

# Monitoring the Structural Health of RC Beam Lap Splices using Wave Propagation and PZT Sensors

Rone<sup>1</sup>, Manjeet Chahar<sup>2</sup>, Manish Kumar<sup>3,\*</sup>

## Abstract

*This paper describes the use of piezoelectric sensors in a wave propagation-based Structural Health Monitoring (SHM) method to identify lap splices in steel reinforcing bars. Straight and lapped steel bars with lap lengths of 10° and 20° were used for the experiments. Lead Zirconate Titanate (PZT) transducers were employed, one of which served as an actuator to produce stress waves and the other as a sensor to record the signals that were delivered. The responses were measured in both the time and frequency domains after a 20 V sinusoidal stimulation was administered in the 10–100 kHz frequency range.*

*The study is predicated on the idea that structural discontinuities such lap splices affect wave propagation, resulting in signal attenuation, reflection, and scattering. The signal amplitude in lapped bars is significantly lower than in straight bars, according to the results, with attenuation varying from 33% to 56% based on lap length. While frequency response analysis makes it easier to distinguish between different lap circumstances, time response analysis shows signal deterioration.*

*The results verify that PZT-based wave propagation is a successful, non-destructive method for monitoring the integrity of reinforced concrete structures and identifying structural abnormalities.*

**Keywords:** Structural Health Monitoring (SHM), Piezoelectric Sensors (PZT), Wave Propagation, Lap Splice Detection, Non-Destructive Evaluation (NDE)

## INTRODUCTION

In present civil engineering, structural health monitoring (SHM) has become an essential instrument for guaranteeing the lifetime, serviceability, and safety of infrastructure systems [1]. Steel reinforcement plays a major role in reinforced concrete structures, and optimal load transfer depends on adequate bonding and lap splicing. Non-destructive evaluation (NDE) techniques are necessary because problems such insufficient lap length and internal discontinuities are hard to find with traditional inspection methods [3]. Electrical energy can be converted into mechanical stress waves and vice versa by piezoelectric materials like lead zirconate titanate (PZT). As these waves go through the structure, they are affected by discontinuities like lap splices and cracks, which causes signals to be scattered, attenuated, and reflected [2], [4]. This study examines straight and lapped steel reinforcement bars with

different lap lengths (10', 20φ) using a wave propagation-based SHM approach. PZT patches are employed as sensors and actuators to produce and receive signals in the 10–100 kHz frequency range. To find differences brought on by lap splices and assess how well the method detects structural discontinuities, the recorded signals are examined in both the temporal and frequency domains [5].

### \*Author for Correspondence

Manish Kumar

E-mail: sharawat1989@gmail.com

<sup>1,2,3</sup>Assistant Professor, Department of Mechanical Engineering, EIT Faridabad, Haryana, India

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## Literature Review

For the aim of determining structural flaws in civil engineering systems, wave propagation-based Structural Health Monitoring (SHM) utilizing

piezoelectric materials has been extensively studied. Early research showed that the great sensitivity and quick response of piezoelectric transducers, especially Lead Zirconate Titanate (PZT), make them useful for producing and sensing guided waves for damage detection [6]. Researchers have demonstrated that structural discontinuities have a considerable impact on wave characteristics including amplitude, phase, and frequency, which makes them useful markers for spotting flaws like corrosion, cracks, and uneven joints [7].

## RESEARCH METHODOLOGY

The present study adopts an experimental research methodology based on the wave propagation technique using piezoelectric sensors for Structural Health Monitoring. For testing, steel reinforcing bars with a diameter of 16 mm and a length of 2600 mm were first chosen. Straight steel bars and lapped steel bars with different lap lengths of 10 $\phi$  and 20 $\phi$  were the two types of specimens that were constructed. These setups were selected in order to examine how lap splice length affects wave propagation behavior. An arbitrary function generator was used to create a 20 V sinusoidal excitation signal in the 10–100 kHz frequency range, which was then applied to the actuator. The sensor recorded the produced stress waves as electrical impulses as they traveled along the steel bars. A mixed-signal oscilloscope was used to record these signals for additional examination, Structural Health Monitoring (SHM) of steel reinforcing bars. The methodology is designed to evaluate the effect of lap splices on signal transmission characteristics in both time and frequency domains.

To ensure reliable measurements, piezoelectric transducers were firmly attached to the reinforcing bars at predetermined locations using a suitable coupling medium to facilitate efficient wave transmission and reception. The experimental arrangement was carefully designed to minimize external disturbances and maintain consistency throughout the testing process. Multiple readings were obtained for each specimen configuration to improve the accuracy and repeatability of the results.

The acquired signals were analyzed in both the time and frequency domains to investigate variations in wave characteristics caused by the presence of lap splices. Parameters such as signal amplitude, arrival time, attenuation, and frequency response were examined to identify changes in propagation behavior. Comparative analyses between straight and lapped reinforcement specimens enabled the assessment of the influence of splice length on wave transmission efficiency.

Furthermore, the recorded data were processed using signal analysis techniques to extract meaningful information regarding energy loss and wave scattering effects. The differences observed in the propagated signals provided valuable insights into the interaction between stress waves and discontinuities introduced by lap splices. The findings contribute to the development of effective non-destructive evaluation techniques for monitoring the integrity and performance of reinforced concrete structures, thereby supporting the implementation of reliable SHM systems in civil engineering applications [8-10].

## EXPERIMENTAL ANALYSIS

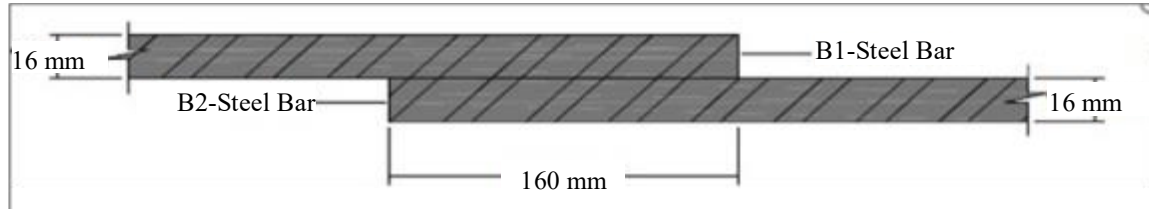
As shown in Figures 1 to 4, tests were carried out on steel bars with varying lap lengths of splicing steel bars. The specifics of the test program are as follows.

- (i) Spliced steel bars with a lap length ten times the bar's diameter (10  $\phi$ ) and straight steel reinforcement bars
- (ii) Spliced steel bars and straight steel reinforcement bars with a lap length 20 times the bar's diameter (20  $\phi$ )

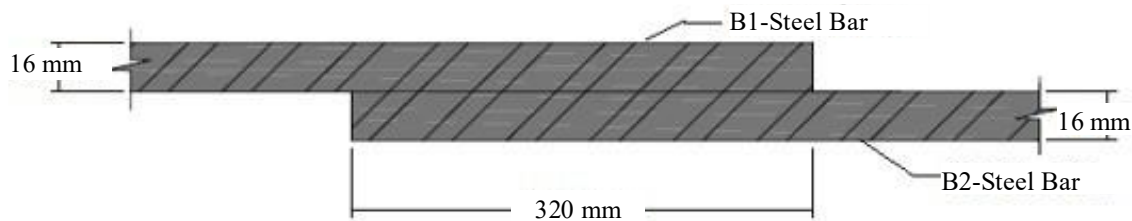
## TEST CONFIGURATION AND INSTRUMENTATION

The SP-5H Patches, which are thin and small piezoelectric lead zirconate titanate (PZT) transducers measuring 20 mm by 20 mm by 0.4 mm, were used. Two attached PZT patches (PZT 1 and PZT 2) that operate independently can function as an actuator and a sensor, respectively. The PZT patches were

adhered to the surface of the steel bars once the bars were properly flattened. The PZTs were bonded using an epoxy adhesive with a high shear modulus and a very tiny thickness, roughly one-third of the thickness of the PZT transducer.

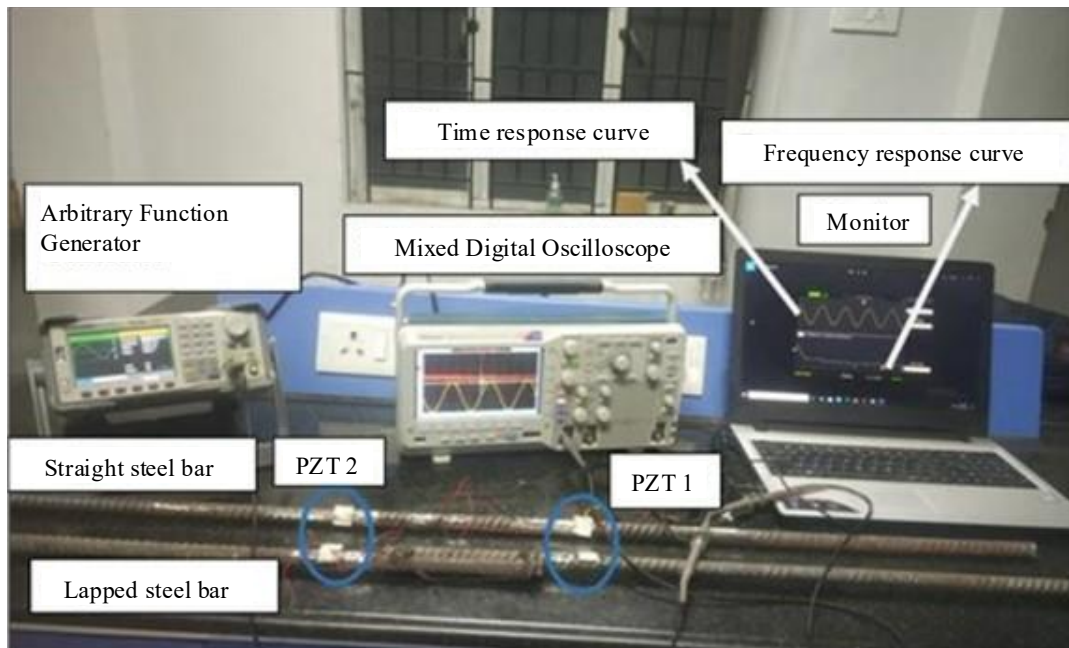


**Figure 1.** Steel bars with 10  $\phi$  lap splice



**Figure 2.** Steel bars with 20  $\phi$  lap splice

The selection of SP-5H PZT patches was based on their high sensitivity, excellent electromechanical coupling characteristics, and ability to generate and detect stress waves over a wide frequency range. Prior to bonding, the steel bar surfaces were cleaned thoroughly to remove dust, rust, oil, and other contaminants that could affect the bonding quality and signal transmission efficiency. Surface preparation was performed carefully to ensure strong adhesion between the transducers and the steel substrate.



**Figure 3.** Instrumentation and test set up

After the adhesive was applied, sufficient curing time was allowed to achieve a stable and durable bond. The thin adhesive layer minimized energy losses at the interface and ensured efficient transfer of

mechanical waves between the PZT patches and the steel bars. Proper alignment of the transducers was also maintained to improve the consistency and repeatability of the experimental measurements.

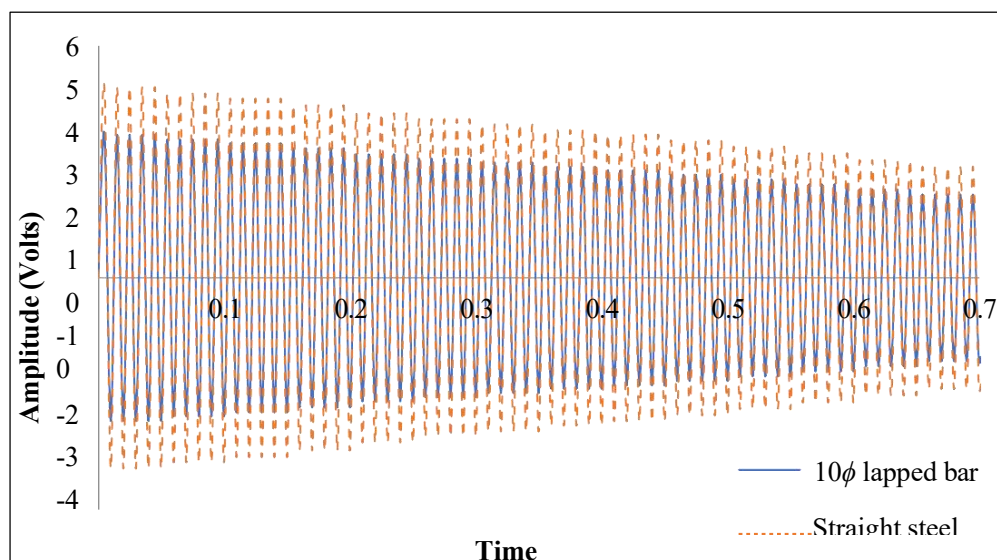
## RESULTS AND DISCUSSION

The following two test programs were conducted in order to assess and determine the sensitivity and effectiveness of the suggested Wave propagation analysis experimental approach; the findings are displayed here:

1. Time response and frequency response curves are obtained by testing straight steel reinforcing bars using the experimental wave propagation technique. The generated signals were recorded and analyzed to establish a baseline response for undamaged and continuous reinforcing bars. The time-domain response provided information regarding wave arrival time, signal amplitude, and attenuation characteristics as the stress waves propagated along the length of the steel bar. These parameters are important for understanding the propagation behavior of guided waves in a homogeneous reinforcement specimen.
2. Time response and frequency response curves are obtained by testing lapped steel reinforcement bars using the experimental wave propagation analysis approach. The recorded signals from the lapped steel reinforcement specimens were analyzed to investigate the influence of lap splices on stress wave transmission characteristics. As the generated waves propagated through the lap region, changes in signal amplitude, arrival time, and attenuation behavior were observed due to the presence of the overlap section. The lap splice acts as a discontinuity in the wave propagation path, resulting in partial reflection, scattering, and energy dissipation of the transmitted waves.

### Time Response Analysis

It has been noted that as time increased, the signal's magnitude in both straight and lapped steel bars reduced. This is because some of the elastic waves produced by PZT 1 (actuator) leak to the surface that is attached. The signals are first transmitted on a steel bar with a lap length of ten times the bar's diameter ( $10\phi$ ). The difference in signal excitation received at PZT 2 is then recorded and compared with the signals recorded from the sensor bonded on the straight bars, as shown in Figure 5.1.

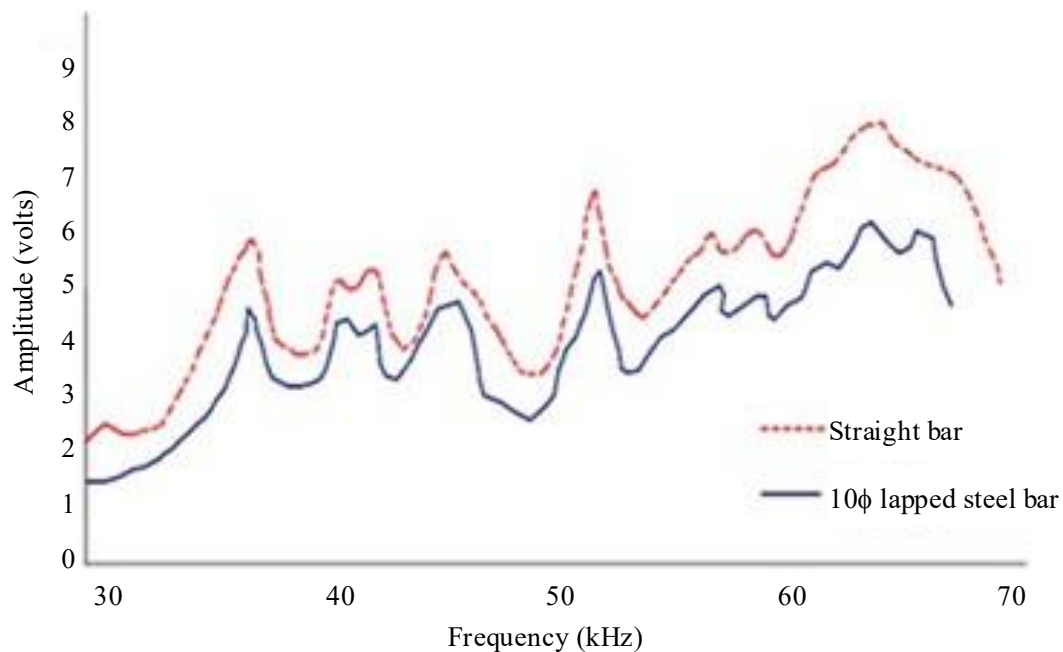


**Figure 4.** Time response curves of straight and  $10\phi$  lapped steel bars

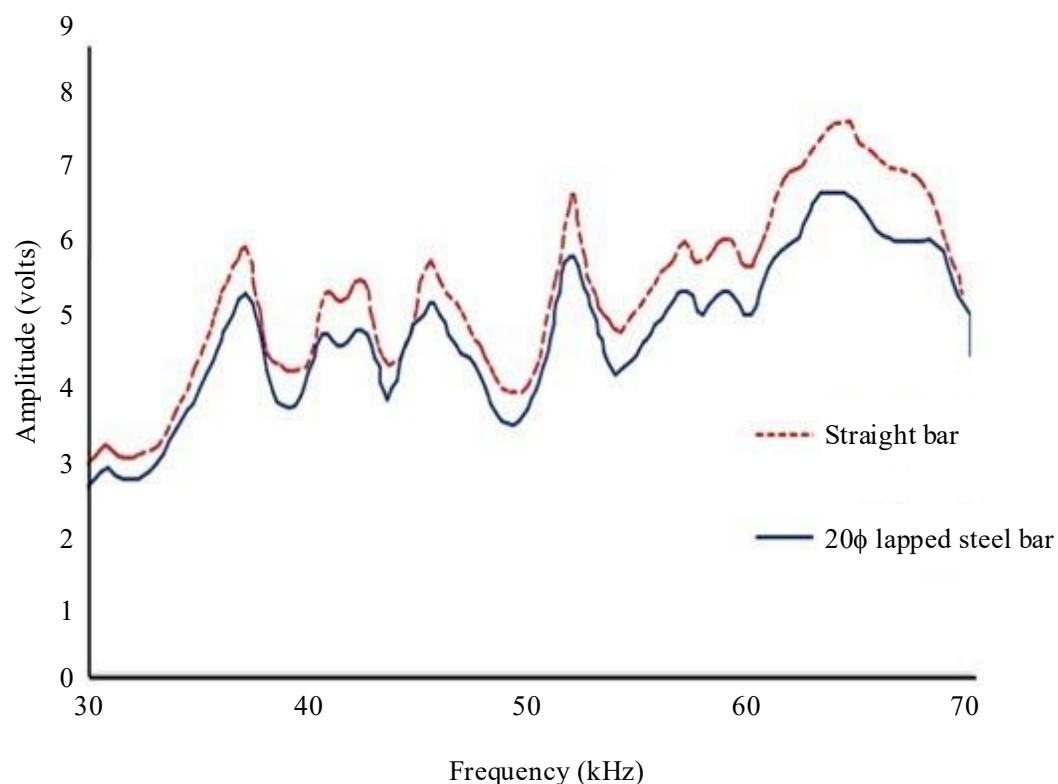
### Frequency Response Analysis

The measured PZT 1 wave propagation analysis vs the frequencies at the range of 30 kHz–70 kHz for the four analyzed cases (straight steel bar, lapped steel bar of 10 times the diameter of a bar ( $10\phi$ ), and 20 times the diameter of a bar ( $20\phi$ )) are shown in Figures 5 or 6. It should be mentioned that Sabet Divsholi & Yang (2014) originally proposed the idea of employing a sub-frequency interval approach

scanning frequency range by 10 kHz to discover signal interruption caused by lapping bars and its position on RC structures. This technology has been expanded to determine the location of structural member damage using signals from numerous PZTs. Using the signals of bonded PZTs in lapped steel bars, this method can be further improved by combining wave propagation analysis and wave transmission processes.



**Figure 5.** Frequency response curves of straight and 10φ lapped bars



**Figure 6.** Frequency response curves of straight and 20φ lapped bars

## CONCLUSIONS

The present investigation effectively illustrates the use of piezoelectric sensors in a wave propagation-based Structural Health Monitoring (SHM) technique to identify lap splices in steel reinforcing bars. The following conclusions are reached based on the study of time and frequency response signals and experimental investigations:

1. Lead Zirconate Titanate (PZT) transducers are a highly effective wave propagation tool for detecting structural discontinuities such lap splices in steel bars.
2. When comparing lapped bars to straight bars, a notable decrease in signal amplitude is seen, indicating that lap splices affect the properties of wave transmission. Depending on the lap length, the attenuation varies from roughly 33% to 56%. Wave reflection, dispersion, and mode conversion brought on by lap splices provide detectable disruptions in the received signals.

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