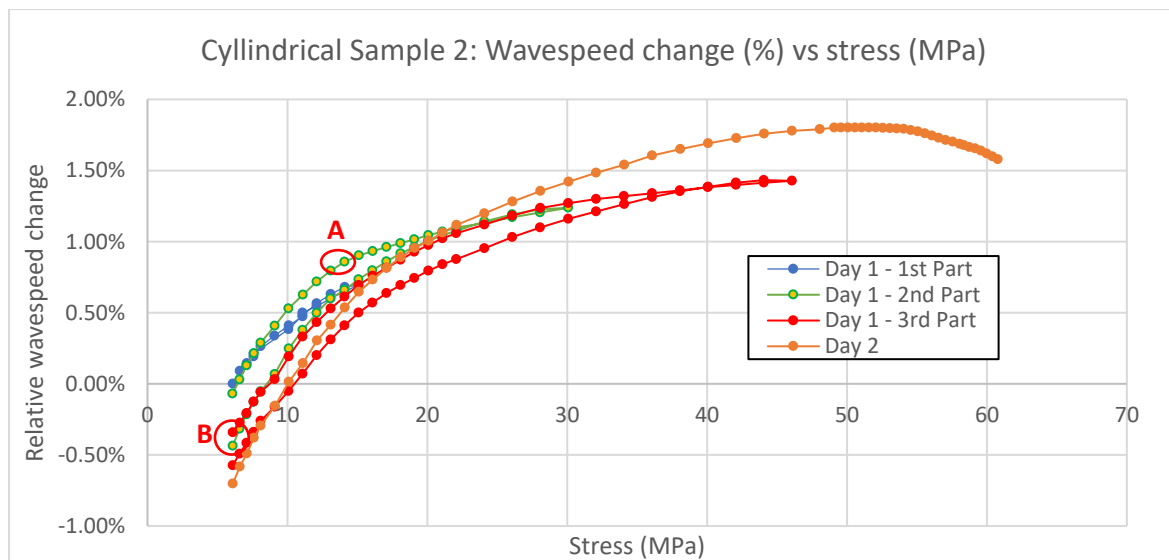


Figure 5.41. $\frac{dv}{v}$ vs stress on the second cylindrical sample.

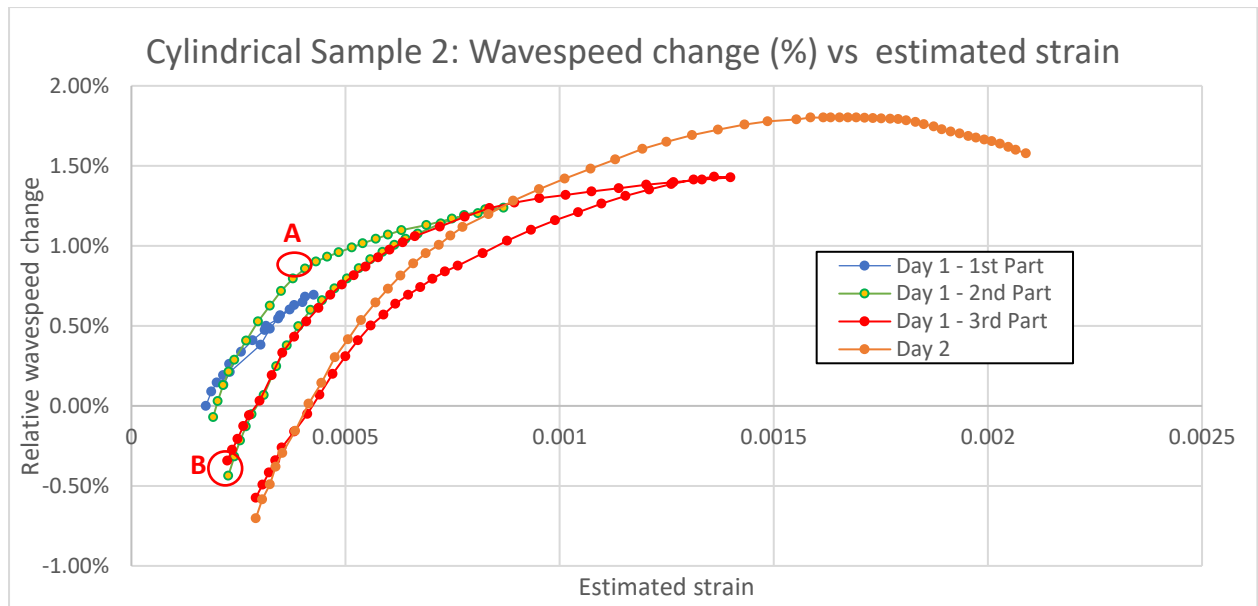


Figure 5.42. dv/v vs strain on the second cylindrical sample.

In general, all load cycles of the wavespeed vs stress (Figure 5.41.) and strain (Figure 5.42.) graphs have similar trend: they tend to start with a linear dv/v vs stress and strain path, followed with decreases of gradient after several load steps (detail A of Figure 5.41. and Figure 5.42.). The unloading phases tend to have lower wavespeed compared to their preceding loading step at the same load level, with an exception for the first cycle, which unloading path closely follows the loading path. An increase in wavespeed was observed after a sustained loading occurred between the second and third load cycle (detail B of Figure 5.41. and Figure 5.42.).

The first negative gradients of both graphs are observed at a load level of 53 MPa, which corresponded to an estimated axial strain of 0.00175. Unfortunately, the capacity of the loading machine was insufficient to load the sample to failure.

In this test, there are only minor differences between the wavespeed vs stress and strain graphs. The most notable one is the presence of 'shifts' of the strain values of final unloaded stages of each load cycles compared to their starting strain values due to permanent deformation. Upon closer inspection, it is also observed that the third loading phase of the first day followed the unloading phase of the second cycle more closely in the wavespeed vs strain graph when compared to the wavespeed vs stress graph.

The initial wavespeed vs stress and strain gradients increase as the specimen was repeatedly loaded. Unlike other tests where irregularities were seen in some of their cycles, the wavespeed vs stress and strain gradients in this test kept on increasing as the loading cycle increased.

Table 5.6. Wavespeed change vs stress initial gradients – 2nd cylindrical sample.

Load Cycle	$\frac{dv/v}{\sigma}$	$\frac{dv/v}{\text{Strain}}$	Previous Maximum Stress (MPa)
1	0.0009218	33.2359	0
2	0.0012895	47.8845	15
3	0.0013009	49.72916	30
4	0.0016334	53.29966	45

After the test had concluded, it was observed that minor spalling on specimen's top did occur. Some parts of the grout edges were also spalled. There was no other visual indication of damage apart from the previously mentioned spalling. The spalling observed in the sample is shown in Figure 5.43.



Figure 5.43. Spalling of the cylinder after the test.

5.4. Discussion

5.4.1. Analysis

In almost all cases, it is observed that $\frac{dv}{v}$ vs stress and strain curves started linearly before their gradients started to decrease after a degree of stress has been reached. In the linear part of the first cycle of loading, it can be confirmed that mostly acoustoelastic effect is in play, which is similar with the findings of Lillamand [23]. As the $\frac{dv}{v}$ vs stress and strain gradients decreases, microcracks formation reduces the wavespeed increase caused by acoustoelastic effect. While it had not been confirmed, Stahler [4], Lillamand [23], and Larose [31] reported this phenomenon as well. On the linear part of the following cycles, however, the closing of previously open microcracks also plays a role in $\frac{dv}{v}$ vs stress and strain initial gradients, making them steeper compared to the first loading phases which are only affected by mostly acoustoelastic effect.

When a certain strain is reached for the first time, the unloading path of the same cycle tend have lower wavespeed at the same strain value when compared to the preceding loading path. Loading the sample will result in microcracking occurrence, which will open upon unloading. For instance, at the unloading phase of a load cycle with a peak strain of 0.001,

the wavespeed at the strain value of 0.0008 on the unloading phase will be slower when compared to the wavespeed at the same strain value during the preceding loading phase. Such decrease of wavespeed is likely to be caused by the formation of microcracks between the strain values of 0.0008 and 0.001 during the loading phase, which are then opens upon unloading, thus decreasing the wavespeed. Such microcracking mechanism during compression is explained in a paper written by Mier [19].

Upon reloading following an unloading cycle, it is observed that in most cases the reloading dv/v vs strain paths follow their pervious unloading dv/v vs strain paths in. This phenomenon can be explained since reloading the sample closes existing cracks which had opened in previous unloading. While the dv/v vs stress graphs also possess similar trend, the reloading paths are not as close with their preceding unloading path in the dv/v vs stress graphs when compared to the dv/v vs strain graphs, especially in loading phases following unloading phases from high stress levels. Such difference is caused by the presence of permanent deformations, which can be observed in the stress vs. strain relationships of the tests. These observations suggest that dv/v vs strain is more indicative to damage progression monitoring compared to dv/v vs stress.

In all samples which failed in the test, major wave form changes and significant wavespeed drops were observed. In the two cubes, which failures were well-monitored due to the use of fine loading steps, the waveform changes are even more pronounced in several load steps before failure. Significant reductions in amplitude were also observed in both cubes several load steps prior failure. CWI was no longer conductible close to the ultimate stress due to the rapidly changing waveform and great reduction of amplitude, which cross-correlation would not yield adequate CC values anymore. When the sample were close to failure, new cracks kept on occurring even without any increase of load, making even two recordings taken in the same load with several seconds interval would not be similar in terms of waveform and arrival time.

In the second cube and the first cylinder, there were time gaps in between the load cycles where the load was sustained at low stress level for a period of time. In both cases, it was observed that after the sustained loading, the wavespeed increased. This effect was initially thought to be related with creep, which is not true since based on the LVDT reading, there were no significant changes in strain during the sustained load. Therefore, it is advised to investigate this phenomenon further in future works.

The initial gradients of the linear part of the dv/v vs stress and strain curves seems to be increasing as the samples are loaded multiple times. Similar phenomenon is also reported by Schurr et. al. [3] and Planès and Larose [12]. However, Planès and Larose stated that damaged or altered concrete will have an initial wavespeed change vs. stress gradient of more than 0.002, while in this study it is found that even the initially damaged concrete cube had an initial wavespeed change vs stress gradient of 0.0012. Therefore, it will be more accurate for comparing the dv/v vs stress gradient of a load cycle to its previous load cycle to assess if the specimen is damaged, compared to just depending on the gradient threshold proposed by Planès and Larose. Additionally, since both the wavespeed change vs stress and strain gradients did reduce in some cases upon reloading, it is also proposed that further study to

be done to assess the initial gradient evolution on previously loaded concrete specimens. The second cubical sample did not follow the mentioned initial gradient trend, which may be caused by its prematurely damaged state. Unfortunately, there is no available literature concerning the wavespeed change vs strain gradients, although these gradients have a similar trend with the wavespeed vs. stress gradients.

In the second cubical specimen test, initial negative dv/v vs stress and strain gradient with low CC on its CWI results in the first load steps were observed. Additionally, starting from the 24 MPa of load in the second loading cycle, another event where negative dv/v vs stress and strain gradients were observed. The fact that major cracks were observed by the end of the second cycle and significant permanent deformation occurred between the start and the end of the second cycle indicated that the negative gradients were caused by premature damage occurrence of the sample. Upon reloading the sample, no new major visible cracks were observed apart from the widening of the existing cracks and no abrupt drop of dv/v nor drop in CC were observed apart from usual gradual changes due to typical damage progression.

A significant drop in wavespeed and significant permanent deformation were observed between the start of the third cycle and the start of the fourth cycle of the first cylinder test. Negative dv/v vs stress and strain gradients were also observed on the last load step of the third cycle, and spalling was also observed at the end of the third cycle, which indicated major damage on the specimen. On the sixth cycle of this test, while the start and the end of the cycle had the same load level and similar wavespeed, the strain at the end of the cycle had increased compared to when it started. It was observed that the sample had undergone a significant permanent deformation, which was confirmed in the stress vs strain graph.

5.4.2. Lesson learned

After conducting the experiment and analyzing the results, several things can be learned:

- Smaller load steps such as 0.5 MPa steps are recommended. Even though at higher stress levels CWI results tend to be more stable, a sudden damage such as crack occurrence like the ones in the second cube and the first cylinder will abruptly change the waveform, calling for smaller monitoring load steps.
- For CWI purposes, it is preferable to keep the sample loaded during breaks, since unloading the sample completely will result in change in interface upon reloading, causing changes in the waveform, leading to lower CC values. For the same reason, it is preferable to complete the test in the same day.

5.4.3. Remarks

After assessing this part of this research, it can be pointed out that

- Wavespeed change vs stress and strain are only linear in lower stress levels. The wavespeed change vs stress and strain gradients will then decrease as the loading proceeds, which is likely to be caused by compressive micro cracking.
- The wavespeed of a sample at a certain strain value will be higher at a preceding loading phase when compared to the following unloading phase. When assessing the wavespeed in respect to the stress, previous statement only valid if the sample had

not undergone major permanent deformation. Since the sample had been altered due to the loading, it is likely that the reduction of wavespeed is caused by alteration of medium structure such as microcracks forming during the previous loading phase.

- Strain seems to be more reliable to be used for CWI interpretation compared to stress in uniform compression loading condition. The observations in this experiment support the suggestion.
- Significant changes in waveform, reductions in signal amplitude, wavespeed, and CC of CWI were observed prior to compressive failure. Multiple cracks propagates actively when a specimen is close to failure, which reduce the pathways that wave can propagates through, reducing the received amplitude, and since the scattering path is heavily altered by the cracks, changing the waveform.

Additionally, a few recommendations can be made for the continuation of this research:

- Tests are better done in climate-controlled area to eliminate climate effects on the result.
- Smaller load steps of 0.5 MPa or less are desirable for CWI to ensure higher CCs among recordings.
- Comprehensive assessment of sustained loading effect on wavespeed should be done. Low-stress sustained loading seems to have positive effect on the wavespeed, but more tests should be done to make sure that this is not a particular event exclusive to these tests.
- Study on initial gradient of wavespeed change vs stress and strain should be done for the future works. While this study shows that initial wavespeed change vs stress and strain to be promising indication of the physical damage of concrete, more samples should be assessed to study the link between previous load level and initial wavespeed change vs stress and strain gradients. Moreover, limited literature concerning the wavespeed change vs strain relationship opens more opportunity to explore this issue.
- More compression tests should be done with standardized loading scheme and no time gaps to eliminate the effect of sustained loading.
- If possible, CT-scans of the specimens during loading are suggested to confirm the existence of micro-cracking which causes change in $\frac{dv}{v}$ vs stress and strain gradients.

6. Coda-wave interferometry on concrete specimen subjected to bending and shear

6.1. Experimental setup

6.1.1. Specimen setup

A concrete beam specimen was used to assess the use of CWI on concrete in shear and bending. The beam was cast with dimensions of 10m-long, 0.3m-wide, and 1.2m-tall, which was supported at 0.5m from both ends. A point load was applied 3 meters from the left support. Between the left support and the load, instruments were installed as shown on Figure 6.1. In this thesis, however, only the five embedded smart aggregates (SA1, SA2, SA3, SA4, and SA5) and one LVDT (LVDT15) were relevant.

The placements of smart aggregates were mainly based on the compressive zone of the cross-section, which calculation is attached in Appendix B. The smart aggregates which were placed in the compressive zone are SA3, SA4, and SA5, of which SA4 was chosen as the source due to its position, which was in between SA5 and SA3, as well it is in the expected compression zone, ensuring full coupling since no crack was expected to propagate through SA4. SA1 and SA2 were located approximately in the middle of the cross section, since it might be useful to assess CWI results of which receivers are in the tensile zone. Moreover, SA1 and SA2 were also used for another research, which is not covered in this thesis. Signals which were received by SA1 is noted as SA1-SA4 in this research. Similar annotations are also used by other signals received by SA2, SA3 and SA5.

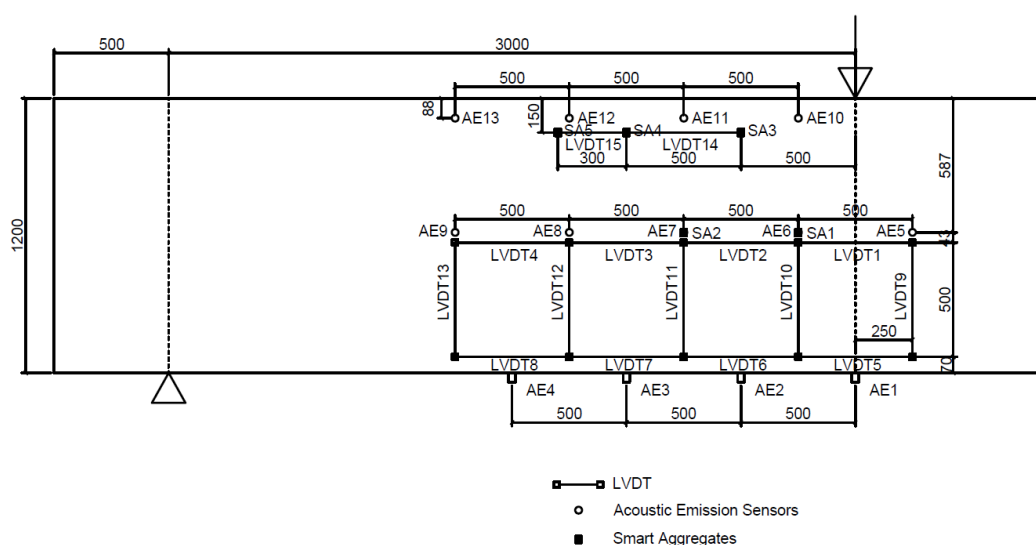


Figure 6.1. Specimen layout and instrumentation.
(Courtesy of Zhang Fengqiao of Stevin II Laboratory TU Delft).

6.1.2. Loading procedure and CWI strategy

The test loading scheme had 5 load levels; 100 kN, 150 kN, 200 kN, 250 kN, and 300 kN, which was done in two days. For each load level, three cycles were done; the first cycles were done stepwise for signal measurements to be used for CWI analysis, while the third cycles were done for another purpose which require the load to be sustained for a period of time. The load scheme is shown on Figure 6.2. and Figure 6.3. The first three load levels (9 cycles) were done on the first day of the test (31st August 2018), while the last two load levels (5 cycles) were done on the second day of the test (3rd September 2018).

The decision regarding loading steps for signal recordings was done based on the maximum stress changes in the compressive zone of which SA4 was located. From the lesson learned from the CWI on samples in compression, it was desirable to keep the stress gap as low as possible, preferably below 0.5 MPa. Based on an approximation calculation done in Appendix B, load steps of 10 kN and 20 kN would result in a stress change of 0.3208 MPa and 0.6416 MPa at SA4 position. Therefore, a load step of 10 kN was taken for the CWI measurements of the 1st cycle, 4th cycle and 7th cycle, while in the 10th and 13th cycle the load step of 20 kN was used for load levels which were previously reached, while a load step of 10 kN was used for load levels which had never been reached previously. The resulting load vs. vertical displacement at the loading point of this test is displayed in Figure 6.4.

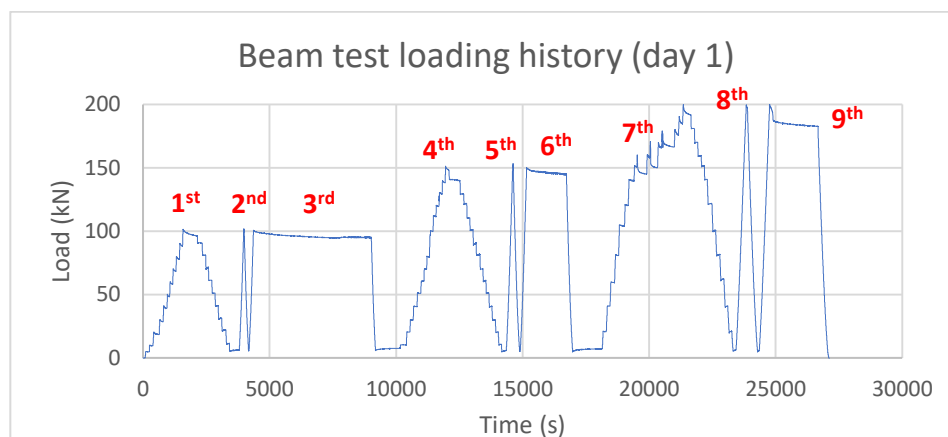


Figure 6.2. Loading history of the test done on 31st August 2018 on beam specimen.

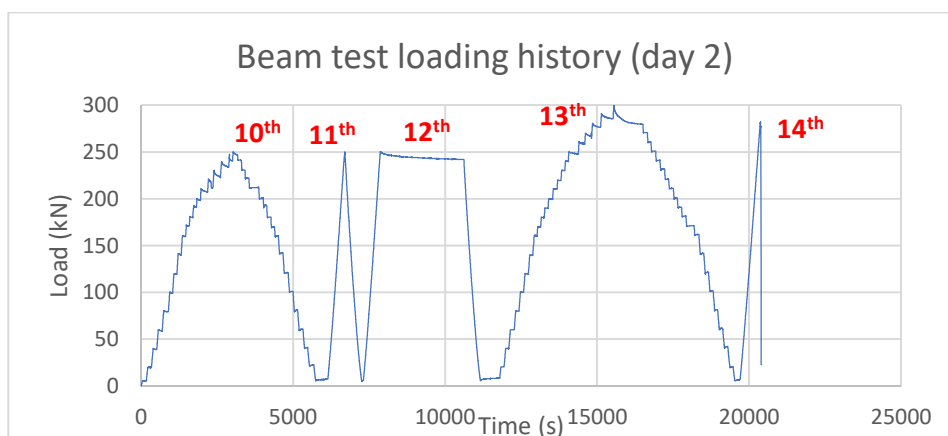


Figure 6.3. Loading history of the test done on 3rd September 2018 on beam specimen.

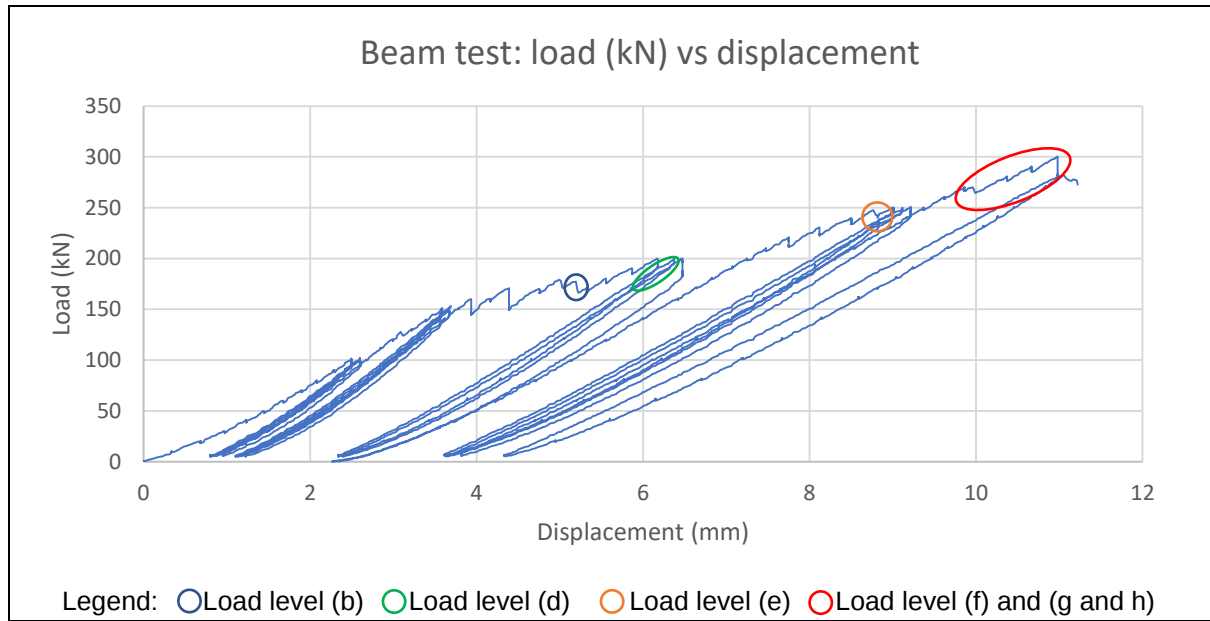


Figure 6.4. Load vs displacement of the beam test. The load levels indicated in the graph will be relevant in section 6.2.2. of this thesis.

Similar with previous experiments, a single sine of 88 kHz was transmitted through SA4, which acted as the source. In this case, 2 millisecond recordings were taken, which were windowed into 41 windows of 8 wave periods. CWI was conducted stepwise, which mean the wavespeed differences between two adjacent load steps were determined for each windows of the recording.

6.2. Coda-wave interferometry result

6.2.1. Relative wavespeed change through loading

After conducting CWI, the $\frac{dv}{v}$ and CC values were plotted for every window of the recordings. Along with these, the two analyzed signals were overlaid together and displayed. The choice of smaller load steps had made most CWI results to be highly correlated, unless cracks or damage happened in between the load steps. A typical CWI result, which in this case is taken from SA5-SA4 pair, is shown on Figure 6.5. Note that earlier arrivals of the signal had higher wavespeed increase than the later parts, since this will be relevant in section 6.2.3. of this thesis.

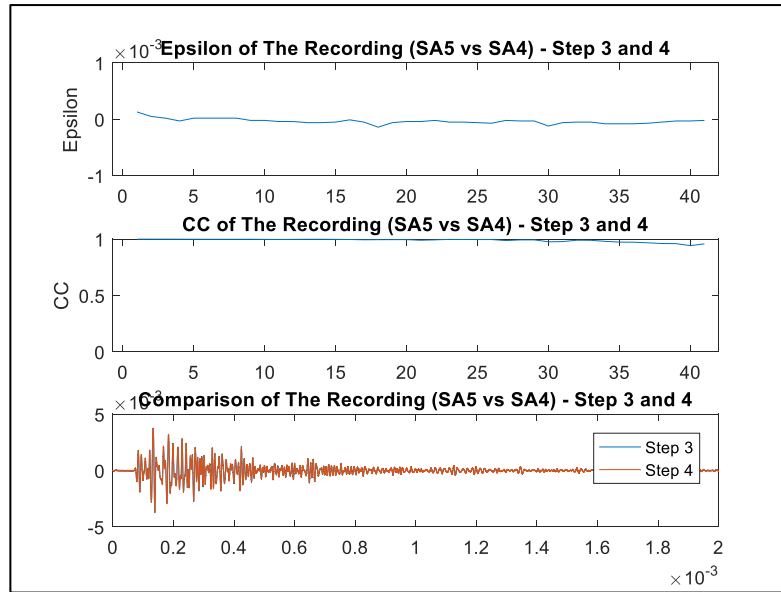


Figure 6.5. Typical CWI result of two signals.

dv/v vs load and dv/v vs vertical displacement graphs are plotted. To determine the wavespeed changes in each load step, any window with a CC under 0.9 is removed. Moreover, only the coda of the recording, which approximately started at 0.22 millisecond from the start of the recording (5th window and beyond) are taken. The wavespeed of the first load step of 5 kN load of the first cycle is used as reference speed.

When assessing the dv/v vs load graphs (Figure 6.6., Figure 6.8., Figure 6.10., and Figure 6.12.), CWI results on the first two assessed cycles (first and fourth cycle) are unequivocal: the first cycle started with linear dv/v vs load with slight negative gradient during the first loading, while the unloading also follows linear dv/v vs load with positive gradient. For nearly all sensor pairs, the loading part of the fourth cycle started off linearly up to the previously reached load level, before the gradients are reduced, extending the previous negative wavespeed change vs load gradient, creating an envelope. The following unloading dv/v vs load paths tend to follow linear path with positive gradient.

Table 6.1. Linear part gradient of dv/v vs load – First day.
(* indicates linear fit of a not-so linear function).

Loading Part	dv/v vs load gradient (kN ⁻¹)			
	SA1-SA4	SA2-SA4	SA3-SA4	SA5-SA4
Cycle 1 Loading	-4.41E-06	-4.40E-06	-2.88E-06	-1.2750E-06
Cycle 1 Unloading	1.14E-05	9.14E-06	1.78E-05	1.53E-05
Cycle 4 Loading	1.18E-05	8.97E-06	1.79E-05	1.62E-05
Cycle 4 Unloading	1.69E-05	1.34E-05	2.48E-05	2.16E-05
Cycle 7 Loading	1.60776E-05	1.28E-05	2.37E-05	2.13E-05
Cycle 7 Unloading	8.14868E-06*	1.17E-05	2.45E-05	2.24E-05

On the other hand, the dv/v vs displacement graphs of the first day of the test (Figure 6.7., Figure 6.9., Figure 6.11., and Figure 6.13.) show S-curved trends in place of the linear parts

seen in the $\frac{dv}{v}$ vs load graphs, except for the first loading paths of the CWI results from SA1-SA4, SA2-SA4, and SA3-SA4 sensor pairs' recordings, which show linear $\frac{dv}{v}$ vs displacement relationship. Permanent deformation was observed in the $\frac{dv}{v}$ vs displacement graphs, as indicated by an increasing unloaded displacement values upon unloading of the sample.

The $\frac{dv}{v}$ vs load and displacement graphs' trend of the third observed cycle (seventh cycle), however, differ in each source-receiver pair. Wavespeed drop of -0.259% is observed in the SA1-SA4 recording pair at 170 kN, along with a significant displacement increase, at the load steps where the first crack appeared (detail A of Figure 6.6. and Figure 6.7.). The $\frac{dv}{v}$ vs load of the following unloading pair did not follow a linear trend, instead it resembles an S-curve where lower gradient is observed at the beginning and end of the unloading. The final unloaded wavespeed is -0.501% relative to the reference speed.

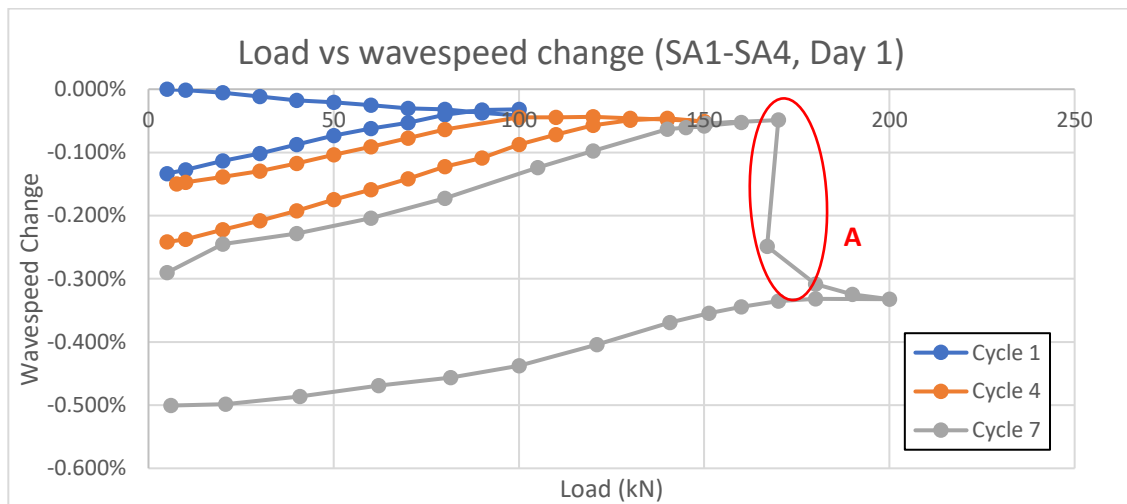


Figure 6.6. $\frac{dv}{v}$ vs load of SA1-SA4 sensor pair, first day test.

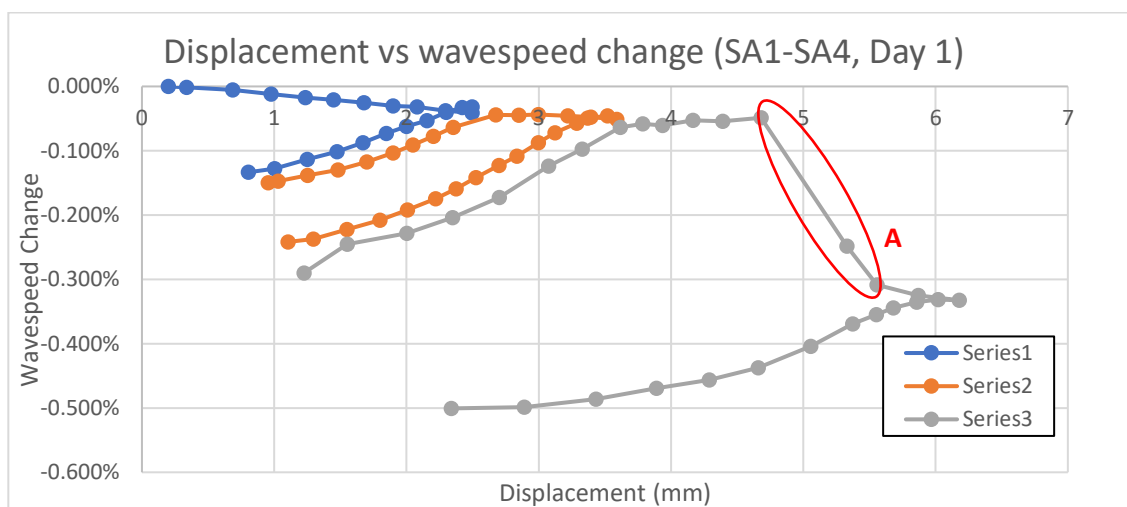


Figure 6.7. $\frac{dv}{v}$ vs displacement of SA1-SA4 sensor pair, first day test.

In the CWI result from the SA2-SA4 sensors pair, the crack emergence did not seem to affect the $\frac{dv}{v}$ vs load (Figure 6.8.) and displacement (Figure 6.9.) relationships, indicated with no significant drop of velocity is observed during the load steps of which the crack initiation happened. The loading phases still follow previous trend of previously linear ($\frac{dv}{v}$ vs load) or S-curved ($\frac{dv}{v}$ vs displacement) increase before change of gradient happen, while the unloading phase of the $\frac{dv}{v}$ vs load curve shows slight tapering at the start and end of the unloading phase, which otherwise can be considered linear. The final load speed is -0.289% relative to reference speed.

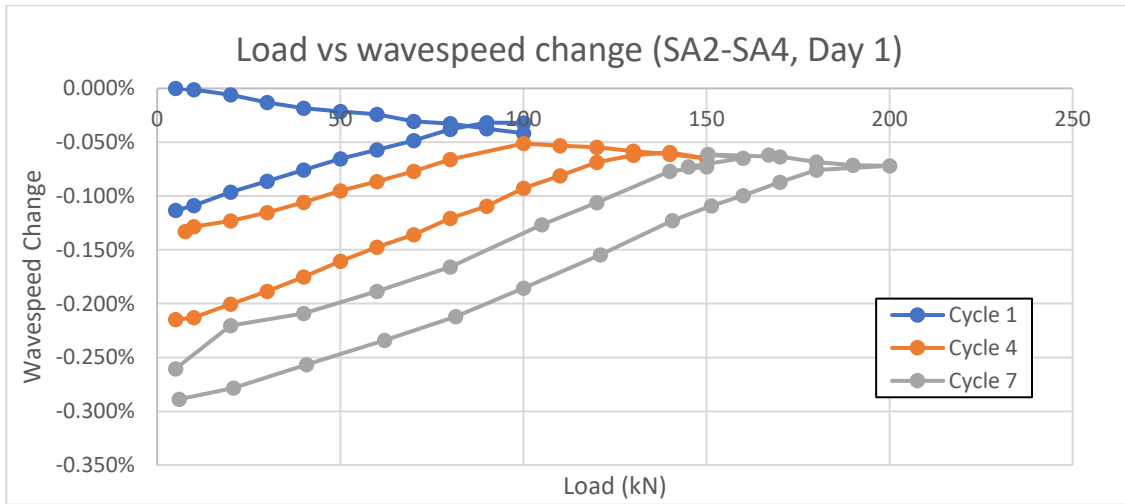


Figure 6.8. $\frac{dv}{v}$ vs load of SA2-SA4 sensor pair, first day test.

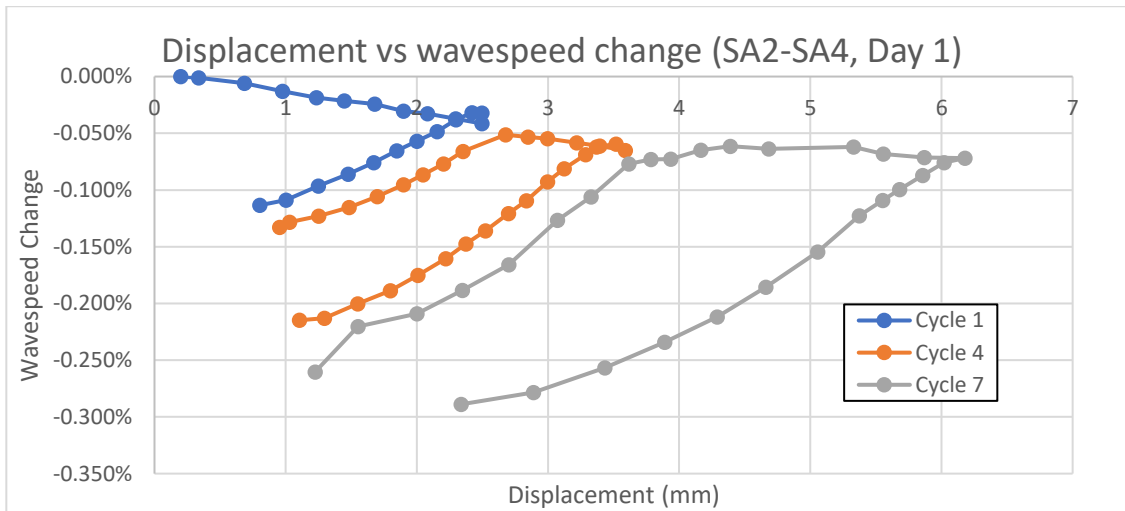


Figure 6.9. $\frac{dv}{v}$ vs displacement of SA2-SA4 sensor pair, first day test.

CWI result from the SA3-SA4 sensor pair's recordings shows slight reduction of 0.017% in wavespeed at 170 kN of load, at the load step which the first crack appeared. In the unloading phase, a linear trend of the $\frac{dv}{v}$ vs load graph (Figure 6.10.) is observed from 120 kN of load and downwards, while the $\frac{dv}{v}$ vs displacement (Figure 6.11.), just like preceding cycles, is S-curved throughout the cycle. The CWI result of the recordings from this sensor pair shows

high reduction in wavespeed, with a wavespeed of -0.501% relative to reference speed at the end of load cycle 7.

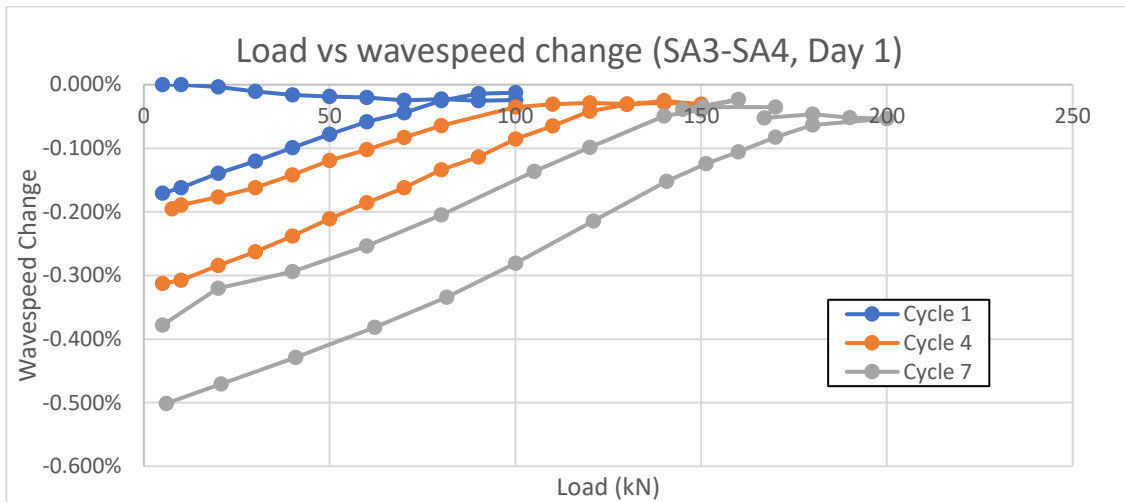


Figure 6.10. $\frac{dv}{v}$ vs load of SA3-SA4 sensor pair, first day test.

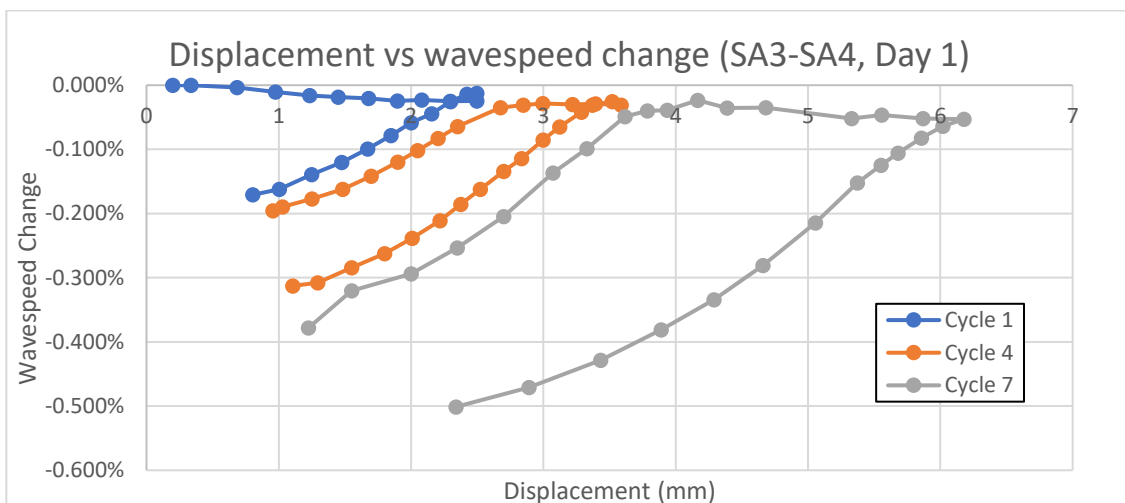


Figure 6.11. $\frac{dv}{v}$ vs displacement of SA3-SA4 sensor pair, first day test.

The CWI result from SA5-SA4 sensors pair does not experience noticeable drop in wavespeed at any load step during the seventh loading cycle. Moreover, both $\frac{dv}{v}$ vs load graph (Figure 6.12.) of the loading and unloading of the cycle is highly linear up to 140 kN of load, and the $\frac{dv}{v}$ vs displacement graph (Figure 6.13.) shows the least skewed S-curve when compared to CWI results from other sensors pairs. At the end of the cycle, the wavespeed recorded is -0.368% relative to the reference speed.

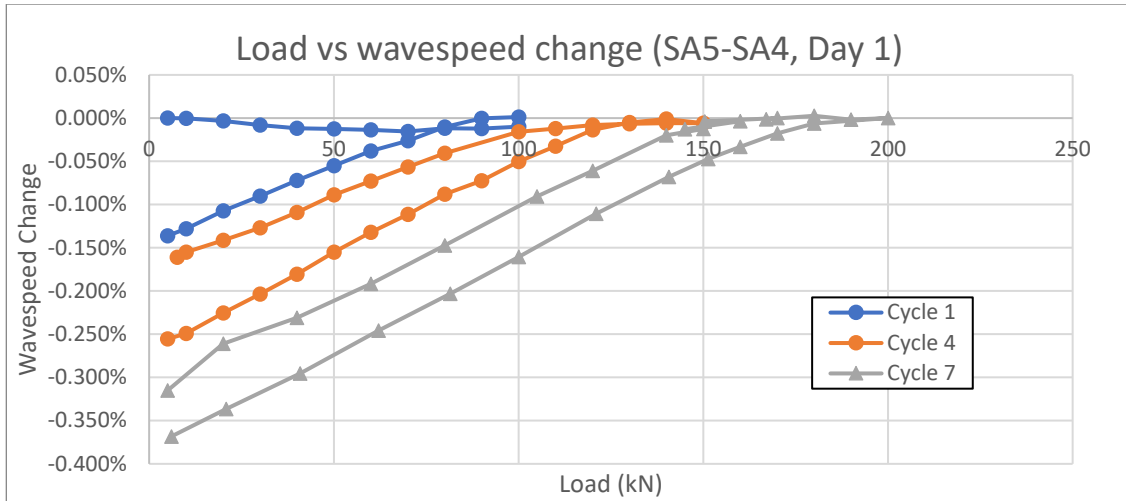


Figure 6.12. $\frac{dv}{v}$ vs load of SA5-SA4 sensor pair, first day test.

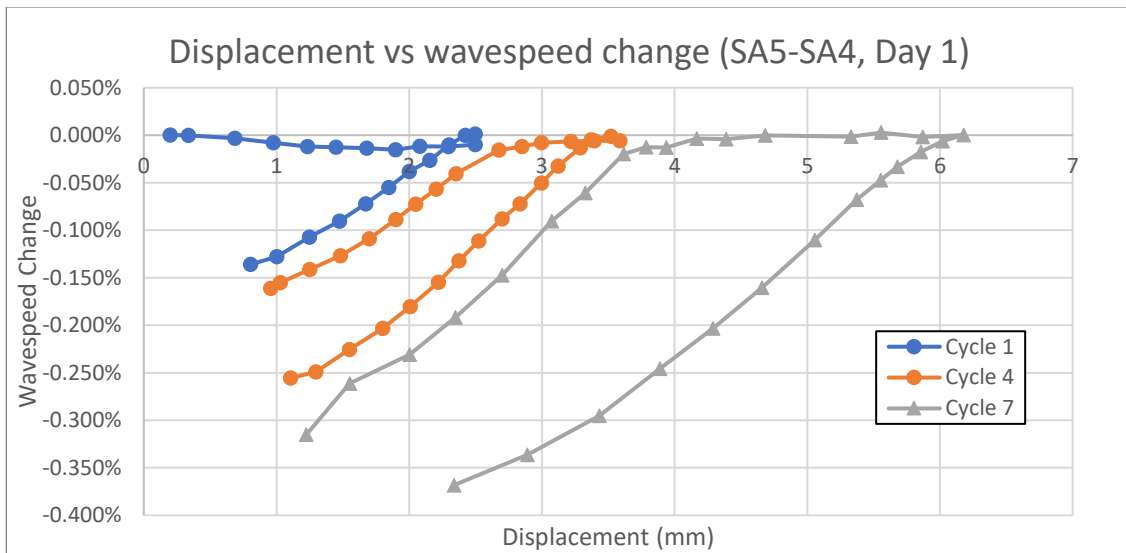


Figure 6.13. $\frac{dv}{v}$ vs displacement of SA5-SA4 sensor pair, first day test.

On the second day of the test, CWI results from SA1-SA4 and SA2-SA4 sensor pairs' recordings differ noticeably when compared to the CWI results from SA3-SA4 and SA5-SA4 sensor pairs' recordings. In all cases except the CWI result of SA2-SA4 recording, the wavespeed at 5 kN of load at the start of the test is observed to be higher compared to the wavespeed at the end of the first day test. Significant drop in wavespeed is observed at 285.8 kN of load in CWI results from all sensor pairs' recordings, which correlated with the appearance of the shear crack.

The CWI results of the SA1-SA4 sensors pair from the recording of the loading phase of the 10th load cycle alternates between negative and positive $\frac{dv}{v}$ vs load (Figure 6.14.) and displacement (Figure 6.15.) gradients, while the unloading phase has mainly positive $\frac{dv}{v}$ vs load and displacement gradients. Unlike the CWI results of the first day test, neither loading nor unloading phase was linear in the $\frac{dv}{v}$ vs load graph. The 10th cycle starts with a relative wavespeed of -0.391% and ends with a relative wavespeed of -0.757%. In the 13th cycle, the

loading phase starts with a wavespeed of -0.876% and ends at -1.515% from reference. Two drops of wavespeed are observed in the 13th cycle: one at 266 kN and the other at 285.8 kN of load.

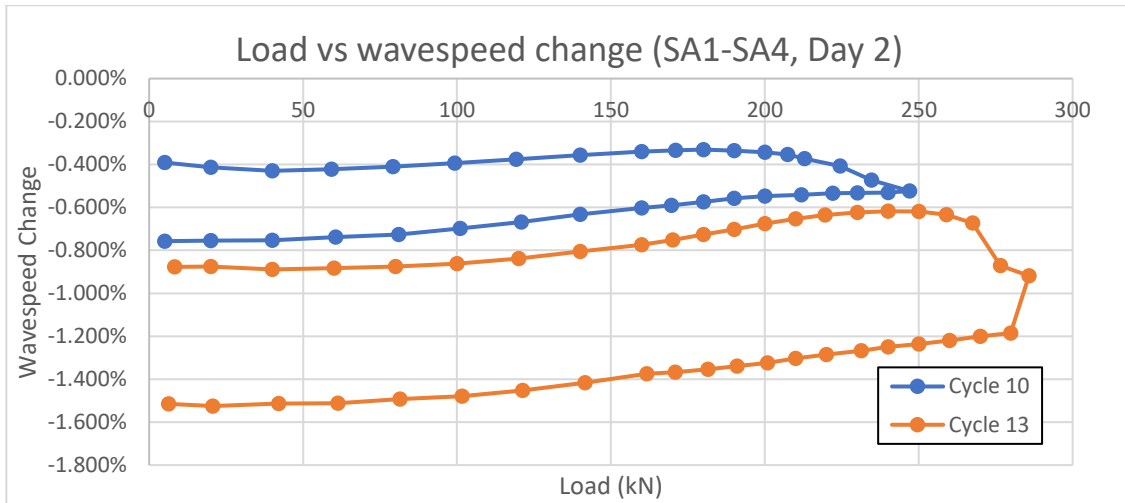


Figure 6.14. $\frac{dv}{v}$ vs load of SA1-SA4 sensor pair, second day test

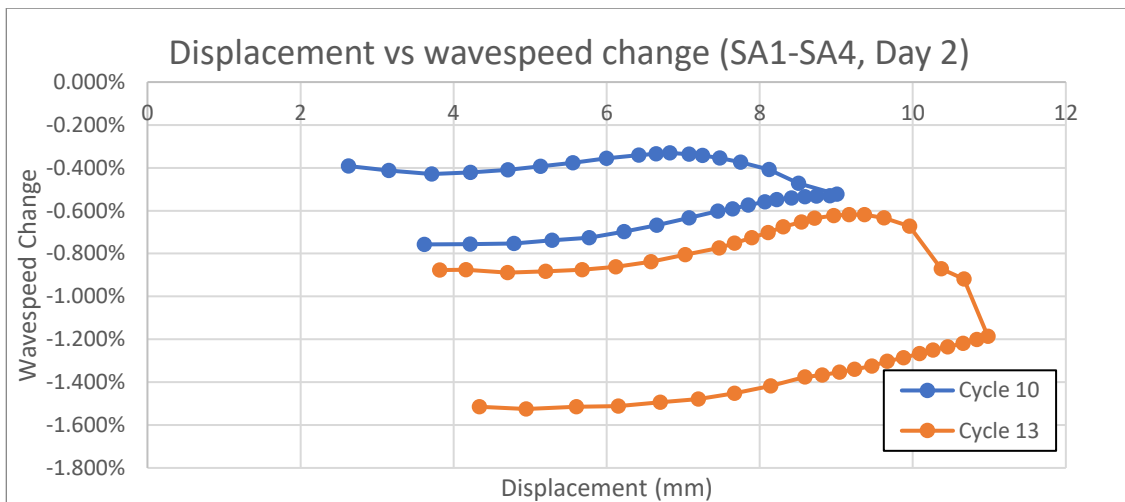


Figure 6.15. $\frac{dv}{v}$ vs displacement of SA1-SA4 sensor pair, second day test

When the CWI results from the first and second day are combined, it can be observed that envelope are present in both the $\frac{dv}{v}$ vs load (Figure 6.16.) and $\frac{dv}{v}$ vs displacement (Figure 6.17.) graphs, which both the $\frac{dv}{v}$ vs load and displacement paths of the 10th cycle's loading phase follow the path of the 7th cycle upon reaching the previously reached load level. Similar phenomenon was also observed between the $\frac{dv}{v}$ vs load and displacement paths of the 10th and the 13th cycle.

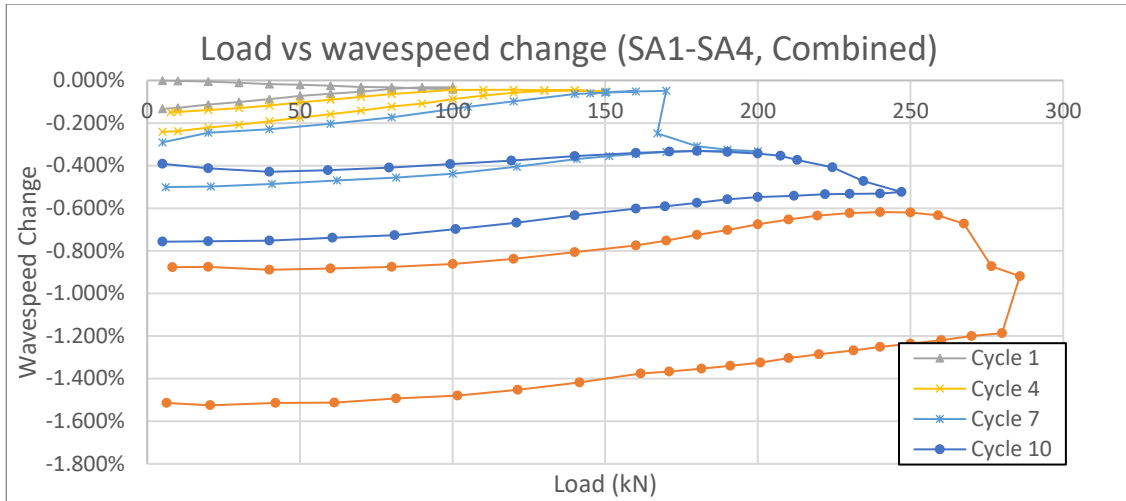


Figure 6.16. $\frac{dv}{v}$ vs load of SA1-SA4 sensor pair, combined.

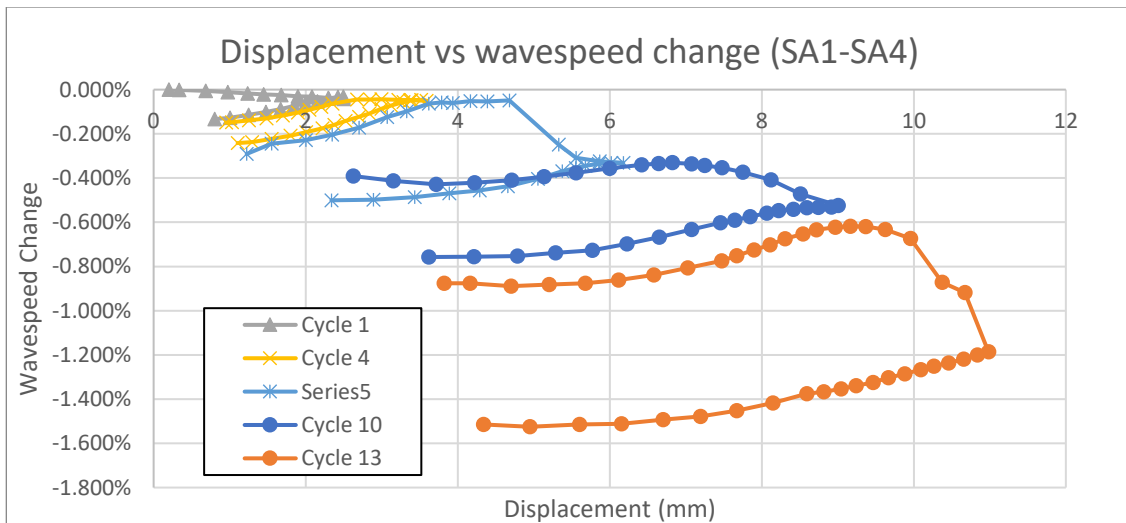


Figure 6.17. $\frac{dv}{v}$ vs displacement of SA1-SA4 sensor pair, combined.

From the CWI result from recordings of SA2-SA4 sensor pairs, it is observed that the 10th cycle starts with a rather low wavespeed of -1.072% compared to the reference speed. While the $\frac{dv}{v}$ vs load (Figure 6.18.) and $\frac{dv}{v}$ vs displacement (Figure 6.19.) graphs show varying gradients along the loading phase, it is observed that the wavespeed from step to step mainly decreases, with significant drop in wavespeed at 224.4 kN to 234.6 kN of load. The load cycle ended with a wavespeed of -1.981% from the reference speed, with minimal change of wavespeed is observed during the unloading phase. The 13th cycle starts with a wavespeed of -2.145% from the reference speed, with alternating $\frac{dv}{v}$ vs load and displacement gradients. Significant drops in wavespeed was observed at 267.5 kN and 285.8 kN of load. The load cycle ends at a wavespeed of -3.377% from the reference speed, slightly higher compared to the wavespeed at the start of the unloading phase (-3.406% from the reference speed).

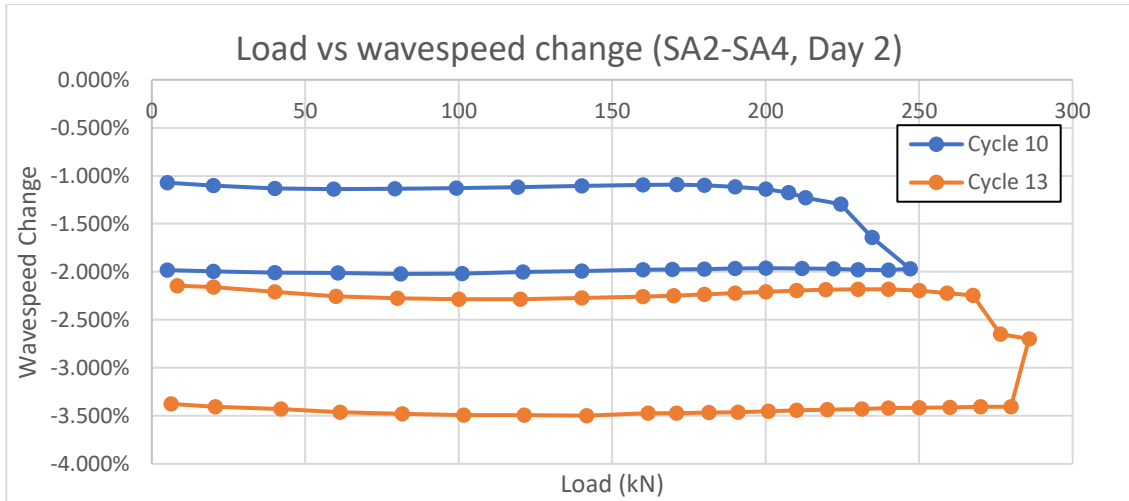


Figure 6.18. $\frac{dv}{v}$ vs load of SA2-SA4 sensor pair, second day test.

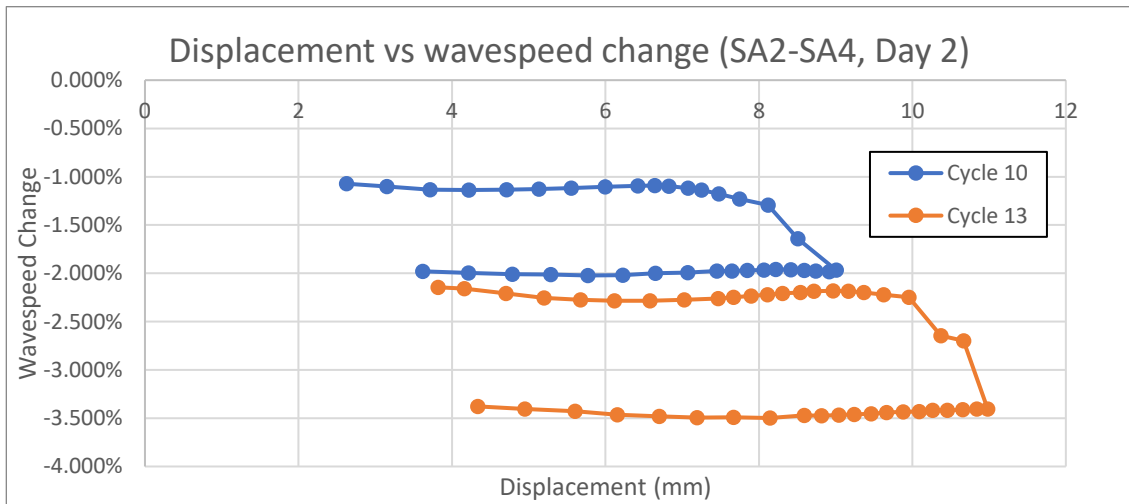


Figure 6.19. $\frac{dv}{v}$ vs displacement of SA2-SA4 sensor pair, second day test.

When the CWI results from the first day and the second day are combined, significant wavespeed change of 0.783% between the end of 7th cycle and the start of 10th cycle is observed. It is also observed that the decrease of wavespeed in SA2-SA4 recordings is the most significant when compared to the other recordings received by all other sensors, with a highest wavespeed drop of 3.498% at 121.3 kN of load in the 13th cycle unloading. The combined $\frac{dv}{v}$ vs load and displacement can be seen in Figure 6.20. and Figure 6.21.

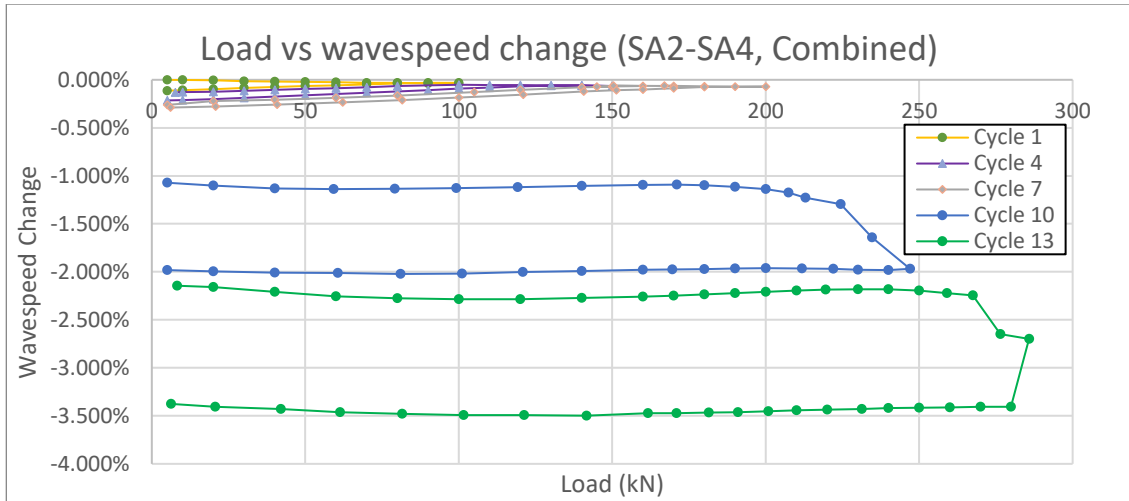


Figure 6.20. $\frac{dv}{v}$ vs load of SA2-SA4 sensor pair, combined.

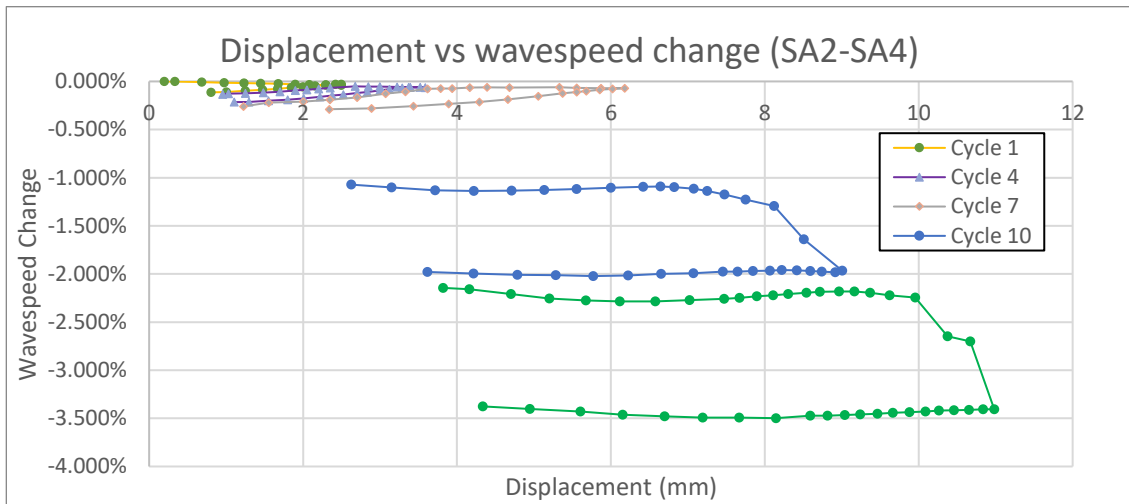


Figure 6.21. $\frac{dv}{v}$ vs displacement of SA2-SA4 sensor pair, combined.

The CWI result of SA3-SA4 recordings shows initial negative $\frac{dv}{v}$ vs load (Figure 6.22.) and displacement (Figure 6.23.) gradients on the 10th load cycle. The wavespeed then increases from load level 40 kN to load level 207.4 kN, before decreases again until the load peak of the cycle. S-curve trend was observed in the $\frac{dv}{v}$ vs load and displacement paths of both the loading and unloading phases of the 10th cycle. The 10th load cycle starts with a relative velocity of -0.332% and ends with -0.741% relative to the reference speed, with a peak speed of -0.089% from the reference speed at 207.4 kN load level. The 13th load cycle loading phase starts at a wavespeed of -0.813% and ends at a load speed of -1.355% from the reference speed. Both the loading and unloading phases followed the S-curve pattern, with the unloading phase displaying less skew compared to the loading phase in both the $\frac{dv}{v}$ vs load and displacement paths. A wavespeed drop of 0.383% was observed at the load step of 285.8 kN to 279.9 kN (dropped from 300 kN).

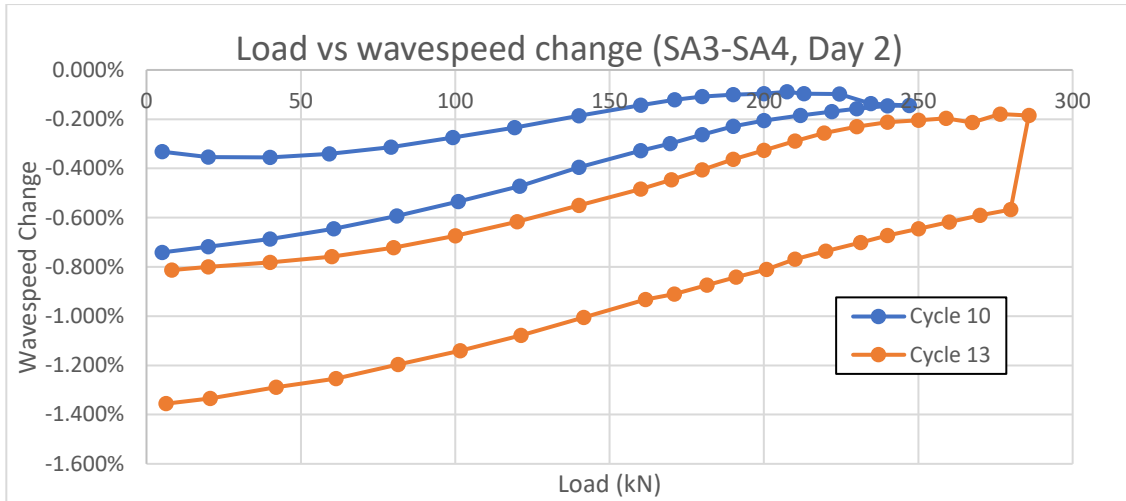


Figure 6.22. $\frac{dv}{v}$ vs load of SA3-SA4 sensor pair, second day test.

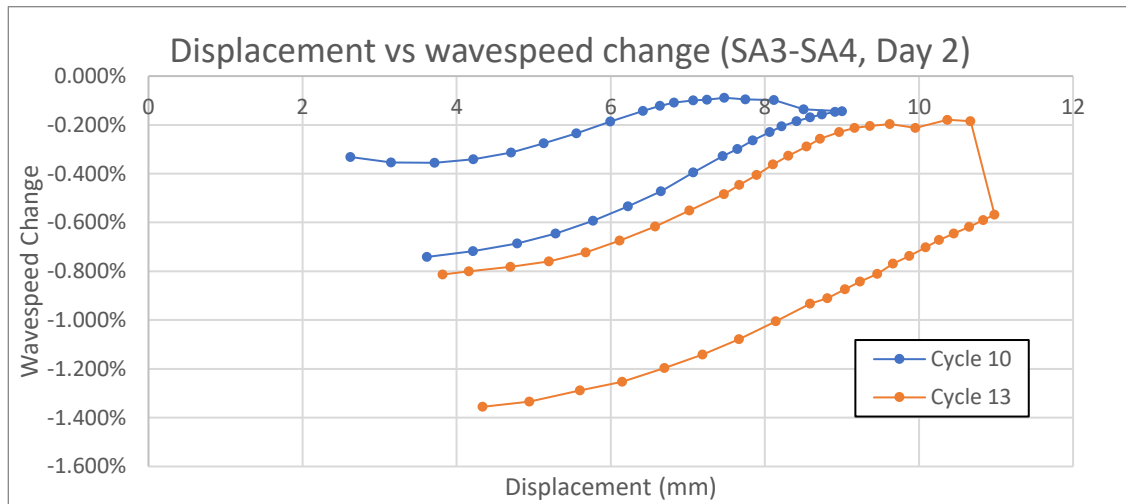


Figure 6.23. $\frac{dv}{v}$ vs displacement of SA3-SA4 sensor pair, second day test.

After combining the CWI results of the first and second day from SA3-SA4 recordings, the combined $\frac{dv}{v}$ vs load (Figure 6.24.) and displacement (Figure 6.25.) graphs show that the 10th load cycle started at higher wavespeed compared to the end of 7th cycle. It is also observed that the $\frac{dv}{v}$ vs load and displacement graphs develop an envelope, similar to the CWI results from other sensor pairs.

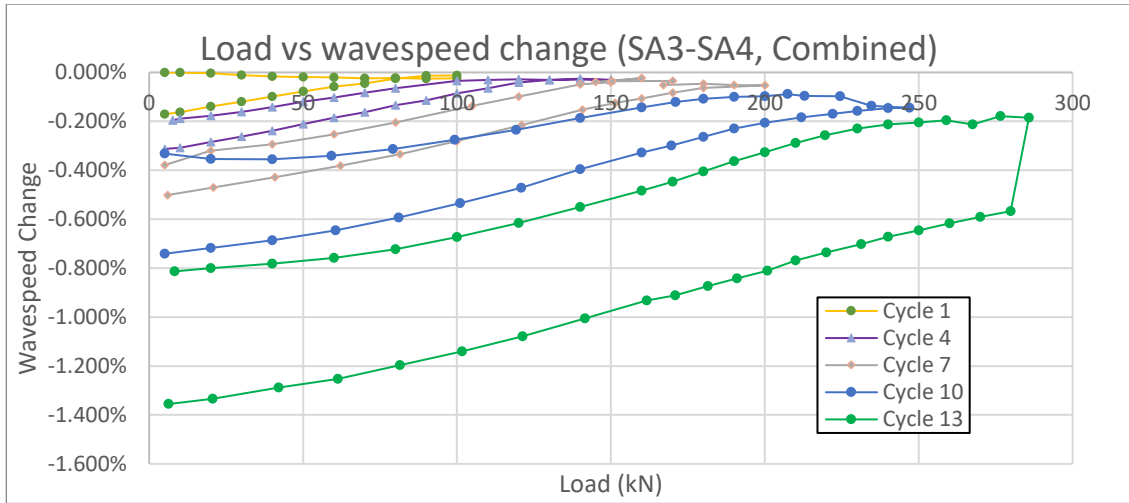


Figure 6.24. $\frac{dv}{v}$ vs load of SA3-SA4 sensor pair, combined.

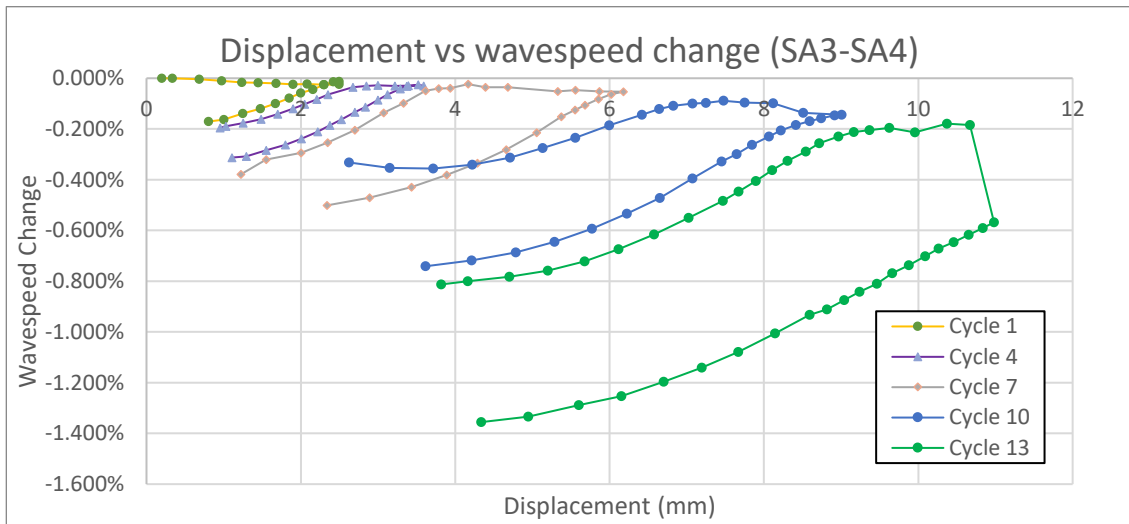


Figure 6.25. $\frac{dv}{v}$ vs displacement of SA3-SA4 sensor pair, combined.

In the $\frac{dv}{v}$ vs load (Figure 6.26.) and displacement (Figure 6.27.) graphs plotted from the CWI results, the $\frac{dv}{v}$ vs load and displacement paths of both loading and unloading phases of the 10th cycle of the SA5-SA4 recording followed the s-curve pattern, which gradients are lower at both ends and starts of the curve. However, the gradients decrease of the unloading curves is more modest compared to the one seen on the loading curve. On the 13th cycle, while the loading part of both $\frac{dv}{v}$ vs load and displacement graphs follow S-curve patterns, the unloading phase of the $\frac{dv}{v}$ vs load graph is observed to be almost linear with a gradient of $2.55877 \times 10^{-5}/\text{kN}$, while the $\frac{dv}{v}$ vs displacement graph still shows S-curve pattern with minimal gradient decrease at higher load levels. Similar with CWI results from other recordings, CWI results of SA5-SA4 recordings also displays a wavespeed drop of 0.442% between 285.8 kN to 279.9 kN (dropped from 300 kN) load step.

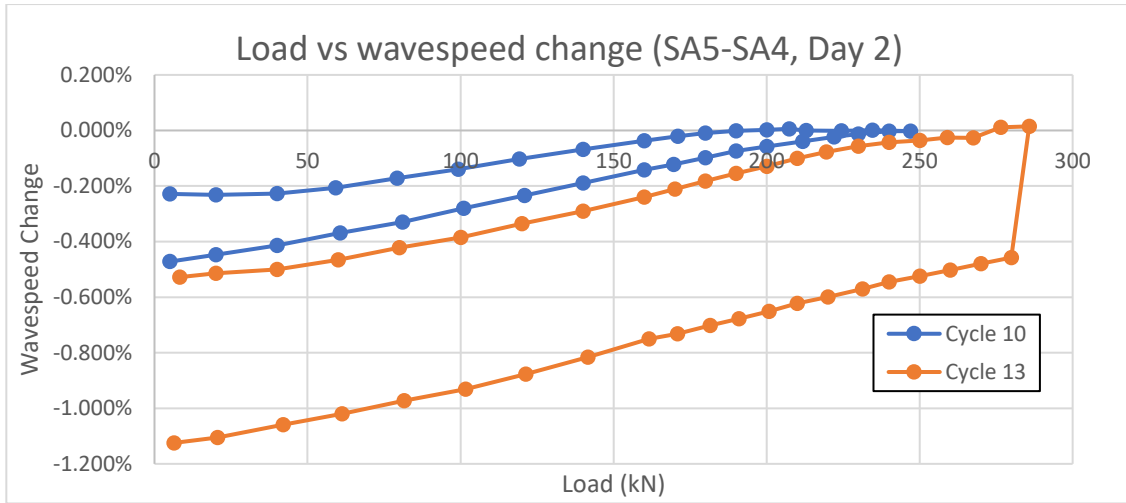


Figure 6.26. $\frac{dv}{v}$ vs load of SA5-SA4 sensor pair, second day test.

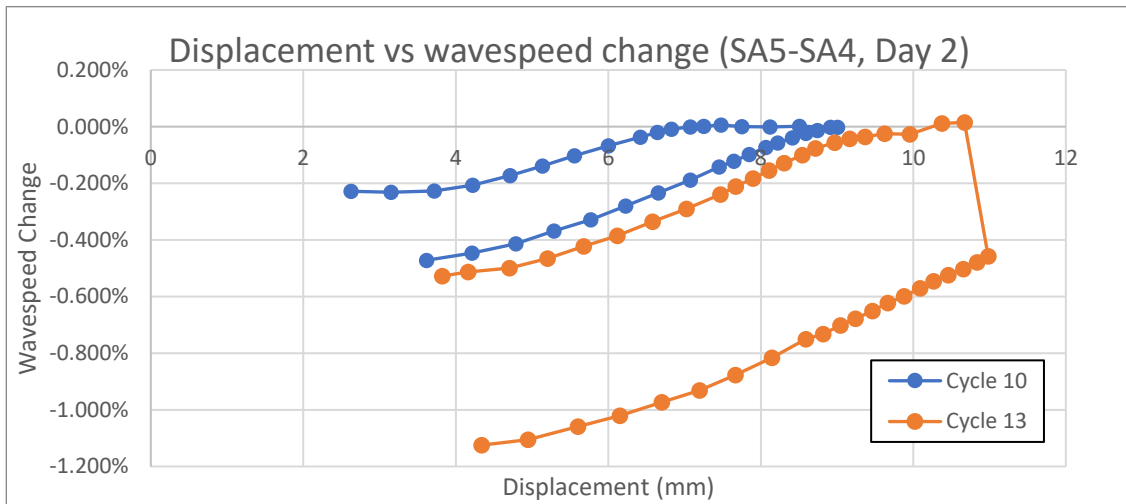


Figure 6.27. $\frac{dv}{v}$ vs displacement of SA5-SA4 sensor pair, second day test.

After combining the CWI results from the first and second day recordings, it is observed that the 10th cycle starts with higher wavespeed compared to the end of the 7th load cycle. Among CWI results from all recordings, the CWI result from SA5-SA4 recordings were the one which shows the least overall wavespeed loss of -1.125% at the end of the 13th cycle. An envelope is observed on both the combined $\frac{dv}{v}$ vs load (Figure 6.28.) and displacement (Figure 6.29.) graphs, in which envelopes the wavespeed hardly reduced until the load reaches 285.8 kN.

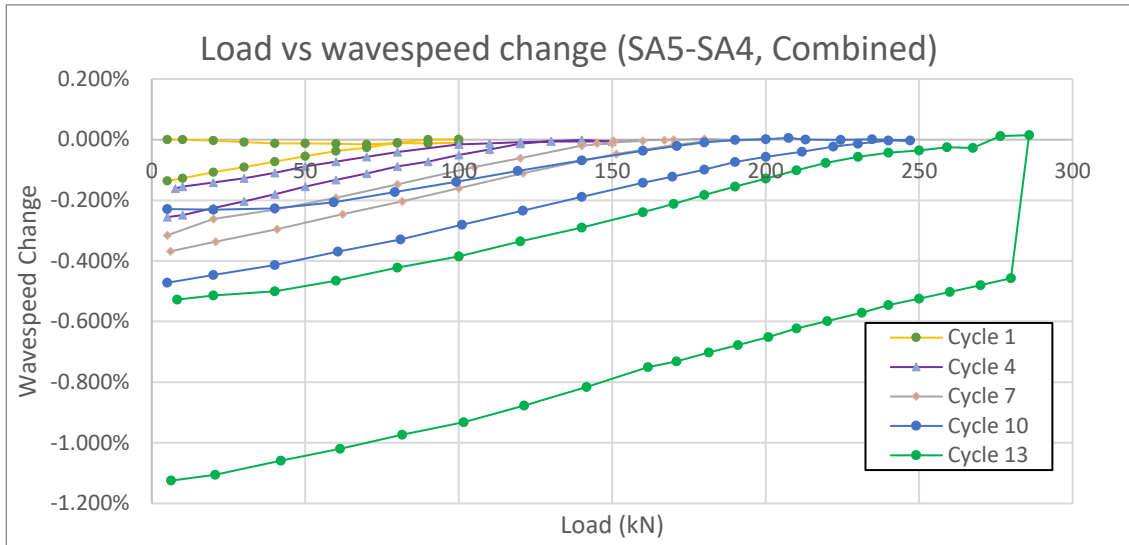


Figure 6.28. $\frac{dv}{v}$ vs load of SA5-SA4 sensor pair, combined.

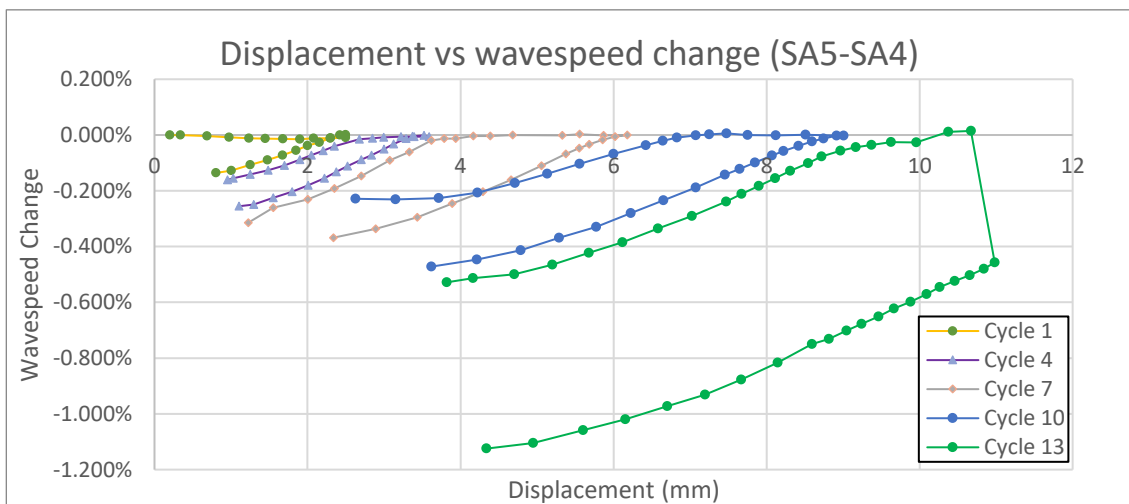
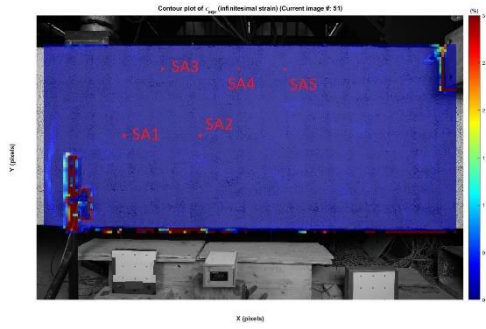


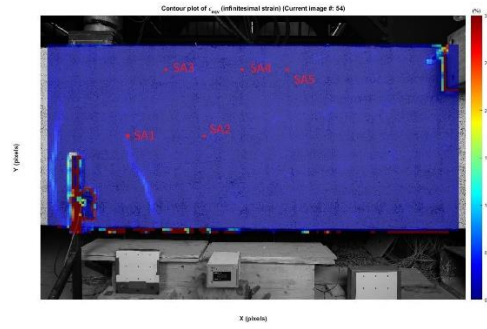
Figure 6.29. $\frac{dv}{v}$ vs displacement of SA5-SA4 sensor pair, combined.

6.2.2.2. CWI sensitivity through space

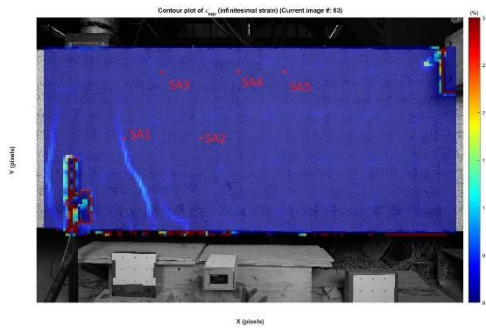
As the digital image correlation (DIC) result can show the evolution of cracking throughout the test, it is interesting to assess how the CWI result correlates with the crack evolution. To do this, the crack evolution is assessed first by observing the DIC results shown in Figure 6.30.



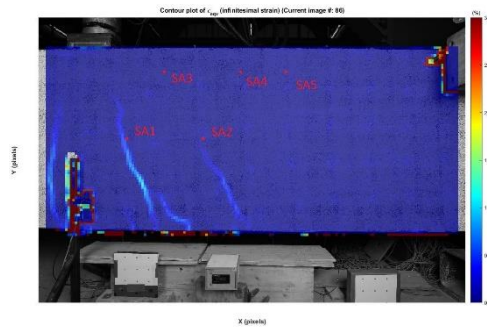
Load level (a) – 170 kN (7th Cycle)



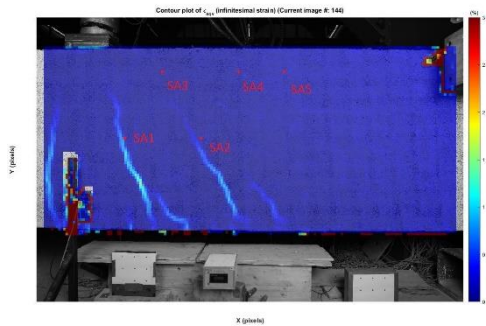
Load level (b) – 177 kN (7th Cycle)



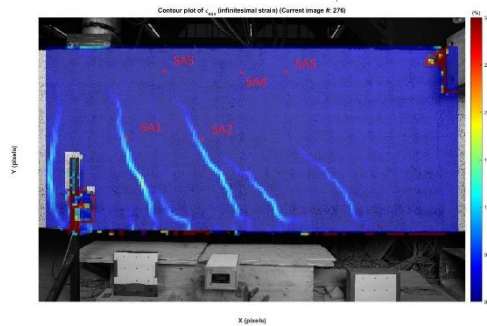
Load level (c) – 199 kN (7th Cycle)



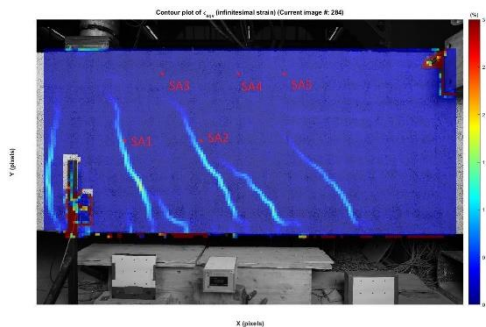
Load level (d) – 187 kN (8th Cycle)



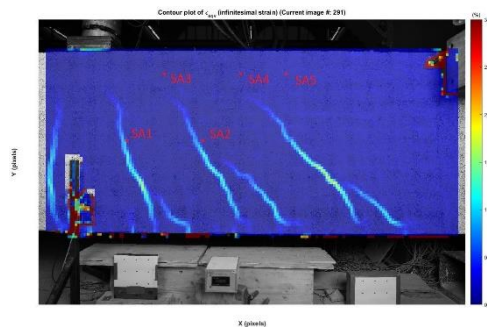
Load level (e) – 239 kN (10th Cycle)



Load level (f) – 266 kN (13th Cycle)



Load level (g) – 299 kN (13th Cycle)



Load level (h) – 283 kN (13th Cycle)

Figure 6.30. DIC measurement of crack evolution of the sample on various load levels. (Courtesy of G. I. Zárate Garnica of Stevin II Laboratory TU Delft).

In Figure 6.30., it is shown that three cracks were formed at the 7th load cycle, one at the 8th load cycle, one at the 10th load cycle, and three at the 13th load cycle. It is observed that the second crack of the 7th load cycle propagated close to SA1 position (Load level (b)), while the crack formed on the 8th cycle propagated close to SA2 position (Load level (d)). Once the peak load of 300 kN was reached (Load level (g)), the cracking grew, and the load gradually decreased as the displacement increased. Just before the unloading part started (Load level (h)), the shear crack had propagated far, and new crack had emerged compared to when the beginning of the particular load step (Load level (g)). The sample failed at 276.9 kN at the loading phase of the 14th cycle. The final crack pattern at failure is shown on Figure 6.31.

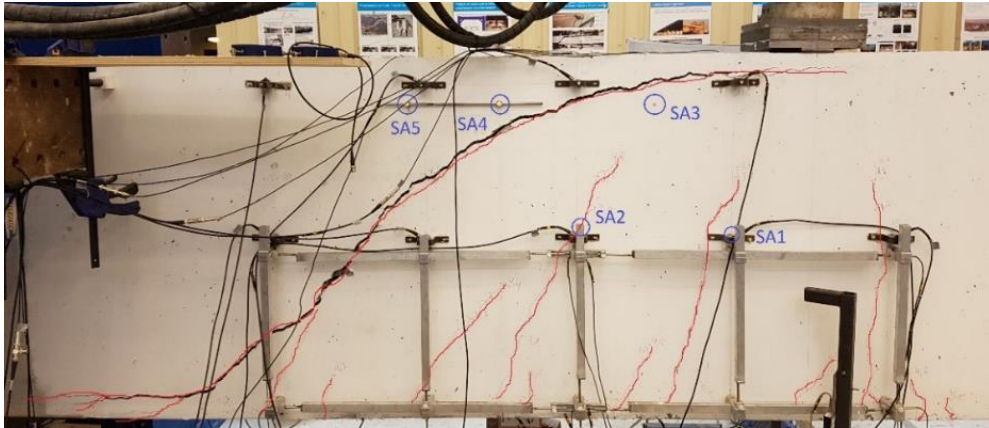


Figure 6.31. Final condition of the beam specimen after failure.

The CWI results of all sensor pairs are assessed by plotting the load level, vertical displacement at the loading point, and CC values of certain windows. Four windows are chosen: one in the early arrival part of the recording, two in intermediate coda, and one in late coda. For the early arrival window, the 5th window is taken since this window is the first window which is completely populated with received signal on the farthest source-receiver pair of SA1-SA4. The 10th window and the 20th window are taken as intermediate coda windows, while the 30th window is taken as the late coda window. By using similar method which was employed in Chapter 4.3.3., the wavespeed of the concrete can be determined as 4500 m/s, which allows the approximate distance travelled to be calculated based on this speed and the window starting time, as summarized in Table 6.2. The load levels of which new crack occurred which are shown in Figure 6.30. are then linked with the drop of CC values observed. From part 5.2.2. of this thesis, it is known that crack widening would cause minimal effect on CC and waveform changes. Since load level (g) and (h) was in the same load cycle, they are merged in the legend in the following figures. The distance between the crack tips and the receivers are shown in Table 6.3.

Table 6.2. Approximate distance travelled at the start of each window.

Window	Window Start Time (s)	Approximate scattering length at window start (m)
5	0.00022048	1
10	0.0004478	2
20	0.00090244	4
30	0.00135708	6

Table 6.3. Approximate distance between receiver and crack tips.

Crack forming at load level	Approximate crack distance from receiver (m)			
	SA1	SA2	SA3	SA5
a	0.4675	0.9672	0.8504	1.5852
b	0	0.5	0.5043	1.1378
c	0.4275	0.4473	0.7996	1.1443
d	0.5	0	0.5094	0.7054
e	0.8386	0.387	0.8808	0.7274
f, g and h	0.85	0.4276	0.5591	0.2887

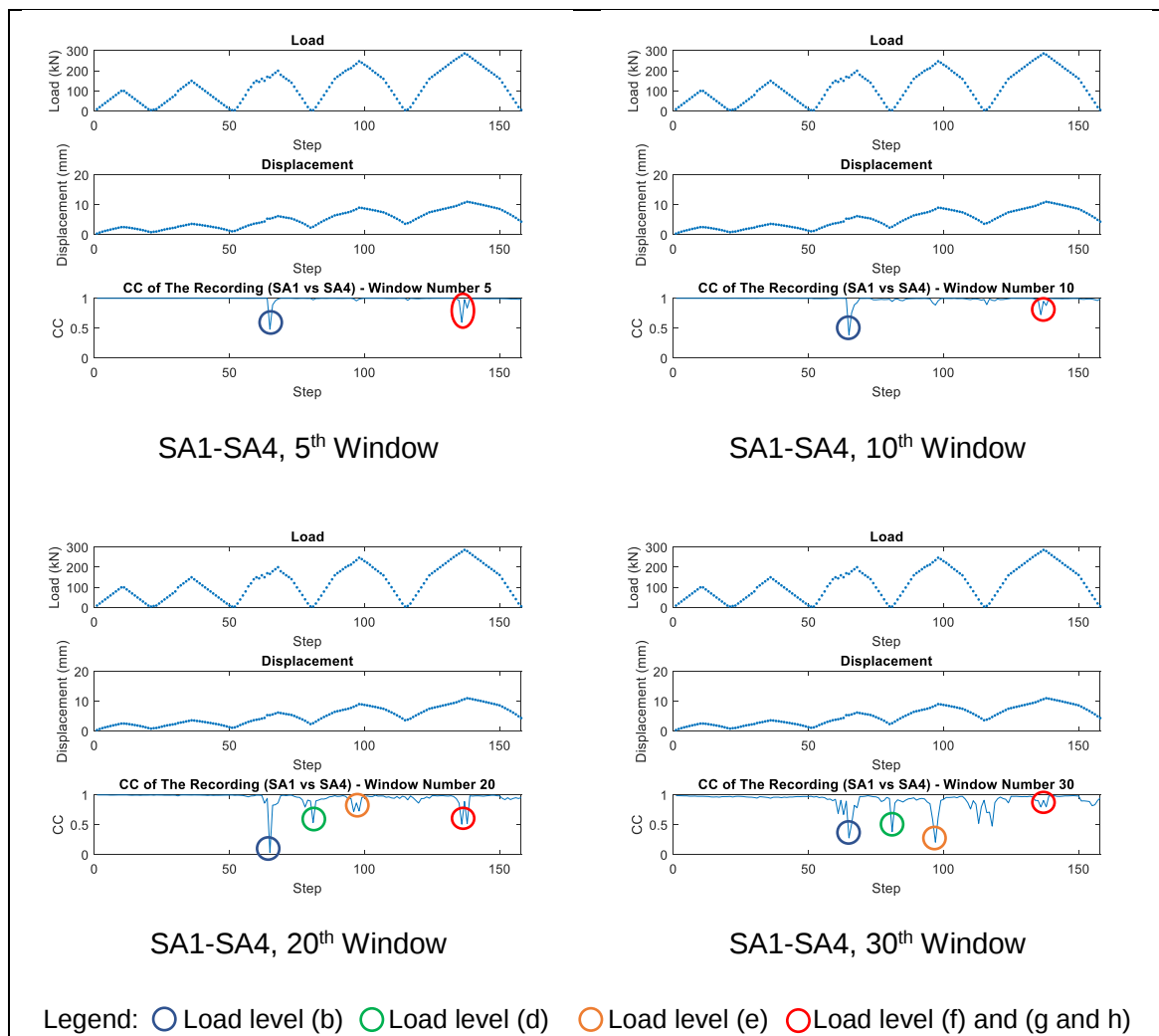


Figure 6.32. Load vs disp. vs CC on various windows, SA1-SA4 pairs.

Figure 6.32. shows that in the CWI results from the 5th and the 10th window of the SA1-SA4 recordings, two major drops of CC occurred. The first one is observed at load level (b), while the second one occurred at load level (f) and (g and h). Minor reduction of CC also occurred at load level (e) in the 10th window, but the correlation coefficient value was still rather high at

0.89 at that point. At the 20th window and the 30th window, however, drop in CC at load level (d) and (e) are also observed. Low CC values in the transition between the 10th and the 13th cycle is observed on the 30th window as well, which does not relate to any notable load level from the DIC result assessment.

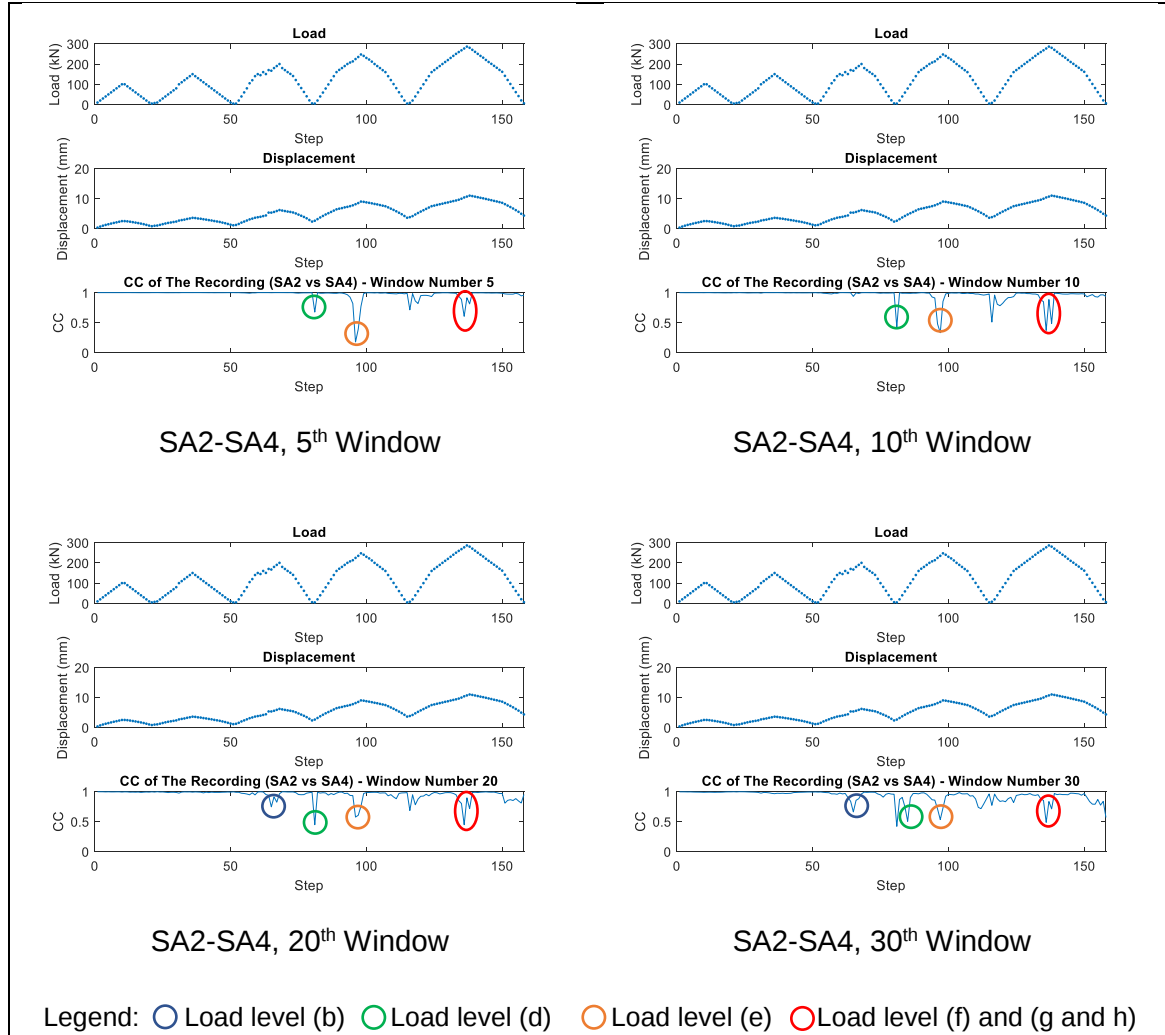


Figure 6.33. Load vs disp. vs CC on various windows, SA2-SA4 pairs.

Even at the 5th and 10th windows, the CWI results from SA2-SA4 recordings are sensitive to the cracks happening in load level (d), (e), and (f and h), as shown in Figure 6.33. The crack which first appeared on the load level (b) is only observed at the 20th and the 30th window. Moreover, some drops of CC values in the transition between the 10th and the 13th cycle are observable in all the windows assessed with varying degree.

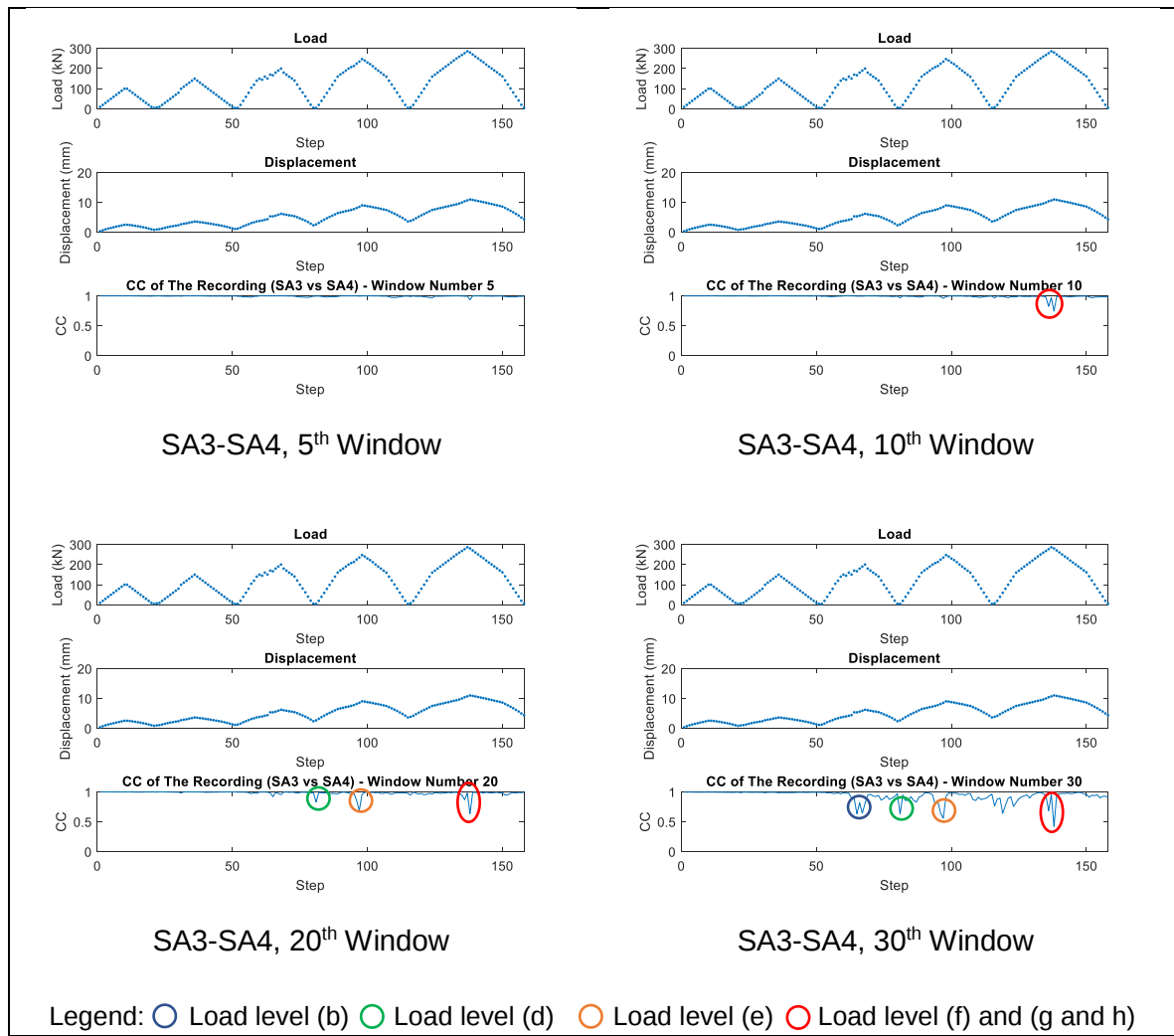


Figure 6.34. Load vs disp. vs CC on various windows, SA3-SA4 pairs.

In the CWI results from the SA3-SA4 recordings, it can be observed in Figure 6.34. that in the 5th window, minimal disturbance is observed throughout the test, indicating the low sensitivity of this part of the signal to medium changes caused by cracks. However, it is also observed that the sensitivity increases in later codas: where the 10th window is sensitive to cracks forming in load level (f and h), 20th window is sensitive to the cracks forming in load level (d), (e), and (f and h), and the 30th windows is sensitive to load level (b) in addition to previously mentioned load levels. Like other CWI results from other sensors, the 30th window picked some low CC values in the transition between the 10th cycle and the 13th cycle. However, such reduction is absent in all other displayed windows.

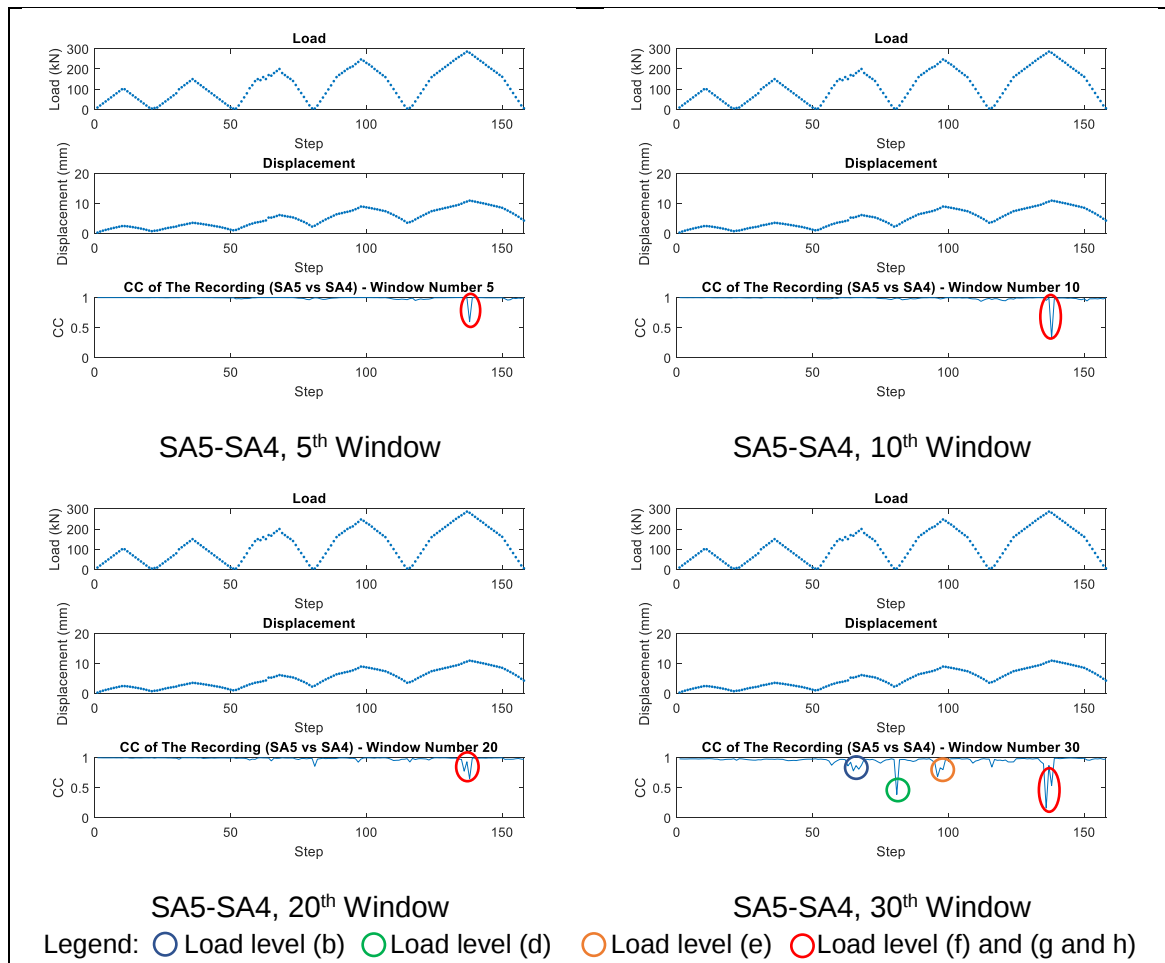


Figure 6.35. Load vs disp. vs CC on various windows, SA5-SA4 pairs.

In the CWI results of the SA5-SA4 recordings which are displayed in Figure 6.35., the 5th and 10th windows are observed to be only sensitive to crack forming in load level (h), indicated with the presence of only one peak observed at 279.9 kN load level in unloading phase instead of two at the 267.5 kN in loading phase and 279.9 kN in unloading phase. Moreover, it is also observed that the 20th window is only sensitive to crack forming in load level (f) and (h). In the 30th window, however, the CWI result is sensitive to the cracks forming in load level (b), (d), and (e) in addition to load level (f) and (h). A small drop in CC is also observed in the transition between the 10th and 13th cycle, but again, its value is still relatively high at 0.84.

In general, from the assessment it can be observed that the later the window is, the more sensitive it is to damage further away from the sensor pairs. It is also observed that load level (a) and (c) are not monitored in the CWI results of all the recordings.

6.2.3. Compression zone analysis through CWI of signal's early arrivals

As the later codas being assessed previously contain information from signals which had scattered throughout the sample, the signals' earlier arrivals had not been analyzed. Earlier arrivals of the signals are indicative of local changes occurring near the source-receiver sensor proximity.

In this section, the earlier arrivals of the signals recorded from SA5-SA4 sensor pair are analyzed. Since the estimated mean estimated strain between the SA5-SA4 sensor pair can be measured from the LVDT15 installed between the locations of the two, it is interesting to assess the wavespeed changes of the earlier arrivals against the local strain. To conduct the analysis, the wavespeed change values of the second window to the fifth window are averaged, which results in a wavespeed change gained from the signals which had a maximum scattering distance of approximately 1m. Therefore, the local strain between the SA5-SA4 sensors pair vs the early arrivals wavespeed change can be plotted. The load vs estimated local strain between SA5-SA4 sensors is also plotted in Figure 6.36.

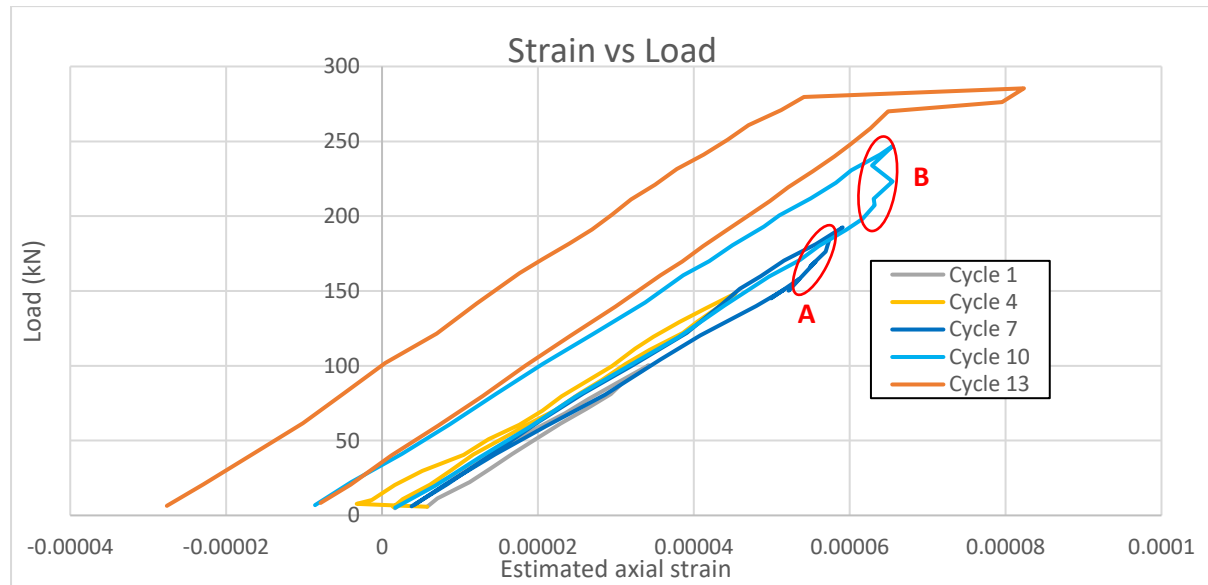


Figure 6.36. Load vs estimated axial strain between SA5-SA4 sensor pair of the test.

Linear $\frac{dv}{v}$ vs strain relationship is observed in both loading and unloading phase of the first load cycle. Instead of initial negative $\frac{dv}{v}$ vs load and displacement gradients which were observed in Figure 6.12. and Figure 6.13., it is observed in Figure 6.37. that the initial strain vs wavespeed change gradient is positive. Wavespeed drop of 0.289% is observed upon unloading. The loading phase of the second cycle is observed to be linear up to a strain level of 0.00002303 and has similar initial gradient when compared to the unloading phase of the first cycle. The gradient is then observed to be decreasing as the strain level increases, and the final part of the loading phase is observed to be linear with higher gradient when compared to the preceding loading phase. Upon unloading, a wavespeed loss of 0.185% was observed compared to the starting point of the second cycle.

In the third cycle, however, the wavespeed-strain relationship is observed to be mainly linear, with a minimal amount of wavespeed loss (0.103%) upon unloading. Interestingly, the increase of strain is observed to be small between load level 150 kN and load level 200 kN, as seen in detail A of Figure 6.36.

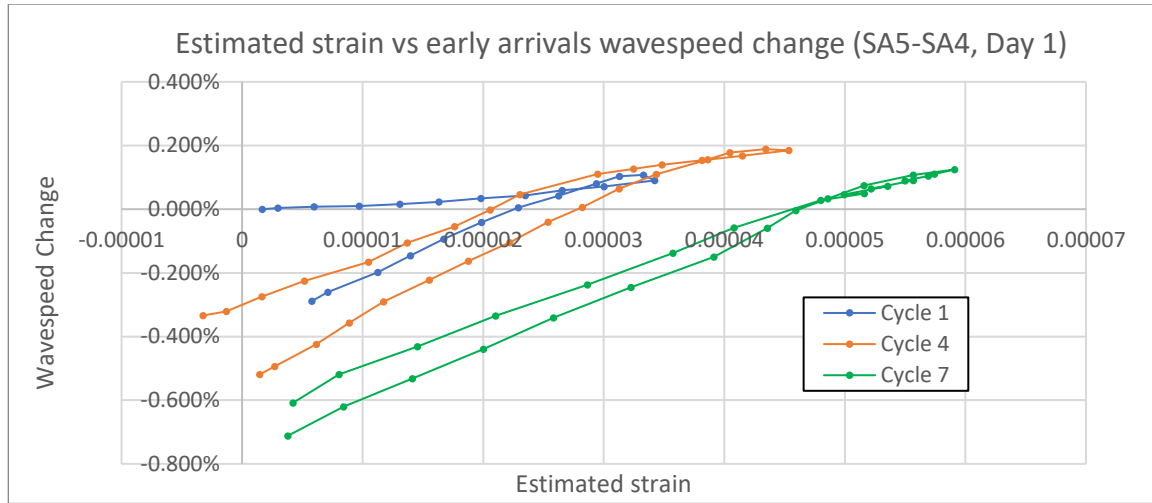
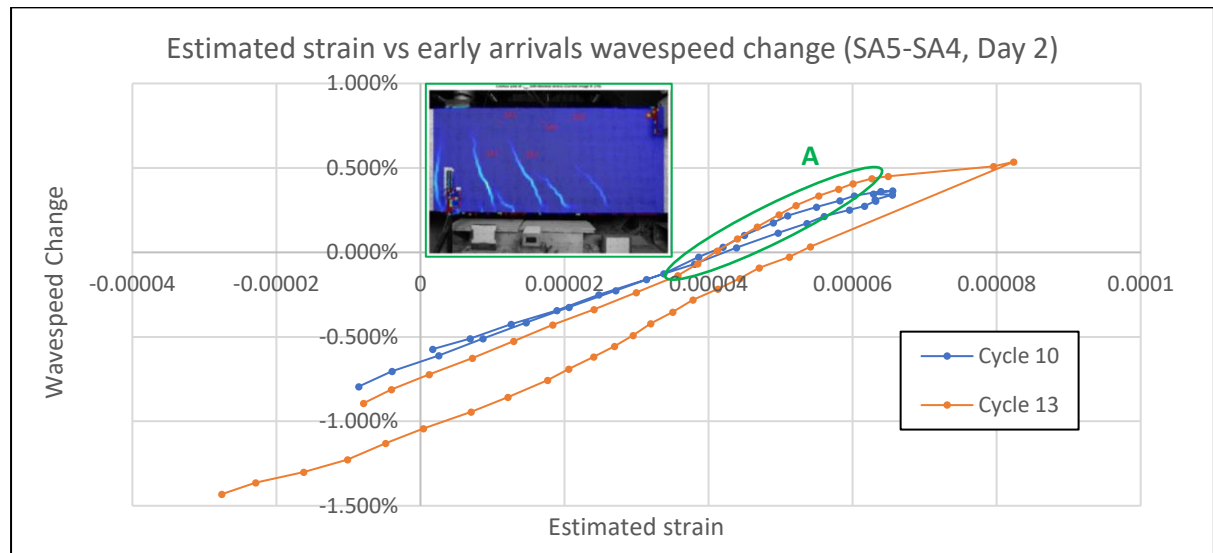


Figure 6.37. Early arrivals $\frac{dv}{v}$ vs estimated local strain between SA5-SA4 sensor pair (Day 1).

The $\frac{dv}{v}$ vs strain relationship (Figure 6.38) of the 10th cycle is observed to be almost linear, with both the loading and unloading phase sharing similar path with minimal wavespeed difference at any given strain value. It is also observed in detail B of Figure 6.36. that in the 10th cycle, the strain change through loading is halted upon reaching 200 kN of load.

An increase of gradient in the $\frac{dv}{v}$ vs strain relationship of the loading phase of the 13th cycle was observed as indicated in detail A of Figure 6.38. The DIC result from corresponding load cycle is also shown in the figure insert, where the bending cracks occurred beneath the SA4 and SA5 smart aggregates. Upon unloading, a significant drop of 0.538% in wavespeed is observed upon unloading, along with a decrease in axial compressive strain of 0.0000197.



**Figure 6.38. Early arrivals $\frac{dv}{v}$ vs estimated local strain between SA5-SA4 sensor pair (Day 2).
DIC result corresponding to the indicated phase is shown.**

When combined, it is observed in Figure 6.39. that the 7th cycle, 10th cycle and the loading phase of the 13th cycle are roughly in a similar path. However, the 13th cycle shows increase of gradients as the loading proceeds, while the 7th cycle does not. The wavespeed of the

beginning of the 10th cycle is higher when compared to the end of the 7th cycle, which is consistent with the findings in section 6.2.1. of this thesis, where the wavespeed of the start of the second day was higher when compared to the wavespeed of the medium at the end of the first day test. It is also observed, however, the 7th cycle did not undergo change in gradient in its $\frac{dv}{v}$ vs strain path, while the 13th cycle underwent significant increase in gradient (detail A of Figure 6.39.).

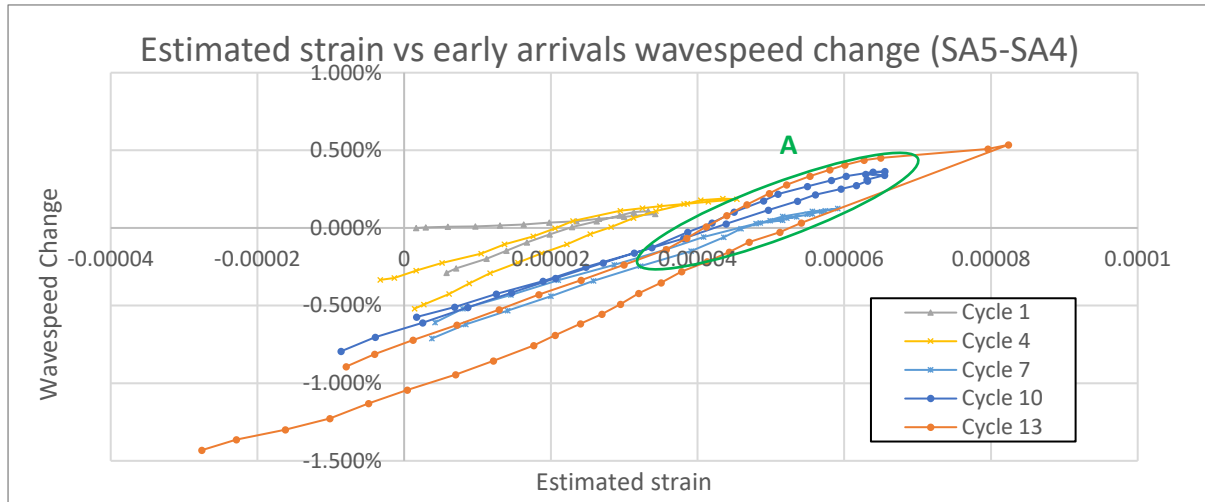


Figure 6.39. Early arrivals $\frac{dv}{v}$ vs estimated local strain between SA5-SA4 sensor pair (Combined)

6.3. Impulse response retrieval by seismic interferometry

The idea of assessing the use of SI in this research is to retrieve impulse responses from existing signals through cross-correlations and determining if the retrieved impulse responses are usable for CWI purposes. For assessment purposes, SI was attempted on the unloaded beam before the loading procedure discussed in previous parts of this chapter was done.

6.3.1. Impulse response retrieval

Signal generated from the hammer hits varied significantly between hits. In some recordings, the signals received by SA4 were not resemble the ones received by SA5 despite of both signals came from the same hit. Moreover, significant differences in amplitude occurred even from signals generated by the same hit. Examples of the received signals are shown in Figure 6.40.

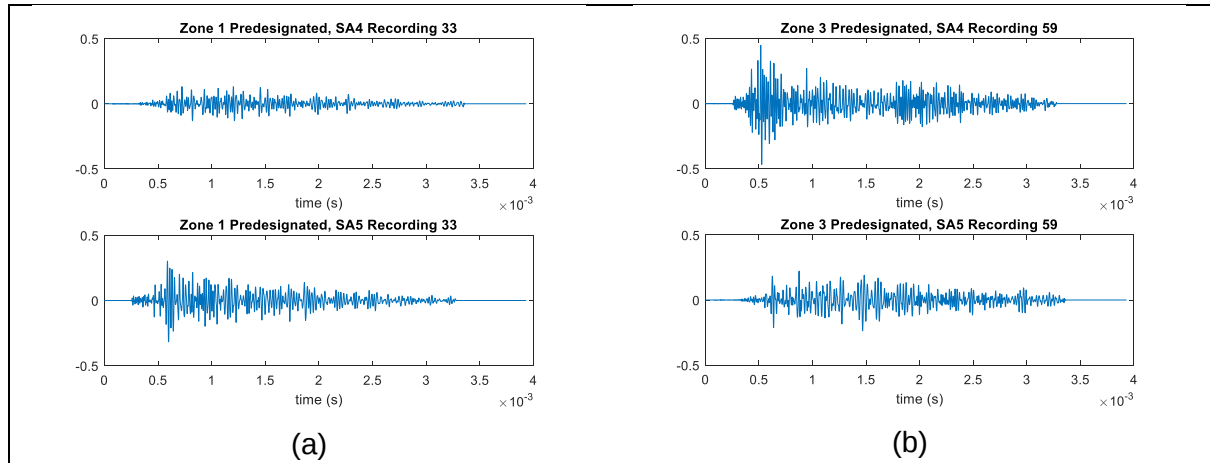


Figure 6.40. Signal recording example of SA4 (top) and SA5 (bottom) from hammer hits from (a) Zone 1 and (b) Zone 3. Note the difference in waveform and amplitude in two signals from the same hit.

These signals were then cross-correlated by using `xcorr` function in MATLAB. SA5 was designated as the virtual source, while the SA4 was designated as the virtual receiver. The cross-correlation products of the signals received by SA4 and SA5 from various hammer hits were then summed.

After summing the cross-correlation products without conducting any normalization apart from the unbiased cross-correlation normalization, it was possible to display the retrieved impulse response. The summation of cross-correlation results of the beats in each zone are displayed first, followed by the total summation of all beats.

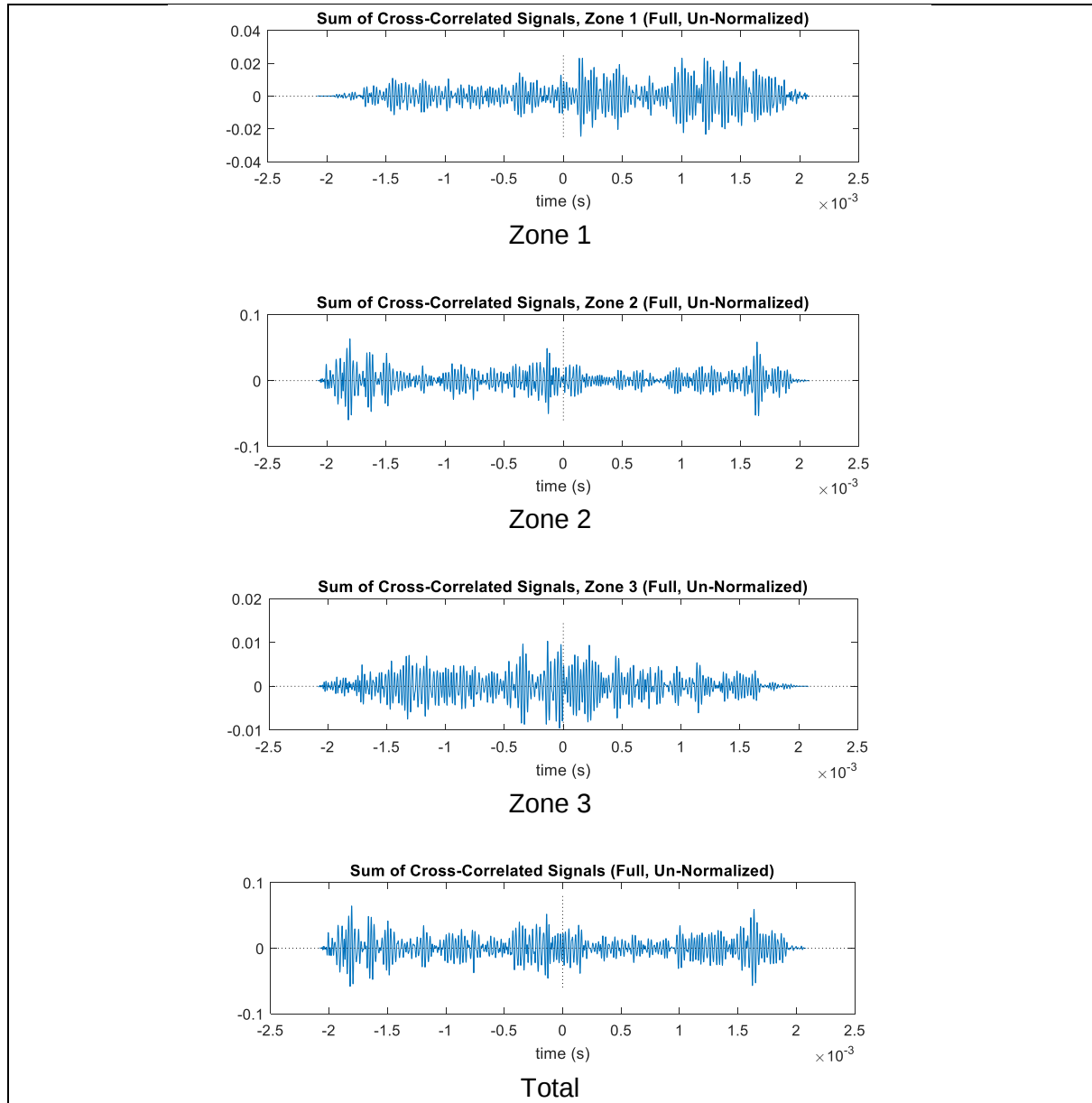


Figure 6.41. Impulse response retrieved from seismic interferometry of unnormalized signals.

The result displayed on the Figure 6.41. shows that the sum of cross-correlation products from the signals generated from the beatings done on the Zone 1 has higher amplitude in the positive time axis compared to the negative time axis, while the other way is valid for seismic interferometry result of Zone 2 and Zone 3 beatings. After summing all the cross-correlation products, it can be observed that the SI product is not symmetric in its waveform, as well as no tapering of amplitude is observed on both positive and negative time axis. The virtual first arrivals are not able to be identified in both positive and negative time axes.

To improve the SI result, normalizations were done. Two approaches were considered: peak amplitude-based normalization and energy-based normalization. As the name suggests, peak amplitude-based normalization normalized the signal pairs by multiplying the signal which had smaller peak amplitude with an amplification factor obtained from the ratio of the two peak amplitudes between the two signals. The energy-based normalization was done by comparing the energy of the signal, which correlates to the sum of absolute square of the signal entries.

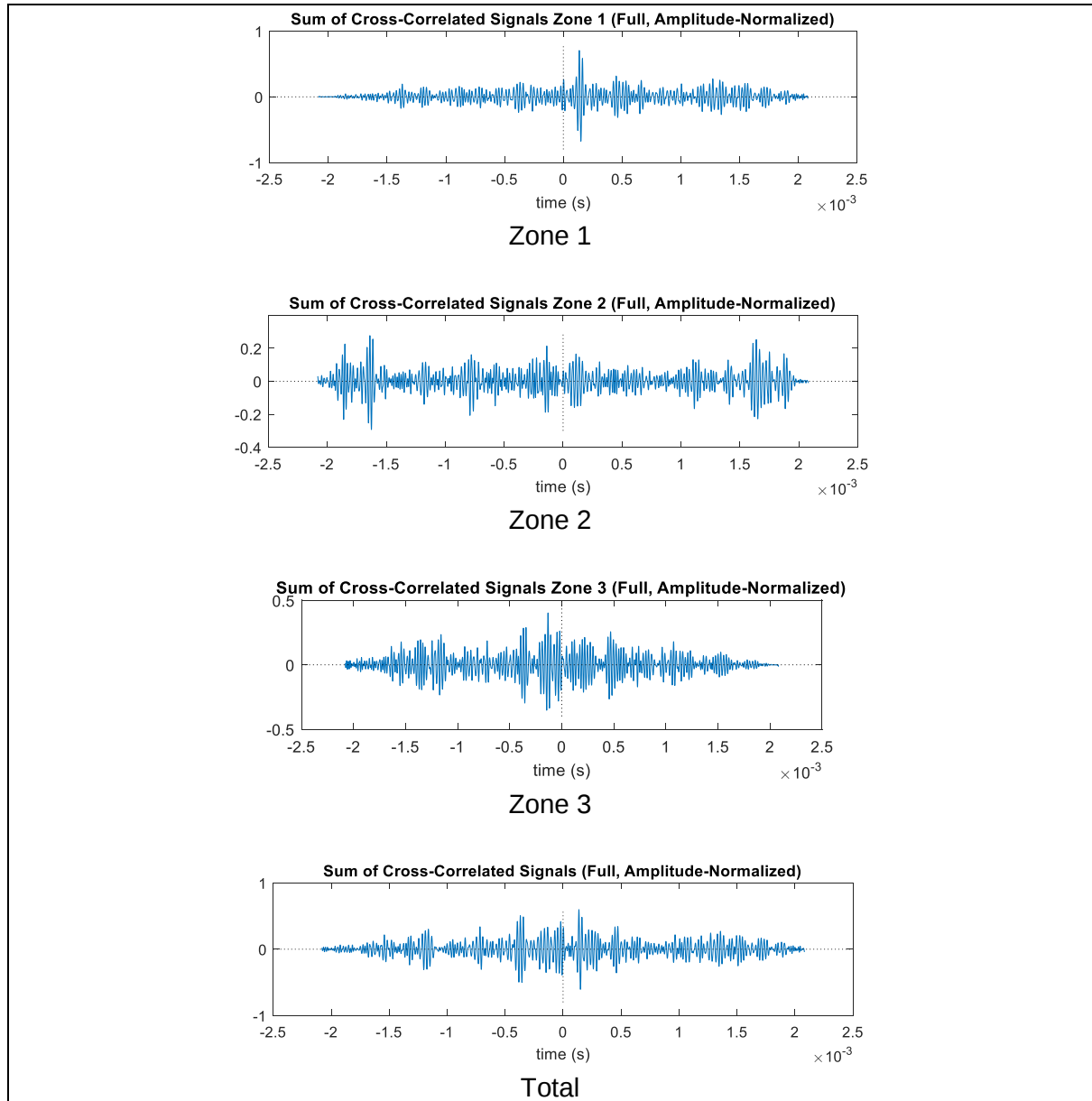


Figure 6.42. Impulse response generated from seismic interferometry of amplitude-normalized signals.

As seen in Figure 6.42., the result of the peak amplitude normalization of the signal generated on Zone 1 and Zone 3 are similar with the ones witnessed on the unnormalized result: the cross-correlation sum of signals from hammering done on Zone 1 has higher energy on positive time axis while the one from Zone 3 hits has higher energy on the negative time axis. From the summation of the cross-correlation products of all the signals, tapering is observed in both positive and negative time axes, but the resulting impulse response is not symmetrical to the 0 time, and the virtual pre-arrival is not observed in both sides of the time domain.

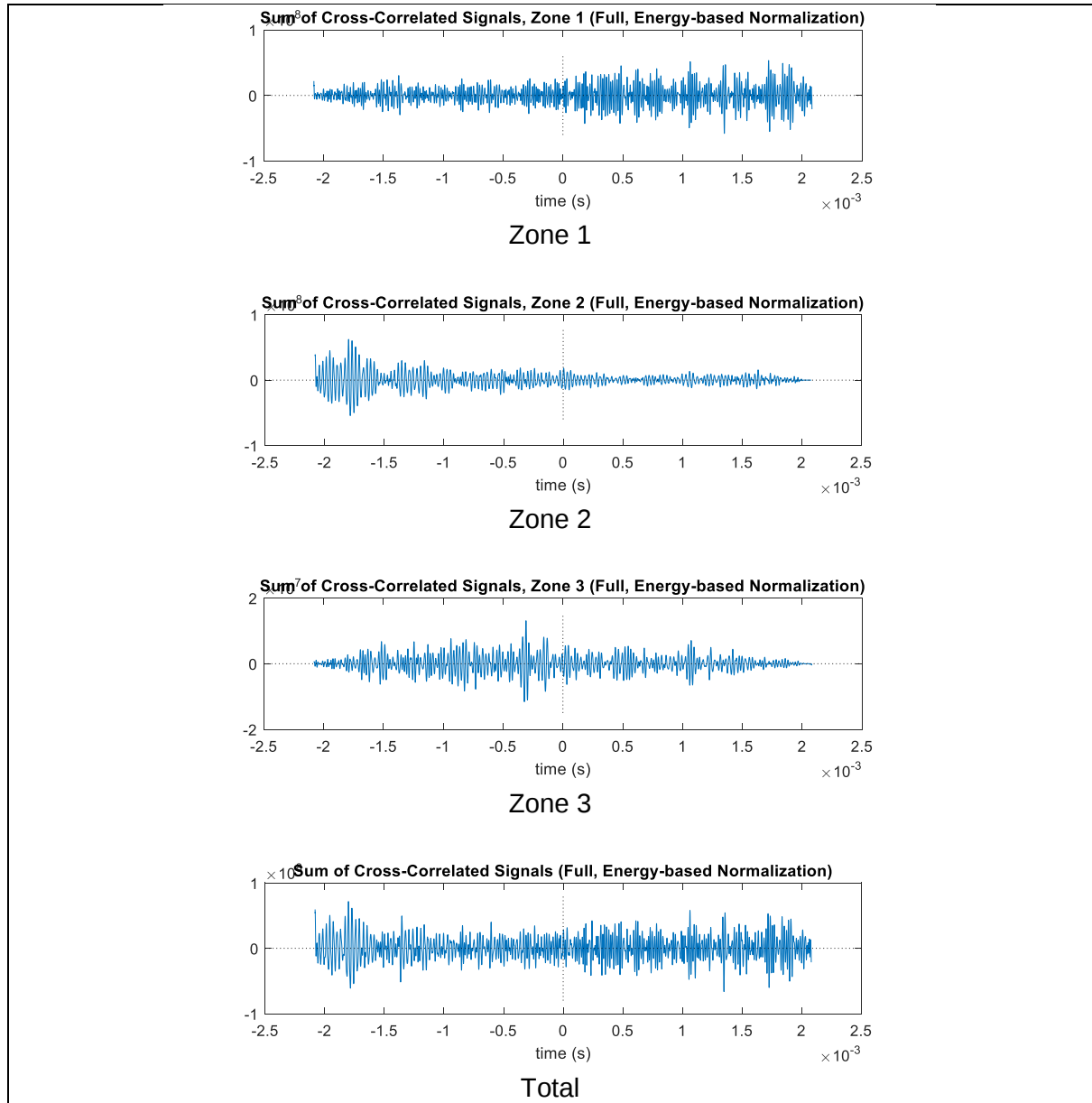


Figure 6.43. Impulse response generated from seismic interferometry of energy-normalized signals.

When assessing the seismic interferometry result of the energy-normalized signals displayed in Figure 6.43., it is found that apart from the phenomenon of the observation of higher energy content in positive time axis for signals from Zone 1 hammer hits and the other way around for signals from Zone 3 hammer hits, the amplitude distribution of seismic interferometry result of the signals from Zone 2 is extremely skewed to the extreme of negative time axis. The summation of all cross-correlated signals also shows little to none similarities to an impulse response, with asymmetric signals between positive and negative time axis, as well as the lack of tapering towards the extremes of the axes.

Since cross-correlating the full recording has not yield desirable results, attempts of processing only the early arrivals and the coda only were done. Since it was observed that the amplitude-based normalization seems to be working best, the following SI of the early arrivals and the codas were done on amplitude-normalized signal. The early arrival signals

were taken by trimming the signal pairs from the first arrival sensed by the first receiving sensor up to three times the travel period of the two sensors, while the coda signals were taken from the full signals with the part which was used for the early arrivals analysis trimmed. In both cases, the signals were first normalized prior to trimming.

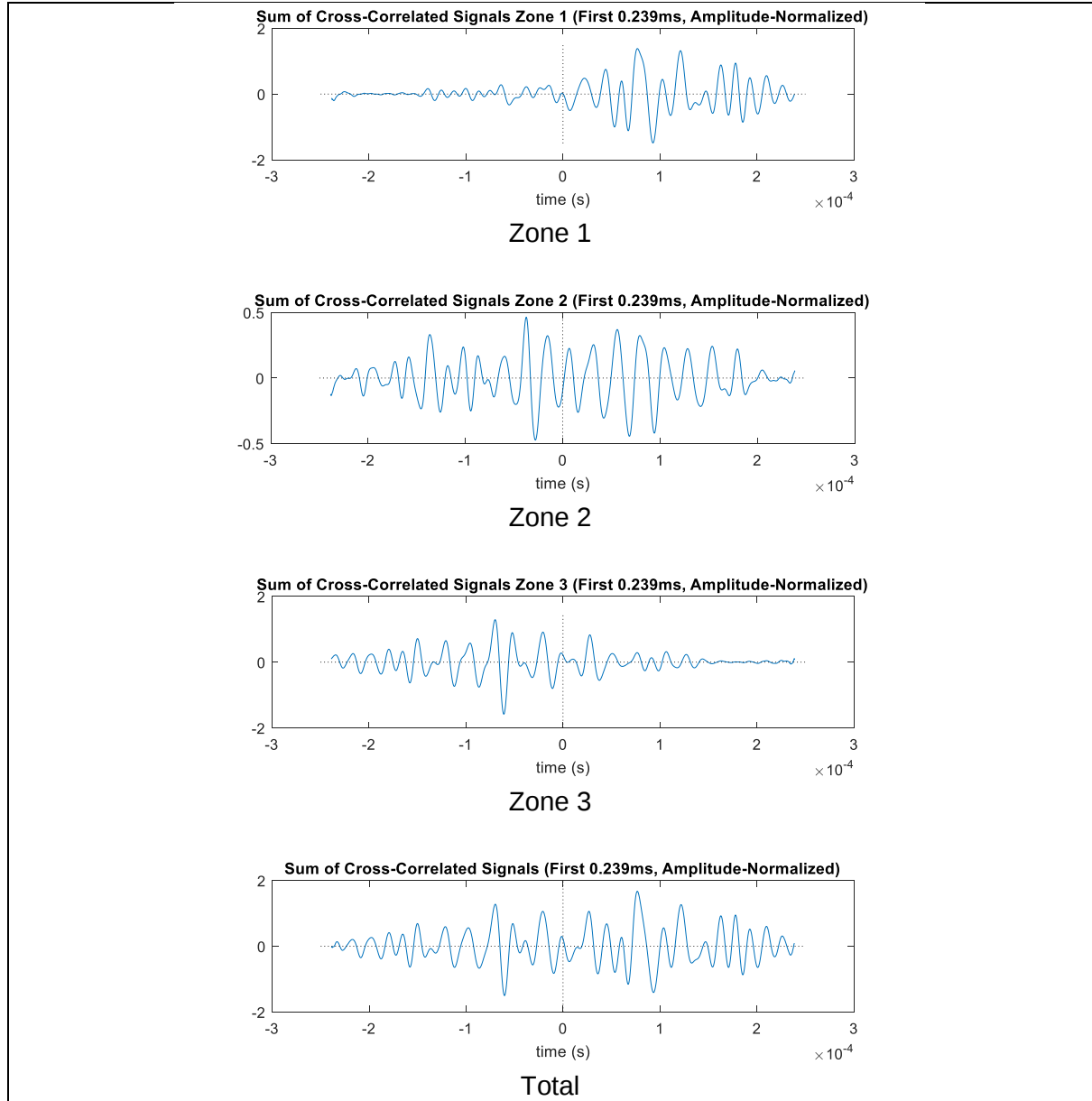


Figure 6.44. Impulse response generated from seismic interferometry of the early arrivals of amplitude-normalized signals.

While it has shorter resulting impulse response due to shortly trimmed signal, it is observed in Figure 6.44. that the sum of cross-correlations of signal from hammer hits on Zone 1 has higher energy on the positive time axis, while the ones from hammer hits on Zone 3 has higher energy on negative time axis. The sum of cross-correlation of signals from hammer hits done on Zone 2 is rather symmetrical. By summing all the cross-correlation products of all hits, it can be observed that the resulting impulse response does looks moderately symmetrical with tapering on both ends of the time axis. However, the symmetry is not perfect, and no pre-arrival part is observed at both positive and negative time axes.

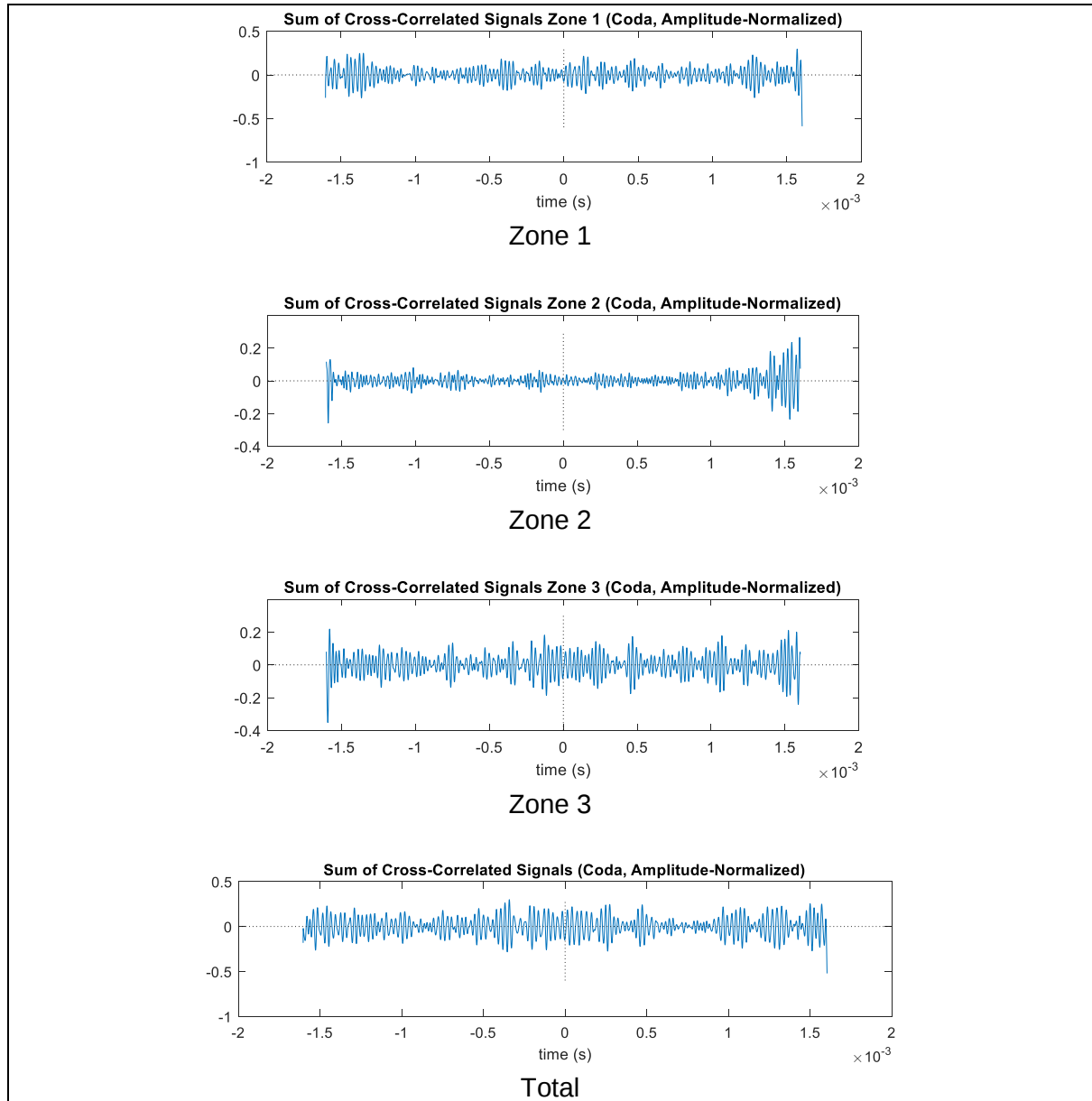


Figure 6.45. Impulse response generated from seismic interferometry of the coda of amplitude-normalized signals.

Figure 6.45. displays the result of SI which was done on the coda part of the signals. On the figure, it is observed that the sum of cross-correlation products of signals generated from hammer hits on Zone 1 and 3 are rather symmetrical, while the one generated from the hammer hits on Zone 2 is heavily skewed on the positive time axis. After summing all the cross-correlation products, it can be observed that the result of SI of signals' coda does not resemble an impulse response at all. No tapering is observed at both ends of the signal, nor any hint of symmetrical envelope of the generated impulse response is observed.

Another trial to retrieve a proper impulse response from the recording was by windowing the signal pairs from both receivers, then normalize each window pair on both signals before conducting the cross-correlation and summing the cross-correlation products to retrieve the impulse response. Rectangular window with a length of three times travel time between the

two sensors was used with 50% overlap between the windows. These pairs of windowed signals are then amplitude-normalized before cross-correlated and summed.

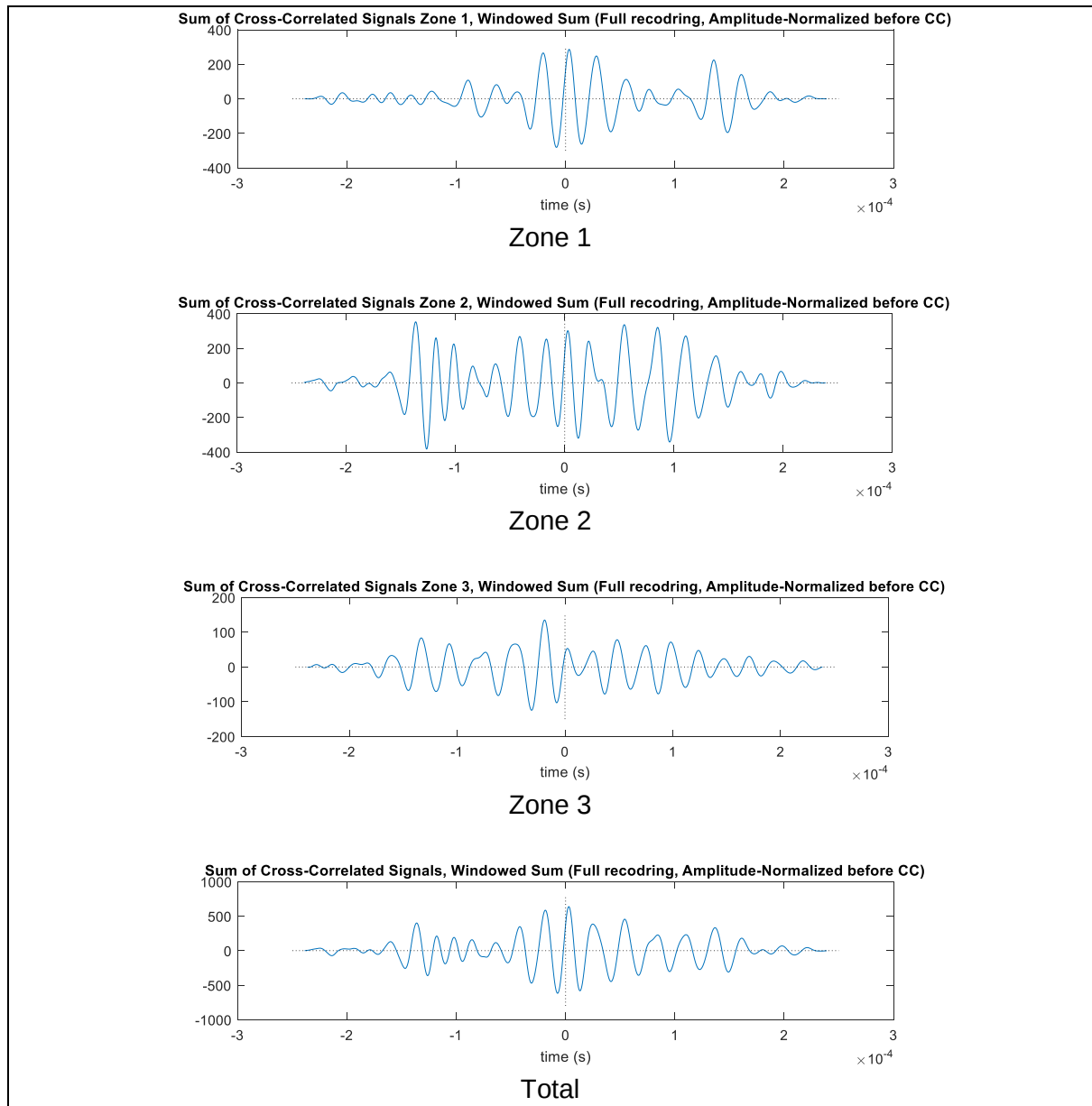


Figure 6.46. Impulse response generated from seismic interferometry of the windowed and amplitude-normalized signals.

The results of this normalization procedure, as seen in Figure 6.46., seem to be center-heavy in all signals from the hammer hits on all zones. It is observed that on the positive time axis has slightly higher energy on the sum of cross-correlated signals generated by hammer hits on Zone 1 compared to its negative axis. While the other way around can also be said on the cross-correlated signal sum from Zone 3 hits, the way the amplitude distributed is different: the one from Zone 1 hammer hits has higher amplitude quite away from the center, while the one from Zone 3 hammer hits has higher amplitude close to the center. Summing all cross-correlation products, the end result does taper towards the end, but neither it is perfectly symmetrical nor has pre-arrival zeros at the center time axis.

Finally, 'one-beat' normalization was attempted to the whole signal. This normalization scheme was done by assigning any positive amplitude entries as 1 and negative amplitude entries as -1. The result of this normalization is shown on Figure 6.47. The normalized signal was then cross-correlated and summed as previously done.

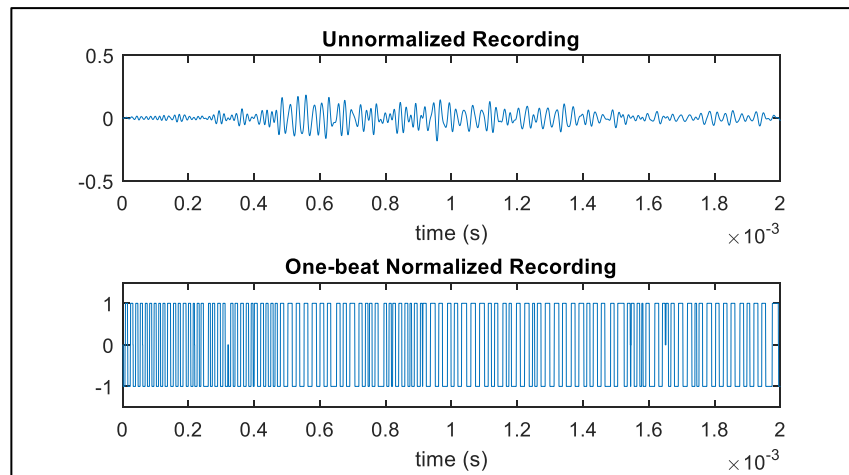


Figure 6.47. One-beat normalization scheme: unnormalized (top) and normalized (bottom)

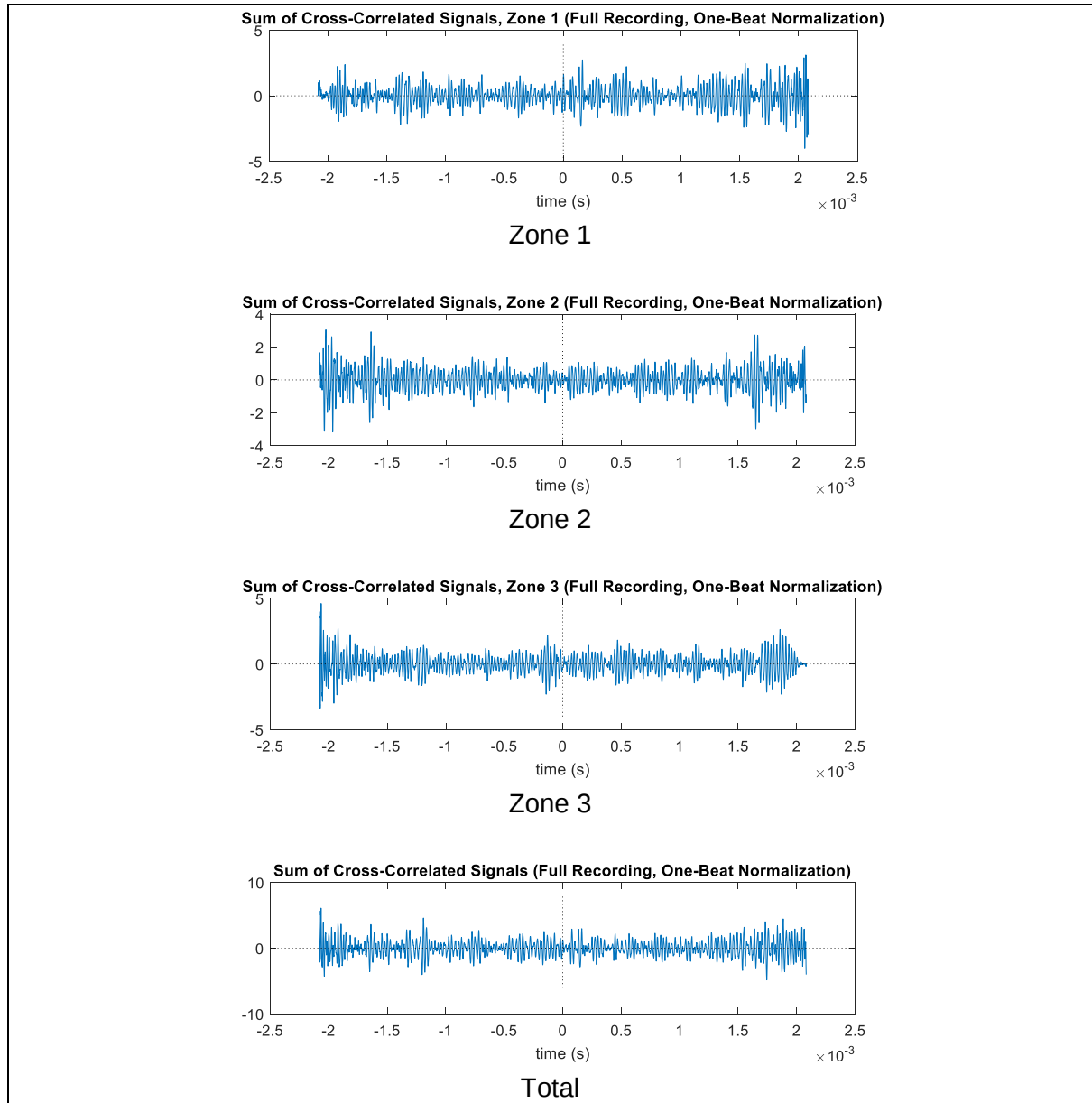


Figure 6.48. Impulse response generated from seismic interferometry of the one-beat normalized signals.

The results of summed cross-correlated one-beat normalized signal can be seen in Figure 6.48. While the summed cross-correlation products of signals from hammer hits on each zone have similar trends with previous SI results, such as higher energy observed on positive time axis of summed cross-correlated products of signals generated by hits at Zone 1, are observed, the total sum of the cross-correlation products does not resemble an impulse response: since it lacks tapering at both ends of time axis and symmetry.

6.4. Discussion

6.4.1. Analysis

In both the relative wavespeed change ($\frac{dv}{v}$) vs load and displacement relationships, the CWI results from the recordings of all pairs of sensors display linearly declining relative wavespeed

change against load and displacement in the first loading phase with varying gradients: CWI results from SA1-SA4 and SA2-SA4 recordings are the ones with the largest negative gradients, while the one from SA5-SA4 recordings has the lowest gradient. The negative gradients themselves seem to be related with microcracking in the tensile area, which even at seemingly linear stress vs strain phase had formed as observed by Calixto [20], in addition to the acoustoelastic effect. Such hypothesis is strengthened by the fact that the wavespeed change values are taken from the 5th window onwards, which means that the signal had scattered for at least 1m, allowing interaction with tensile area of the beam.

Upon the first unloading phase, the microcracks caused by compression opened while the ones created by tension closed, which affected wavespeed change in addition to acoustoelastic effect. Such phenomenon may explain why during the unloading phase, SA3-SA4 pairs suffers the most decrease in wavespeed of -0.171% loss, since the path between SA3 and SA4 smart aggregates was in compression, which cause the CWI results of SA3-SA4 recordings to be affected more by the compression microcracking opening compared to the CWI results from SA1-SA4 and SA2-SA4 recordings, which only suffered -0.134% and -0.113% wavespeed decrease, respectively, upon the first unloading phase.

Instead of following linear path, the wavespeed change vs displacement paths of the first unloading phase display S-curve trends, while the wavespeed change vs load paths of the same phase show linear paths. The same can be said to the following loading and unloading paths of the first day test. By calculating the stress level of the compression zone (Appendix B), it is known that the maximum compressive stress caused by the first day loading is 6.42 MPa, were linear wavespeed change vs. stress, hence, load, is expected according to the observations from Chapter 0 of this thesis. Figure 6.4. shows that the load vs displacement relationship is not linear, which explains the nonlinearity of the wavespeed change vs displacement, given the wavespeed change vs load paths are linear.

Like the ones in the compression tests, the reloading paths of the first day of the test do have similar gradient (wavespeed vs load) and skew (wavespeed vs displacement) with their preceding unloading paths. During the reloading paths, microcracks in the compression zone closes and previously-existed microcracks in the tension zone opens. Once the previous peak load point is reached, the gradients abruptly change to match the ones on the previous loading phase, where new microcracks will form and will start reducing the wavespeed.

On the third loading cycle of the first day, it is observed in Detail A of both Figure 6.6. and Figure 6.7. that a significant drop in wavespeed is observed at 170 kN to 167 kN (dropped from 180 kN) load step on signal received by SA1. Milder drop in wavespeed at the same load level is also observed on the signals received by SA3 (Figure 6.10. and Figure 6.11.). Along with the wavespeed drop, a significant increase of displacement is also observed in the same load step. This drop aligns with a new major crack forming, which is shown on Load level (b) on Figure 6.30., where the crack propagates close to the location of SA1. Similar explanation can be used to explain the initial wavespeed drop of the signal received by SA2 on the start of cycle 10 when compared to the end of load cycle 7, since new crack opening at load cycle 8 in load level (d) in Figure 6.30. which cuts through the SA2 location is noticed, as well as the drop of wavespeed observed in all receivers at the peak load of the 13th load cycle, which corresponds to the development of shear crack shown on load level (g) and (h) in Figure 6.30.

Apart from the SA2-SA4 sensor pair, CWI result shows that the signals taken in the first load step of the 2nd day test have higher wavespeed compared to the signals taken in the last load step of the 1st day. Unlike the previous loading phases, the first loading phase of the 2nd day started with negative $\frac{dv}{v}$ vs load and displacement gradients, which gradually increased as the loading proceeds. Since the envelope of the loading paths of the 10th cycle do merge with the envelope of the unloading paths of the 7th cycle, the change in initial wavespeed does not seem to be caused by climate effect, which will cause gaps in the envelope between the loading phase and the preceding unloading phase. Instead, something structural should have happened during the time gap, which may include self-healing or other microcrack sealing mechanism. However, there is no other measurement of any kind taken during the test which can be used to verify this hypothesis.

Unlike linear $\frac{dv}{v}$ vs load trend observed on the first day test (except for the unloading phase of 7th cycle of SA1-SA4 signals), most loading and unloading phases on the second day test does show s-curve like trend, where the $\frac{dv}{v}$ vs load gradient is lower in the beginning and in the end of the phase, while the gradient is the highest around the middle of the phase (at between 100-150 kN of load in the 10th cycle and between 150-200kN in the 13th cycle). The lower $\frac{dv}{v}$ vs load gradient at higher load, especially on the loading phases, seem to be corresponding to the 'envelope', where the beam had reached a load level it had not reached previously. However, the lower $\frac{dv}{v}$ vs load gradients in the lower load indicate something more than acoustoelastic effect may be in play, which is worthy to be investigated in future works.

Figure 6.32. to Figure 6.35. show that the later the window, the more sensitive it is to changes further away from the source-receiver pairs. The later windows contain signals which had scattered farther away compared to the earlier arrivals, thus increasing its sensitivity to medium changes. It is also observed that some source-receiver pairs are more sensitive to others. For instance, SA1-SA4 pair senses crack occurring on load level (b) in its early arrival, while SA3-SA4 and SA5-SA4 are only able to sense it on the 30th window of its recording. Such phenomenon is related to the distance between the crack occurrence to either receiver or source location, which from Table 6.3. it is known that the crack occurring on load level (b) is close to the SA1 location. In a similar manner, it is observed that low CC value is observed on the transition between the 7th to the 10th cycle of the CWI results from SA2-SA4 recordings, even in earlier windows, which correlates to load level (d) and may explain why significant drop in wavespeed is observed on Figure 6.20. Between the first day and the second day test.

Drops of CC value are observed in the events of crack occurrences in Figure 6.32. to Figure 6.35. These drops of CC values in certain windows indicate changes of waveform of the signal, which indicate changes in medium occurring in between the load step. Crack formation will alter the waveform since the path previously passed by the signal is now reflected by the crack.

When attempting to assess local strain effect on the wavespeed change of the earlier arrival part of the signals, positive early arrivals $\frac{dv}{v}$ vs local strain gradient is observed as opposed to negative gradients observed in the $\frac{dv}{v}$ vs displacement graphs in section 6.2.1. Since only

the early arrivals are taken, the signals tend to scatter close to the smart aggregates proximity, which in this case is located in the compressive zone. It is observed in Figure 6.5. that early arrivals of the signal tend to have positive dv/v compared to the negative dv/v on the later arrivals due to the lack of signal parts which had scattered through the tensile zone is analyzed.

While a drop of wavespeed upon unloading is commonly observed after new load level had been reached, minimal wavespeed drop of 0.103% is observed between the start and the end of the 7th cycle (Figure 6.37.). Moreover, the early arrivals dv/v vs local strain graph of the 10th cycle (Figure 6.38.) shows hardly any wavespeed difference between the loading phase and the unloading phase at any given strain value. Small change of mean strain between SA4 and SA5 is observed between the 150 kN load level to the 200 kN load level in the 7th cycle (Detail A in Figure 6.36.), which explain the minor wavespeed loss upon unloading on that particular cycle. Similar explanation can also be used to explain the lack of wavespeed loss in the 10th cycle unloading phase, since hardly any increase of strain is observed between the 200 kN to 250 kN load level of that cycle (Detail B in Figure 6.36.). Such findings support the observations in Chapter 0, where it is observed that wavespeed change is more influenced by strain compared to stress.

Detail A of Figure 6.38. shows an increase of dv/v vs strain gradient, along with the DIC result displaying the crack pattern of that particular cycle attached in the insert figure. The DIC result shows bending cracks beneath the location of SA4 and SA5. In that case, a change of stress distribution along the cross-section is expected, as shown in Figure 6.49. Since the compression zone is smaller, more stress increase in the compression zone is expected as the beam is loaded further when compared to the uncracked section. In linear-elastic materials, higher stress translates to higher strain level (Figure 6.50.), which explain the increase of the dv/v vs strain gradient.

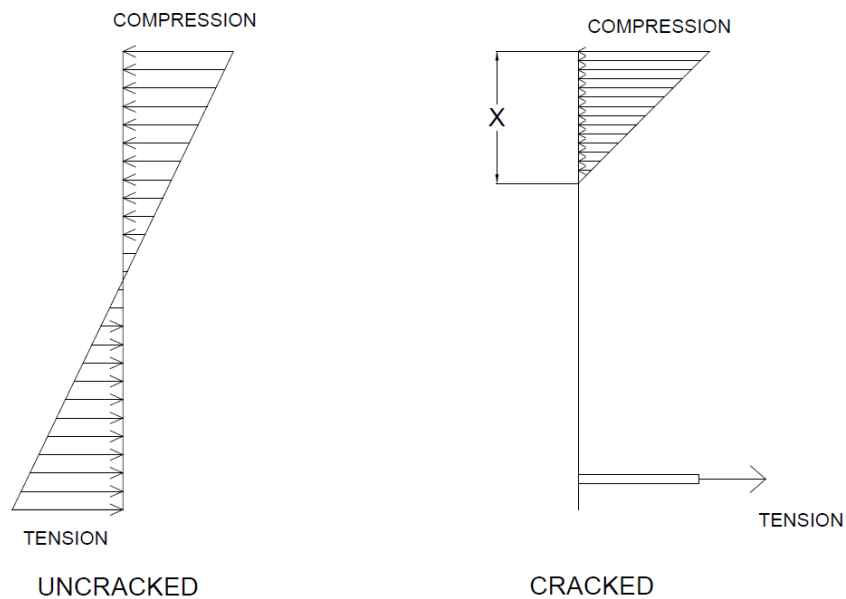


Figure 6.49. Stress distribution of uncracked and cracked section of reinforced concrete in bending.

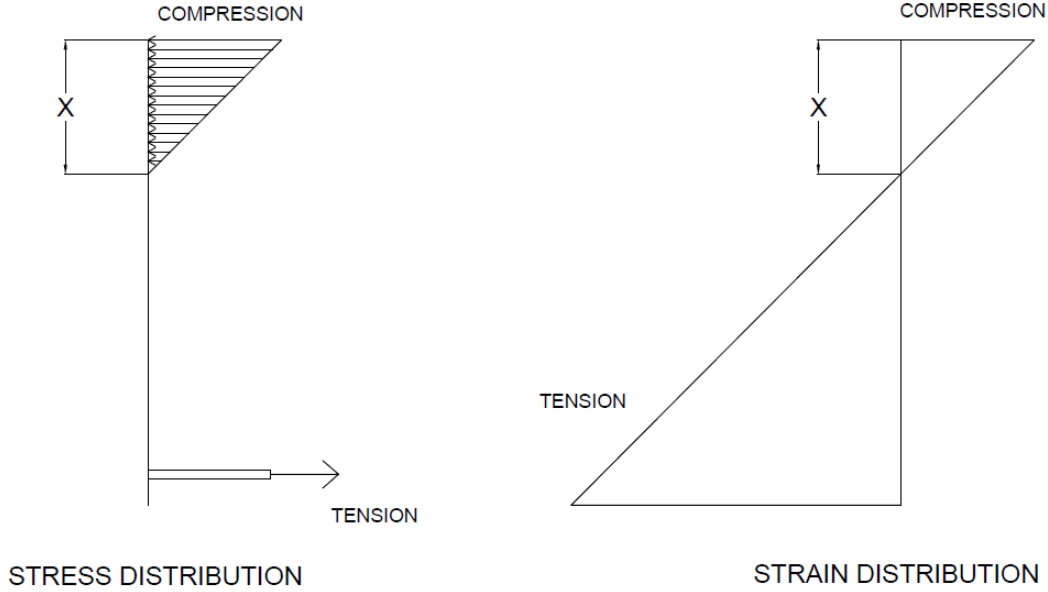


Figure 6.50. Stress and strain distribution of cracked section of reinforced concrete in bending.

The summation of cross-correlated signals generated by hits at Zone 1 shows high energy content in the positive time domain. Such phenomenon is expected, since the cross-correlation algorithm assigns SA5, which is located between Zone 1 and SA4, as the virtual source. Therefore, positive travel time of signal emitted from SA5 and received by SA4 is expected. The other way around is also valid on the signals from hits at Zone 3.

The attempt to retrieve the impulse response between SA4 and SA5 sensors had not been successful. This is indicated by the asymmetric nature of the SI products in both positive and negative time axis, as well as the lack of low amplitude or 'zeros' around the center of time axis, replicating the pre-arrival part of the time travelled between the two sensors. Such unsuccessful attempts may be traced from two issues: the inability to create uniform signal from each hit, and the inability to properly recreate the diffuse wavefield necessary for seismic interferometry. According to Equation 22, the cross-correlation product of the signals is essentially the impulse response of the system convoluted by the autocorrelation of the wavelet function. In the case of non-uniform beatings, as shown in Figure 6.51., the wavelet functions of one hammer hit and another will not be identical, resulting in misleading SI product. The other issue of the impulse response retrieval is that the hammer hits on the top of the beam and random hits on the top and sides of the beam may not be sufficient to create a diffuse wavefield, since an evenly distributed hammer hits enveloping the sensor pairs are required to create a proper diffuse wavefield. While such illumination should still result in somewhat symmetrical SI products, the uniformity of hammer hits may cause the SI products to be asymmetrical.

$$\{G(x_2, x_1, t) + G(x_1, x_2, t)\} * S_s(t) = u(x_1, t) \otimes u(x_2, t). \quad (22)$$

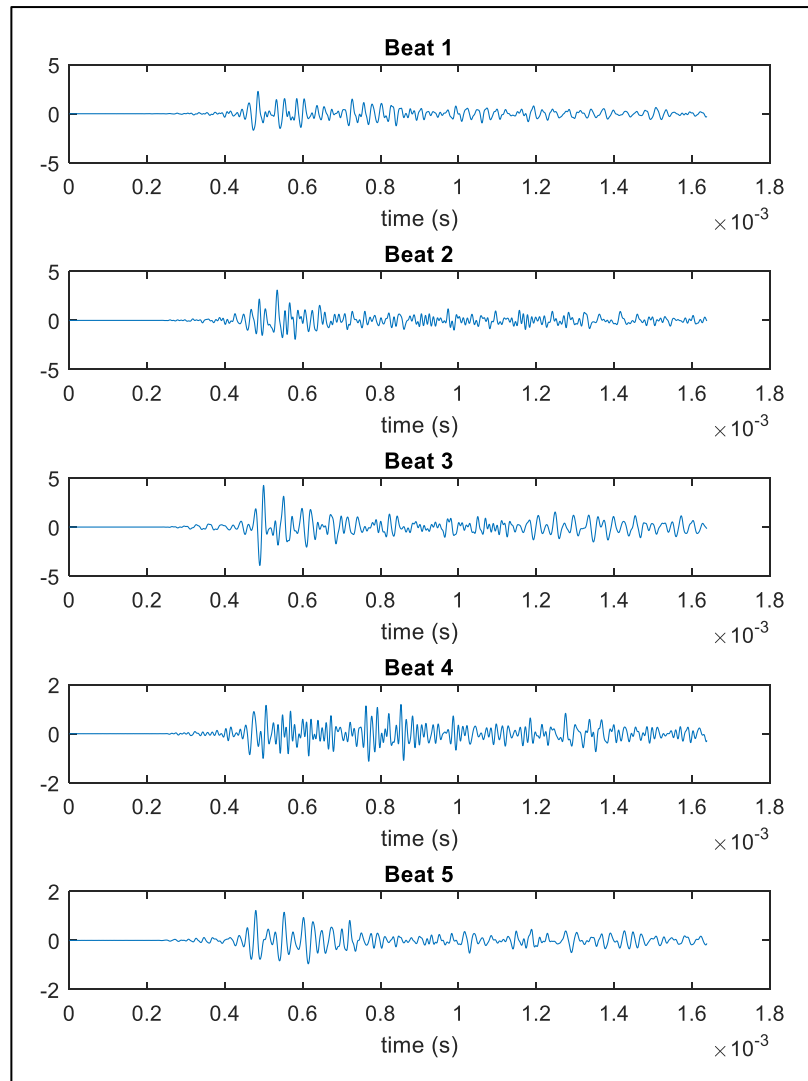


Figure 6.51. Repeatability check of the hammer hits. These five signals are generated by hammer hits done in a same location and received by the same sensor. Notice the unsimilarity among the waveform of these signals.

6.4.2. Lesson learned

In general, the experiment conducted in this part of the research is conducted well. However, several things can be improved in future works:

- After major crack has occurred, even smaller load steps of 5 kN is advised to be used for higher correlation coefficients.
- The use of impulse hammer as shown in Figure 3.13. is not recommended due to repeatability issues.
- Temperature and humidity of the testing area should be monitored for further study.

6.4.3. Remarks

After conducting the experiment and analyzing the result, several points are able to be pointed out:

- CWI results of the signals received by all receivers in Section 6.2.1. show negative dv/v vs load and displacement gradient in the first loading phase. This phenomenon is possibly caused by microcracking in tensile area in addition to acoustoelastic effect, since the coda of these signals scattered through the tensile section of the beam. This argument is supported by the positive dv/v vs load gradient upon reloading, which is expected since no new tensile microcracks is formed and the effect is mainly acoustoelastic and microcracks closing of compressive part of the sample.
- Similar to the compression analysis, dv/v vs load and displacement of reloading paths will mimic their preceding unloading paths, since the reloading parts do not implicate new damage prior of reaching previously achieved load level.
- CWI sensitivity varies depending the section of the recording used and the proximity of the source-receiver pair to the occurring cracks.
- Crack widening does not significantly affect CC, while crack formation does. This statement is supported by crack pattern shown on Figure 6.30., as well as the fact that drop of CC only occurs when the cracks first appear (Figure 6.32. to Figure 6.35.). Cracks will create new interfaces which will change the way the signals propagate, altering their waveforms.
- Wavespeed increase is observed in earlier arrivals of the signals received by SA5 and SA3 during the first loading phase of the first day, while wavespeed decrease is observed in the later arrivals. Both the source and the receiver smart aggregates are located in the compression zone, which means earlier arrivals are mainly scattered in the compression zone of the beam.
- SI trial in this research is not successful due to poor repeatability of the hammer hits and inability to create proper diffuse wavefield in the beam.

Some recommendations are also proposed to improve future works:

- CT scan may be done to assess internal microcracks if possible.
- Verification method needs to be developed to confirm CWI findings.
- CWI should also be done on the moments leading to failure.
- Phenomenon causing lower dv/v vs load and displacement gradients at lower load level in later cycles should be investigated.

7. Concluding remarks

7.1. Conclusions

After conducting this research and analyzing the result, research questions presented are now able to be answered.

The CWI can be used for measuring concrete properties evolution, such as modulus of elasticity. In addition, several things are also concluded:

- Wavespeed increases as concrete ages. Such phenomenon is caused by microstructure forming through cement hydration process. Changes in waveform due to hydration process are also observed, especially in the later coda.
- Embedded smart aggregates perform best compared to the smart aggregates attached by using acoustic gel. Embedded sensors provide near-perfect coupling with the medium, while gel-attached sensors may be displaced during the course of its service time. While first-arrival assessment is not heavily affected, CWI is definitely affected.

By conducting CWI on concrete subjected to cyclic loading in compression and bending, it can be concluded that:

- dv/v decreases as the loading increases.
- dv/v vs strain graphs are more reliable to be used for CWI interpretation in compression samples when compared to the dv/v vs stress and load graphs.
- The reloading phases of dv/v vs stress and strain paths of compressive specimens and dv/v vs load and displacement paths of the bending and shear specimen are likely to mimic their previous unloading phases, because in both unloading and their following reloading phases, it is unlikely that new cracks or major alteration in the concrete structure will form until the loading reached previously loaded load level.
- Significant drop of wavespeed upon unloading indicates damage progression, since specimen's further damage had altered its structure, reducing the wavespeed compared to its previous state.
- Crack widening does not affect CWI result as much as crack formation. Possible explanation of this phenomenon is that wave scattering does not alter much due to crack widening, while crack formation alters the scattering of the signal by introducing new interfaces.
- Concrete in compression has initial linear positive trend in the dv/v vs stress and strain graphs, which gradients will then decrease as the loading proceeds due to the formation of microcracks.
- In CWI done in the bending and shear beam test, it is revealed that the dv/v vs load and displacement of the first loading phase are linear negative, which is caused by formation of tensile microcracks forming in the tensile part of the beam.
- When conducting CWI of the bending beam by using smart aggregates located in the compressive zone, earlier arrivals of signals recorded in the first loading phase have positive wavespeed changes as the loading increases, while later arrivals have negative wavespeed changes. Earlier arrivals of the recording contain signals which

scattered close to the sensors' proximity, which in this case scattered mainly in compression zone.

- It is possible to detect the shift in stress distribution of a concrete section in bending by assessing CWI of the early arrivals signals recorded from smart aggregates located in the compression zone.

The attempt to retrieve the impulse response by SI has not yield desirable result, most likely due to inability to generate repeatable signals by hammer hits, as well as due to inability to create proper diffuse wavefield.

7.2. Outlook for future works

In addition to the conclusions, improvements and advancement can be proposed for future researchers interested in this topic.

- Concrete age experiment may be repeated with smaller time gaps to improve result resolution.
- Compressive test with standardized load scheme on multiple samples should be done, since only two cylindrical samples and cubical samples were tested.
- CT scans may be used to confirm microcracks or damage invisible from the specimens' surfaces.
- Tests may be done in climate-controlled area.
- Sustained loading effect on CWI result may also be assessed.

For implementation of CWI in real functional structure for structure health monitoring, several recommendations can also be proposed:

- Embedded smart aggregates perform exceedingly better when compared to gel-attached smart aggregates.
- $\frac{dv}{v}$ vs stress and $\frac{dv}{v}$ vs strain gradients may be used to indicate the structure's condition.
- In proof-loading tests, smaller load steps are desirable for CWI implementations.

Appendix A: Concrete Elasticity-modulus Projection through *fib* Model Code

To determine the projected modulus of elasticity of the concrete sample in Chapter 4 of this thesis, *fib* Model Code is referred. The concrete which is used has the following properties

Appendix Table 1. Concrete parameters

Parameter	Value
f_{ck}	60 MPa
f_{cm}	68 MPa
s	0.2

From the strength information, it is possible to determine the projected elasticity-modulus of the 28th day by using equation (5.1-20) available in *fib* Model Code.

$$E_{c,28} = E_{c0} \cdot \alpha_E \cdot \left(\frac{f_{ck} + 8}{10} \right)^{\frac{1}{3}},$$

$$E_{c,28} = 21500 \cdot \left(\frac{60 + 8}{10} \right)^{\frac{1}{3}} = 39508 \text{ MPa}.$$

Since the expected modulus of elasticity had been obtained, the projection of elasticity-modulus can be determined. To achieve this, the projection factor β_E should be determined. In this case, the β_E and ultimately the E_c of the 8th day, 12th day, 15th day, 19th day, 22nd day, 28th day, and the 35th day are to be determined.

$$E_{ci}(t) = \beta_E(t) \cdot E_{c28},$$

$$\beta_E(t) = \left[\exp \left\{ s \cdot \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\} \right]^{0.5}.$$

Appendix Table 2. Projected modulus of elasticity of CWI by *fib* Model Code

t (day)	β_E	E_c (MPa)
8	0.9166	36213
12	0.9486	37478
15	0.9640	38087
19	0.9788	38671
22	0.9873	39005
28	1	39508
35	1.0106	39927

Appendix B: Compression zone height and compressive stress estimations of reinforced concrete in bending

When reinforced concrete is cracked from bending moment, the tensile force is transferred by the reinforcement bars, while the compressive force is taken by concrete. The beam used in Chapter 0 has 8 reinforcement bars with diameter of 25mm, of which the centre of gravity is located 1145mm from the top of the section. The compression zone of the section can be calculated as the following:

$$X = d \cdot \left(-\alpha \cdot P \cdot \sqrt{(\alpha \cdot P)^2 + 2 \cdot \alpha \cdot P} \right),$$

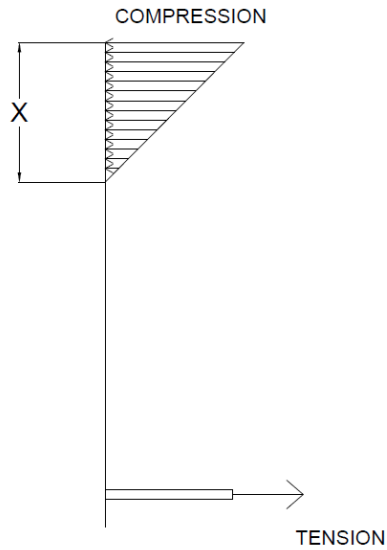
where X is the compressive zone depth of the section as shown in Appendix Figure 1, d is the distance of the centre of gravity of the reinforcing bars to the top of the beam (1145mm), α is the ratio of the steel's to concrete's elasticity modulus, and P is the reinforcement ratio of the section.

In this particular section, both α and P can be calculated. It is known from the concrete's specification that the concrete's elasticity modulus is 40,000 MPa, while the steel's elasticity modulus is 210,000 MPa. For P calculation, A_s is the reinforcement area of the section and b is the section width.

$$\alpha = \frac{210,000}{40,000} \approx 5.3,$$

$$P = \frac{A_s}{b \cdot d} = \frac{\frac{8 \cdot \pi \cdot 25^2}{4}}{300 \cdot 1145} = 0.0114,$$

$$X = 1145 \cdot \left(-5.3 \cdot 0.0114 \cdot \sqrt{(5.3 \cdot 0.0114)^2 + 2 \cdot 5.3 \cdot 0.0114} \right) = 335.2mm \approx 300mm.$$



Appendix Figure 1. Stress distribution of cracked reinforced concrete section in bending.

Three smart aggregates (SA3, SA4, and SA5) are implanted approximately in the middle of the compression zone to prevent coupling loss due to cracks. From the stress distribution displayed in Appendix Figure 1, as well as the beam's loading plan shown in Figure 6.1., the stress increase due to load increment, as well as maximum compressive stress at each load level can be calculated:

Appendix Table 3. Increase in compressive maximum stress due to load increment.

Load increment (kN)	Stress increment (MPa)
10	0.32
20	0.64

Appendix Table 4. Maximum compressive stress at each load levels.

Cycle	Max. load (kN)	Max. stress (MPa)
1 st	100	3.21
4 th	150	4.81
7 th	200	6.42
10 th	250	8.02
13 th	300	9.62

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