EFFECTS ON IMPACT-ECHO SIGNALS CAUSED BY ADJACENT STEEL REINFORCING BARS AND VOIDS IN LAP-SPLICE REGIONS: EXPERIMENTAL STUDY

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Abstract

Previous studies have identified the impact-echo method as a viable technique for detecting voids around steel reinforcing bars in reinforced concrete (RC) members. Voids can form around reinforcement as a result of corrosion, alkali-silica reactions, delayed ettringite formation, freezing and thawing, and other deterioration mechanisms. This paper investigates the feasibility of using impact echo testing on RC members to evaluate voids in lap-splice regions. In lapped bars challenges exist because adjacent bars may have different void conditions. A small-scale experimental setup for making this determination is designed to replicate field conditions.

KEYWORDS: impact-echo; void around reinforcing bar; alkali-silica reaction; corrosion; steel-concrete interface; impact-echo transfer function.

1 INTRODUCTION

Almost three decades of research on the use of the impact-echo method have produced a plethora of information on a wide range of practical applications [1]. Impact-echo is a nondestructive testing (NDT) method that monitors transient stress wave reflections created with short duration impact [1]. To correlate the results of this testing with structural performance, bond must be assessed in bond-critical regions. Bond critical regions include lap-spliced sections of RC members where reinforcement is lapped to ensure continuity between discontinuous sections of reinforcement.

In this study, a set of small-scale samples is examined using the impact-echo method to determine whether the state of current research is suitable for detecting bond loss (voids around steel reinforcement) in lap-splice regions. The motivation for this study stems from current research by the Texas Department of Transportation (TxDOT) that seeks to gain an understanding of potential structural implications resulting from Alkali-Silica Reaction (ASR) and Delayed Ettringite Formation (DEF) in RC structures. Petrographic analysis of a limited number of cores taken from these structures shows ASR gel at the steel-concrete interface, as well as the potential for DEF (see Figure 1). These two reactions create expansive by-products that, in many cases, may expand and form voids around steel reinforcement. These expansive products could introduce voids at the steel-concrete interface, reducing bond, and may result in unusual modes of failure such as bond failure in lap-splice regions. The ability to nondestructively detect these voids will assist engineers and owners in determining the performance and safety of structures exhibiting ASR and DEF.

Impact-echo was selected as a method for detecting voids around steel reinforcement as this test method is readily available, relatively inexpensive, and has been used in previous studies [2] to detect voids around reinforcing bars. In this method, impacting a small steel sphere on the surface of a concrete member

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generates stress waves. As these waves come in contact with interfaces of two acoustically different materials, portions of the waves are reflected back to the surface from which they came. A displacement transducer adjacent to the impact point records the surface displacements caused by the wave arrivals. The time-displacement signal is transformed to the frequency-amplitude spectrum where the frequencies of reflecting waves can be used to determine the depths of internal interfaces [1]. In recent years, the classic methodology has been refined with the goal of using impact-echo to assess the quality of bond in RC structures. These refinements revolve around the use of proposed transfer functions that normalize the amplitudes of the original frequency-amplitude spectrum using the amplitudes of corresponding frequencies in the impact force spectrum [3,4]. The result is a set of amplitudes and corresponding frequencies that can be used to compare results from individual tests.

The potential increase in the likelihood of bond failure in ASR/DEF-affected concrete structures can be assessed using destructive and non-destructive methods. NDT methods are more cost effective and it has been reported that these methods can locate voids around the reinforcement in field structures [4,5]. However, voids resulting from ASR and DEF and bond critical regions such as lap-splice areas have not been investigated. This research will investigate whether impact-echo testing can differentiate between bonded and unbonded conditions when these conditions occur adjacently on parallel bars (*i.e.* in lap-splice regions).

2 MATERIALS AND METHODS

2.1 General

Two laboratory samples are fabricated for this study. The dimensions of both specimens are 130 mm in depth (D), 250 mm in width (W), and 1.2 m in length (L). The resulting aspect ratio (D/W) of 0.50 falls within the range such that higher frequency modes of vibration are diminished in the response. This allows for more clarity at higher frequencies, such as those associated with the voids under examination. Metric No. 25 reinforcing bars with a measured average diameter (d) of 24 mm were placed in both specimens at a cover depth (c) of 51 mm. The bar diameter-to-cover-depth ratio (d/c) of 1.2 is sufficient such that reflections from the concrete-steel interface will be present in the response of a non-voided section. The length of the void along the bar (l_v) and the thickness of the void (t_v) are the two variables included in the investigation. To correlate results, the control sample will include only one reinforcing bar. The layouts of the control and lap-splice sample are shown in Figure 2 and Figure 3, respectively. Table 1 shows the ranges of the experimental variables.

2.2 Materials and mixture proportions

Concrete was mixed with a water-to-cement ratio (w/c) of 0.48 for a target 28-day compressive strength of 35 MPa. The cement is Type III cement and the maximum size of aggregates (MSA) is 25 mm. Standard potable tap water was used for the concrete. The speed (C_p) of the P-wave in concrete is the material characteristic required to predict the reflection frequencies observed in the impact-echo response. C_p is measured for each specimen as part of the impact-echo procedure. Grade 60 reinforcement meeting ASTM A615 specifications is used in all samples. Voids around rebar are simulated by applying multiple coats of spray rubber with acoustic impedance assumed to be much less than that of concrete.

2.3 Methods for assessment and analysis

Impact-echo testing

To determine the C_p in each sample, dual transducer wave-speed testing is performed on each sample. In this method, a steel sphere is used to impact the surface of a concrete samples. Two displacement transducers spaced at a known distance (L) record the arrival times of the P-wave. The difference in the arrival times (Δt) can then be used to determine C_p using the equation [1]

$$C_p = \frac{L}{\Delta t} \tag{1}$$

Impact-echo testing is performed directly above each reinforcing bar on the 250 mm by 1.2 m face. Ten responses are recorded in each one inch interval along the full length of the samples. Special care is taken to only accept waveforms with a well-shaped R-wave signal. These are defined as those that include the R-wave arrival (point a in Figure 4), followed by the relatively large and continuous drop to the trough of the R-wave and continuous rise back to zero (point b in Figure 4). Contact time (t_c) was measured as the difference between points *a* and *b* for the purpose of determining the maximum usable frequency (f_{max}) in the frequency-amplitude spectrum using [1]

$$f_{max} = \frac{1.25}{t_c} \tag{2}$$

Signal processing is performed in the form of the simulated transfer function proposed by [5] and refined in [3]. To implement this method, a value of 0.20 is assumed for Poisson's ratio, resulting in S-wave speeds equal to 61% of the measured P-wave speeds [6]. A value of 1.1 is assumed for the dimensionless arrival time of the R-wave with respect to the arrival time of the S-wave (γ). The value of the radial distance of the displacement transducer from the point of impact (r) is 40 mm. Once the frequency-amplitude spectrum is normalized with respect to the impact force, the normalized amplitudes are averaged in an attempt to account for uncertainty resulting from variability in the impact-receiver distance and random noise. A three-dimensional surface plot is used to show the variation in average impact-echo response amplitude as a function of both frequency and distance along the length of the concrete specimen

In the frequency-amplitude response spectrum for a test conducted on a specimen with no void at the steel reinforcement-concrete interface, the expected response includes two frequency peaks (f_{D1} and f_{D2}) associated with the first two vibration modes for the full depth of the sample, calculated using the equations [1]

$$f_{D1} = \frac{\beta C_p}{2D} \tag{3}$$

where β is a shape factor equal to 0.96 for this study, and [1]

$$f_{D2} = 2 f_{D1} \tag{4}$$

In the surface plots used to display results, these peaks create horizontal lines of constant amplitude along lengths that do not contain voids. The expected response also includes a variety of closely spaced peaks resulting from multiple paths of reflection and refraction of the P-wave in the bar. The frequency at the highest peak in this set is predicted using the equation [1]

$$f_{bar} = \frac{\zeta C_p}{4c} \tag{5}$$

where the factor ζ can be determined empirically using the following relationship [1]

$$\zeta = -0.6\frac{d}{c} + 1.5 \leq 1.0 \tag{6}$$

The data presented in Cheng and Sansalone [7] suggests that these peaks range from f_{bar} to approximately 1.15 times f_{bar}. In the surface plot of results, this creates a wide horizontal band in lengths that do not contain a void. With this in mind, the mean amplitude over this frequency range can be plotted against the location of the impact-echo test. In this domain, a dip in the transfer amplitude represents a loss in contact between concrete and steel, indicating the possible presence of a void.

Tests conducted over a section with a void at the reinforcing steel-concrete interface expected to show three other indicators of the void. The first is a shift of the two peaks associated with the first two vibration modes to a lower frequency value. This is due to the reduction in stiffness from the original cross section. In full-scale RC structures, conditions such as other voids or distributed cracking due to ASR or DEF can also cause a reduction in the stiffness of the cross-section, meaning that this indicator may not correlate well to impact-echo testing performed on full-scale structures. However, it will be used in this paper to help validate other void indicators. In the surface plots of test results, this shift causes an interruption in the horizontal lines of constant amplitude associated with the first two vibration modes. The second indicator is a peak corresponding to the vibration of the thin section of concrete above the void. In surface plots, this will indicator will appear as an additional horizontal line of similar amplitude over a voided section. However, no simple method is available to predict the location of this line. A third indicator is the frequency of the P-wave reflections from the face of the void (f_{void}), which can be predicted using the equation [1]

$$f_{void} = \frac{\beta C_p}{2A} \tag{7}$$

where A is equal to the difference between the cover depth and void thickness [1]. In the surface plots, this indicator will appear as a line of similar amplitude above the voided length near the predicted frequency f_{void}. These predictions for the responses for the two different void conditions will be used to interpret the results of impact-echo testing. Table 2 reports the mean values of 30 P-wave speed measurements performed on each specimen, as well as the subsequent predicted frequency peak values.

3 RESULTS

The results of impact-echo testing on the control sample are presented to establish a baseline for the lap-splice sample. Experimental results show the contributions of adjacent reinforcement to the impact-echo response. Figure 5 shows the results from the impact-echo testing on the control sample. The abscissa shows the location of the impact along the length of the beam, while the ordinate shows a range of frequencies containing all of the predicted peak frequencies. The contrast in the black and white surface shows the mean transfer amplitude from the ten impact-echo tests performed on each 25 mm interval. Figure 6 shows the mean transfer amplitude over the predicted steel frequencies as a function of location along the length of the sample. Figure 7 shows the results of impact-echo testing on Sample 2. Figure 8 shows the mean value of the transfer amplitude over the predicted steel frequencies of Sample 2.

4 DISCUSSION

In Figure 5, there is an interruption in the line of relatively high amplitude peaks between 15 kHz and 20 kHz that are attributed to the first mode of vibration (f_{D1}). There is also a similar interruption in the lines near 25 kHz (f_{bar}) and 31 kHz (f_{D2}). These three discontinuities are strong qualitative evidence that the void is present. One other qualitative observation can be made by looking at this figure. Both the peak corresponding to the reflection from the face of the void and the peak resulting from the vibration of concrete above the void are not obvious in the response. Due to this observation, and because the two lines of modal frequency peaks may not correlate with full-scale structures, any interruption in the broad band of peaks caused by reflections from the concrete-steel interface is found to be the best indicator of a void around steel reinforcement. This band is examined in Figure 6, which shows the mean transfer amplitude over the predicted steel frequencies. A dip in transfer amplitudes on the interval is visible from 12 in. to 20 in., an interval that matches the actual void location in this specimen and validates impact-echo as technique for detecting voids around reinforcement.

As was the case with the control (Sample 1), Figure 7 shows an interruption of the line of first mode frequency peaks (f_{D1}) between 15 kHz and 20 kHz corresponding to the void induced stiffness loss. The line of peaks associated with the second mode (f_{D2}) is also discontinuous. The peak corresponding to the reflection from the face of the void and the peak resulting from the vibration of concrete above the void are not obvious in the response. The interruption in the line of peaks associated with the reflections from the steel reinforcing bar is also present, but less apparent than before due to the high transfer amplitudes of the first thickness frequency. Figure 8 shows a dip is observed in the interval where the void is present. However, this dip appears to be relatively smaller than that of the control, indicating that the adjacent bar likely influences the response.

5 CONCLUSIONS

The objective of this study is to determine the effects of adjacent reinforcement on the ability of impact-echo to detect voids around steel reinforcing bars. To do so, two concrete samples are cast with similar void lengths and thicknesses. The first sample contains only the bar with a void, while the second contains an adjacent bar with no void. Ten impact-echo tests are performed on each 25 mm interval of the samples, and data is processed using the impact-echo transfer function. The resulting data is viewed both as a three-dimensional plot of average transfer amplitude as a function of impact location and frequency and as two dimensional plot of mean transfer amplitude of the predicted steel frequencies as a function of impact location.

Several conclusions are made based on this study. Determining the location of a void is best done by examining the mean transfer amplitude over the predicted steel frequencies. In this domain, voids appear as dips in the mean transfer amplitude. The comparison of the mean transfer amplitudes over the steel frequencies between Sample 1 and Sample 2 shows a reduced qualitative clarity of void evidence in the presence of adjacent reinforcement, possibly due to reflections from the non-voided adjacent bar.

6 REFERENCES

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Table 1–Values of void length and void thickness for experiment samples

Sample No.	No. of Bars	Void Length (l_v)	Void Thickness (t_v)
1-Control	1	200 mm	0.24 mm
2	2	200 mm	0.25 mm

Table 2: Mean values measured of P-wave speeds and predicted frequency peaks

Sample No.	C_p	f_{D1}	f_{D2}	f_{bar}	f_{void}
1	4200 m/s	16 kHz	31 kHz	25 kHz	41 kHz
2	4300 m/s	17 kHz	34 kHz	26 kHz	42 kHz

Figure 1: A portion of a core removed from an ASR-affected structure showing cracking parallel to the main reinforcement. Petrographic analysis of this specimen shows ASR gel (white areas) at the steel concrete interface.

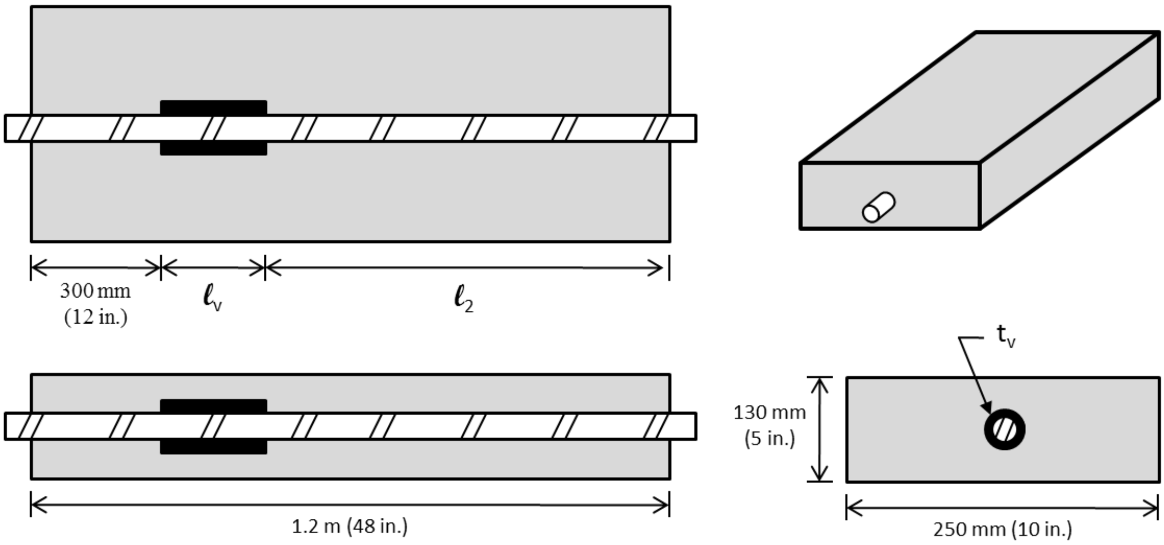

Figure 2: Specimen geometry for control sample

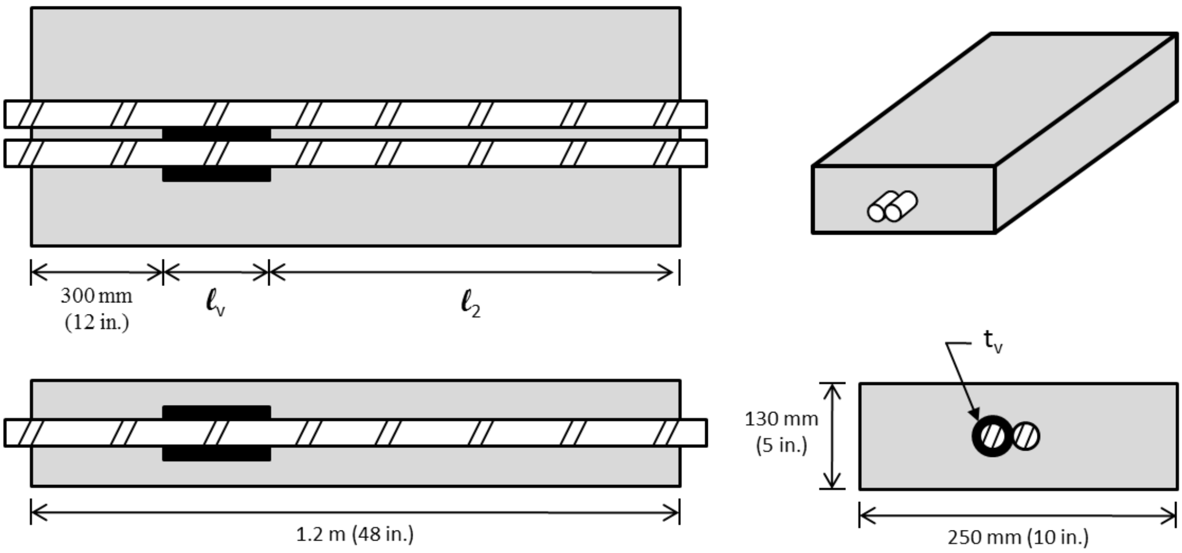

Figure 3: Specimen geometry for lap-splice sample

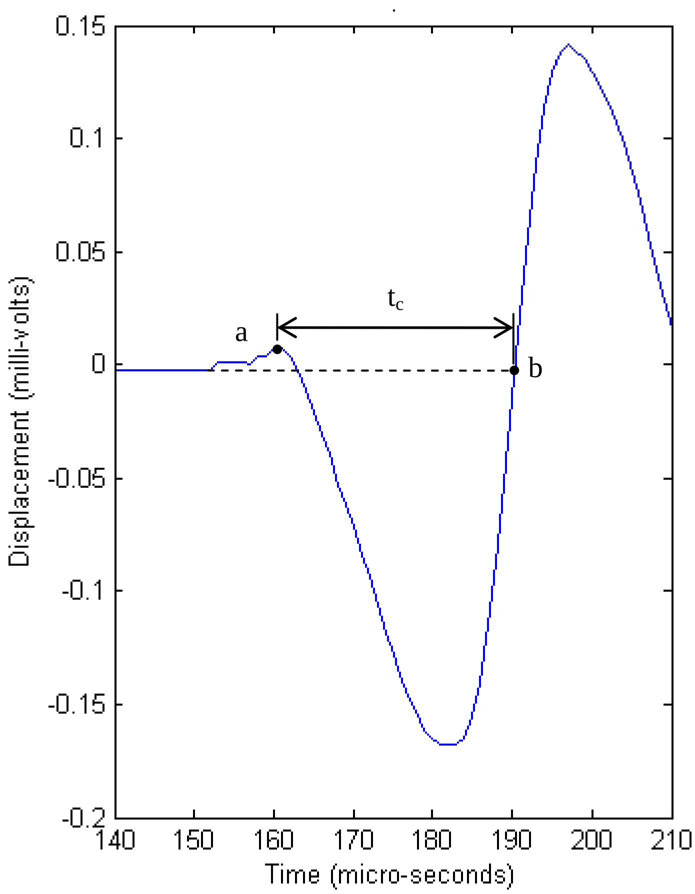

Figure 4: Typical R-wave with measured contact time

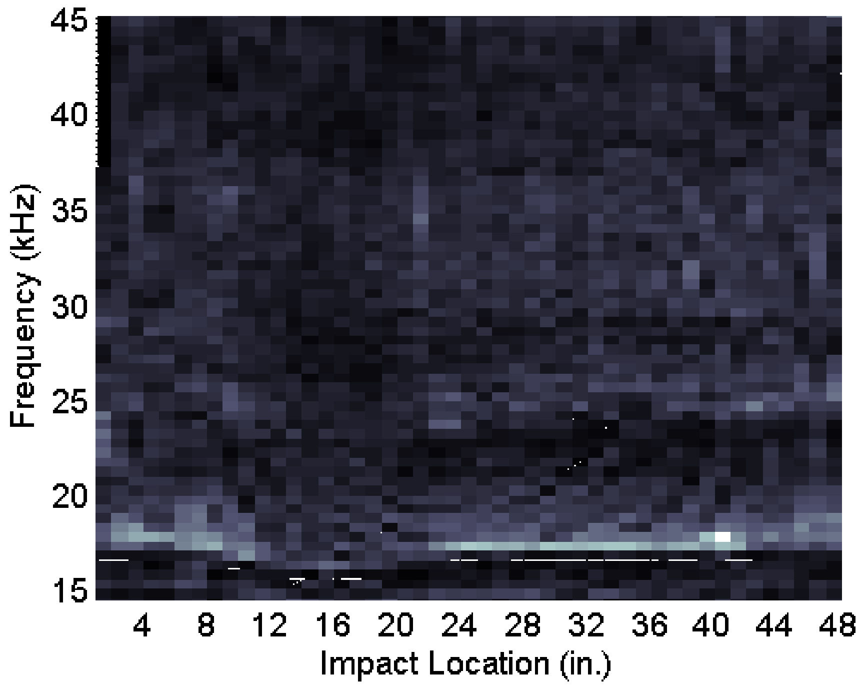

Figure 5: Impact-echo results from Sample 1

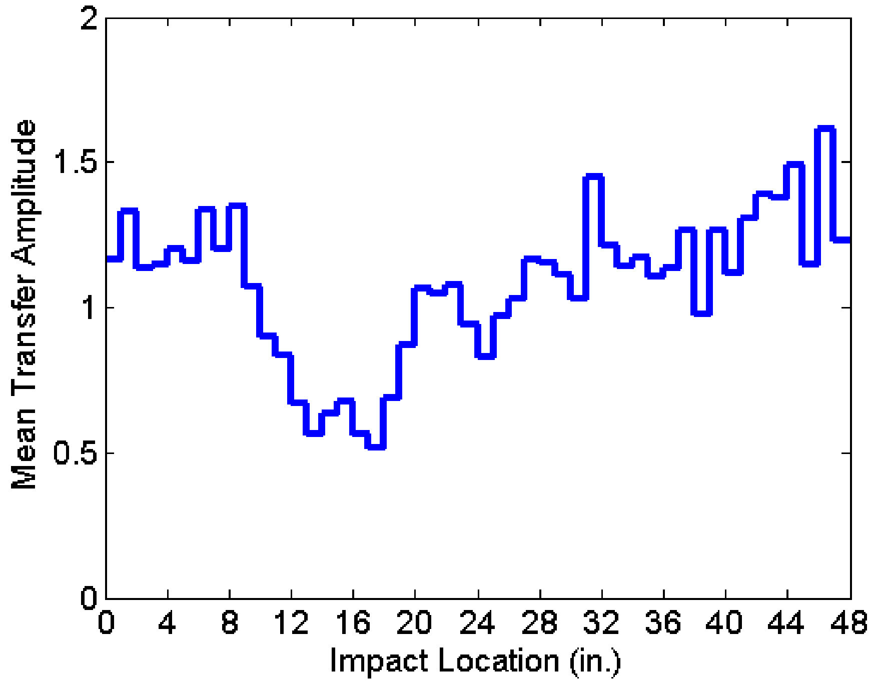

Figure 6: Mean transfer amplitude over predicted steel frequencies along Sample 1

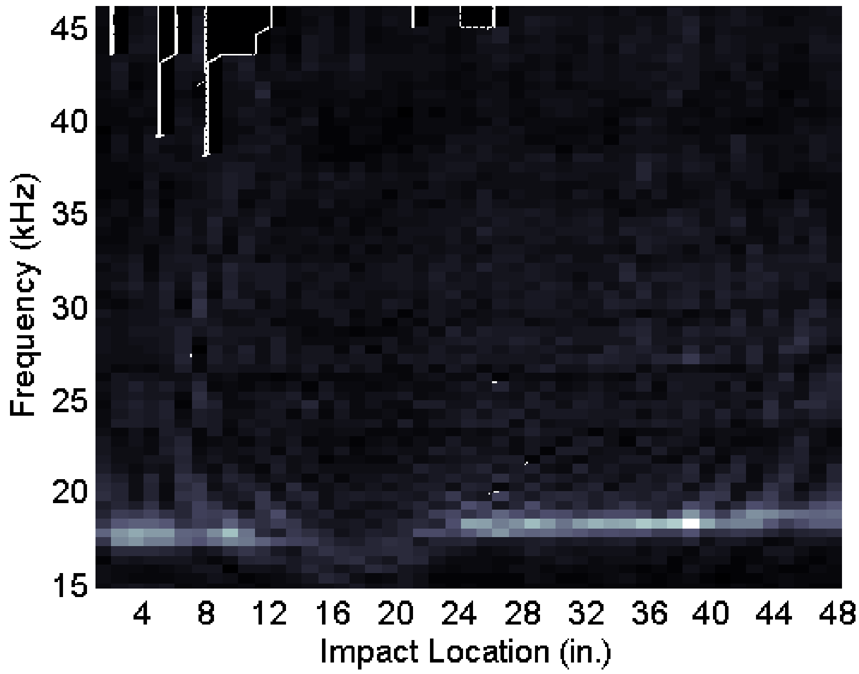

Figure 7: Impact-echo results from Sample 2

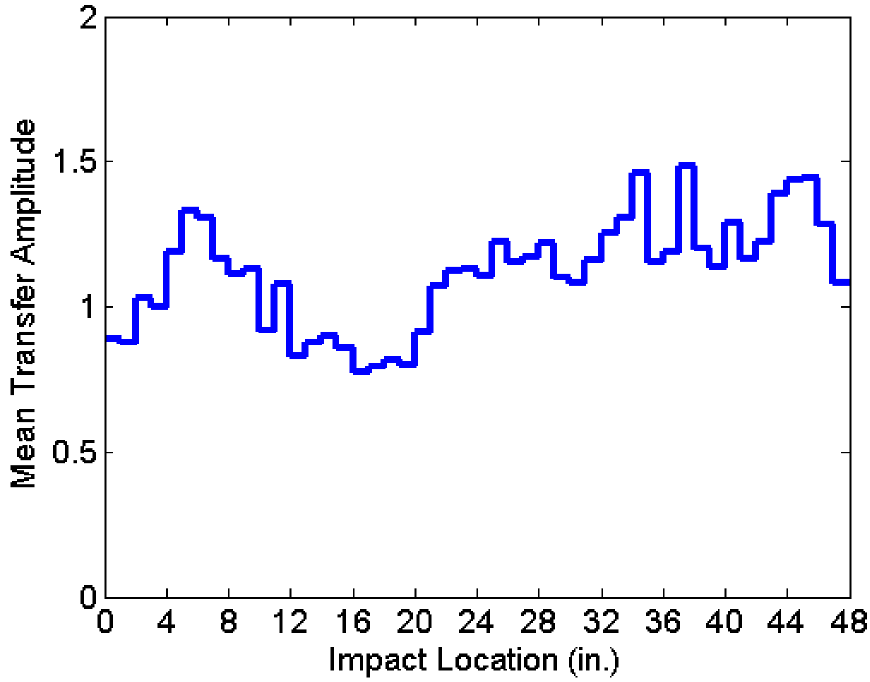

Figure 8: Mean transfer amplitude over predicted steel frequencies along Sample 2