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Non-Contact Laser Ultrasonics based Monitoring of Civil Infrastructure

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Periodic and reliable assessment of civil infrastructure is imperative for their sustainability. Traditionally, these assessments are based on visual inspection, which makes them highly laborious and subjective. Travelling wave based techniques have proved to be proficient in identifying localized damages in structural members. Recent developments in Laser Ultrasonics wherein remote inspection can be done via non-contact and non-invasive means through generation and detection of ultrasonic waves have opened up opportunities for remote inspection of large structures. In the present study, mild steel bars with simulated damage in the form of grooves of various sizes have been monitored through Laser Ultrasonics and conventional piezo material based techniques. By comparing the obtained signals in time, frequency and through the use of statistical distance based measurement, the variations in signals have been quantified. The results of the current investigation confirms the competency of Laser Ultrasonics in establishing the extent of damage and the location of the damage.
KEYWORDS: Laser Ultrasonics, Interferometry, non-destructive testing, time of flight.

1 INTRODUCTION

OECD countries are facing the challenge in maintaining ageing infrastructure with ever shrinking budgets (Schieb, 2007). Conditional evaluation of structures are still primarily undertaken through subjective techniques such as visual inspection. Vibration based techniques have been attempted to automate the process. However, damages occurring locally in the structural members cannot be easily detected by these techniques. Travelling wave based techniques have proved to be proficient in identifying localized damages in structural members (Raghavan and Cesnik, 2007). Ultrasonic travelling waves travel through the structural members, interact with the damages and by analysis of the received signal waveform, the condition of the structure can be established.

Contemporary piezo based contact type travelling wave techniques have been used for detection of onset of corrosion in steel bars (W.-B. Na & Kundu, 2003; Sharma & Mukherjee, 2010, 2011) and de-bonding detection (W. Na, Kundu, & Ehsani, 2002). Low energy (µJoules) output and unreliability of contact between the structure and the sensor are some of the limitations of using contact based systems. The attenuative nature of concrete and large length of civil infrastructure further restricts the implementation of these techniques for on-site applications. In laser ultrasonics, a high power pulsed laser (energy ≈1 Joule) is used to generate travelling ultrasonic waves, comprising of a wide frequency range for assessment of structural members. The travelling waves interact with structural elements and are received through a Laser Vibrometer. The use of laser based ultrasonics have been earlier used for health monitoring of structural elements (Jacobs & Whitcomb, 1997; Monchalin, 2004), to study attenuation properties of ultrasound in Concrete (Owino & Jacobs, 1999), crack propagation (An, Park, & Sohn, 2013) and debonding studies

(Park, An, & Sohn, 2014). The use of this technique is not ubiquitous to civil engineering labs for health monitoring.

In the present study, the ultrasonic signals in mild steel specimens generated by Laser based ultrasonics and conventional piezo based ultrasonics have been compared. The signals from pristine bar have been compared with that of grooved specimen simulated at different stages of damage through reduction of cross section area. The signals have been analysed in time and frequency domains to extract their traits in case of a simulated damage.

2 NON-CONTACT LASER BASED ULTRASONICS

The term 'Laser' is an acronym for 'Light Amplification by Stimulated Emission of Radiation'. A Laser emits light by the process of optical amplification based on stimulated emission of electromagnetic radiation. A laser differs from other sources of light as it emits a continuous stream of monochromatic and coherent light. To increase the power output the Laser is made to radiation in pulses and not in a continuous form. Thus, a 'Pulsed Laser' is used when a large power output is required. In applications which requires the production large energy, pulsed lasers are used. When the released energy by the Laser is built up and released at intervals, the energy per pulse increases tremendously as the energy builds up in between the pulses. The continuous Lasers are run in pulsed mode by a technique called 'Q-switching'. Q-switching is achieved by using a variable attenuator inside the laser's optical resonator. The variable attenuator is commonly called a "Q-switch". Typically, Q-switched lasers with pulse width of approximately 5 – 10 ns and pulse energy of up to 1 J are used for ultrasound generation in large structures, resulting in ultrasound pulses with the frequencies up to 10 – 50 MHz. The characteristic ultrasonic frequencies generated in a structure depends on the material properties and attenuation of waves in particular material. Propagation of waves of a particular frequency may prevail over other generated frequencies based on structure of the mode in a media at the particular frequency.

2.1 Ultrasound generation:

When a high-power laser pulse is directed towards the surface of the material to be monitored, a portion of the incident electromagnetic energy is absorbed by the material and the remaining portion of the incident energy is converted into thermal energy. As the absorption of this energy takes place within a very small area, typically of a few nanometres, a rapid increase in temperature occurs locally. These thermal conditions gives rise to transient thermo-elastic stresses and strains in the surface layer as the material attempts to expand. These thermal stresses gives rise to the generation of a compressional wave which travels normal to the surface of incidence. Thus, an ultrasonic wave is produced as a manifestation of the rapid thermal stresses generated in the material on account of incidence of high power Laser pulse (Scruby, 1989).

2.2 Ultrasound reception:

The reception of ultrasound is done using a Laser Vibrometer. The Vibrometer works on the principle of Laser interferometry. The laser interferometer is setup based on the configuration of Michelson interferometry. The Michelson interferometer produces interference fringes by splitting a monochromatic coherent light source (a Laser in this case), such that one beam strikes the fixed mirror (M1) and the other to the target surface (M2) whose displacement is to be measured. An interference pattern is formed when the reflected beams are brought back together and is detected by the photo detector.

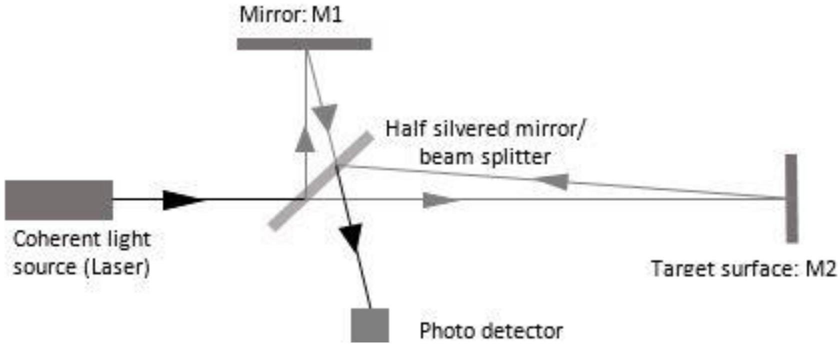

Figure 1Working principle of Interferometer

3 EXPERIEMENTAL SETUP

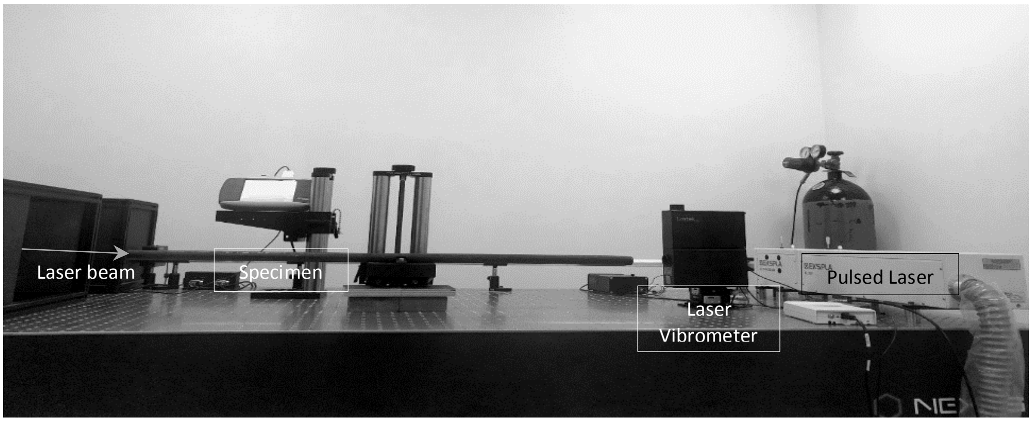

Figure 2 Experimental setup for Non-contact type Laser Ultrasonic system

Figure 3 Steel bars used in the experimental study

The experimental monitoring scheme has mild steel bars with grooves of varying percentage reduction in diameter to simulate different degrees of mass loss due to damage. The ultrasonic signals characteristics for the specimen with grooves have been compared with a pristine specimen. The ultrasonic signals are generated and acquired using two different approaches namely the contact type PZT (lead zirconium titanate) based system and non-contact Laser based system. In case of Laser based generation of ultrasound a Q-switched pulsed Laser operating at 1064 nm (EKSPLA, Model NL303HT) was used and the reception part was done a Laser Vibrometer of wavelength 670 nm (figure 2). A beam diameter measuring ~8 mm was incident on the bar specimen and as a result of the ablative regime on account of the incidence of the laser beam an ultrasonic pulse is generated in the specimen. The setup was assembled by Lastek Pty Ltd. The data was digitised using a National Instruments USB 5132 data acquisition system.

A pair of 1 MHz central frequency PZT based transducers of make Olympus IMS were used in transmission mode for generation and reception of ultrasonic compressional waves. The diameter of contact for the transducers was 10 mm (figure 4). A Pulser-Receiver system of make JSR Ultrasonics and model number DPR 300 was used as a source for excitation for the PZT transducers. The ultrasonic data was digitized using PicoScope 6 version 6.4.64.0, modular oscilloscope. The transducers were firmly held in contact with a uniform contact pressure and grease was used as a couplant between the transducers and the surface of the bars. Five mild steel bar with a diameter of 24mm, one pristine bar and four bars with 20 mm long groves of various percentages reduction in its cross section area representing different levels of damage in the bars were used. All the bars were of 900 mm length. The nomenclature of B_1, B_2, B_3 and B_4 (figure 3) shall be followed for bars with 8%, 25%, 50% and 75% reduction in the diameter respectively. The pristine specimen shall be referred to as B_0.

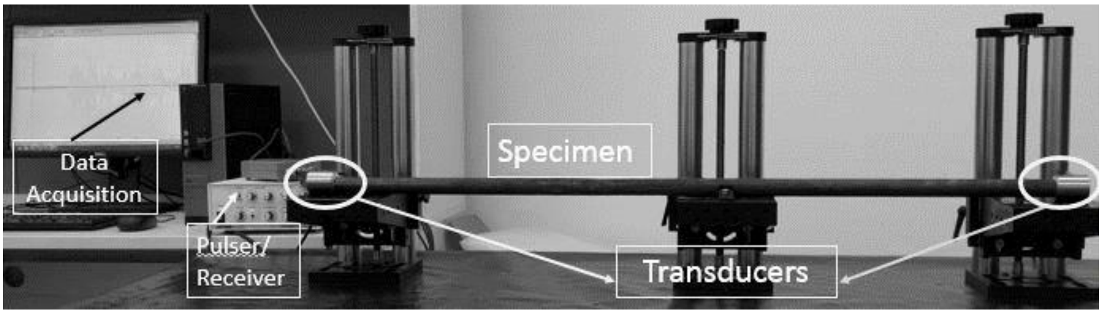

Figure 4 Experimental setup for contact type PZT based Ultrasonic system

4 COMPARISON OF ULTRASONIC SIGNALS

The comparison of time signals across various specimen have been undertaken using statistical distances measurement and cross correlation analysis between the signals. A statistical distance comparison in the form of Euclidean distance between the pristine specimen (B_0) and bars of various simulated damages (B_1, B_2, B_3, B_4). The Euclidean distance (d_E) between two vectors say f(t) and g(t) which in this case are two time series waveforms is calculated as per equation1. The Euclidean distance between two signals increases as their extent of dissimilarity increases. The Euclidean distance between the time series data of pristine bar (B_0) and bars with various degrees of simulated damages (B_1, B_2, B_3 and B_4) have been calculated using equation 1 and are enlisted in table1.

$$d_E = \sqrt{\sum_{i=1}^{n} (f_i - g_i)^2} \qquad (1)$$

The cross correlation analysis is a commonly used analysis for comparison of features in signals. In the present study a zero lag cross correlation analysis has been undertaken to compare the characteristic differences in the ultrasonic signals between the pristine bar (B_0) and the other bars with simulated damages (B_1, B_2, B_3 and B_4) (Table1). The general formula for cross correlation between two signals say f(t) and g(t) at an time instance or lag of 'n' ($1< m ,n<N$) as indicated in equation 2.

$$(f * g)[n] = \sum_{i=1}^{N} f[m]g[m+n] \qquad (2)$$

The zero lag cross correlation value between the signals decreases when there is a decrease in the similarity between two signals and it has been executed using 'xcorr' function in Matlab. In the later part of the paper, the cross-correlation coefficient $(f*g)[n]$ shall be referred to as 'r'.

5 RESULTS AND DISCUSSIONS

The ultrasound signals generated by non-contact Laser based monitoring and PZT transducers based contact type schemes in the various specimen have been presented in this section. The characteristic signal in time and frequency domain for non-contact laser based monitoring schemes are as shown in figure 5. In figure 5(a) two distinct signal peaks can be observed, the former commencing around 170µs and the later commencing around 500 µs. Among these two primary peaks, the first peak corresponds to the reception of the ultrasonic wave at the receiving end of the bar after its generation. The later peak corresponds to it's reflection of the initial signal from the internal edge of the bar and repeated arrival at the location of reception. The first arrival peak corresponds to the Time of Flight (ToF) information which is used establish the velocity of travelling wave as per equation 3. This shall be used to back calculate the location of simulated groove damage. The frequency plot of the ultrasonic time signal is shown in Figure 5(b). Unlike the contact based system, as the reception technique in a non-contact system is sensitive to a range of frequencies, it is possible to obtain the response of any system in terms of a wide frequency band. In case of a contact based system, the excitation and reception is done by a banded piezo based receptor, which is sensitive in a particular frequency band. The presence of peaks corresponding to several frequency components as indicated in figure 5(b) establishes this fact.

$$v = \frac{l_{bar}}{ToF} \qquad (3)$$

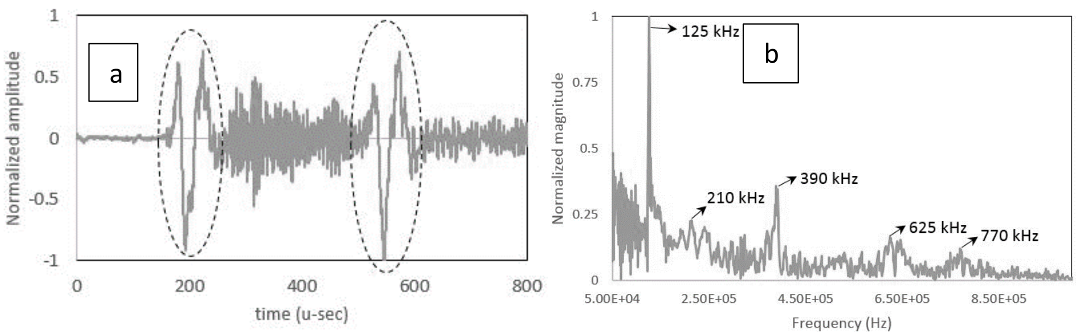

Figure 5 Signal acquired using non-contact technique (a) Time series data and (b) Frequency data

The magnitude of simulated damage can be directly related to the changes in the wave characteristics and presence of additional peaks supplementary to the two arrival peaks which were observed in case of B_0 specimen. It can be observed that as the percentage reduction in the cross section at the groove increases, the magnitude of the secondary peak between the two primary peaks also increases. In figure 6(a), around the 340 µsec interval, the development of an additional peak marks the presence and the location of the groove in the bar. As the reduction in percentage area corresponding to the groove increases, the prominence of the secondary peak from the reflection of the groove can be observed through figures, 6b, 6c and 6d. A significant relative reduction in the first primary peak proportional to the percentage reduction in cross section for the specimen B_1, B_2, B_3 and B_4 can be observed. In case of figures, 6c and 6d the amplitude of secondary peak from the groove reflection is greater than the two primary peaks. This is due to the reduction in the energy transmitted by the wave on account of reduction in the cross sectional area of the bar.

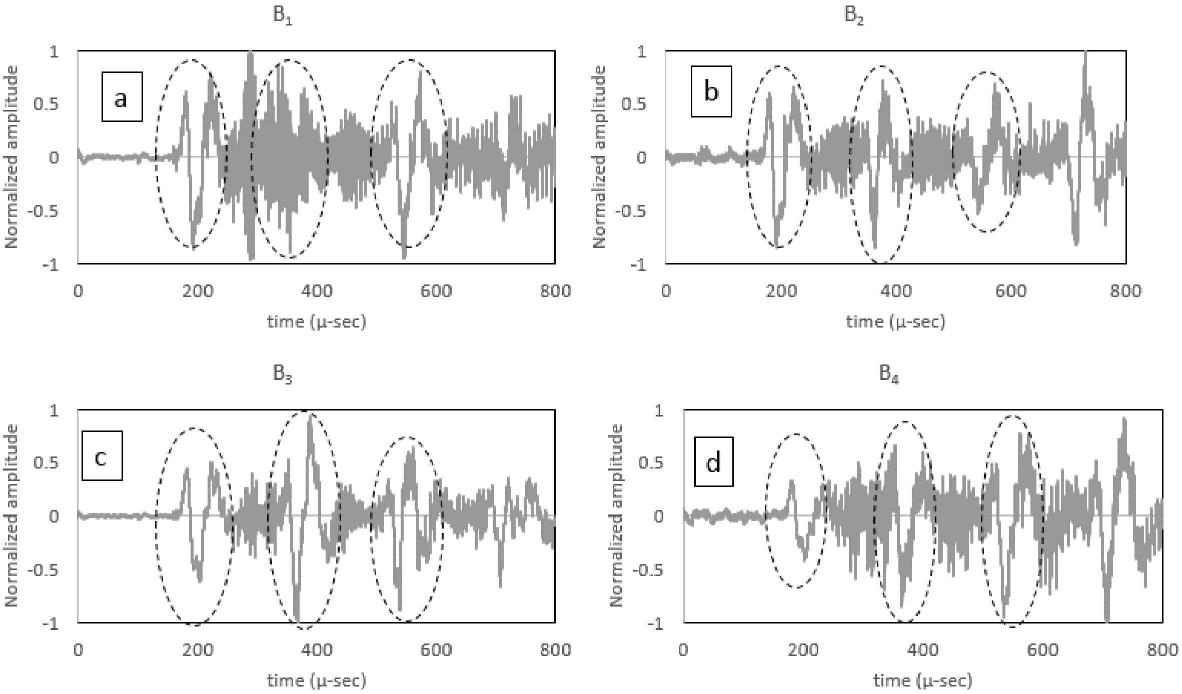

Figure 6 Time series data acquired using non-contact monitoring technique with different percentages of reduction in cross section area

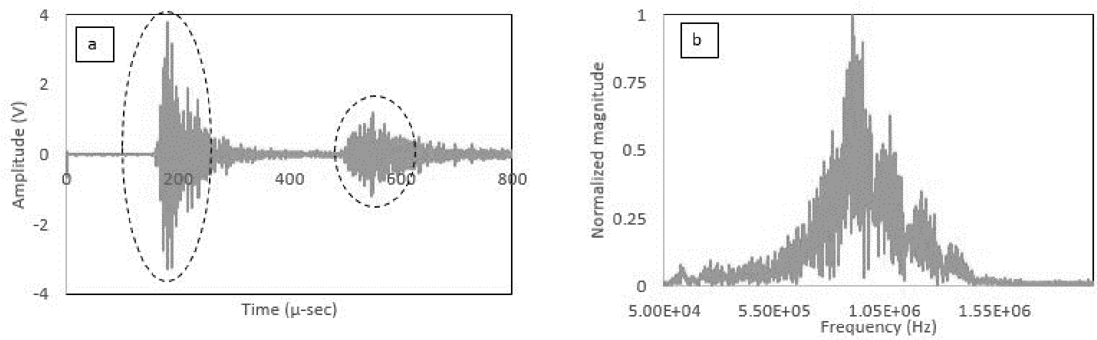

Figure 7 Signal acquired using contact based PZT system of 1MHz transducers (a) Time series data and (b) Frequency data

The characteristics of time and frequency domain signals for a piezo based contact system of central frequency 1 MHz is shown in figure 7. The time domain signal has two characteristic primary peaks, the former around 170 µsec and the later around 500 µsec corresponding to the first arrival of the incident ultrasonic wave and the arrival for the reflected part of the same incident wave.

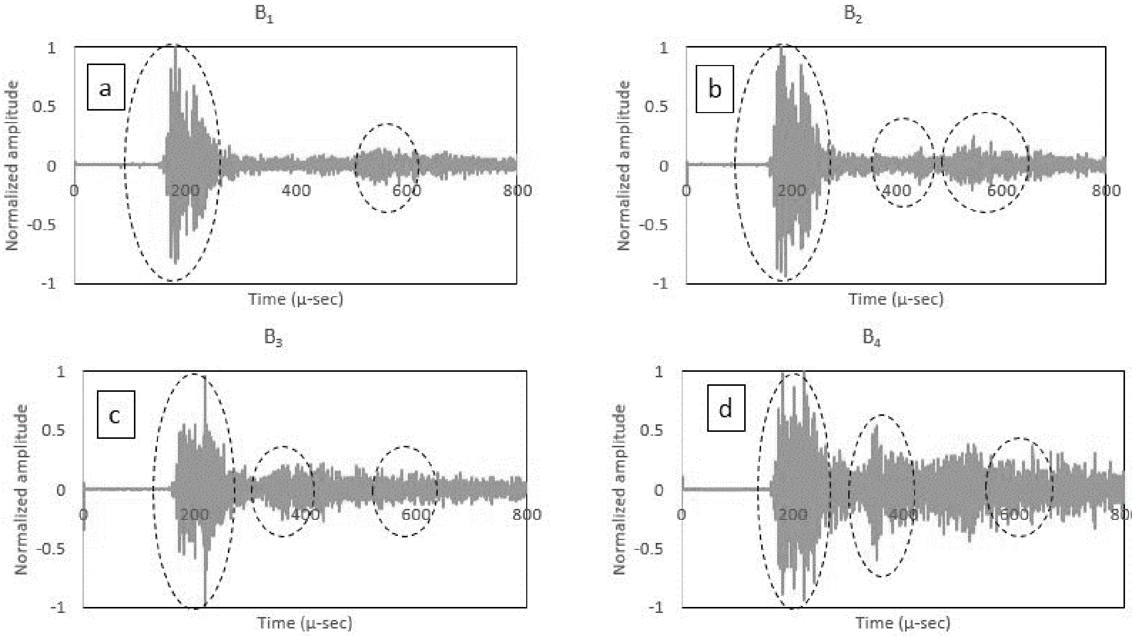

Figure 8 Time series data acquired using contact type monitoring technique (1MHz transducers) with different percentages of reduction in cross section area

The frequency domain signal shows a peak at 1 MHz mark which is the central frequency of the piezo transducers used. In the contact type systems as it is centred on a particular frequency, the response of the system is sensitive and focused around the central frequency. Additional peaks from the reflection of the groove appears around 350 µsec in figure 8. The relative magnitude of these peaks increase as the percentage reduction in the cross section area increases. Considerable changes in the signal attributes can be observed especially in case of B_3 and B_4 (figure 8c and 8d).

Table1: Comparison of statistical distances and cross correlation index of signal of Contact type and Non-contact type systems.

Comparison	Non-Contact System		Contact System(1MHz)	
	d_E	r	d_E	r
B_0-B_1	15.315	197.23	6.391	18.113
B_0-B_2	21.573	119.097	7.420	9.507
B_0-B_3	26.245	70.510	7.341	6.540
B_0-B_4	26.257	16.198	11.880	-11.630

The features from the received time series ultrasonic signals have been compared using the procedure as described in section 3 and the output is presented in Table 1. Euclidean distance and zero lag cross correlation coefficients between the pristine bar and bars with various echelons of grooves have been compared for contact based and non-contact based systems. All the cases of grooved bars could be easily and clearly distinguished from the pristine specimen across both type of monitoring schemes. Overall, a constant decrease in the value of correlation and an increase in the Euclidean distance has been observed for both types of systems as the extent of simulated damage in form of groove increases. In case of contact based system the value of d_E for cases B_0-B_2 and B_0-B_3 wavers from the observed trend slightly, but the expected trend is observed in the case of cross correlation analysis. It can be noted that the specimen B_1 to B_4 were distinguishable from the pristine specimen (B_0).

6 CONCLUSIONS

The veracity of laser ultrasonic as a non-contact, non-invasive health monitoring scheme for civil engineering infrastructure has been explored in the present study. Clear and distinct changes in the time signal at the location of simulated damages have been observed in cases both contact and non-contact based systems. A statistical distance based approach have been used to quantify the difference in signal characteristics between a pristine specimen and specimen with various degrees of damage in the form of grooves. The elimination of coupling related issues and the system sensitivity to a wide range of frequencies in case of non-contact system are amongst the advantages over conventional contact based ultrasonic monitoring system.

The results presented in the current work are based on experimental scheme undertaken on laboratory scale specimen. The sensitivity and veracity of this technique has been established for these specimen. The extension of laser based monitoring paradigm in monitoring actual large scale civil engineering structures is promising and is subject to future investigations in the upcoming experimental work being undertaken.

7 ACKNOWLEDGEMENT

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