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Enhancing Grout Filling Quality Assessment in Precast Concrete Sleeve Connections through a Collaborative Sensing Approach

Bolin Jiang [1,2], Shanshan Wu [2,3], Qidong Xiong [2,4] and Yongsheng Yao [2,*]

[1] Department of Science and Technology, Chongqing Vocational Institute of Engineering, Chongqing 402260, China; bolinjiang@cqvie.edu.cn
[2] School of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China; shanshanwu84@163.com (S.W.); xiongqd20@163.com (Q.X.)
[3] School of Railways and Architecture, Chongqing Vocational College of Public Transportation, Chongqing 402247, China
[4] Intelligent Construction Institute, Chongqing Jianzhu College, Chongqing 400072, China
* Correspondence: yaoyongsheng23@cqjtu.edu.cn

Abstract: This study presents a collaborative sensing approach that integrates the pre-embedded sensor method and the impact-echo technique to enhance the accuracy of grout filling quality assessment for precast concrete sleeve connections. The pre-embedded sensor method, which relies on vibration energy attenuation, enables continuous monitoring of the grout filling process; however, its accuracy is limited at low filling degrees, as vibration energy values remain constant at approximately 255 when the filling degree is below 70%. In contrast, the impact-echo technique, based on the principle of impact elastic wave propagation, demonstrates high accuracy in evaluating grout filling degrees across various levels, with reflected waveform amplitude increasing accordingly. This collaborative approach establishes a functional relationship between vibration energy values from the pre-embedded sensor method and grout filling degree, allowing for a comprehensive assessment of grout filling quality. In field demonstrations, the calculated grout filling degree values deviated by less than 5% from the set values. Practical guidelines for implementing the collaborative sensing approach are also provided. The method developed in this study offers a reliable solution for assessing grout filling quality in precast concrete sleeve connections, addressing the limitations of individual testing methods.

Keywords: precast concrete; sleeve connections; grout filling quality; collaborative sensing; pre-embedded sensor; impact-echo technique

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1. Introduction

Precast concrete structures have emerged as a highly industrialized form of construction, offering a range of advantages, including environmental friendliness, low-carbon footprint, rapid installation, stability, and comparable mechanical performance to traditional cast-in-place concrete structures [1–3]. The key to the success of precast concrete structures lies in the seamless integration of the precast members into a monolithic system, which is primarily achieved through the connections between various structural elements, such as the beam-column and slab-column joints [4].

In the realm of precast concrete structures, the connections between different components play a crucial role in determining the overall structural performance [5,6]. These connection points are typically the locations where the highest stresses and deformations are concentrated, and their quality and integrity directly impact the safety, stability, and serviceability of the entire building [7]. Depending on the construction method, precast concrete connections can be broadly classified into two categories: wet connections and dry connections.

Wet connections, such as the grouted sleeve connection, have become the predominant choice in the majority of precast concrete structures due to their ability to create a continuous load transfer path and achieve a monolithic behavior [4,8]. In a grouted sleeve connection, the precast members are connected by inserting the reinforcing bars into a sleeve, which is then filled with a cementitious grout material [9,10]. The quality and completeness of the grout filling within the sleeve directly influence the structural integrity and load-bearing capacity of the connection [7,11–13].

Ensuring the quality of grouted sleeve connections is of paramount importance for the overall safety and stability of precast concrete structures. Deficiencies in the grout filling can lead to a reduction in the load-bearing capacity, compromising the structural integrity and potentially jeopardizing the entire building [14]. To address this critical aspect, a comprehensive quality control regime is essential, involving a range of testing methods and equipment to assess the quality of the grouted connections.

The quality inspection methods for grouted sleeve connections can be broadly categorized into two groups: destructive testing and non-destructive testing. Destructive testing, such as core sampling and pull-out tests, provides direct information about the grout properties and the integrity of the connection. However, these methods are invasive and can potentially compromise the structural integrity of the precast members. On the other hand, non-destructive testing techniques offer a more viable solution, as they can assess the grout quality without causing any physical damage to the structure [15–17].

Among the various non-destructive testing methods, the embedded sensor method and the impact-echo technique have gained widespread recognition in the assessment of grouted sleeve connections [18]. The embedded sensor method involves the installation of sensors within the grouting sleeve during the construction phase. After the grouting process is complete, the sensors collect data on the vibration energy, which can be used to evaluate the degree of grout filling and the quality of the connection [19]. The impact-echo technique, on the other hand, utilizes the principle of stress wave propagation to detect defects and density variations within the grouted sleeve [20,21]. By analyzing the reflected stress waves, the technique can provide insights into the integrity and compactness of the grout filling. Each of these non-destructive testing methods has its own strengths and limitations [22]. The embedded sensor method is particularly well-suited for in-situ applications, where the sleeves are already embedded within the precast concrete elements [19,23]. In such scenarios, the lack of access to the exposed steel reinforcement ends prevents the direct application of the impact-echo technique. Conversely, the impact-echo method can provide more detailed information about the internal condition of the grouted sleeve, including the presence of voids or defects, but it requires access to the exposed steel reinforcement ends for the excitation of the stress waves [24].

To overcome the limitations of the individual testing methods and leverage their respective advantages, a collaborative sensing approach can be developed by exploring the correlation between the vibration energy values obtained from the embedded sensor method and the density information derived from the impact-echo technique [25,26]. By establishing a relationship between these two parameters, it becomes possible to enhance the accuracy and reliability of the grouting quality assessment for sleeve connections, particularly in situations where the impact-echo technique cannot be directly applied.

This study aimed to investigate the relationship between the vibration energy values measured by the embedded sensor method and the density information obtained from the impact-echo technique, and to establish a method for the collaborative sensing of grouting filling degree in sleeve connections. The research workflow is presented in Figure 1. The performance of the embedded sensor method in assessing the grout filling degree of sleeve connections under varying levels of grout filling was analyzed. The effectiveness of the impact-echo technique in determining the grout filling degree of sleeve connections was evaluated, and a correlation between the detected density and the actual grout filling degree was established. A collaborative sensing approach was developed by exploring the relationship between the vibration energy values from the embedded sensor method and

the density information from the impact-echo technique to enhance the accuracy of grouting quality assessment for sleeve connections. Finally, the proposed collaborative sensing approach was validated through field demonstration and provided practical guidelines for its implementation in real-world precast concrete construction projects.

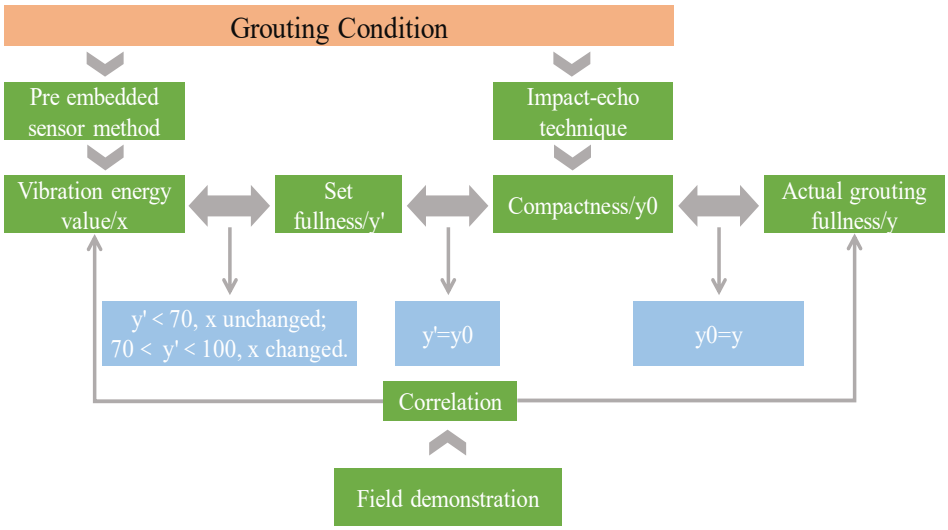


Figure 1. Research flowchart of this study.

The structure of this paper is organized as follows. Section 2 presents the materials and methods used in the study, including the detailed procedures for the embedded sensor method and the impact-echo technique, as well as the design of the experimental models. Section 3 discusses the results obtained from the laboratory experiments and the field demonstration, and analyzes the correlation between the vibration energy values and the grout filling degree. Finally, Section 4 summarizes the key findings of the study and provides recommendations for future research and practical applications.

The research presented in this paper contributes to the body of knowledge on the quality assessment of grouted sleeve connections in precast concrete structures. By developing a collaborative sensing approach that combines the strengths of the embedded sensor method and the impact-echo technique, the study offers a more comprehensive and reliable solution for evaluating the grout filling degree, which is critical for ensuring the structural integrity and safety of precast concrete buildings. The findings of this research can be valuable for practitioners, researchers, and policymakers in the precast concrete industry, helping to improve the quality control and construction practices for precast concrete structures.

2. Materials and Methods

2.1. Embedded Sensor Method

The embedded sensor method utilizes damped sensors to measure the vibration energy values. In this study, the ZBL-G1000 detector and SDA1003 damping vibration sensor from the Beijing ZBL Science and technology Co., Ltd. (Beijing, China) were used to detect the fullness of grouting. The principle is based on the damped vibration amplitude attenuation, wherein the sensor vibrates under the applied signal and experiences the effects of friction and medium resistance, causing the amplitude to decay over time. By analyzing the different vibration amplitude decay patterns, the surrounding medium environment of the sensor can be inferred, and the grout filling degree within the sleeve can be assessed.

According to the Chinese technical specification for inspection of sleeve grouting quality of precast concrete structures (T/CECS 683-2020) [27], the grout filling degree can be evaluated based on the following criteria: when the vibration energy value is more than

100, the grout filling is considered complete; when the vibration energy value is between 100 and 150, the grout filling is essentially complete; and when the vibration energy value is >150, the grout filling is incomplete.

The testing procedure for the embedded sensor method is illustrated in Figure 2. Figure 2a includes (1) weighing grouting material, (2) mixing grouting material, (3) sealing the lower end of the sleeve, (4) grouting, (5) testing, and (6) data acquisition. First, the damped sensor is inserted through the grout outlet, ensuring that the sensor reaches the bottom of the sleeve and is tightly sealed with a rubber plug. After the grouting is completed, the signal cable is connected to the instrument's sensor interface at one end, and the two clips are attached to the signal lines of the pre-embedded sensor within the tested sleeve. By clicking the sampling button or the sampling key on the main interface, the system automatically starts continuous sampling, and the waveform area displays the collected dynamic waveform. Upon completion of the sampling, the data are stored, and the next sleeve can be tested. This process is repeated until all the sleeves have been tested, and then the stop button is clicked.

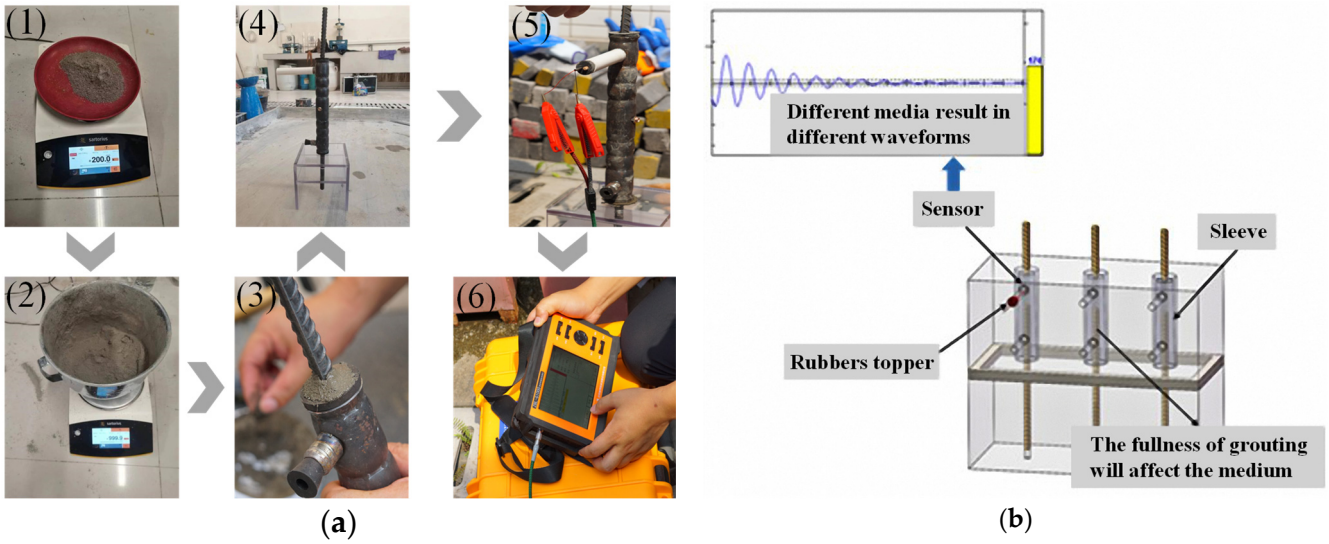


Figure 2. Process and schematic diagram of embedded sensor method testing: (**a**) testing flow, (**b**) schematic diagram.

2.2. Impact-Echo Technique

The impact-echo technique utilizes the principle of impact elastic wave propagation for testing. The test setup used in this study is shown in Figure 3. The detection instrument is the SRB-MATS-B multi-function rock anchor tester manufactured by Sichuan Sheng-Tuo (Chengdu, China), which is based on the impact elastic wave principle. The testing procedure involves using an impact hammer to strike the exposed reinforcement end at the center of the sleeve, generating an elastic wave. The sensor then records the elastic wave data, and through the analysis of the properties of the excitation and received signals (wave velocity, amplitude, and dominant frequency), the grout filling density within the sleeve can be qualitatively evaluated.

The testing procedure for the impact-echo technique is illustrated in Figure 4. The test requires the collaboration of two personnel. First, the sleeve is positioned on the fixture of the test bench to prevent the test component from shaking under external force during the test. A coupling agent is applied to the exposed reinforcement end of the sleeve, ensuring that the entire surface is not covered, leaving a portion exposed for manual excitation. The detection instrument is the SRB-MATS-B multi-function rock anchor tester manufactured by Sichuan Sheng-Tuo, which is based on the impact elastic wave principle. The detection instrument is composed of a signal receiver and a main instrument. The signal receiver (with a magnetic base) is then attached to the coupling agent surface, and the

receiver is connected to the main instrument. One of the personnel then gently strikes the reinforcement end with the impact hammer, while the other personnel monitors the data displayed on the instrument and adjusts the excitation force to obtain the optimal waveform. In this experiment, the optimal waveform is obtained with a specific quantification of the impact force measured at 12.15 N, corresponding to the impact force of a 50 g steel ball falling from a height of 30 cm. The distance between the excitation position and the sensor should be maintained at 0.02~0.03 m, and the instrument's sampling frequency should be set to 250 kHz. To ensure proper adhesion between the sensor and the contact element, the surface of the contact element should be polished prior to testing. The signal receiver is equipped with a magnetic base to prevent experimental errors caused by poor connection with the contact element.

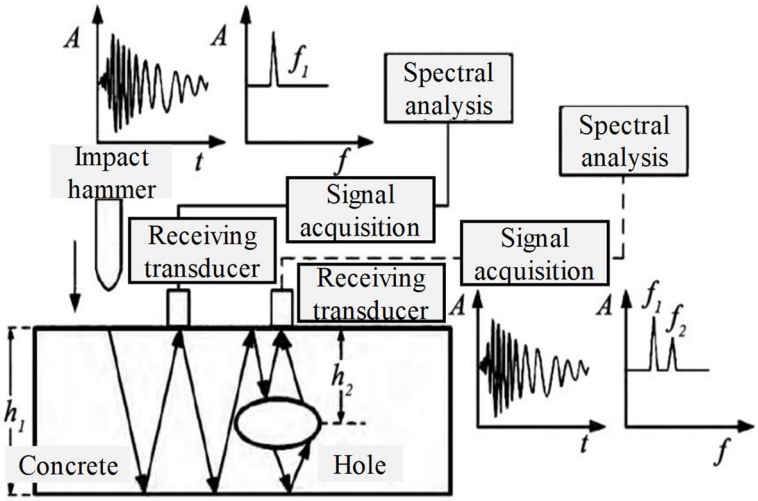


Figure 3. Impact-echo technique.

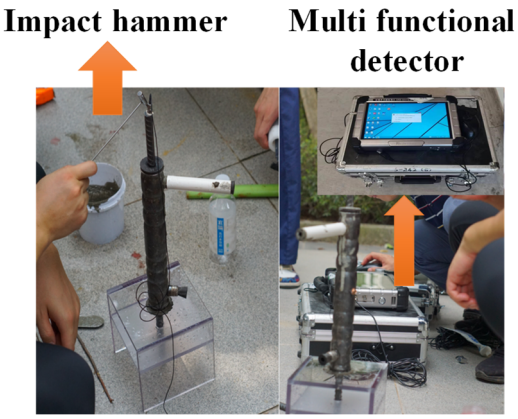


Figure 4. Schematic diagram of impact echo technique testing.

2.3. Experimental Model

The experimental model used in this study is shown in Figure 5, and it is composed of reinforcing steel, connection sleeves, cementitious grout, sealant, and a base. The red marker is the Grout stopper for Grout outlet. For the experiments, sleeves with different grout filling degrees were set up and used for testing. The grout filling degree is defined as the ratio of the actual grout volume within the sleeve to the maximum grout volume that can fill the sleeve completely, expressed as a percentage.

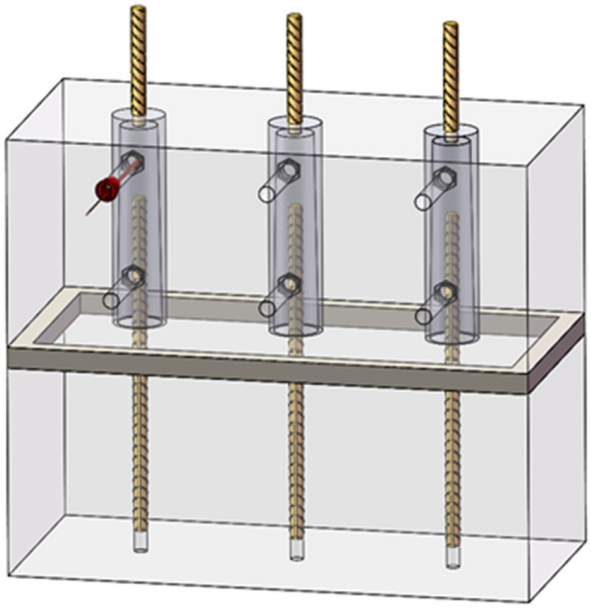


Figure 5. Experimental model for grouting quality of sleeve connection nodes.

Based on engineering experience, the grout filling degree of the sleeve is not only determined by the grout volume, but also influenced by the grout viscosity, grouting speed, sleeve diameter, and sleeve wall thickness. In this study, by referring to existing research and combining it with engineering practice, sleeve connection specimens with grout filling degrees of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% were fabricated in the laboratory to simulate the various grout filling scenarios [26,28].

2.4. Field Demonstration

The field demonstration of the proposed testing methods was conducted on a precast shear wall structure. The schematic diagram of the field demonstration is shown in Figure 6. The precast shear wall contains multiple sets of sleeve connections, with known sleeve configurations and volumes. The steps of the field demonstration are as follows:

(1) The sleeves were first flushed with high-pressure water to remove any residual debris;
(2) The grout and bedding mortar were prepared, and the bedding mortar was used to seal the bottom of the sleeves;
(3) The damped vibration sensors were installed at the grout outlets, and the grout filling degree testing instrument was used to ensure the proper functioning of the sensors;
(4) The grout was then pumped into each set of sleeves using a high-pressure grouting machine;
(5) After the grouting was completed, the grout filling degree testing instrument was used to measure the waveform and vibration energy values of the grouted sleeves.



Figure 6. Schematic diagram of field demonstration.

3. Results and Discussion

3.1. Pre-Embedded Sensor Method

The experimental results obtained using the pre-embedded sensor method for different grout filling degrees are shown in Figure 7. The analysis of the results reveals the following:

From the measured vibration energy values and waveform plots, it can be observed that as the set grout filling degree increases, the vibration energy values initially remain unchanged and then decrease. Similarly, the number of waveforms gradually decreases and the waveform amplitude becomes smaller. When the set grout filling degree is 100%, the vibration energy waveform trends towards a straight line, which is consistent with the current specification for evaluating the grout filling degree based on the vibration energy values.

When the set grout filling degree is less than 70%, the vibration energy values remain unchanged, essentially maintaining a value of 255, and do not accurately reflect the changes in the grout filling degree. This is due to the fact that in the pre-embedded sensor method, the core testing component, the damped vibration sensor, is exposed to the air and not completely covered by the grout. This indicates a limitation in using the vibration energy values from the pre-embedded sensor method to assess the grout filling degree.

When the set grout filling degree is between 70% and 100%, the vibration energy values decrease as the grout filling degree increases. This is because, in this range, the grout covers the damped vibration sensor first, and then a portion of the grout recedes, causing the measured vibration energy values to change accordingly. This suggests a correlation between the vibration energy values and the grout filling degree in this range. It is worth noting thar there is no linear relationship between grouting fullness and vibration energy value. When the set grout filling degree is between 70% and 100%, the relationship

between grouting fullness and vibration energy values in this study can be represented by Equation (1).

$$y = 0.0725x^2 - 14.175x + 810.75 \quad (1)$$

where y represents the vibration energy values and x represents the grouting fullness.

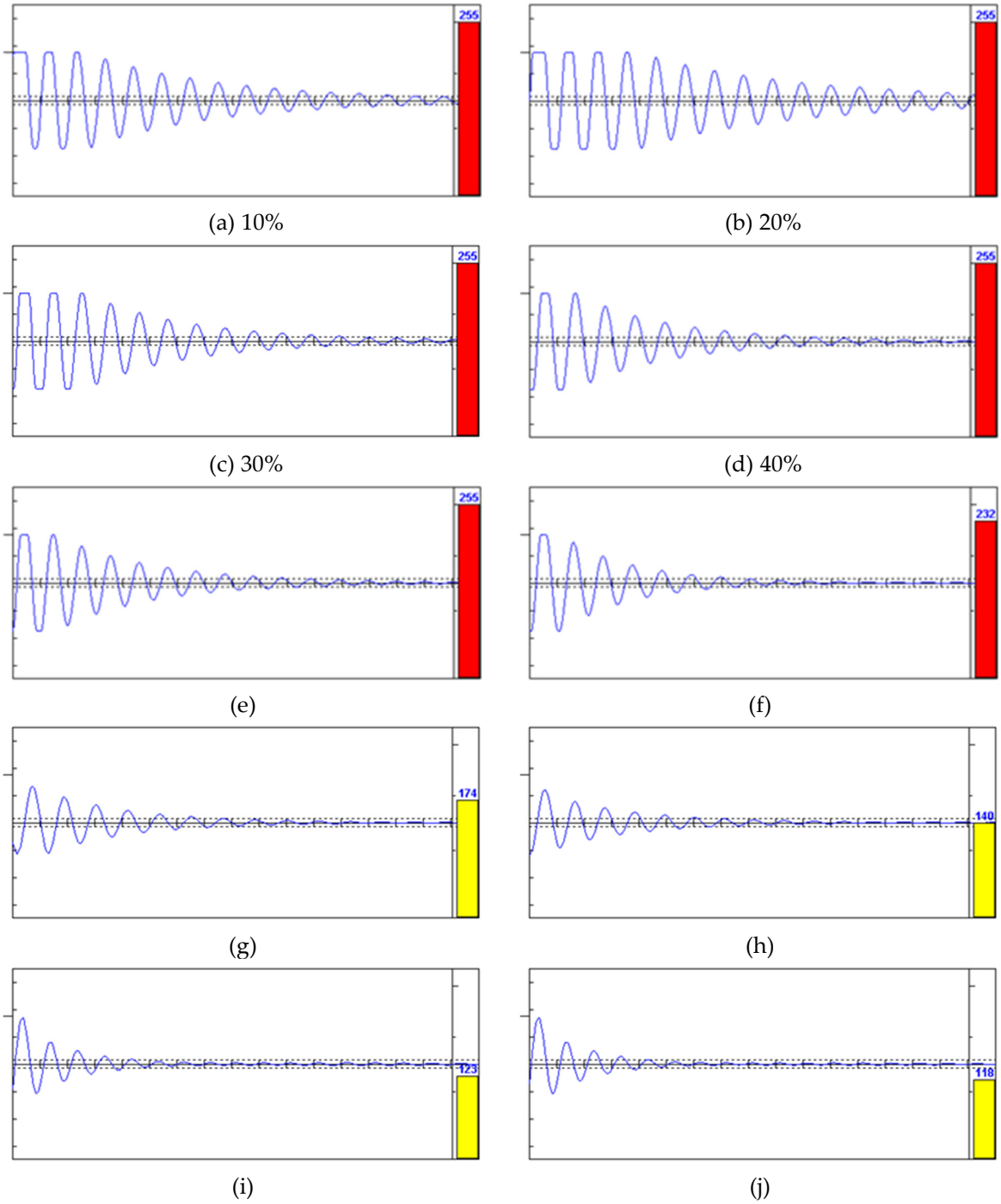


Figure 7. Test results of pre-embedded sensors under different grouting fullness: (**a**) 10%, (**b**) 20%, (**c**) 30%, (**d**) 40%, (**e**) 50%, (**f**) 60%, (**g**) 70%, (**h**) 80%, (**i**) 90%, (**j**) 100%.

3.2. Test Results of Impact-Echo Technique

The test results of the impact-echo technique for different grout filling degrees are shown in Figure 8. To ensure the accuracy of the experimental data, each set of grout filling degree was tested five times.

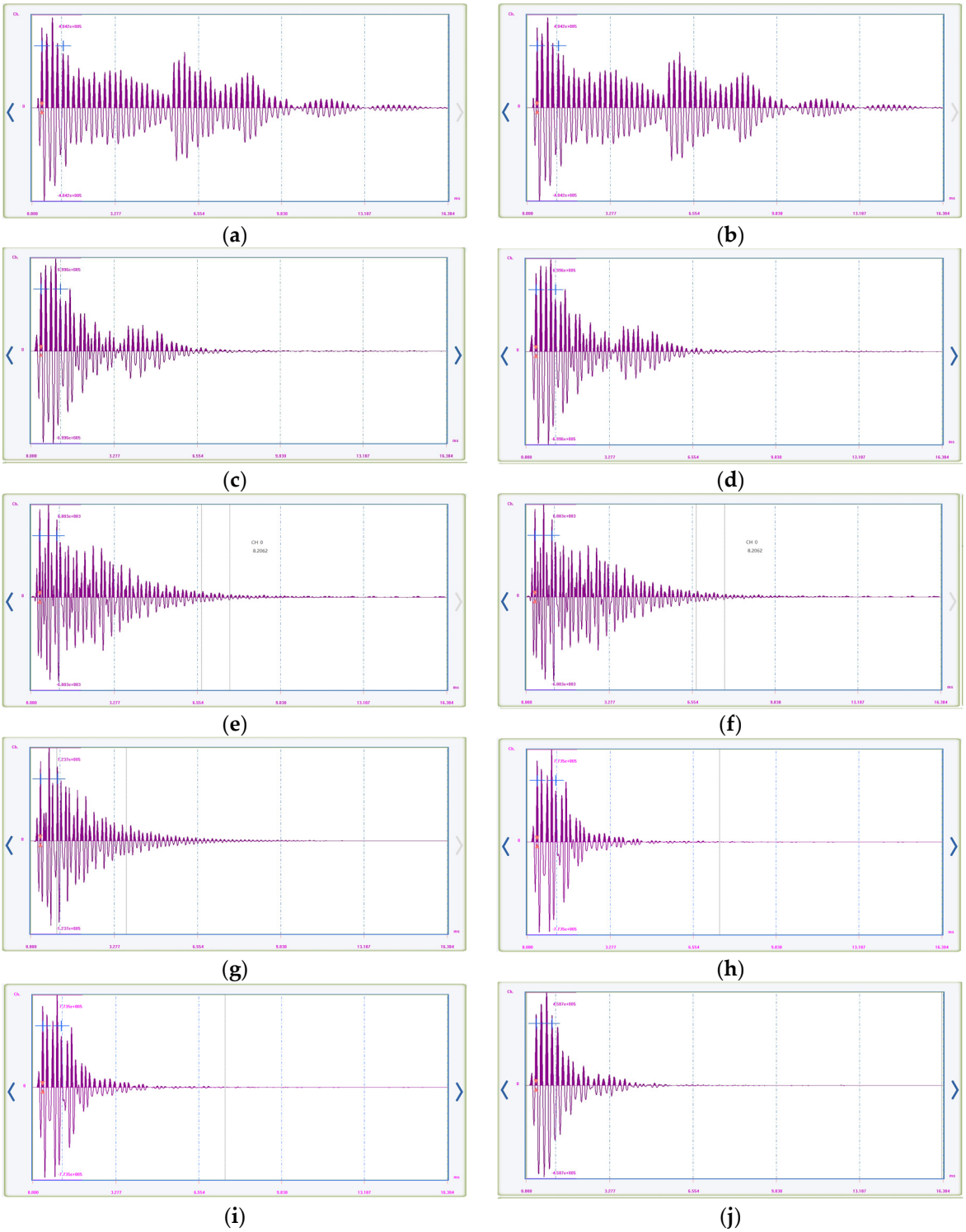


Figure 8. Test results of impact-echo technique under different grouting fullness: (**a**) 10%, (**b**) 20%, (**c**) 30%, (**d**) 40%, (**e**) 50%, (**f**) 60%, (**g**) 70%, (**h**) 80%, (**i**) 90%, (**j**) 100%.

The analysis of the results indicates that the reflected waveforms differ for different grout filling degrees. As the grout filling degree increases, the reflected waveforms received by the impact-echo detection instrument become stronger.

The experimental data obtained using the impact-echo technique are summarized in Table 1. The analysis of the data shows that the standard deviations of the measured filling degree results are relatively small (<2.5), indicating the stability of the test data and the absence of significant errors. Additionally, the percentage deviations of the test data are within 5%, which is an acceptable range, demonstrating that the measured data can accurately reflect the actual grout filling quality. This suggests that the impact-echo technique can reliably evaluate the grout filling degree in sleeve connections.

Table 1. Test results of impact-echo technique.

Fullness Setting Value/%	Fullness Detection Value/%	Average Value/%	Standard Deviation	Deviation/%
10	10 9 9 9 11	9.6	0.80	4.00
20	19 20 22 18 19	19.6	1.36	2.00
30	28 29 32 30 28	29.4	1.50	2.00
40	39 39 38 40 41	39.4	1.02	1.50
50	50 49 51 49 48	49.4	1.02	1.20
60	55 56 61 57 58	57.4	2.06	4.33
70	69 70 73 68 68	69.6	1.85	0.57
80	78 75 76 81 79	77.8	2.14	2.75

Table 1. *Cont.*

Fullness Setting Value/%	Fullness Detection Value/%	Average Value/%	Standard Deviation	Deviation/%
90	87 90 89 88 91	89	1.41	1.11
100	95 97 96 98 96	96.4	1.02	3.60

Note: Deviation = ((Detection value − Setting value)/Setting value) × 100%.

The impact-echo technique uses a multi-function rock anchor tester that is based on the principle of impact elastic wave propagation. When the stress wave encounters an interface with different acoustic impedance, it will be reflected, and the resonance phenomenon will cause changes in the surface displacement of the concrete. By placing receivers around the excitation point, the displacement signals can be collected and analyzed using the fast Fourier transform (FFT) to evaluate the internal defects and density of the structure [29–31].

The impact-echo technique has the advantages of high energy, strong penetration, convenient operation, and fast testing speed, making it particularly suitable for precast structures with single-sided access [32]. It also demonstrates a high accuracy in detecting the grout filling degree of both large and small diameter corrugated sleeves. In the field cases, under specific conditions, the impact-echo technique's results for the grout filling degree of large diameter corrugated sleeves were found to be consistent with the core sampling results.

3.3. Correlation Analysis

The analysis of the results from Sections 3.1 and 3.2 reveals that the vibration energy values obtained from the pre-embedded sensor method can reflect the grout filling quality within a certain range, while the density values measured by the impact-echo technique are highly correlated with the set grout filling degree.

Under field construction conditions, since the sleeves are pre-embedded in the concrete members, it is not possible to directly use the impact-echo technique for grout filling degree detection, as the excitation point can only be placed on the surface of the concrete member, and not on the exposed reinforcement ends. Therefore, this section explores the correlation between the grout filling degree and the vibration energy values obtained from the pre-embedded sensor method, which can help directly obtain the grout filling degree in the field construction environment using the pre-embedded sensor method.

To investigate the correlation between the vibration energy values obtained from the pre-embedded sensor method and the set grout filling degree, and to better reflect the relationship between the two, this study added three additional sets of grout filling degree experiments based on the pre-embedded sensor method test data, and the compiled test data are summarized in Table 2.

The fitting analysis of the data in Table 2 shows that the vibration energy values obtained from the pre-embedded sensors and the fullness values obtained from the impact-echo technique follow an exponential relationship, and the function relationship can be expressed as:

$$y' = 5978.5 \times \exp(-x/22.4) + 67.8 \quad (2)$$

where x is the vibration energy value ranging from 70% to 100%, and when $x < 70\%$, $y' = 255$.

As shown in Figure 9, the fitting curve has an R^2 value of 0.995, indicating a high degree of fit, which can be used to express the relationship between the vibration energy value and the set grout filling degree.

Table 2. Test results of pre-embedded sensors and impact-echo technique.

Pre-Embedded Sensors Vibration Energy Value (x)	Impact-Echo Technique Fullness Detection Value (y′)/%
255	<70
174	70
152	75
140	80
131	85
125	90
120	95
118	100

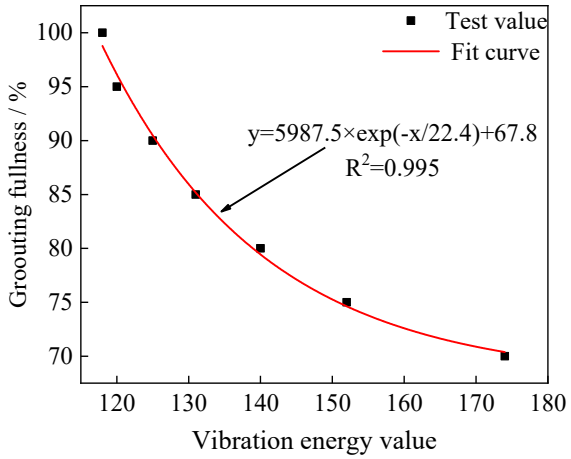


Figure 9. Fitting analysis of vibration energy value and grouting fullness.

Furthermore, since the density values measured by the impact-echo technique are essentially the same as the grout filling degree within the sleeve, i.e., $y' = y$, the function relationship derived in this section between the vibration energy values from the pre-embedded sensor method and the fullness values from the impact-echo technique can be used to represent the relationship between the vibration energy values and the grout filling degree within the sleeve.

3.4. Test Results of the Field Demonstration

To verify the accuracy of the function relationship between the vibration energy values and the grout filling degree, as fitted in Figure 9, for field experiments, this section conducted field tests using the pre-embedded sensor method to measure the grout filling degree after grouting. The precast shear wall used in the experiment contained multiple sets of sleeve connections. According to the design information of the shear wall, the internal structure and volume of the sleeves were known. The field experiment set the grout filling degrees at 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, and 100%, a total of nine test conditions.

To avoid deviations in the grout filling degree test results for each set of sleeve connections due to factors such as internal structure and residual debris, the grout filling degree detection instrument was used to test each set three times, and the average value was taken.

After the experiment, the grout filling degree was calculated based on the test results and the function relationship in Equation (1), using the vibration energy values. The set grout filling degree and the experimentally calculated values are shown in Figure 10.

The analysis of Figure 10 shows that in the field experiment, the grout filling degree calculated from the vibration energy values measured using the pre-embedded sensor method, through the fitted function in Equation (1), has a small deviation from the set grout filling degree and a high reliability. This also indicates that Equation (1) can be used to represent the relationship between the vibration energy values and the grout filling degree within the sleeve, i.e., the grout filling degree can be directly evaluated through the pre-embedded sensor method.

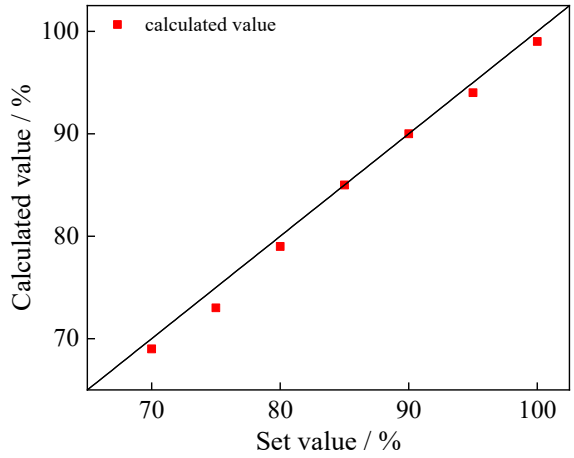


Figure 10. Deviation between set value and calculated value.

3.5. Comparison of Testing Methods

The pre-embedded sensor method and the impact-echo technique have their respective advantages and limitations in evaluating the grout filling degree of sleeve connections, as summarized in Table 3.

Table 3. Comparison of pre-embedded sensor method and impact-echo technique.

Characteristics	Pre-Embedded Sensor Method	Impact-Echo Technique
Principle	Vibration energy attenuation	Impact elastic wave propagation
Evaluation target	Vibration energy value	Density/Impedance
Applicability	Embedded sleeve	Exposed reinforcement end
Accessibility	Convenient, no special access required	Requires access to reinforcement end
Test duration	Short, continuous monitoring	Relatively longer, point-by-point testing
Accuracy	Limited at low filling degrees	High accuracy across filling degrees
Limitations	Air exposure of sensor, limited range	Requires access to reinforcement end

The pre-embedded sensor method has the advantage of convenient and continuous monitoring, as the sensors are pre-embedded in the sleeve and do not require special access for testing [33,34]. However, the method has limited accuracy in evaluating the grout filling degree, particularly when the filling degree is low, due to the air exposure of the sensor.

The impact-echo technique, on the other hand, demonstrates high accuracy in assessing the grout filling degree across different filling levels, as it is based on the principle of impact elastic wave propagation and can effectively detect the internal density/impedance changes [35–37]. However, the technique requires access to the exposed reinforcement ends for excitation, which may not be feasible in some field conditions.

To leverage the strengths of both testing methods and improve the overall accuracy of grout filling quality assessment, a collaborative sensing approach has been developed, as discussed in the following section.

3.6. Practical Guidelines for Implementation

Based on the findings from the laboratory experiments and the field demonstration, the following practical guidelines are provided for the implementation of the collaborative sensing approach in precast concrete construction projects:

(1) Pre-installation of embedded sensors:

During the prefabrication stage, install the damped vibration sensors at the grout outlets of the sleeve connections, ensuring that the sensors are properly sealed and integrated into the sleeve assembly.

Ensure the proper functioning of the pre-embedded sensors and the compatibility with the grout filling degree testing instrument. The grouting fullness detector is required to meet an amplitude linearity specification of within ± 1.0 dB for every 10.0 dB, with a frequency bandwidth between 10 kHz and 100 kHz. A damping vibration sensor should be utilized, ensuring that the diameter of the core component at the end does not exceed 10.0 mm, and the diameter of the steel wire connected to the core component is maintained between 2.0 mm and 3.0 mm. Additionally, the sensor and rubber plug should be designed as an integrated unit, with the diameter of the hole through which the steel wire passes matching the diameter of the steel wire, and the diameter of the exhaust hole being no less than 3.0 mm;

(2) Grout filling and testing procedure:

Flush the sleeves with high-pressure water to remove any residual debris before grouting.

Prepare the grout and bedding mortar, and use the bedding mortar to seal the bottom of the sleeves.

Connect the pre-embedded sensor signal cables to the grout filling degree testing instrument, and initiate the continuous monitoring of the vibration energy values during the grouting process.

After the grouting is completed, record the final vibration energy values for each sleeve connection;

(3) Collaborative data analysis:

Use the function relationship in Equation (1) to convert the vibration energy values from the pre-embedded sensor method into the corresponding grout filling degree values.

If access to the exposed reinforcement ends is available, conduct the impact-echo technique testing to obtain the density information and cross-validate the grout filling degree results.

Integrate the vibration energy-based grout filling degree and the impact-echo-based density information to establish the collaborative assessment of the grout filling quality;

(4) Quality assurance and decision-making:

Compare the collaborative assessment results with the specified grout filling degree requirements, as per the relevant technical specifications.

Identify any sleeve connections with inadequate grout filling and prioritize them for remedial actions, such as additional grouting or replacement.

Implement the collaborative sensing approach as a standard quality control procedure for precast concrete sleeve connections, ensuring consistent and reliable grout filling quality.

By following these practical guidelines, construction teams can effectively implement the collaborative sensing approach to enhance the assessment of grout filling quality in precast concrete sleeve connections, leading to improved structural integrity and long-term performance of the precast concrete structures.

4. Conclusions

This study developed a collaborative sensing approach that combines the pre-embedded sensor method and the impact-echo technique to enhance the accuracy of grout filling qual-

ity assessment for precast concrete sleeve connections. The key findings and conclusions drawn from the research are as follows:

(1) The pre-embedded sensor method, based on the principle of vibration energy attenuation, can provide continuous monitoring of the grout filling process. However, its accuracy is limited at low filling degrees due to the exposure of the sensor to air;
(2) The impact-echo technique, utilizing the principle of impact elastic wave propagation, demonstrates a high degree of accuracy in evaluating the grout filling degree across different filling levels. It can reliably detect the internal density and impedance changes within the sleeve connections;
(3) The collaborative sensing approach establishes a functional relationship between the vibration energy values obtained from the pre-embedded sensor method and the grout filling degree, thereby leveraging the strengths of both testing methods. This approach can provide a comprehensive and accurate assessment of the grout filling quality, even in field conditions where direct access to the reinforcement ends is not feasible;
(4) The field demonstration has validated the effectiveness of the collaborative sensing approach, with the calculated grout filling degree values closely matching the set values. This indicates the practical applicability of the proposed method in real-world precast concrete construction projects;
(5) Practical guidelines have been provided for the implementation of the collaborative sensing approach, including the pre-installation of embedded sensors, the grout filling and testing procedure, the collaborative data analysis, and the quality assurance and decision-making process. These guidelines can assist construction teams in the effective implementation of this approach in their projects.

The collaborative sensing approach developed in this study offers a reliable and comprehensive solution for assessing the grout filling quality in precast concrete sleeve connections, contributing to the overall structural integrity and performance of precast concrete structures. By integrating the strengths of both the pre-embedded sensor method and the impact-echo technique, this approach can overcome the limitations of each individual method and provide a robust and accurate evaluation of the grout filling quality.

Future research directions may include the investigation of advanced data analysis techniques, the exploration of wireless sensor integration, and the development of automated monitoring and decision-making frameworks to further streamline the implementation of the collaborative sensing approach in the construction industry.

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