

Article

Ultrasonic Morphology-Based Characterization of Rebar Depth and Effective Diameter in Reinforced Concrete

Wael Zatar * and Hien Nghiem

Encova Center for Engineering and Safety, Department of Civil Engineering, Marshall University, Huntington, WV 25755, USA; nghiem@marshall.edu

* Correspondence: zatar@marshall.edu

Abstract

An experimental morphology-based information extraction methodology is presented for locating reinforcing bars and estimating their effective ultrasonic scattering diameters in reinforced concrete (RC) members using ultrasonic pitch–catch (UPC) non-destructive testing combined with synthetic aperture focusing technique (SAFT) reconstruction. Reinforced concrete slab specimens with known reinforcement layouts were constructed and tested using a commercial ultrasonic device equipped with dry point contact shear wave transducers in a pitch–catch configuration. The collected ultrasonic data were post-processed using an in-house software package to reconstruct two-dimensional (2D) SAFT images of the specimens. In the reconstructed images, embedded rebars consistently produced characteristic bipolar scattering responses composed of dominant trough–crest waveform pairs. Based on these repeatable scattering response features, an empirical morphology-based procedure was developed in which rebar depth was estimated from the midpoint of the dominant trough–crest pair, while the effective ultrasonic scattering diameter was characterized using their vertical separation. The experimental results obtained from twelve reinforced concrete slab specimens demonstrated reliable depth estimation and a strong monotonic relationship between reconstructed scattering response width and nominal rebar diameter under the investigated testing conditions. Regression analysis indicated that larger rebars generally produced broader reconstructed bipolar scattering responses due to cylindrical wave interaction, diffraction, interference, finite transducer aperture effects, and SAFT reconstruction characteristics. The proposed methodology does not attempt to reconstruct the exact physical boundary of the reinforcement or solve the full elastodynamic inverse problem. Instead, the proposed methodology provides a practical and computationally efficient morphology-based information extraction framework that transforms reconstructed ultrasonic scattering responses into quantitative morphological descriptors for embedded reinforcement characterization. By extracting repeatable scattering response features from SAFT-reconstructed images and establishing an empirical mapping between these descriptors and reinforcement characteristics, the proposed approach enables the quantitative interpretation of ultrasonic images without requiring computationally intensive full waveform inversion.

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1. Introduction

Non-destructive testing (NDT) techniques have gained wide acceptance for the evaluation and characterization of reinforced concrete structural members [1,2]. Impact-echo and ultrasonic testing methods are capable of detecting internal defects and inclusions, such as ducts, tendon ducts with flaws, honeycombs, voids, and reinforcing bars, based on elastic wave propagation principles [3–6]. Recently, low-frequency dry point contact (DPC) shear wave transducers have been developed as self-contained ultrasonic measurement systems capable of detecting embedded objects in full-scale reinforced concrete structures [7–15]. Contemporary ultrasonic testing devices employing DPC transducer arrays improve the transmission of ultrasonic energy into concrete by reducing the acoustic impedance mismatch between air and solid materials. Compared with conventional ultrasonic transducers, DPC transducers eliminate the need for couplants or smooth contact surfaces and allow for testing on rough or uneven concrete surfaces with minimal surface preparation [8,16].

In the assessment of reinforced concrete slabs, the reliable characterization of reinforcing bars and concrete cover conditions is essential for evaluating structural integrity and durability. However, limited studies have investigated the quantitative estimation of embedded reinforcement characteristics using ultrasonic pitch-catch tomography devices. Previous studies primarily focused on reconstructing ultrasonic images in which reinforcing bars were visible and their approximate locations could be identified [9,10,17,18]. Choi et al. [12] employed an ultrasonic shear wave tomography device to estimate concrete cover depth and demonstrated that rebars with approximately 35 mm cover depth could be detected, although the accuracy decreased within shallow near-surface regions.

Physics-based inversion approaches, such as full waveform inversion (FWI), have been investigated for the quantitative ultrasonic characterization of concrete structures [19,20]. FWI iteratively minimizes the misfit between measured and simulated wavefields through repeated numerical solutions of the elastodynamic wave equation, enabling the high-resolution reconstruction of subsurface properties. Existing studies [19,20] have demonstrated the potential of ultrasonic FWI for recovering detailed material information under controlled experimental conditions. However, the practical implementation of ultrasonic FWI generally requires accurate a priori material properties, careful parameterization of inversion models, and substantial computational resources [19,20]. In addition, inversion stability and convergence may be sensitive to the initial model assumptions and the quality of measured ultrasonic data [20]. Consequently, there remains a need for computationally efficient and experimentally robust methodologies capable of characterizing embedded reinforcement directly from measured ultrasonic responses.

Recent studies have also explored artificial intelligence (AI) and data-driven approaches to enhance the ultrasonic inspection of reinforced concrete structures. Bórquez et al. [21] developed an augmented reality and ultrasonic sensor-based system for field rebar inspection. Yang et al. [22] employed deep neural networks to improve ultrasonic array tomography for crack recognition and cross-sectional image reconstruction, while Hou et al. [23] combined ultrasonic testing, numerical simulations, and artificial neural networks to evaluate reinforcement corrosion. These studies demonstrate the growing interest in the AI-assisted interpretation of ultrasonic data.

Recent image enhancement and restoration methods, including Bayesian-based variational models and diffusion-based approaches, have demonstrated improvements in image quality for various optical and remote sensing applications [24,25]. These approaches provide potentially useful concepts for image enhancement; however, the image formation and degradation mechanisms in optical and remote sensing applications

differ from those governing ultrasonic SAFT reconstruction in concrete, where the reconstructed response is influenced by elastic wave attenuation, scattering, diffraction, interference, transducer aperture, and coherent signal superposition. Therefore, the direct applicability of such image restoration techniques to quantitative ultrasonic scattering morphology requires specific validation to ensure that the morphological features used for quantitative characterization are preserved.

Although previous studies have demonstrated the capability of ultrasonic pitch-catch testing and synthetic aperture focusing technique (SAFT) imaging for reinforcement detection and depth estimation, limited research has investigated the relationship between reconstructed ultrasonic scattering morphology and reinforcement size characteristics. In particular, the spatial extent of the reconstructed bipolar response generated by cylindrical reinforcing bars has not been systematically evaluated as a diameter-sensitive scattering feature.

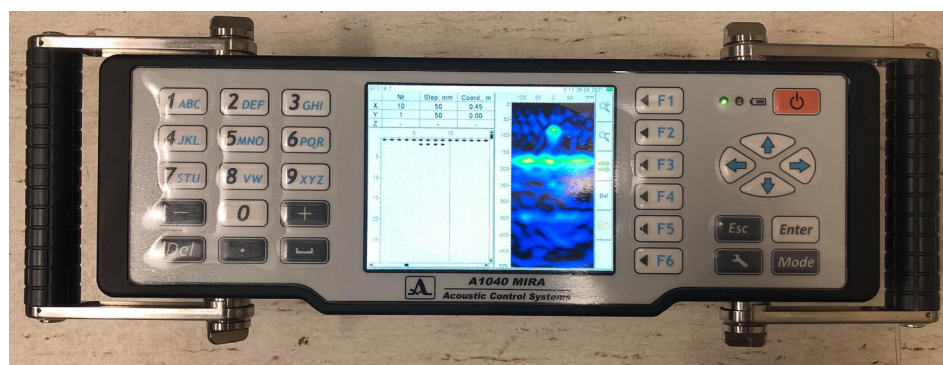
This study investigates the feasibility of estimating embedded reinforcement depth and effective diameter characteristics through a morphology-based information extraction framework applied to SAFT-reconstructed ultrasonic images obtained from ultrasonic pitch-catch testing. From an information processing perspective, the proposed methodology constitutes a morphology-based information extraction and feature engineering framework for the quantitative interpretation of SAFT-reconstructed ultrasonic images. Rather than relying solely on image visualization, the framework automatically extracts repeatable trough-crest scattering features from reconstructed bipolar responses and transforms them into quantitative morphological descriptors for reinforcement characterization. An empirical data-driven mapping is then established between the extracted scattering response descriptors and reinforcement characteristics, providing a computationally efficient alternative to full waveform inversion for the practical ultrasonic characterization of embedded reinforcement. Larger reinforcing bars are hypothesized to produce broader reconstructed scattering responses due to increased cylindrical wave interaction, diffraction, interference, finite transducer aperture effects, and SAFT reconstruction characteristics. Experimental investigations were conducted on reinforced concrete slabs containing multiple reinforcement sizes and arrangements to establish the empirical relationship between reconstructed scattering response morphology and reinforcement diameter characteristics. The proposed methodology provides a computationally efficient information extraction framework for the quantitative interpretation of ultrasonic images without requiring computationally intensive full waveform inversion. It is empirical in nature and is intended to characterize effective ultrasonic scattering morphology rather than reconstruct the exact physical boundaries of embedded reinforcement.

2. Basic Principles of UPC Device

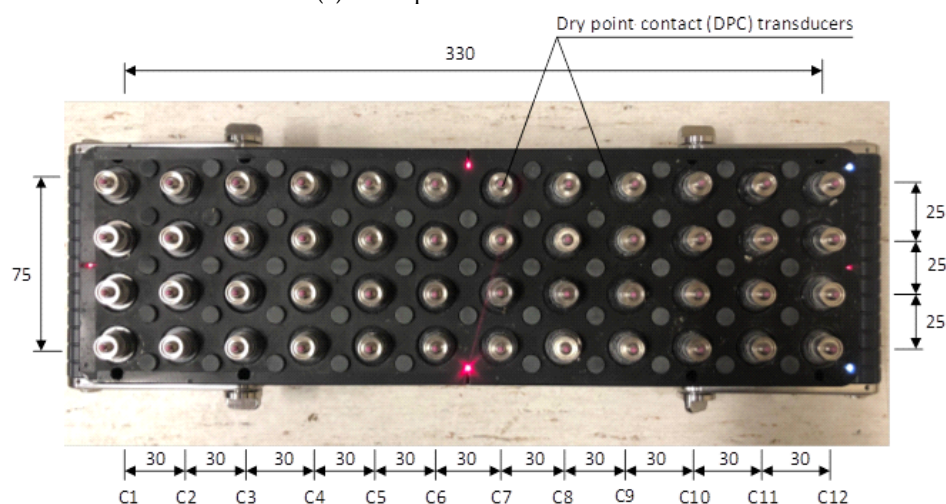
The UPC device is a low-frequency ultrasonic shear wave tomography device that could be employed to evaluate the condition of concrete structures. Figure 1a shows the UPC device's control/display, and Figure 1b shows its measurement unit/transducers. The measurement unit includes 48 dry point contact (DPC) transmitting and receiving transducers with ceramic wear-resistant tips. The transducers are arranged in a matrix with 12 channels spaced at 30 mm, called channels C_1 through C_{12} . Each channel is composed of four transducers transversely spaced at 25 mm (Figure 1b).

Figure 2 shows the basic principles of a UPC device based on the ultrasonic pulse-echo and the pitch-catch methods (Figure 2a). When one channel C_i ($i \in [1 : 11]$) emits shear wave signals into the test object, the other channel C_j ($j \in [(i + 1) : 12]$) sequentially picks up direct and reflected signals (a.k.a. echo) from objects embedded in concrete structures [26]. As a result, the 1st channel only acts as a transmitter, while the 12th

channel always serves as a receiver, and other channels act as both transmitters and receivers. There are a total of 66 transmitting–receiving pairs or 66 signal arrays for each scan based on this principle. Figure 2b shows the first channel acting as the transmitter and other channels acting as receivers that pick up the reflected signal from the bottom of the concrete slab.



(a) Front panel of UPC device



(b) Total of 48 low-frequency DPC transducers

Figure 1. Commercially available UPC device (unit is mm).

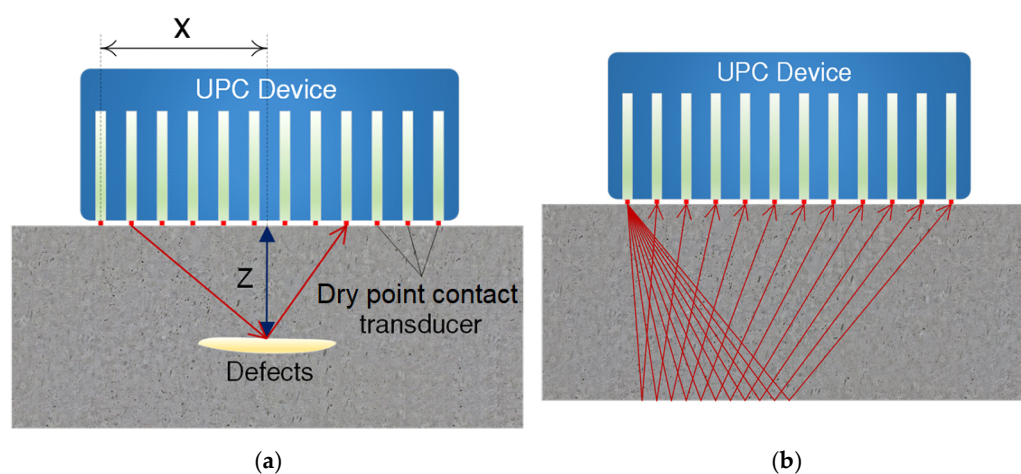


Figure 2. The basic principles of the UPC device. (a) Transmitting and receiving transducers in a “pitch–catch” configuration. (b) The first channel of transducers transmitting signals and other channels subsequently receiving them.

3. Determination of Rebar Depths and Effective Diameters

The synthetic aperture focusing technique (SAFT) was employed to reconstruct two-dimensional (2D) images of the test specimens from ultrasonic pitch-catch (UPC) measurements. In the UPC configuration, ultrasonic signals transmitted by one transducer and received by another after interaction with embedded objects were recorded. In this study, a total of 66 transmitter–receiver signal pairs were collected at each scan location. These signals were coherently superimposed over all transducer pair combinations within the sampling aperture to generate reconstructed images, commonly referred to as SAFT B-scans [27].

Recent studies have demonstrated that SAFT-based reconstruction can significantly enhance spatial resolution and reliability for characterizing embedded objects in concrete structures. In this work, linear synthetic apertures were used to obtain 2D reconstructions represented as B-scan cross-sections. The theoretical background and implementation details of the SAFT algorithm incorporated into in-house software have been presented previously [28] and are therefore not repeated here. In the authors' previous study [28], the trough and crest coordinates of the reconstructed bipolar response were used to estimate rebar depth based on their midpoint; however, the spatial separation between these features was neither investigated nor proposed as a parameter for rebar diameter estimation. In the present study, this spatial separation is systematically investigated as a diameter-sensitive scattering feature for quantitative rebar characterization.

Prior to SAFT reconstruction, the acquired ultrasonic signals were subjected to frequency-domain filtering based on Fourier analysis to suppress undesired high-frequency components. The direct arrival portions of the signals from multiple transmitter–receiver pairs were subsequently evaluated to estimate the effective shear wave velocity. Measurements that did not provide reliable direct arrival information or produced abnormal velocity estimates were excluded from the velocity estimation procedure. The resulting shear wave velocity was then used in SAFT reconstruction. These signal-domain processing and quality control procedures were performed before image reconstruction and morphology-based feature extraction. The retained ultrasonic data were subsequently processed using the modified SAFT reconstruction procedure described previously [28], which incorporates coherent signal superposition and apodization to improve reflector localization and reconstructed image quality.

In the SAFT-reconstructed images, reinforcing bars typically appear as localized regions of high amplitude accompanied by characteristic shadowing effects and are identified based on the characteristic bipolar scattering response generated by cylindrical steel reinforcement, as illustrated in Figure 3a. Rebar locations can be identified from the reconstructed signal responses in both the vertical and horizontal directions. In particular, along the vertical direction (Figure 3b), the rebar response is consistently characterized by a waveform exhibiting a dominant negative peak followed by a positive peak associated with ultrasonic wave scattering, diffraction, interference, and SAFT reconstruction effects. These two features were observed to be stable and repeatable across multiple measurements and specimens.

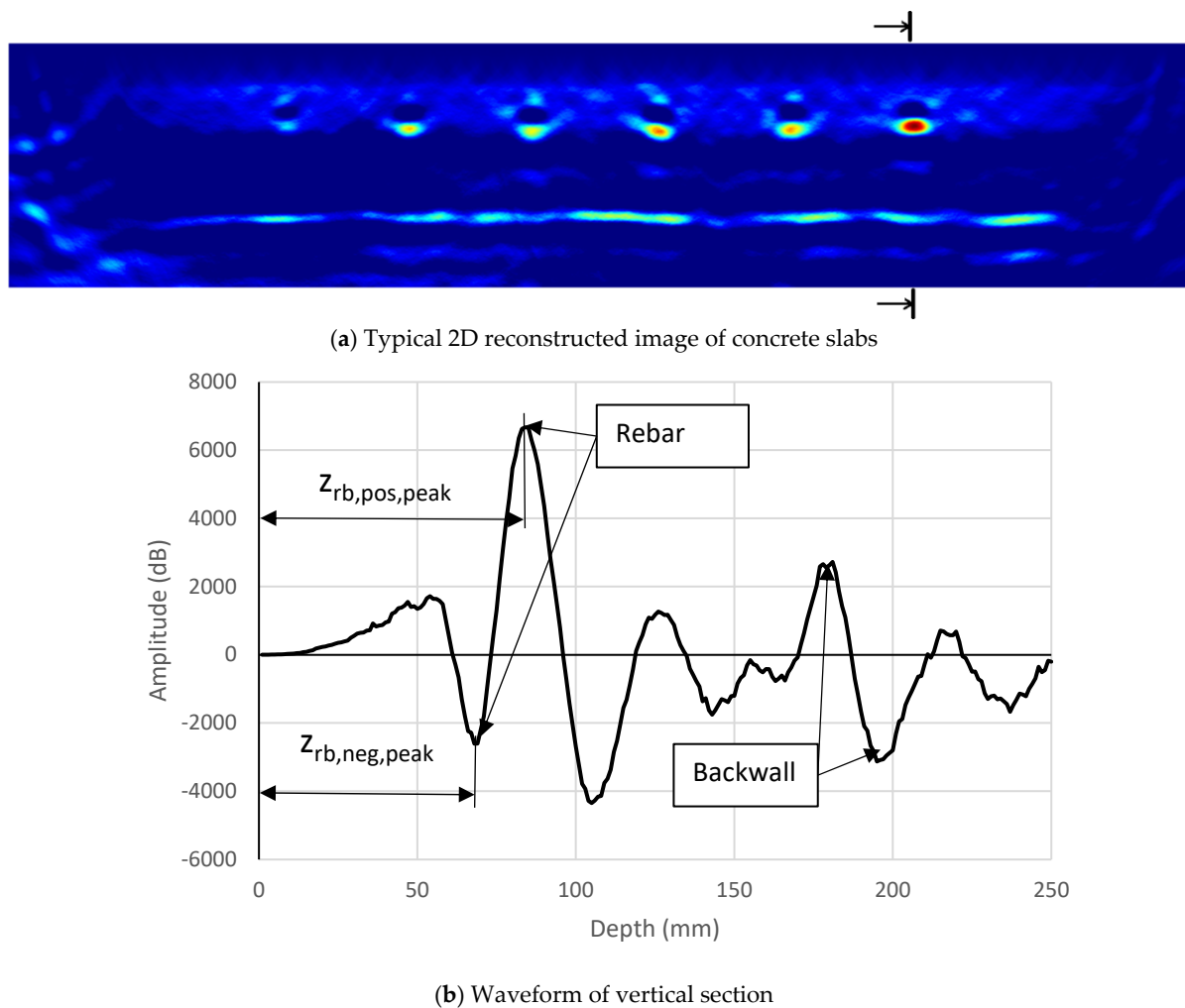


Figure 3. Reconstructed image and waveform.

Based on these observations, an empirical image-based measurement procedure was adopted to estimate rebar depth and effective diameter. The rebar depth was approximated as the midpoint between the vertical coordinates of the negative and positive peaks, expressed as follows:

$$z_{rb} = \frac{z_{rb,pos} + z_{rb,neg}}{2} \quad (1)$$

where $z_{rb,neg}$ and $z_{rb,pos}$ are the vertical coordinates of the negative and positive peaks of the waveform, respectively.

The spatial separation between the positive and negative extrema was defined as the reconstructed scattering response width W_s :

$$W_s = |z_{rb,pos} - z_{rb,neg}| \quad (2)$$

The parameter W_s does not represent the exact physical boundary-to-boundary diameter of the reinforcement. Instead, it characterizes the effective spatial extent of the reconstructed ultrasonic scattering response associated with the cylindrical rebar. Larger rebars were observed to generate broader bipolar scattering responses due to increased cylindrical wave interaction, diffraction, interference, finite transducer aperture effects, and SAFT reconstruction characteristics. Consequently, the relationship between W_s and nominal rebar diameter was determined empirically using regression analysis.

Based on the experimental observations, the effective rebar diameter $D_{rb,eff}$ was estimated empirically from the reconstructed scattering response width as follows:

$$D_{rb,eff} = aW_s + b \quad (3)$$

where a is the empirical calibration coefficient and b the empirical offset coefficient.

The proposed approach is morphology-based and utilizes the reconstructed ultrasonic scattering signature of the embedded reinforcement rather than attempting to reconstruct the exact physical boundary of the rebar. Consequently, the estimated diameter should be interpreted as an effective ultrasonic scattering diameter derived from the spatial characteristics of the reconstructed bipolar response.

It should be noted that Equations (1)–(3) are empirical relationships and do not represent analytical solutions of the elastodynamic wave equation. The reconstructed bipolar response is influenced by ultrasonic wave scattering, diffraction, interference, finite transducer aperture effects, and the SAFT reconstruction process. Larger cylindrical rebars generally produce broader reconstructed scattering responses because the ultrasonic interaction region increases with the target size. Consequently, the separation of the dominant trough–crest pair increases with rebar diameter and serves as a repeatable morphology-based descriptor for reinforcement characterization.

The approximately linear relationship expressed by Equation (3) was established empirically from the experimental measurements obtained in this study. No theoretical derivation was presented to suggest that this relationship is universally linear. Rather, linear regression was adopted because it provided the best fit to the experimental data for the investigated range of reinforcement sizes (#3–#8) and testing conditions while maintaining a simple and practical calibration for engineering applications. Accordingly, the proposed regression should be interpreted as an empirical calibration applicable to the investigated UPC system, SAFT reconstruction parameters, and laboratory conditions. Different transducer configurations, excitation frequencies, reconstruction algorithms, or reinforcement geometries may require recalibration or alternative regression models.

The SAFT reconstruction and feature extraction procedures were implemented in an in-house software package with a graphical user interface developed using Embarcadero Delphi. In addition to SAFT-based imaging, the software incorporates: (1) an empirical procedure for estimating shear wave velocity from the direct arrival times of multiple transmitter–receiver pairs; (2) a superposition algorithm for generating panoramic reconstructions from overlapping scans; and (3) the automated identification of embedded objects based on the morphology of the reconstructed bipolar response in both the vertical and horizontal sections of the reconstructed images.

No additional post-reconstruction image enhancement or restoration processing was applied prior to feature extraction. The proposed methodology intentionally operates directly on the SAFT-reconstructed images because the SAFT algorithm inherently improves reflector localization and suppresses incoherent noise through the coherent superposition of multiple transmitter–receiver measurements. Furthermore, the proposed morphology-based characterization relies on the spatial characteristics of the reconstructed bipolar response; additional image enhancement or restoration procedures may alter the location, spatial extent, or morphology of the trough–crest features and consequently influence the extracted descriptors. Although recent image enhancement and restoration techniques may potentially improve image quality and feature visibility, their application to quantitative ultrasonic SAFT images requires specific validation to ensure that the scattering response morphology used for feature extraction is preserved. The integration and systematic evaluation of such techniques within the proposed information extraction framework represent an important direction for future investigation.

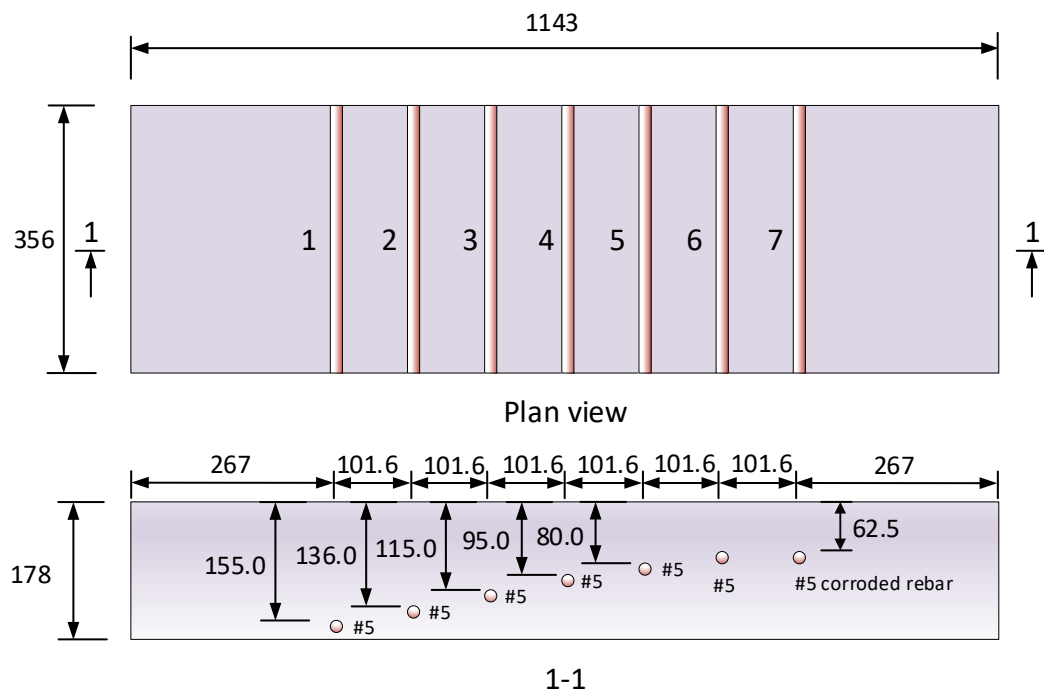
The estimated shear wave velocity was used for image reconstruction and depth calculation. For each scan, the direct arrival time was identified from the first dominant

arrival in the recorded ultrasonic signals, and the effective shear wave velocity was determined from the linear relationship between propagation distance and arrival time. The estimated shear wave velocities exhibited consistent linear trends with high coefficients of determination for the investigated specimens, resulting in stable depth reconstruction under the tested laboratory conditions. Because reconstructed depth is directly proportional to the assumed shear wave velocity, uncertainty in velocity estimation may influence the reconstructed depth and scattering response width. Variations in concrete heterogeneity, moisture condition, reinforcement congestion, surface roughness, transducer orientation, and signal interpretation may introduce additional uncertainty in practical applications. Accordingly, the proposed methodology should be interpreted as an empirical morphology-based information extraction framework applicable to the investigated testing conditions and reconstruction configuration.

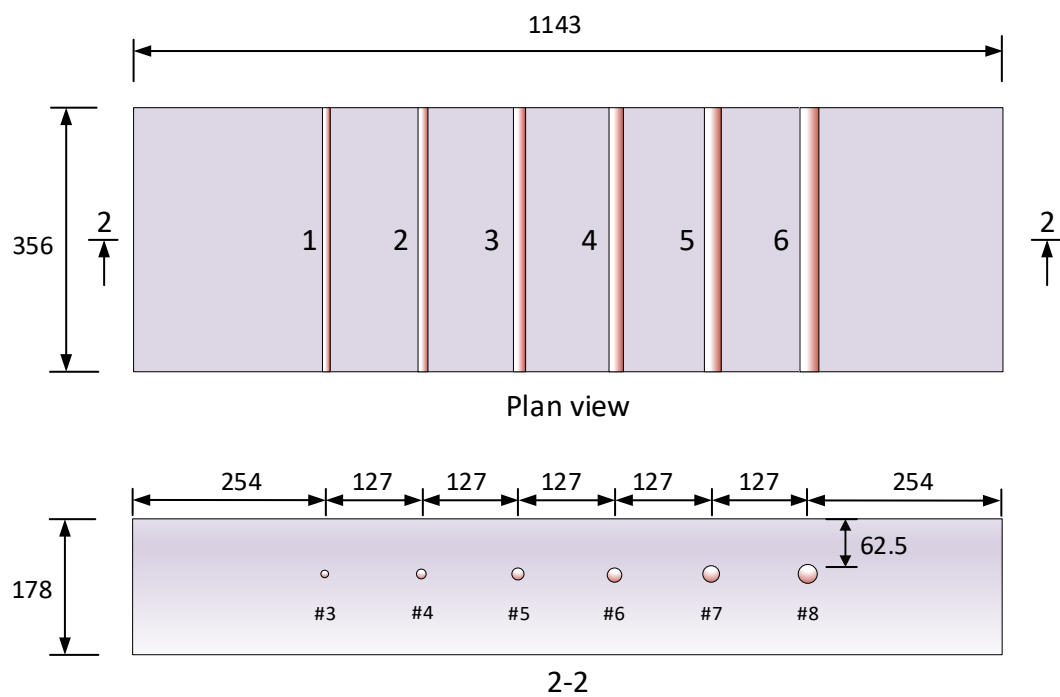
4. Experimental Program

4.1. Specimen Preparation and Details

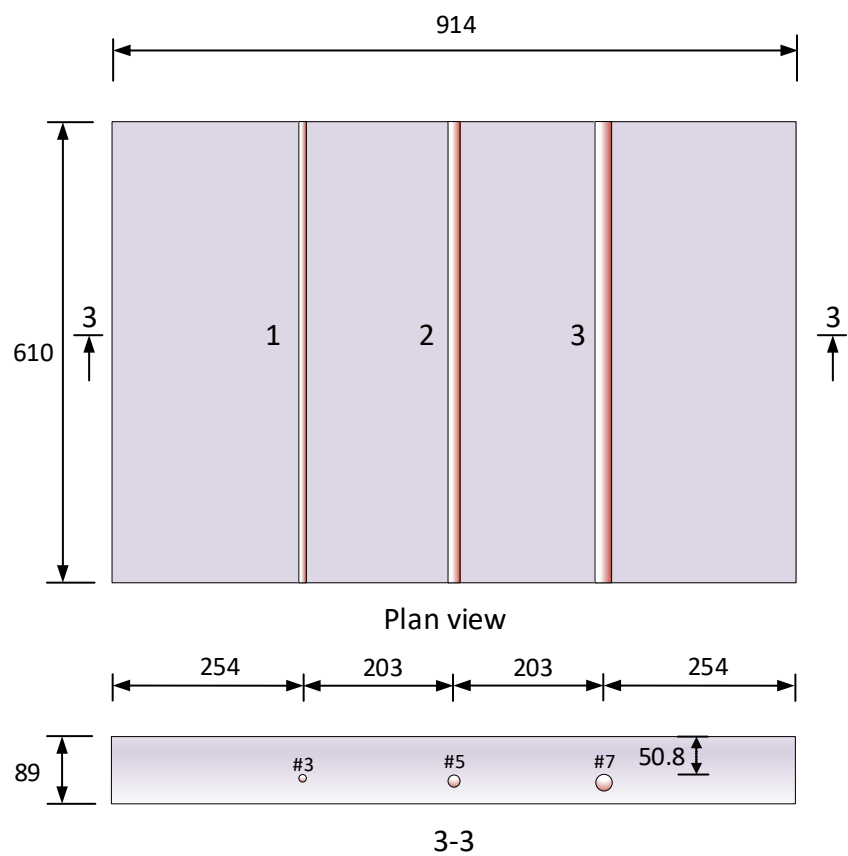
Four groups of reinforced concrete (RC) slab specimens (with a total of 12 RC slab specimens) were designed with embedded steel rebars with different configurations to validate the proposed method in the determination of rebar locations and diameters (Figure 4). The overall dimensions of the RC slabs in the first and second specimen groups (denoted as SPC1 and SPC2, respectively) were $1143 \times 356 \times 178$ mm (length $\times$ width $\times$ thickness). In the first specimen group (i.e., SPC1), seven rebars with the same diameter of #5 were located at different depths and with an identical spacing of 101.6 mm (Figure 4a). Six rebars with diameters varying from #3 to #8 were embedded in the second specimen group (i.e., SPC2) at the same depth and with an identical spacing of 127 mm. Similarly to the first and second specimen groups, the third RC slab specimen group (SPC3) was designed with one layer of steel rebars (Figure 4c). Three different diameters of rebars (#3, #5, and #7 with nominal diameters of 10 mm, 16 mm, and 22 mm, respectively) were embedded in the RC slabs to investigate the effects of near-surface rebars on reflected signals. The overall dimensions of the SPC3 specimen group were $910 \times 610 \times 89$ mm (length $\times$ width $\times$ thickness). In the final specimen group (SPC4), larger RC slabs with the dimensions of $1219 \times 1143 \times 178$ mm (length $\times$ width $\times$ thickness) were used to evaluate the effects of multiple rebar layers on their depths and diameters. The SPC4 specimen group contained two layers of #5 steel rebars in both the longitudinal and transverse directions (Figure 4d). The RC slab specimens were cast using ready-mix concrete from in-transit mixers, then cured and tested in laboratory conditions.



(a) SPC1 specimen group (five RC slab specimens)



(b) SPC2 specimen group (one RC slab specimen)



(c) SPC3 specimen group (five RC slab specimens)

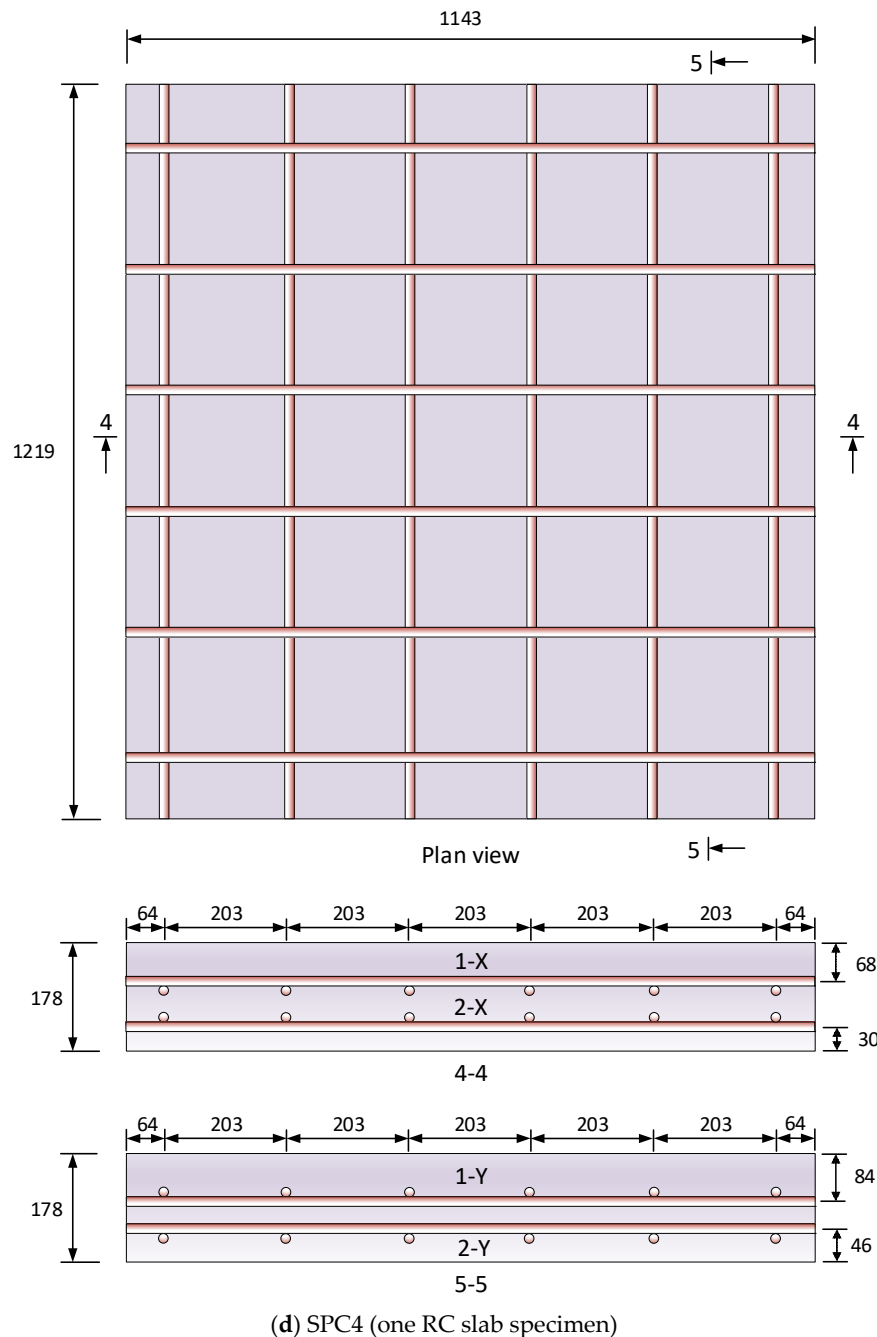
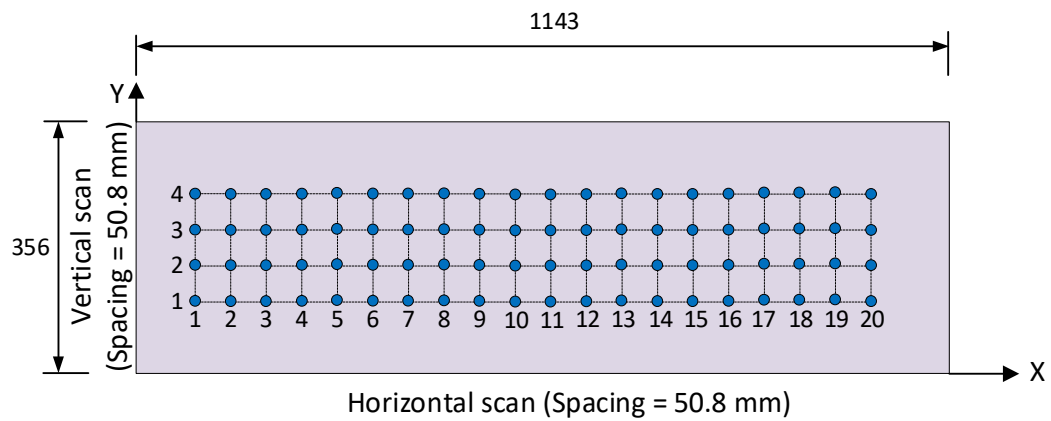


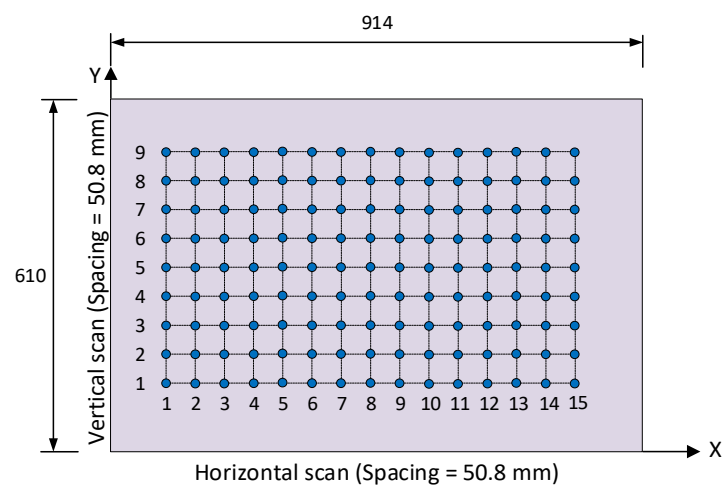
Figure 4. Four specimen groups of RC slabs (unit is mm).

4.2. Data Collection Parameters

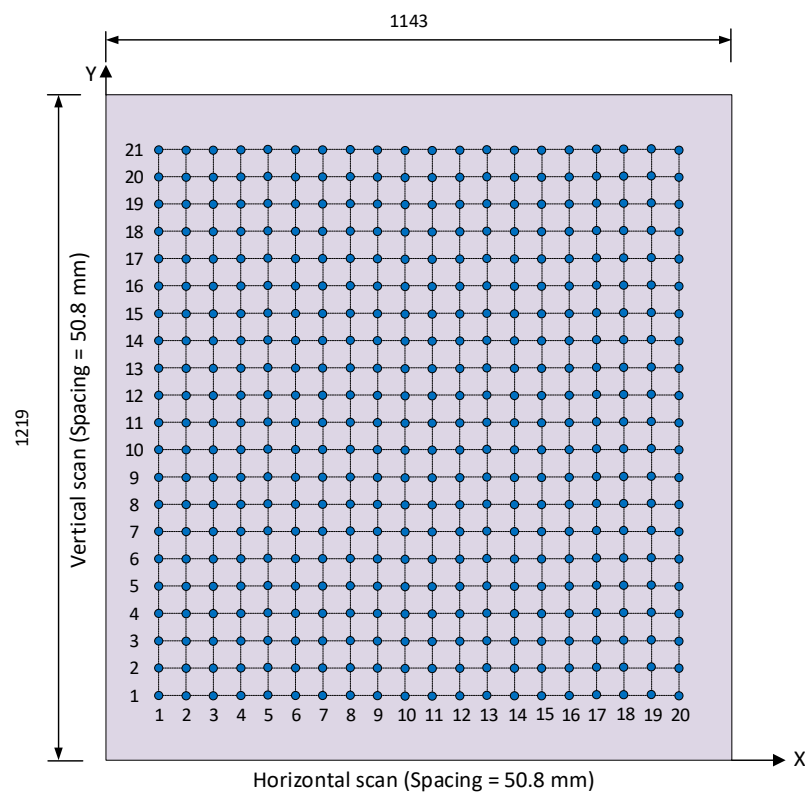
Each validation RC slab group has a different number of collected data points (corresponding to the grid point locations with equal spacing of 50.8 mm in Figure 5). Operating frequency was set to a default value of 50 kHz, while shear wave velocity was set to be determined by actual measurements [16]. It should be noted that a shear wave pulse velocity of 2450 m/s was assumed for concrete, and this value was used to reconstruct screen images using the SAFT via the device. By turning on the “using the measured velocity” option, the time for the pulse to travel through the device (a.k.a. “delay” time) was automatically measured (delay time is 22 microseconds).



(a) SPC1 and SPC2 specimen groups



(b) SPC3 specimen group



(c) SPC4 specimen group

Figure 5. Grid points of collected data.

5. Results and Discussions

The accuracy of the proposed morphology-based characterization framework depends on the reliability of the shear wave velocity used for SAFT reconstruction. Therefore, the local shear wave velocity estimation procedure implemented in the proposed software is first examined before discussing the reconstructed images and rebar characterization results. Because the reconstructed depth and the morphology of the bipolar scattering response depend on the assumed shear wave velocity, accurate local velocity estimation is essential for reliable image reconstruction and subsequent feature extraction. In the proposed software, the effective shear wave velocity is estimated independently at each scan position from the first arrival travel times measured by multiple transmitter–receiver pairs rather than assuming a constant velocity for the entire specimen.

Figure 6 presents a representative example of the local shear wave velocity estimation procedure. The effective shear wave velocity was determined from the linear relationship between propagation distance and the first arrival travel time after excluding abnormal transmitter–receiver measurements. In this example, the regression produced an estimated shear wave velocity of 2319.6 m/s with a coefficient of determination of 0.999. For the investigated specimens, the regression analyses typically retained 51–66 valid transmitter–receiver pairs and generally yielded coefficients of determination exceeding 0.99, indicating highly consistent travel time measurements and stable local velocity estimation. Because the reconstructed depth is directly proportional to the assumed shear wave velocity, this local estimation procedure reduces one of the principal sources of uncertainty in the proposed morphology-based characterization framework.

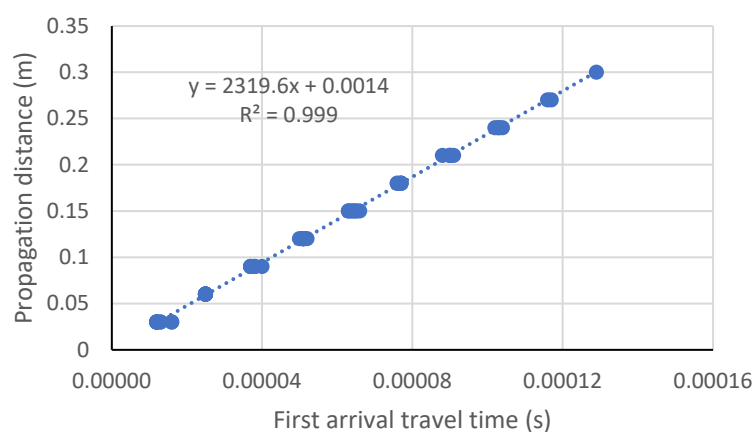
**Figure 6.** Representative estimation of local shear wave velocity.

Figure 7 shows 2D reconstructed images for all specimens in jet color spectra obtained from the developed software. The colors in a spectrum varying from dark blue to dark red were plotted next to the 2D images to represent the signal amplitudes interpreted from raw data using the SAFT algorithm. The color code of a pixel was mapped to its signal amplitude by using the following equation:

$$c = c_{min} + \frac{(g - g_{min})}{(g_{max} - g_{min})}(c_{max} - c_{min}) \quad (4)$$

where c is the color code; c_{max} is the color code for dark red; c_{min} is the color code for dark blue; g is signal amplitude; g_{max} and g_{min} are the maximum and minimum signal amplitudes, respectively.

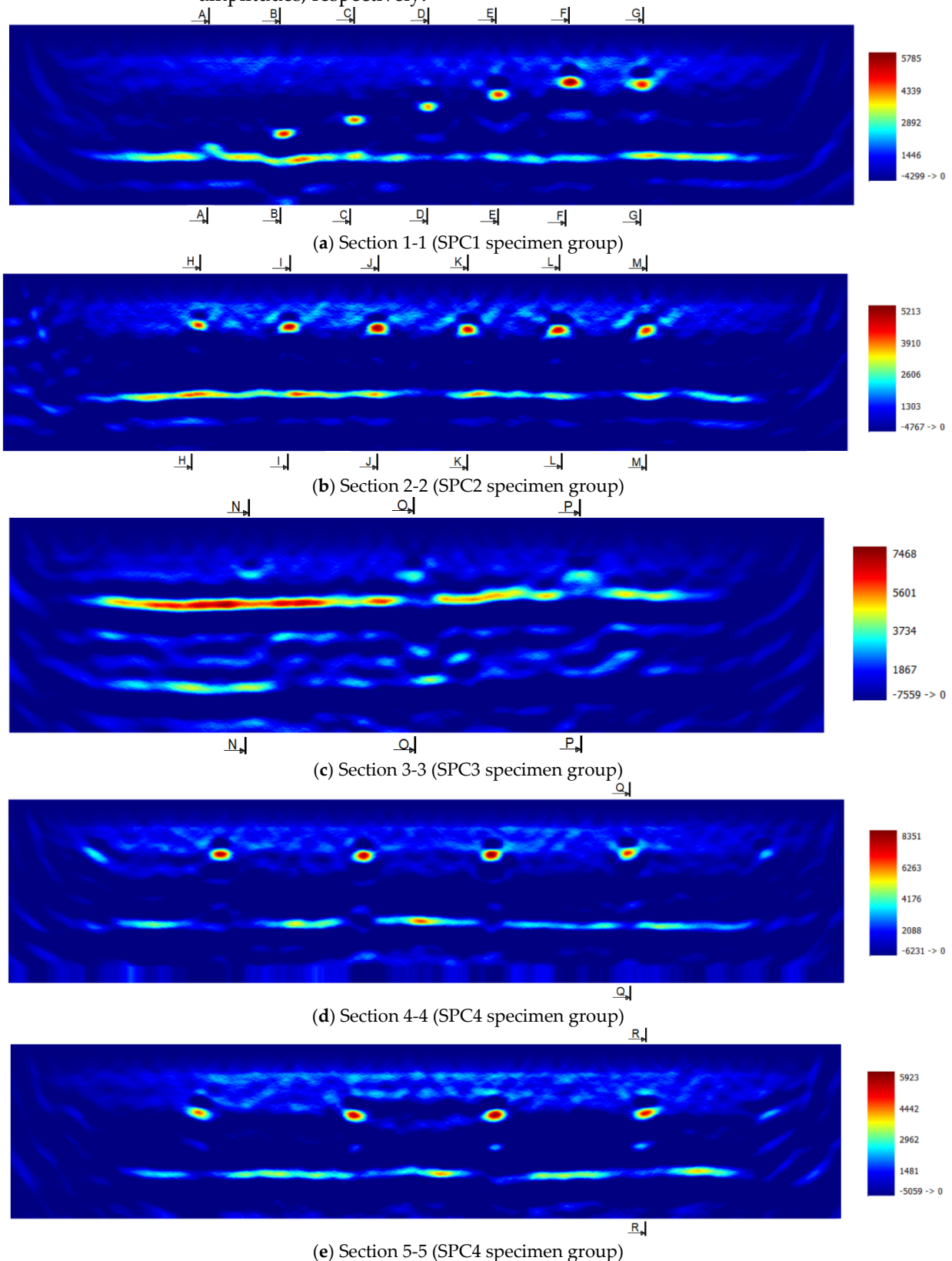
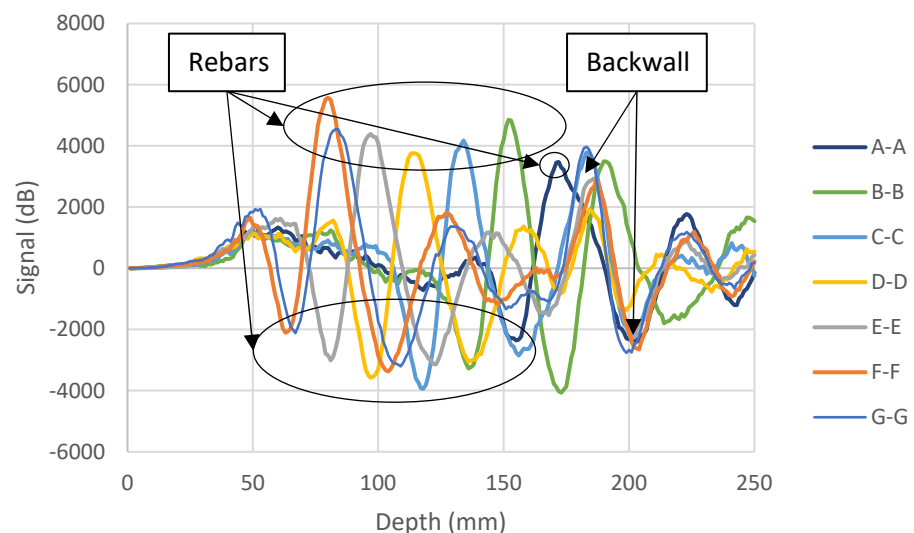


Figure 7. 2D reconstructed images of all specimen groups (SPC1 through SPC4).

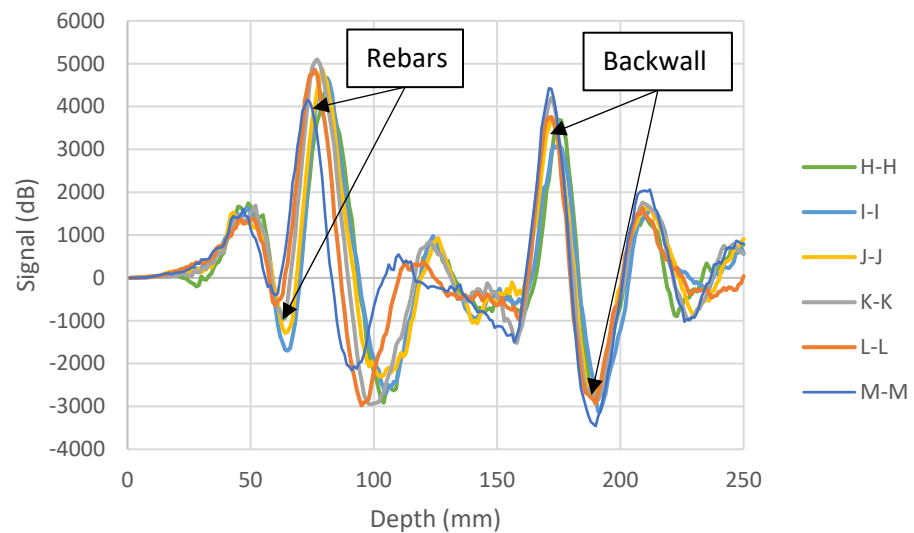
The two-dimensional (2D) SAFT-reconstructed images consistently display the bottom surfaces of the concrete slabs (backwall reflections), characterized by a polarized

dark red–dark blue pattern with a dark red band above a dark blue band. Embedded rebars in the SPC1–SPC3 specimen groups and in the first reinforcement layer of the SPC4 group are clearly identifiable as localized, ellipse-like regions of high amplitude (yellow to dark red), accompanied by darker shadowing effects above the rebar locations.

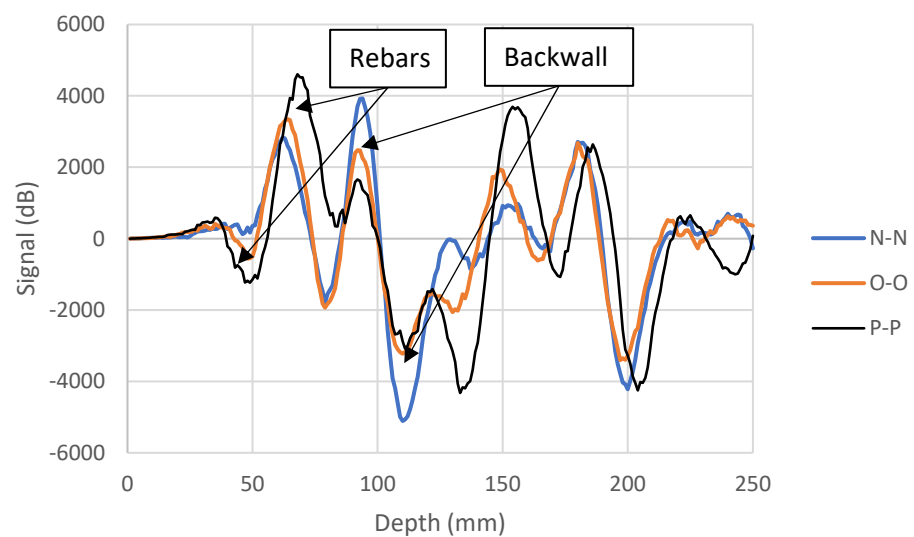
For the SPC1 specimen group (Figure 7a), the #5 rebars embedded at varying depths are distinctly visible, with the apparent size and contrast of the reconstructed features decreasing with increasing depth. The highest visibility is observed for the shallowest rebars, whereas the deepest rebar located near the slab bottom exhibits reduced clarity due to attenuation during wave propagation and interference from the backwall reflection. Figure 8a presents the vertical waveforms extracted through the centers of the rebars (sections A–A through G–G). The rebar response is consistently characterized by a trough followed by a crest. While the maximum peak amplitudes vary irregularly among rebars, the trough–crest pair remains identifiable, indicating that this feature is stable even when amplitude varies. These observations suggest that the proposed feature-based procedure is primarily governed by the spatial position of the waveform extrema rather than their absolute amplitudes. Table 1 summarizes the predicted depths and effective diameters (averaged over five specimens) for the SPC1 group. Rebar depths were estimated with high accuracy, and for #5 rebars (16 mm nominal diameter), the discrepancies in the effective diameter estimates ranged from approximately 1 mm to 2 mm.



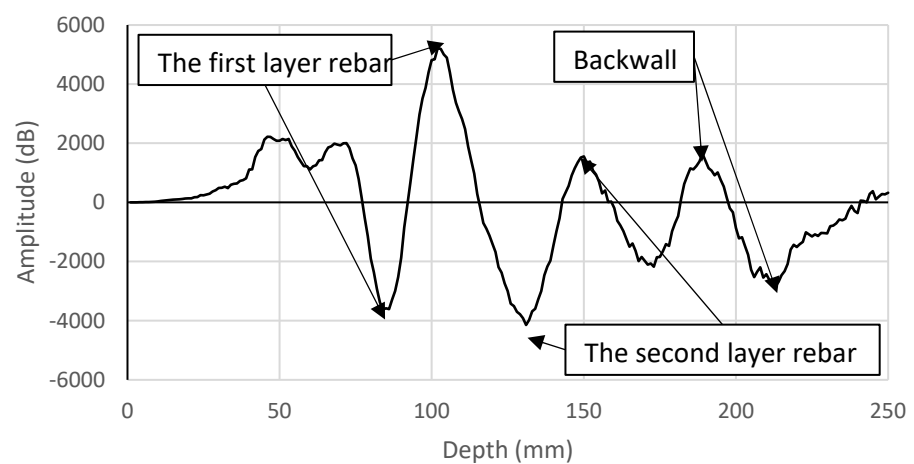
(a) Vertical sections of SPC1 specimen group



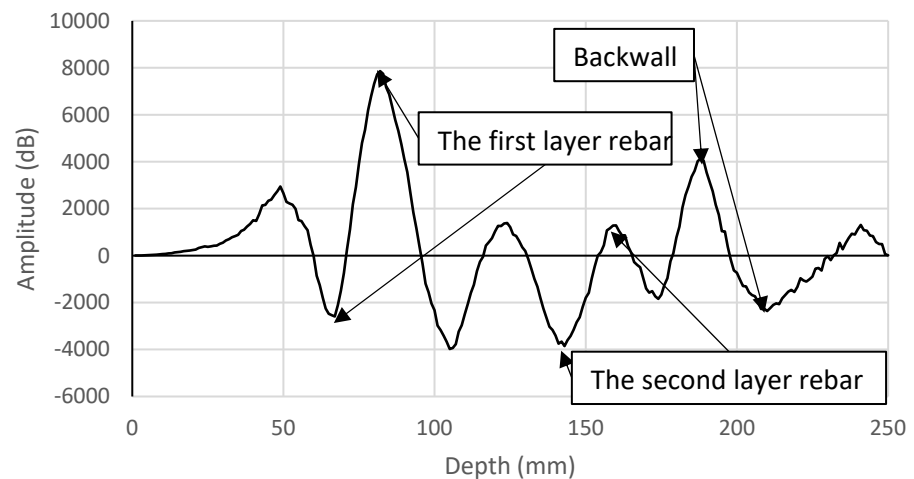
(b) Vertical sections of SPC2 specimen group



(c) Vertical sections of SPC3 specimen group



(d) Vertical section Q-Q of SPC4 specimen group



(e) Vertical section R-R of SPC4 specimen group

Figure 8. Cross-sectional waveforms of 2D images of all specimen groups (SPC1 through SPC4).**Table 1.** Comparisons of depths and diameters of rebars in SPC1 specimen group.

Rebar	Zrb,pos,peak (mm)	Zrb,neg,peak (mm)	Cal. Depth (mm)	Measured Depth (mm)	Cal. Diameter (mm)	Measured Diameter (mm)
1	165	150	157	159	15	16
2	146	130	138	141	16	16
3	127	111	119	120	16	16
4	109	93	101	101	16	16
5	93	77	85	83	16	16
6	74	58	66	65	17	16
7	76	59	67	65	17	16

In the SPC2 specimen group (Figure 7b), rebars with diameters ranging from #3 to #8 were embedded at the same nominal depth. The ellipse-like reconstructed features appear similar in overall size for most rebars, except for the smallest (#3) rebar. A systematic shift in the vertical position of the feature centers is observed with increasing rebar diameter. Figure 8b shows that the extracted vertical waveforms exhibit similar overall shapes across the slab depth, while the positive peak magnitude generally increases with rebar diameter. Table 2 compares the predicted and measured depths and diameters. Depth estimates remain highly reliable, whereas effective diameter estimates tend to be underestimated for larger diameters (#5 to #8) and overestimated for smaller diameters (#3 to #4). This trend reflects the empirical nature of the proposed measurement operator and suggests that the relationship between trough–crest separation and true diameter is influenced by factors such as wave bandwidth and reconstruction resolution.

Table 2. Comparisons of depths and diameters of rebars in SPC2 specimen group.

Rebar	Zrb,pos,peak (mm)	Zrb,neg,peak (mm)	Cal. Depth (mm)	Measured Depth (mm)	Cal. Diameter (mm)	Measured Diameter (mm)
1	73	61	62	69	12	10
2	75	61	65	70	14	13
3	77	62	66	72	15	16
4	80	63	70	73	17	19
5	82	63	71	75	19	22

6	83	63	71	76	20	25
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For the SPC3 specimen group (Figure 7c), three rebars (#3, #5, and #7) were embedded in thin slabs (89 mm thickness) at similar depths close to the slab bottom. In this configuration, the rebar responses are significantly affected by interference with the backwall reflection, resulting in weaker and less distinct image features. Nevertheless, the trough–crest waveform signature remains detectable, as shown in Figure 8c. The vertical coordinates of the troughs are similar across rebars, while the crest positions shift systematically with increasing diameter. Using these coordinates, rebar depths and effective diameters (averaged over four specimens) were estimated and found to be reasonably accurate (Table 3), demonstrating that the proposed feature-based procedure retains utility even under unfavorable imaging conditions.

Table 3. Comparisons of depths and diameters of rebars in SPC3 specimen group.

Rebar	Z _{rb,pos,peak} (mm)	Z _{rb,neg,peak} (mm)	Cal. Depth (mm)	Measured Depth (mm)	Cal. Diameter (mm)	Measured Diameter (mm)
1	64	51	58	54	13	10
2	67	51	59	57	16	16
3	70	50	60	60	20	22

Figure 7d,e illustrate the reconstructed images for the SPC4 specimen group containing two layers of reinforcement. The second rebar layer in both orthogonal directions is not clearly visible in the 2D images due to the cumulative attenuation and shadowing caused by the first layer. Despite this limitation, the characteristic trough–crest waveform associated with the second layer is still observable in the extracted vertical sections (Figure 8d,e). The corresponding depth and effective diameter estimates are summarized in Table 4. Within the tested range, rebar depth does not appear to significantly influence the accuracy of the effective diameter estimation for the first reinforcement layer, while the second layer exhibits increased uncertainty due to reduced signal clarity.

Table 4. Comparisons of depths and diameters of rebars in SPC4 specimen group.

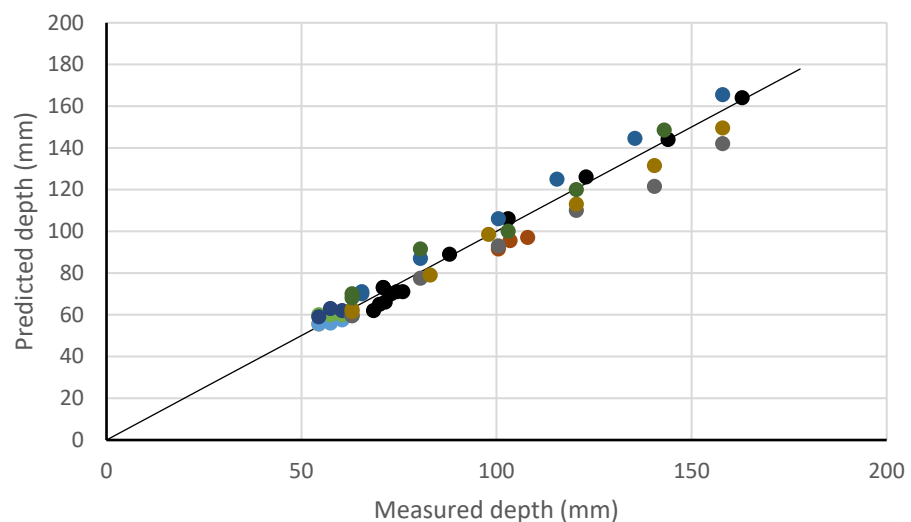
Rebar	Z _{rb,pos,peak} (mm)	Z _{rb,neg,peak} (mm)	Cal. Depth (mm)	Measured Depth (mm)	Cal. Diameter (mm)	Measured Diameter (mm)
1-X	82	66	74	68	16	16
1-Y	101	84	92	84	17	16
2-X	162	144	153	148	18	16
2-Y	146	128	137	132	18	16

Figure 9 illustrates the predicted and measured rebar depths and determination of rebar diameters for all twelve specimens. The results demonstrate consistently good agreement for rebar depth estimation across all configurations, as shown in Figure 9a. Figure 9b shows the relationship between the reconstructed scattering response width, W_s , and the nominal rebar diameter for all twelve specimens. The results indicate a clear monotonic increase in reconstructed scattering response width with increasing rebar diameter. Regression analysis produced the following empirical relationship:

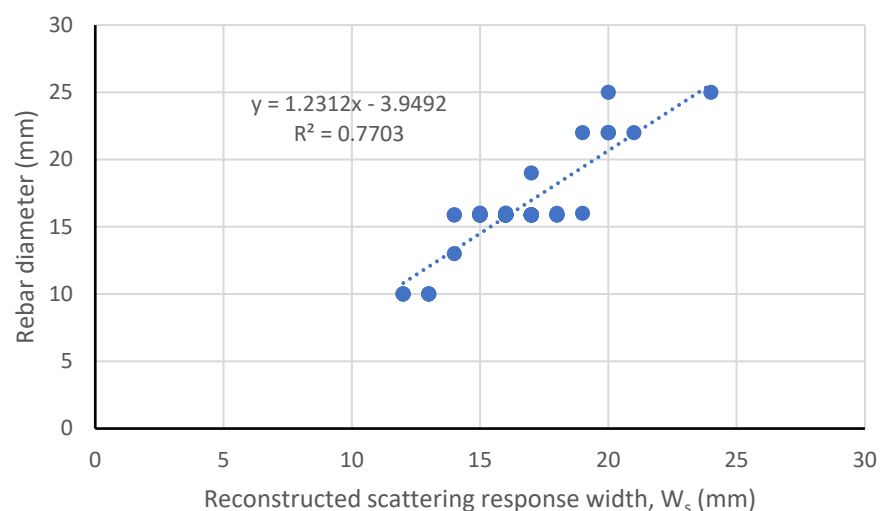
$$D_{rb,pred} = 1.2312W_s - 3.9492 \quad (5)$$

with a coefficient of determination of $R^2 = 0.7703$ based on 60 experimental rebar measurements, where $D_{rb,pred}$ is the predicted effective ultrasonic scattering diameter, and W_s is the reconstructed scattering response width obtained from the separation of the dominant trough–crest pair in the SAFT-reconstructed images. The observed non-zero intercept suggests the presence of intrinsic system broadening associated with finite wavelength effects, transducer aperture, ultrasonic scattering behavior, and SAFT reconstruction characteristics. These results indicate that the reconstructed scattering response width provides a reasonable diameter-sensitive descriptor under the investigated laboratory conditions.

The results indicate that larger rebars generally produce broader bipolar scattering responses in the reconstructed images. This behavior is attributed to increased cylindrical wave interaction, diffraction, interference, finite transducer aperture effects, and SAFT reconstruction characteristics associated with larger embedded cylindrical scatterers. Although the proposed approach does not reconstruct the exact physical boundary of the reinforcement, the observed monotonic relationship demonstrates that the morphology of the reconstructed ultrasonic scattering response can serve as a practical diameter-sensitive feature under fixed testing conditions.



(a) Comparison of rebar depths



(b) Determination of rebar diameters

Figure 9. Comparison of rebar depths and determination of rebar diameters.

These observations motivate future work on calibration refinement and uncertainty quantification, as well as hybrid approaches that combine feature-based estimation with physics-based inversion.

The empirical relationship expressed by Equation (5) was established from 60 experimental measurements obtained from twelve laboratory-cast reinforced concrete slab specimens using a single ultrasonic tomography device operating at 50 kHz and reconstructed with one SAFT implementation. Consequently, the regression equation should be interpreted as an empirical calibration applicable to the investigated testing conditions rather than as a universal predictive model. The regression coefficients implicitly reflect the characteristics of the ultrasonic system, including the transducer configuration, excitation frequency, SAFT reconstruction parameters, and the material conditions represented by the investigated specimens. The proposed calibration has not yet been validated on in-service reinforced concrete structures, where variations in concrete properties and heterogeneity, moisture conditions, surface roughness, reinforcement congestion, deterioration, and environmental conditions may influence ultrasonic wave propagation and the reconstructed scattering morphology. Therefore, the application of Equation (5) to different ultrasonic systems, operating frequencies, reconstruction algorithms, concrete materials, or field conditions may require recalibration using representative experimental data. Additional validation using larger and statistically independent datasets, particularly measurements from in-service structures under variable field conditions, together with uncertainty quantification and sensitivity analyses, is recommended to further evaluate the robustness and general applicability of the proposed methodology.

The proposed empirical relationship was established using laboratory specimens tested under controlled conditions and therefore does not explicitly account for variations in concrete heterogeneity, aggregate size, moisture content, transducer orientation, surface roughness, or other factors that may influence ultrasonic wave propagation and image reconstruction. Among these variables, only the shear wave velocity was directly considered through the velocity estimation procedure used for SAFT reconstruction. Variations in these factors may alter wave attenuation, scattering behavior, the signal-to-noise ratio, and the morphology of the reconstructed bipolar response. Consequently, the proposed calibration should be interpreted as applicable to the investigated testing conditions. Additional experimental studies involving broader material properties, environmental conditions, and testing configurations are required to quantify the influence of these variables and to establish a more generalized calibration.

Unlike conventional amplitude-based analyses, the proposed methodology utilizes the spatial morphology of the reconstructed bipolar scattering response rather than its absolute signal amplitude. Signal amplitude is influenced by coupling conditions, wave attenuation, material heterogeneity, propagation distance, and acquisition settings, whereas the reconstructed trough-crest morphology was found to provide a more repeatable descriptor under the investigated testing conditions. Furthermore, the proposed methodology operates on SAFT-reconstructed images, in which coherent summation improves reflector localization and enhances the visibility of the bipolar scattering response compared with conventional B-scan inspection. Although full waveform inversion (FWI) can potentially provide detailed quantitative subsurface characterization through iterative physics-based inversion, it generally requires greater computational effort, accurate material models, and suitable initial conditions. Recent AI-based approaches can extract complex relationships from ultrasonic data and reconstructed images but typically require representative training datasets and independent validation to ensure generalizability. In contrast, the proposed methodology provides a computationally efficient and interpretable empirical information extraction

framework that does not require iterative wave equation inversion or model training. However, unlike FWI and AI-based approaches that may potentially capture more complex subsurface characteristics, the present empirical calibration is dependent on the ultrasonic system, reconstruction configuration, and investigated material conditions and requires further independent and field validation. A direct quantitative benchmark against FWI and AI-based methods was not performed because comparable implementations applied to the same experimental dataset were not available.

The applicability of the proposed methodology should be interpreted within the investigated experimental conditions. In the present study, successful characterization was demonstrated for nominal reinforcement sizes ranging from #3 to #8 and for depth-to-diameter ratios of approximately 9 or less. These values represent the experimentally investigated range rather than theoretical detection limits. The minimum detectable reinforcement diameter, maximum detectable depth, and minimum signal-to-noise ratio required for reliable morphology-based characterization were not systematically investigated and therefore remain subjects for future research.

6. Conclusions

This study presents an experimental, image-based methodology for locating reinforcing bars and estimating their effective diameters in reinforced concrete members using ultrasonic pitch-catch (UPC) non-destructive testing combined with synthetic aperture focusing technique (SAFT) reconstruction. In the SAFT-reconstructed images, rebars are consistently characterized by a dominant trough-crest waveform pair in the vertical direction. Based on this repeatable signal feature, an empirical measurement procedure was adopted in which rebar depth is estimated as the midpoint between the trough and crest coordinates, while the effective rebar diameter is inferred from their vertical separation.

The proposed approach and the accompanying in-house software were evaluated using four sets of reinforced concrete slab specimens, comprising a total of twelve slabs with single and double layers of embedded steel reinforcement. The results indicate that rebars in the first reinforcement layer are clearly identifiable in the two-dimensional reconstructed images, whereas rebars located in deeper layers or near the slab bottom exhibit reduced image clarity due to wave attenuation and signal interference. Despite this limitation, rebar depths were consistently estimated with high reliability across all specimens.

For rebars with nominal sizes ranging from #3 to #8 and depth-to-diameter ratios up to approximately nine, regression analysis demonstrated a strong monotonic correlation between the reconstructed scattering response width and nominal rebar diameter, with $R^2 = 0.7703$ under the investigated testing conditions. It is emphasized that the proposed method is not intended to provide a first-principles analytical solution or full waveform inversion of the ultrasonic response but rather a practical and computationally efficient measurement framework for ultrasonic rebar characterization. The results demonstrate that the method can serve as a useful complementary tool for the rapid assessment of reinforcement layout and size in reinforced concrete structures, particularly in field applications where computationally intensive inversion techniques may be impractical.

Although the experimental results demonstrated clear morphology-based trends between reconstructed scattering response width and nominal rebar diameter, the present study was conducted using a limited number of reinforced concrete slab specimens under controlled laboratory conditions. Additional investigations involving larger experimental datasets, broader concrete variability, and field-scale structural members are recommended to further evaluate the statistical robustness and general applicability of the proposed methodology.

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Abbreviations

The following symbols are used in this paper:

Z _{rb}	rebar depth
Z _{rb,neg}	vertical coordinates of the negative peak of the waveform
Z _{rb,pos}	vertical coordinates of the positive peak of the waveform
W _s	reconstructed scattering response width
D _{rb,eff}	effective rebar diameter
D _{rb,pred}	predicted rebar diameter
a	empirical calibration coefficient
b	empirical offset coefficient
c	color code
C _{max}	color code for dark red
C _{min}	color code for dark blue
g	signal amplitude
g _{max}	maximum signal amplitude
g _{min}	minimum signal amplitude

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