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Feasibility of application of Non-Destructive Testing (NDT) methods to detect hidden damage in masonry structures

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Abstract: Due to their inherent structural characteristics, masonry structures are prone to hidden damage, such as voids. Hidden damage that accumulates over time poses a threat to the safety of the structure. Non-destructive testing (NDT) technology has gained popularity in the field of detection. NDT techniques are effective tools for detecting hidden damage in masonry structures. However, there is an incomplete understanding of hidden damage, and confusion still exists regarding the selection of suitable NDT method. Therefore, in this paper, the application and research directions of Non-Destructive Testing (NDT) in civil engineering at this stage are summarized through bibliometric analysis. It has been found that integrated methods and intelligent techniques are effective ways to detect hidden damage in masonry structures.

Keywords: masonry structure; non-destructive testing (NDT); bibliometric analysis; integrated testing methods; intelligence detection

1. Introduction

Masonry is one of the most commonly used building materials in the civil engineering sector worldwide. It is a conglomerate of several materials, such as brick or stone and mortar, each of which has different durability and resistance to external factors [1]. In China, masonry residential buildings, pagodas, city walls, and other masonry constructions have been widely distributed for several centuries throughout of history.

In primitive times, people used natural stones to build hiding places, and then gradually constructed castles, tombs, or temples. The three Great Pyramids were built in the Nile Delta at Giza between 2723 and 2563 BC, as shown in Figure 1(a). These are precise square pyramids, the largest of which is the Pyramid of Khufu. It has a height of 146.6 meters, a base length of 230.6 meters, and was constructed from 2.3 million blocks of stone, each weighing 2.5 tones. As the stone processing industry developed, the art and skill of stone masonry improved. The Roman Colosseum, built between 72 and 80 AD as shown in Figure 1(b), used block construction. The building's plan is oval, with a long axis of 189 meters and a short axis of 156.4 meters. The total height of the building is 48.5 meters, divided into four floors. It can accommodate an audience of 5 to 8 million people. The Potala Palace in Tibet, China, built in the seventh century, is shown in Figure 1(c). It covers an area of 4 million square meters, with a floor space of 1.3 million square meters. The main building, the Red Palace, is 115.703 meters high. Located at an altitude of 3700 meters on the Red Mountain, it holds significant cultural value. Throughout history, masonry structures have played a significant role in the transmission of human civilization, owing to their unique advantages.

Figure 1. Examples related to masonry structures. **(a)** The three Great Pyramids in Egypt. **(b)** The Roman Colosseum in Italy. **(c)** Potala Palace in China.

1.1. Feature of masonry

Brick masonry is a prevalent construction method that involves bricks (including porous bricks, with a porosity of at least 15%–30%) and mortar combined as a single unit. The brickwork should be staggered both vertically and horizontally, both inside and outside the lap masonry, to ensure the strength and integrity of the brickwork. Stone masonry is a solid material composed of stone and mortar, stone and mud, or stone and concrete. It is generally divided into stock, rubble, and concrete rubble masonry. Block masonry is a monolithic material made of blocks and mortar. It is primarily used as a load-bearing or enclosing wall in residential, office, school, and other civil or industrial buildings.

The advantages of masonry can be summarized as follows:

- **Easily accessible materials.** Clay, sand, and stone are the raw materials used to make bricks, mortar, and stone. They are a natural material, widely available, easy to source locally, and relatively inexpensive compared to building materials such as cement, steel, and wood.
- **Good fire resistance and durability.** In general, it can withstand nearly 400 °C. The masonry in a typical building is sufficient for the expected service life.
- **Arbitrary construction process.** Masonry does not require the use of molds and special construction equipment, which saves a significant amount of timber compared to concrete structures.
- **High usability.** It has good heat preservation, thermal insulation, and energy-saving properties.

However, it is a heterogeneous material constructed from units and joints. High specific mass, low tensile strength, shear strength, and ductility are the limitations of masonry structures [2]. These limitations mean that masonry walls are susceptible to damage over the years. Hence, it is essential to understand the condition of existing masonry through periodic testing and continuous monitoring, especially for heritage masonry.

1.2. Protective works on masonry

It is of great value for conservation work on existing buildings. Cultural heritage, especially, encompasses not only buildings with long histories but also plays a crucial role in supporting the economy. It generates substantial revenue through tourism by attracting tourists and providing livelihoods to various segments of society. Long-term environmental damage, the impact of crowds, and the passage of time can all degrade the ability of masonry to perform, which can affect its structural integrity. Due to the unique characteristics of masonry, various methods have been developed to evaluate the safety of existing masonry structures. These methods typically involve in-situ inspections, surveys, sampling, and testing. However, these methods can be resource- and labor-intensive. Long-term structural health monitoring (SHM) and periodic testing of critical areas are essential for heritage conservation. It has many successful applications in the preventive protection of masonry structures, as shown in Table 1. Ultrasonic testing, digital image processing, and infrared thermography *etc.* have become effective tools for assessing heritage buildings. Moreover, Structural Health Monitoring (SHM) systems monitor acceleration, displacement evolution, tensile stress, compressive stress, building material deterioration, humidity, temperature, *etc.* The collected data is subsequently harvested, transmitted, and deployed as input parameters in various computational methods to forecast structural damage and devise mitigation measures [3].

Table 1. A list of protective works on masonry.

	Project	Methods	Main conclusion	Reference
Detection	The National Stadium of Heraklion in Crete	● Digital Image Processing (DIP) ● Infrared Thermography (IRT) ● Ground Penetrating Radar (GPR) ● Ultrasonic testing	The use of innovative non-destructive techniques, validated in lab, and the acquired advanced scientific results, when integrated into tools like CAD and GIS have major contribution to the preservation and management of built cultural heritage, leading to its sustainable development.	[4]
	Malatya Tashoran Church	● Schmidt hummer testing ● Ultrasonic pulse velocity ● Infrared thermography (IRT) test	NDT procedures can be used for determining the elastic properties of masonry structure.	[5]

Table 1. *Cont.*

	Project	Methods	Main conclusion	Reference
	Nossa Senhora do Rosario dos Pretos Church	● Ultrasonic Testing	Ultrasonic tests can be applied for characterizing wall homogeneity, offering useful information for control of maintenance or retrofitting measures.	[6]
	Santa Croce in Italy	● Infrared thermography (IRT)	Active thermography is able to highlight the different behaviours and moisture contents of a wall.	[7]
	Vleeshuis Museum in Belgium	● Infrared thermography (IRT) ● Nuclear magnetic resonance (NMR) ● Holographic radar ● Ultrasonic	Proposed an indirect monitoring methodology aimed at evaluating the masonry thermal performance and its variation according to moisture distribution.	[8]
	Kaiyuan pagoda in China	● Ambient vibration test	Proposed a new arrangement scheme of spatial measuring points (Co-parallel test) to effectively measure the translational and torsional modal components of the pagoda.	[9]
Monitoring	the Town Hall in in Rieti	● Accelerometers ● Temperature	Observed in the statistical correlations between frequencies and temperature.	[10]
	Santa Croce in Italy	● Materials' characterization ● Soil and underground water characterization ● Monitoring of moisture in the walls ● Monitoring of climatic data, and air monitoring inside the building	Provided reliable and quantitative results on the "health state" of the buildings under investigation and proposed the superficial nature of the groundwater, owing to the long-term soil subsidence and consequent lowering of the structure.	[11]
	the Mogadouro clock tower in Portugal	● Accelerometers ● Temperature ● Humidity	Temperature variations affect a masonry structure's static and dynamic behavior because they induce changes in the stress field and in the crack distribution over the structure.	[12]
	The Candia Bridge in Italy	● Tiltmeters ● Temperature	The difficulties in detecting scour induced effects from the measure of pier rotations on masonry arch bridges.	[13]
	Potala Place in China	● Displacement	Proposed an improved outlier identification algorithm based on density to improve the quality of monitoring data cleaning.	[14]

This paper reviews developments in the field of nondestructive testing technology. First part, it is used to understand the NDT methods for masonry structures and to analyze the research directions in bibliometric analysis. Second part identifies commonly used non-destructive testing methods for masonry walls and summarizes their applications, shortcomings, and points of improvement, respectively. The present study provides a comprehensive overview of NDT methods for masonry structures, laying the groundwork for more in-depth reviews by future researchers.

1.3. Bibliometric analysis of NDT masonry

Bibliometric analysis was initially introduced by Alan Pritchard in 1989 [15]. Since then, it has garnered increased attention, especially due to advancements in evidence-based science, the widespread use of computers, the accessibility of the internet, and the availability of bibliometric software (e.g., VOSviewer, CiteSpace, and Biblioshiny) [16]. Excellent progress has also been made in the development of scientific databases that can be used in conjunction with bibliometric software packages, such as Web of Science, Scopus, and PubMed. Bibliometrics analyze databases, and the statistical data is used to demonstrate the distribution of contributions, hotspots, and predicted trends. Bibliometrics, as an essential analytical tool, aids in examining researchers' findings and their alignment with broader areas of scholarship and knowledge. CiteSpace is a bibliometric data analysis and visualization software. The software enables the localization of knowledge domains by analyzing bibliographic archives collected from specific databases. It generates and visualizes co-occurrence network graphs of co-authors, keywords, and co-citation networks of cited authors. To identify the hot topics and trends in heritage masonry, the keywords related to NDT were evaluated using science mapping. The analysis included the yearly publication trends, the most important institutions and authors, the countries/regions of co-authorship, and the keywords.

The search was conducted in the Web of Science (WOS) database to identify the relevant publications. WOS is widely praised for being the largest and most comprehensive literature database [17]. The first step was formulating the research questions and identifying the goals of the review. The review goal is to analyze research trends to the utilization of NDT in masonry structure to spot the research gaps and identify future research needs. Then, the search inquiry was set up after an extensive screening of literature available on using NDT in masonry. The unconstrained search returned a vast amount of literature, composing 3907 pieces of publications, about NDT methods.

The keyword search method was used to summarize research spanning from 2000 to 2022 using the Web of Science (WOS). The keywords are presented in Table 2, and science mapping was conducted using CiteSpace to gain a comprehensively understanding of the research progress. The number of publications searched by Web of Science (WOS) is 3907, mostly about construction buildings. It can be observed that the number of publications is relatively higher for quantitative NDT techniques. Hence, this emphasizes that the conservation of heritage is on the rise, and newer NDT techniques are being discovered. In Figure 2, the number of publications about non-destructive testing (NDT) in masonry structures per year shows an upward trend, with the maximum number reaching 498 in 2021. In 2022, there is a downward trend in the number of relevant studies. Figure 3 shows the number of publications per country. Italy is the most researched country in the field of non-destructive masonry conservation from 2000 to 2022, with a total of 769 publications, accounting for 19.68% of the database. The USA is the second most researched country with 466 publications, representing 11.93% of the database, and China ranks third with 436 publications, accounting for 11.16% of the database. It is related to the historical origin of the regions. Italy has a large number of masonry structures, and much of its cultural heritage is related to these structures. In essence, research on non-destructive testing (NDT) of heritage masonry is closely linked to the local cultural context and the level of development.

Figure 4(a) and (b) illustrates the author relations in this field. Lourenço PB in Portugal, Roca P in Italy, and Milani G in Italy are the top influential scholars.

Table 2. Queries used for categories number of publications obtained in WOS.

Category	Query	Publications (2000–2022)
NDT method	“masonry structure” OR ‘‘heritage masonry” OR ‘‘historic masonry” AND ‘‘non-destructive method” OR ‘‘NDT” OR ‘‘non-destructive”	3907
Infrared Thermography Technology (IRT)	“masonry structure” OR ‘‘heritage masonry” OR ‘‘historic masonry” AND ‘‘infrared thermography” OR ‘‘IR technique” OR ‘‘IR thermography” OR‘‘IR”	1290
Ground-Penetrating Radar (GPR)	“masonry structure” OR ‘‘heritage masonry” OR ‘‘historic masonry” AND ‘‘Ground-Penetrating Radar” OR ‘‘GPR”	1068
Ultrasonic Testing (UT)	“masonry structure” OR ‘‘heritage masonry” OR ‘‘historic masonry” AND ‘‘Ultrasonic Testing” OR ‘‘UT”	932
Acoustic Emission (AE)	“masonry structure” OR ‘‘heritage masonry” OR ‘‘historic masonry” AND ‘‘Acoustic Emission” OR ‘‘AE”	698

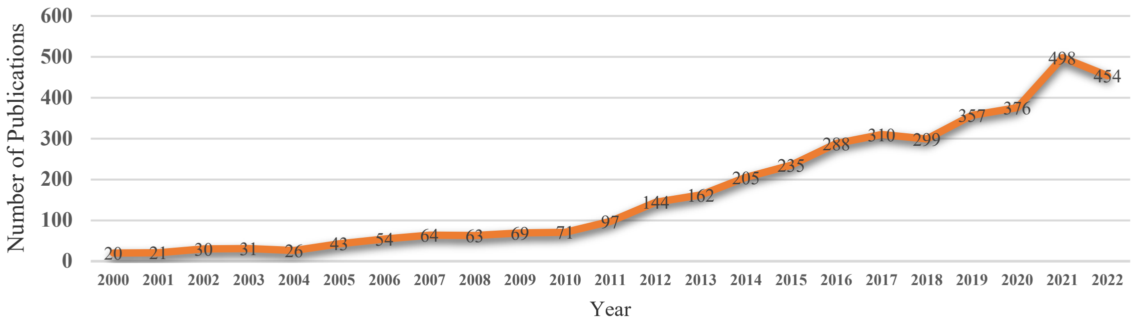
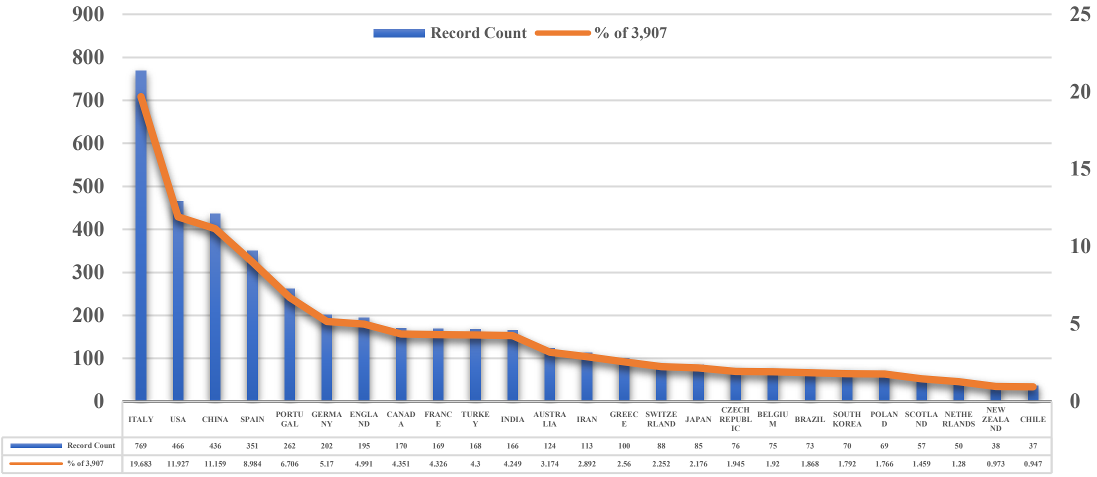


Figure 2. Number of publications per year. Period span from 2000 to 2022 (Source: Prepared by the authors using Wos data).



	ITALY	USA	CHINA	SPAIN	PORTUGAL	GERMANY	ENGLAND	CANADA	FRANCE	TURKEY	INDIA	AUSTRALIA
Record Count	769	466	436	351	262	202	195	170	169	168	166	124
% of 3,907	19.683	11.927	11.159	8.984	6.706	5.17	4.991	4.351	4.326	4.3	4.249	3.174

	IRAN	GREECE	SWITZERLAND	JAPAN	CZECH REPUBLIC	BELGIUM	BRAZIL	SOUTH KOREA	POLAND	SCOTLAND	NETHERLANDS	NEW ZEALAND	CHILE
Record Count	113	100	88	85	76	75	73	70	69	57	50	38	37
% of 3,907	2.892	2.56	2.252	2.176	1.945	1.92	1.868	1.792	1.766	1.459	1.28	0.973	0.947

Figure 3. Number of publications per country. Period span from 2000 to 2022 (Source: Prepared by the authors using Wos data).

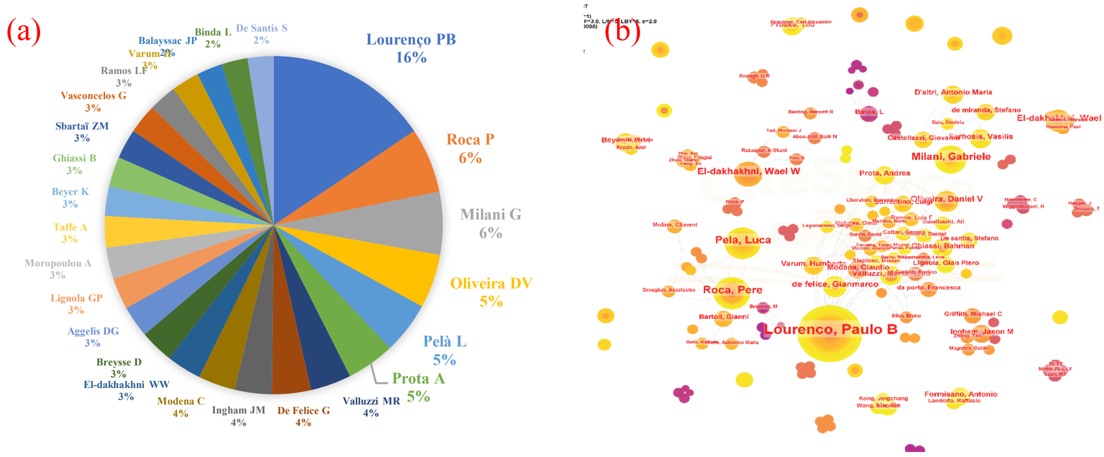


Figure 4. Author relations. Period span from 2000 to 2022 (Source: Prepared by the authors using Wos data). **(a)** Percentage of authors' studies. **(b)** Relations of authors.

Keywords from the analyzed articles were examined using VOSviewer to create a co-occurrence map and determine the main research directions through keyword clustering. Figure 5 displays the most frequent keywords and the co-occurrence network of keywords over a 22-year time span (2000–2022). The size of the circles indicates the importance of the relevant topics. It is divided into four clusters. The first cluster is the most common methods in NDT of masonry structures. Acoustic emission, ultrasonic pulse velocity, infrared thermography, ground-penetrating radar are the most frequently used methods. The second cluster is seismic performance analysis of structures with damage. The third cluster is finite element methods with damage. The fourth cluster is behavior analysis with damage.

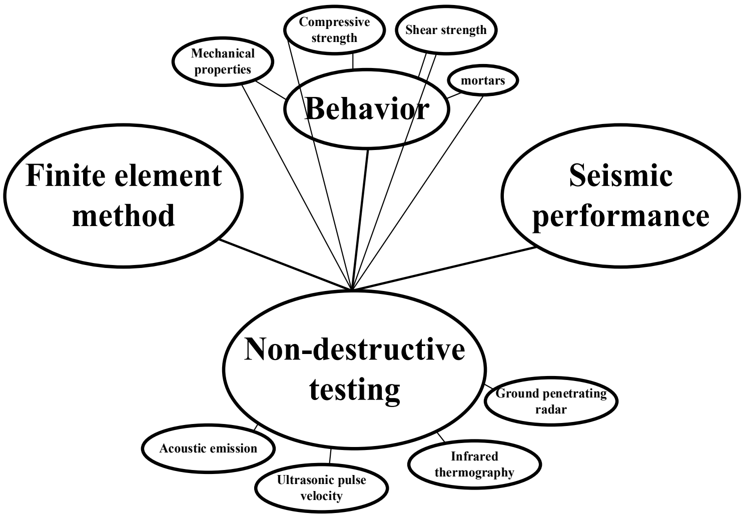


Figure 5. Connections between keywords. Period span from 2000 to 2022 (Source: Prepared by the authors using Wos data).

Figure 6 presents the results of the temporal analysis of the most occurred keywords conducted using VOSviewer. The mapping of the keywords represents their co-occurrence. Seismic vulnerability, compressive strength of concrete and masonry, and structural health monitoring are the four clusters in CiteSpace. Keywords (30%) were found to be predominantly used in 2000–2010, including NDT methods, seismic performance analysis and compressive performance. The use of these keywords declined after 2010, and tended to structure performance with damage. Since 2020, detection entered an intelligent stage. These keywords indicate a research trend in automating the inspection of masonry structure using NDT. These keywords include automation and robotics. Also, it includes machine learning, learning systems, deep learning, neural networks, and convolutional neural networks. Detection methods range from the simple determination of mechanical property parameters to the use of algorithms such as deep learning to predict damage. This approach facilitates intelligent detection.

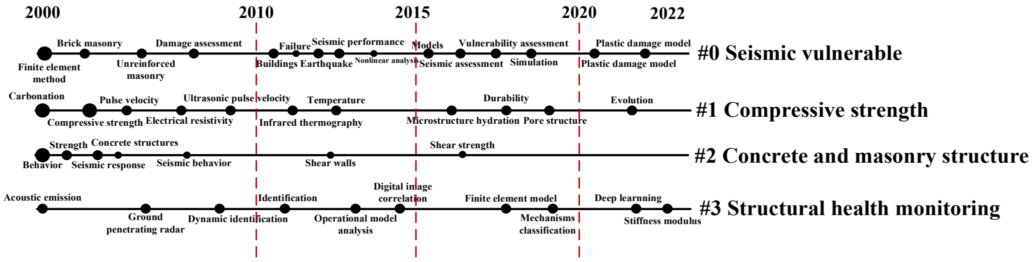


Figure 6. Keyword cluster analysis timeline display. Period span from 2000 to 2022 (Source: Prepared by the authors using Wos data).

In a word, Performance analysis with damage is the basis for a comprehensive assessment of the condition of the structure. Inspection, monitoring integration and performance analysis are inseparable and form the basis for lifetime performance analysis of structures. The advent of intelligent algorithms has accelerated the progress of specific research. Acoustic emission, ground-penetrating radar, infrared thermography, and ultrasonic pulse velocity are the most frequently used detection methods in masonry structure. Acoustic emission represents active detection, while the remaining techniques are classified as passive.

The keywords were used for leaning about AE, IRT, UPV, GPR, shown in Table 2. This study analysed the research on the use of NDT methods for masonry structures using the number of publications in Table 2.

Figure 7 illustrates the number of publications per year from 2000 to 2022. It is divided into three periods of growing trends: (i) Initial stage, 2000–2010; (ii) Fast development stage, 2010–2019; (iii) Plateau, 2019–2022. All non-destructive testing (NDT) methods have shown a downward trend in 2022.

- Initial Stage (2000–2009)

During this period, damage detection methods during this period were primarily used for qualitative studies.

- Fast Development Stage (2010–2018)

There is a tendency to quantify the damage to masonry structures.

- Plateau (2019–2022)

It is an intelligent detection stage. NDT is used not only to quantify damage but also to assess structural performance and condition with the assistance of artificial intelligence (AI).

The infrared thermography technology has a wide range of applications, and the number publications on IRT, GPR, UPV exceed than that of other NDT methods. Acoustic emission has relatively few applications. Thus, this paper focuses on three passive detection methods, like IRT, UPV, GPR.

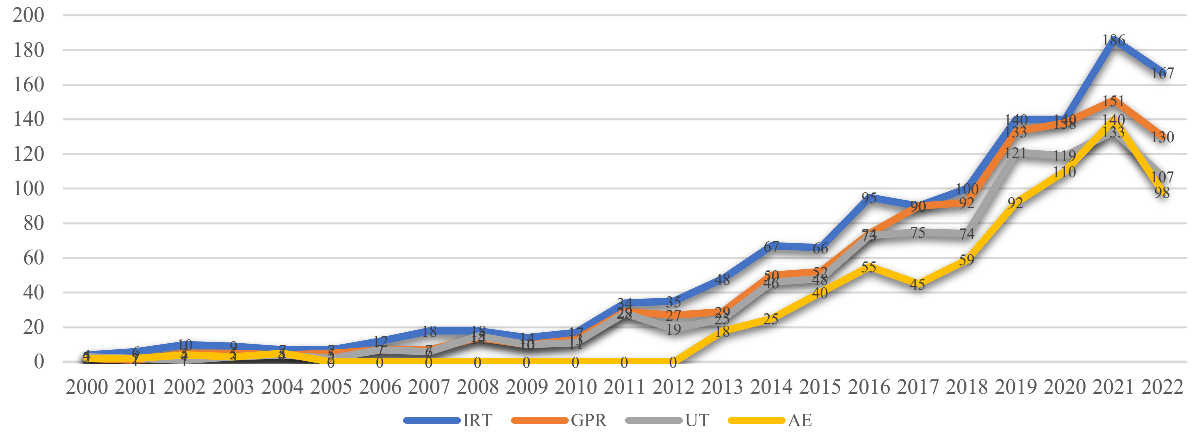


Figure 7. Number of publications per year of each NDT method period 2000 to 2022. (Source: Prepared by the authors using Wos data).

Bibliometric analysis can only identify the most commonly used NDT methods for masonry structures and determine the general direction of research. Therefore, it is of great value for conducting a comprehensive systematic review to gain a deeper comprehension of the employment of GPR, IRT and UPV in detection of masonry structure.

2. Ground-Penetrating Radar (GPR)

Ground-Penetrating Radar (GPR) is a representative of high-resolution non-destructive technology based on electromagnetic waves [18]. It uses high-frequency electromagnetic waves to determine the distribution of damage patterns on the target object, based on the reflection and scattering at its discontinuous locations. The GPR system consists of a transmitting antenna, a receiving antenna, and a control and processing unit. An electromagnetic wave is emitted with a central frequency ranging from 1 MHz to 10 GHz through the transmitting antenna [19]. The wave then interacts with the air, targets the object, and propagates. Since the propagation follows Fermat's principle and Snell's law, reflection and refraction occur when it encounters the damage [20]. Then, it is received by the receiving antenna. Finally, analyze the received signal to achieve the detection goal.

During inspection, GPR signals are affected by various noises, which significantly affect the inspection results.

Time series analysis is a commonly tool for the denoising the signals. Frequency filtering [21], matched filtering [22], wavelet analysis [23], neural network [24], empirical mode decomposition (EMD) and singular value decomposition (SVD) are commonly used to attenuate the effect of noise on the signal. Liu *et al.* [25] proposed a random noise and direct wave eliminating method for GPR signal using SVD. It can recover the GPR profile and eliminate random noise and direct wave by choosing the appropriate singular values. This type of algorithm can reduce the clutter and noise in the GPR image, thereby reducing the signal-to-noise ratio. Li *et al.* [26] employed the fractal dimension to quantify the complexity and irregularity of distinct signal components, and proposed an integrated approach that combines FastICA with negative entropy maximization, which is used to further process and separate the signal components. However, due to the attenuation and dispersion of the underground medium, the echo of ground-penetrating radar is a non-stationary signal, which presents significant challenges for GPR detection using time series analysis.

Time-frequency analysis is an effective tool for the analysis of non-stationary signals. It includes the short time Fourier transform (STFT), Wigner-Ville distribution (WVD), wavelet transform and S transform. These have been widely applied to GPR signals. Santos *et al.* [27] extracted features from GPR using power spectral density (PSD), short-time Fourier transform (STFT) and Wigner-Ville distribution (WVD) methods. These algorithms provided a small contrast between the types of real materials. Among the aforementioned methods, S transform represents a synthesis of the strengths of the STFT and wavelet transform. It is a particularly promising approach for the analysis of non-stationary signals. However, S transform is susceptible to the issue of poor energy concentration in certain applications due to the fixed Gaussian window function, which ultimately results in a decline in performance. In order to overcome the defect of the S transform, researchers have proposed the implementation of alternative generalized S transforms, which entail modifications to the window function. Cai [28] proposed a method based on the generalized S transform to de-noise MT data. It is used to improve the time-frequency localization of the different signal components. Xue *et al.* [29] proposed a new generalized S transform with parameters optimization to analyze GPR signal. It can enhance energy concentration in time-frequency domain and improve the profile resolution of subsurface layer effectively. However, achieving optimal results in practical applications remains a challenge due to the difficulty of extracting anomalies from complex background.

With the advances in computer technology and digital signal processing, machine and deep learning have been employed to detect major pavement anomalies using GPR. Nuaimy *et al.* [30] combined neural network, signal and image processing techniques. The system provided a high-resolution image of the subsurface in near real-time, thus facilitating straightforward data interpretation and accurate depth and azimuth location information. To recognize GPR records automatically, Szymczyk *et al.* [31] focused on a new kind of neural networks-the Laplace transform artificial neural networks. The complex manual processes are the main obstacles. The combination of GPR and deep learning algorithm may provide an effective method of detection. Li *et al.* [32] used the state-of-the-art machine learning method XGBoost with Bayesian hyper-parameter optimization (BHPO) method to build the model. It achieved higher accuracy and less time cost for recognizing moisture damage.

Deep learning models have been widely applied in detecting cracks. *Tong et al.* [33] employed CNN to provide appropriate models for the automatic recognition, location, length measurement, and 3D reconstruction of concealed cracks. Furthermore, to gain more accurate results, more advanced deep learning model, like CNN features (R-CNN), Fast R-CNN, Faster R-CNN, and RepPoints, appeared with the rapid development of deep learning technologies. These methods have high accuracy, low detection speed. You Only Look Once (YOLO), Single Shot MultiBox Detector (SSD), RetinaNet and CenterNet accelerate the speed of object detection by simplifying detection processes. Li *et al.* [34] employed the YOLO series to detect concealed cracks combined with GPR. However, Insufficient data sets is an obstacle in automatic GPR data processing. The combination of experience and simulation results can expend the training data set. Li *et al.* [35] proposed a GPR subsurface distress recognition model based on deep learning and signal processing, using data set that combined the experience and simulation. Xiong *et al.* [36] compared to using the YOLOv3 or U-net model alone, to achieve a more accurate estimation of the buried depth of internal istress.

In a word, deep learning as a promising technology in the field of target detection.

In summary, signal processing of GPR as well as automatic damage identification are currently more popular research topics. The construction of masonry structure is random and complex. This poses a challenge to detection accuracy.

3. Infrared Thermography (IRT)

Infrared Thermography technology (IRT) is one of the most widely used, studied, and well-developed NDT methods in the world [37]. It can be classified as active and passive according to the method of excitation. The active method is similar to the visible light imaging process. It involves applying artificial excitation to the object being measured, followed by using an infrared receiver to capture an image of the object. The passive method does not require any external excitation; it utilizes the infrared light emitted by the object for measurement [38]. The operations of IRT are based on the theory of thermal radiation. All objects in nature that have an absolute temperature above zero (-273 °C) constantly emit radiant energy into the surrounding space and the masonry structure. Temperature affects the infrared radiation properties of an object, enabling accurate damage assessment by measuring the object's radiated infrared energy. Infrared radiation is a form of electromagnetic radiation with wavelengths ranging from 0.75 μm to 1 mm, situated between microwaves and visible light.

Infrared thermal imaging technology employs the thermal radiation characteristics of objects to ascertain the temperature distribution on surface. This information is then visualized through the use of an infrared thermal imager to achieve target recognition and analysis. With the advancement of digital image processing and machine learning technology, automatically detecting cracks is possible by combining engineering and computer science knowledge. Image processing techniques can be applied to thermal images to automatically near-surface defects in concrete structures. Segmentation typically divides an image into a number of sub-regions or objects. Huang *et al.* [39] employed initial curves with implicit representations to automatically locate the level boundaries according to pre-selected level values. Omar *et al.* [40] used image analysis based on the k-means clustering technique to segment the mosaic and identify objective thresholds. Furthermore, the application of segmentation deep learning networks in the infrared thermal image NDT is a noteworthy direction. Luo *et al.* [41] applied deep cross learning strategy based segmentation models to detect detection of composite materials. It is resulted that cross learning strategy of VGG-Unet can basically reach the better performance in the spatial-oriented model.

It is preferred by researchers to detect the cracks with infrared thermal imaging based on deep learning. The deep learning (DL) based approaches are comprehensively superior to the machine learning based methods in terms of accuracy and speed. Puliti *et al.* [42] considered the multiple shapes and sizes of building, and obtained the digital 3D model from IR images used as input for the SFM algorithm. Liu *et al.* [43] applied deep learning and infrared thermography to classify asphalt pavement crack severity. EfficientNet-B3 had the highest accuracy on all three types of images for both deep learning from scratch and transfer learning. They also [44] applied infrared thermography and deep leaning for multiple-type distress detection in asphalt concrete pavement. Four CNN object detection models underwent evaluation on the dataset, employing transfer learning, and were assessed based on accuracy, complexity, and memory usage. it is resulted that fusion images could emerge as an accurate, efficient, and reliable alternative solution.

The deep leaning method is data-demanding and requires a large amount of high-quality data to train the neural network. Therefore, a dataset for crack segmentation in masonry structures is urgently desired. Deep leaning models are becoming increasingly complex, which necessitates large datasets to avoid overfitting. To solve this conflict, transfer learning (TL) emerges as an appropriate solution. Huang *et al.* [45] built a medium-sized pixel-labeled dataset of masonry structure cracks, including five types of images: RGB, IR, fused, RGB_T, and RGB_IR. The RGB_IR image exhibited superior performance across almost all networks and performs slightly below the Fused image in the commonly used TL training strategy.

IRT has the advantages of being convenient, fast, and non-destructive in assessing in thermal defects and heat loss in the building envelope. However, hand-held IRT has limitations for inspecting high-rise building facades, roofs, building cluster, or larger areas. The development of small, lightweight sensors has been significantly advanced by the rapid advances in microelectronics and microelectromechanical systems (MEMS). This has enabled the use of airborne IRTs in safer and more flexible Unmanned Aerial Vehicles (UAVs). UAV-IRT improves the resolution of thermal infrared images and the accuracy of temperature measurements [46]. To address registering thermal images into BIM, Zhang *et al.* [47] proposed a new multi-source image fusion framework. It is resulted that proposed framework can accurately register and map thermal images onto as-is BIM to obtain a thermal textured BIM.

Deep learning models have made progress in the intelligent recognition of diseases by infrared thermal imaging. However, the differences in the wavelength range, resolution, thermal sensitivity, temperature measurement range, and imaging mode of infrared thermography hardware devices present a challenge to the collection of small-scale real data sets, which in turn hinders the technological development in this field. Consequently, it is imperative to devise methodologies for enhancing infrared thermography data, with the objective of enhancing the quality, diversity, and scale of infrared thermography datasets. This entails optimizing the pre-training model and developing an intelligent recognition method for infrared thermography data enhancement, with the aim of improving the accuracy and generality of the model.

4. Ultrasonic Pulse Velocity (UPV)

Ultrasound is a mechanical wave that propagates mechanical vibrations in an elastic medium. In terms of frequency and human perception, sound waves are divided into infrasonic waves, audible waves, ultrasonic waves, and lattice vibrations [48]. When the ultrasonic wave propagates through an object, it can generate reflection, diffraction, and scattering waves, thereby facilitating the inspection process. Ultrasonic Pulse Velocity (UPV) is a popular method for assessing the condition of masonry in the built environment and evaluating the effectiveness of ground injection [49]. The propagation of ultrasonic waves in a solid structure can be influenced by the presence of cracks or voids, and the scattering characteristics of the waves can be utilized to pinpoint the defects.

The ultrasonic pulse velocity test is used to analyze the uniformity of masonry, determine the depth of cracks, and detect any internal cavities.

UPV method in assessing the mechanical properties of concrete, masonry, and other building stones. It has been widely investigated for the non-destructive estimation. It has been mainly reported to predict the compressive strength of materials through linear regression analysis using few parameters. Ultrasonic velocity can be very useful to study the homogeneity and the quality of steel fiber reinforced concrete and it is an effective way for the assessment of the consolidation level during and after the curing period [50]. Furthermore, the ultrasonic method is reliable for initial and final setting determination, provided that a simultaneous measurement of P-wave and S-wave velocity. P-wave propagation is less sensitive to setting process than S-waves since setting is related to shear modulus and E-modulus, which are in term related to V_S, whereas V_p is the result of the building of bulk modulus, most of which develops before final setting [51]. Carrillo *et al.* [52] proposed empirical relationships for estimating the dynamic modulus of elasticity and Poisson's ratio of concrete reinforced with steel, synthetic and hybrid fibers, using results measured during the UPV test. Sarkar *et al.* [53] measured the parallel and normal to the bed joint and parallel to the wall thickness directions, conducted compressive and flexural strength tests after the UPV testing. The material properties determined from the UPV testing can be incorporated in finite element (FE) modelling to provide an acceptable prediction on the structural performance of full-scale masonry buildings. Mata *et al.* [54] proposed a new correlation method based on probability interpretations to infer the compressive concrete strength from in-situ UPV measurements. It is possible to determine the confidence interval for the concrete compressive strength given a certain percentile of the UPV measured in situ. Kozubal *et al.* [55] implemented deep leaning to build an error removal method and UPV universal detection mechanism without human interference. Based on this, it is described the multivariate correlations of unconfined compressive strength with material UPV, maturation time and cement content.

Although changes in the material properties of the test object can be known by UPV. The current level of automation and intelligence in detection and the consideration of various types of distress is still insufficient.

5. Discussion

GPR, IRT, and UPV has their own advantages and limitations in masonry structures. However, complex wall environments may introduce various sources of interference, and all three methods are affected by environmental factors, but infrared thermography is more sensitive to the effects of the external environment. This requires that the raw data collected needs to be processed in a complex manner to extract relevant information about the damage. This requires expertise and experience.

The key to detecting internal defects by GPR is the extraction, analysis and processing of echo features from GPR images. Image processing of GPR remains a challenge. Future research should focus on improving the efficiency of automatic identification of large numbers of ground-penetrating radar images and the accurate classification of defects.

Infrared thermography can quickly scan large areas of masonry structures in a short period of time. It can be implemented to capture surface temperature changes to detect anomalous areas such as cold and hot spots. It is particularly suitable for detecting damage to shallow surfaces. However, environmental factors, such as weather and solar radiation, may affect thermal imaging results, which will require calibration and compensation. Although infrared thermography is suitable for surface damage detection, it may reduce sensitivity to deeper damage. The application of deep learning to infrared thermography enables the intelligent recognition of targets within thermal images, thereby enhancing the quality of the thermal images themselves. Deficiencies such as limited real-world data and scale have hindered further development of the technology.

Ultrasound is sensitive to material changes. The extraction of damage information from ultrasound data necessitates the application of complex processing and interpretation techniques, which require the utilization of specialized knowledge and skills. Future research will focus on building comprehensive databases of various types of injuries and analyzing the data using various techniques (machine learning, neural networks and deep learning).

Here are some future perspectives based on damage characteristics of masonry structures and NDT methods features.

The accumulation of hidden damage can lead to a decrease in the structural integrity of masonry buildings. The development of hidden damage can lead to structural collapse, injuries, and fatalities, resulting in immeasurable damage. It is important to address the issue seriously. The hidden damages are complex and difficult to diagnose due to their subjective nature, multiple contributing factors, and intricate form [56].

The analysis of hidden damage causes can consider the characteristics of the masonry wall, environmental factors, human factors, and external loads [57]. The characteristics of the wall itself include wall construction, material type, and uneven settlement, *etc.* Environmental factors mainly include temperature, humidity, wind, and biological damage [58]. Human factors mainly refer to human activities and vehicle movements [59]. External loads include the self-weight of the wall, seismic effects, and other similar factors [60]. The absence of one-to-one correspondence between hidden damage and its cause, as well as the possibility of multiple causes for the same damage, does not significantly impact our study of damage itself. The field of morphology encompasses various features such as voids, separations, cracks, moisture, and biological diseases [61].

Table 3 summarizes the measurement range of the detection methods. In the context of ground-penetrating radar, it can be observed that an increase in frequency results in a reduction in resolution. The device operates at a frequency of 600 MHz and can detect depths of 4–5 meters. it is mainly used for mapping subsurface structures. At a detection frequency of 200 MHz, the detection depth is approximately 1 meter. Although the dielectric constant varies among subjects, this is a valuable finding. The device is frequently used to detect wall width and texture. A relatively high frequency is required for detecting holes in walls and moisture. This is related to the necessity for testing.

Table 3. Summary of measurement range of the detection methods.

Detection method	Frequency/MHz	Maximum thickness/m	Velocity/ m/ns	Type of damage	Reference
Ground-Penetrating Radar (GPR)	800	0.4-0.5	0.12	internal structure	[62]
	600/1600	4-5/1	0.10	wall thickness/ internal features	[63]
	1600	0.41	-	8 mm layers	[64]
	1600	0.20	0.12	internal void	[65]
	1600	0.50	0.15-0.18	moisture/internal cracks	[66]
	2000	1	0.29	Internal void	[67]
	3000	-	0.17	textures	[68]

Table 3. *Cont.*

Detection method	**Frequency/MHz**	**Maximum thickness/m**	**Velocity/ m/ns**	**Type of damage**	**Reference**
	Pixels	Maximum thickness/m	Spectral range/μm	Type of damage	Reference
Infrared Thermography Technology (IRT)	160×120	shallow surface	7.5-13	moisture/ crack	[69]
	320×240	shallow surface	7.5-13	shallow surface crack	[70]
	320×240	0.1	7.5-13	2 mm layers	[64]
	320×240	shallow surface	7.5-13	shallow surface crack	[71]
	640×480	0.04-0.05	7.5-13	voids	[65]
	Frequency/kHz	Maximum thickness/mm	Velocity/m/s	Type of damage	Reference
Ultrasonic Pulse Velocity (UPV)	35	300	1730	Voids	[72]
	54	300	675-2379	Stripped walls	[73]
	54	100	2719-2745	Voids	[74]
	100	-	599-1121	Internal flaw	[62]

The resolution of IRT image is related to pixels. The device is capable of detecting thicknesses of approximately 0.1 meters and is typically used to identify shallow surface flaws and moisture distribution. It has a broader range of applications in the comprehensive assessment of structural damage. The positioning of the camera determines the detection range. The closer the distance, the smaller the detection range, and the higher the accuracy.

Ultrasonic Pulse Velocity (UPV) is primarily used for localized inspection. In addition, ultrasound is highly attenuated in the medium, making it challenging to detect damage at deeper levels. The ultrasonic method has been demonstrated to exhibit high detection accuracy and is a valuable tool for detecting small areas of homogeneous materials.

The three inspection methods introduced above can also complement each other's shortcomings effectively, making them superior choices for detecting hidden damage in masonry structure. In a nutshell, the integration of Ground-Penetrating Radar (GPR), Infrared Thermography (IRT), and Ultrasonic Pulse Velocity (UPV) enables detection across various scales, from local to global, and depths ranging from shallow to deep. This is a future direction for masonry inspection.

An integrated approach to testing allows each result to be interpreted in conjunction with others, thus enabling an accurate assessment of damage. It is of paramount importance to propose an integrated approach to the detection of hidden damage in masonry structures. Previous studies have employed integrated testing methods, yielding encouraging results. As illustrated in Table 4, the detection methods were combined in various ways, in accordance with the specific objectives of each study. In addition to simply combining different detection outcomes, Image Fusion [75] is a more promising approach for further investigation of GPR, IRT and UPV. The fusion process often places a significant emphasis on identifying common features between modalities, potentially overlooking the distinctive characteristics inherent in the targets and textural details of the ambient background. The modality-specific distinctions play a crucial role in discerning specific target features for object detection and instance segmentation [76].

The objective of image fusion is to integrate two or more images into a unified composite image. This results in a single synthetic image that encompasses the information from all the individual images [77]. The image fusion algorithms include:

(1) Weighted Average

This method involves averaging of the grey values of the corresponding pixels in the original image to create a new image. It is a relatively straightforward and rapid fusion method. However, its fusion results are also inferior to those of other algorithms.

Intensity-Hue-Saturation (IHS) spatial transformation method

The IHS model is a color perception model based on the principles of vision. It defines three easily predictable, interrelated colors based on the characteristics of human color recognition. These are luminance (I), hue (H), and saturation (S). The image fusion techniques typically involve applying the HIS transform to the original RGB image, which helps to separate the intensity. The final stage of the process involves the HIS inverse transformation, which produces the fusion image with improved visual recognition.

(2) Principal Component Analysis

Principal component analysis (PCA) algorithm is a frequently employed methodology for data analysis and processing. PCA transforms the original data into a set of linearly independent representations in each dimension through linear transformation. This transformation can be used to extract the main feature components of the data and achieve the purpose of reducing the dimensionality of high-dimensional data.

(3) Discrete Wavelet Transform (DWT)

The process of image fusion based on the discrete wavelet transform begins with the decomposition of the original image into two-dimensional discrete wavelets, which subsequently generates a wavelet pyramid of the image. Subsequently, each decomposition layer is fused individually to yield the fused wavelet gold tower. It should be noted that various frequency components of each decomposition layer can be combining using different operators. Finally, wavelet inversion is performed on the fused wavelet pyramid to obtain the fused image.

The utilization of ultrasonic pulse velocity, infrared thermography and ground-penetrating radar can help overcome the limitations of each technique. The combination of these three methods is a promising approach for detecting hidden damage in masonry structures and assessing the overall structural integrity.

The advent of non-destructive testing (NDT) technology has brought about a significant degree of convenience. However, the fact that different distress or structures may produce similar echo characteristics makes the interpretation of echo characteristics somewhat vague and open to multiple solutions. Furthermore, challenges such as inefficient manual processing and environmental influences persist in detection. The non-destructive testing technologies mentioned above all require complex data processing and interpretation. In practical applications, due to the differences in individuals' knowledge structures and understanding, the interpretation of NDT results is prone to divergences, which can easily lead to misjudgment of abnormal echo signals. Furthermore, this process is inefficient. Therefore, it is urgent to implement automatic recognition.

Table 4. Summary of the integrated testing methods.

Detection method	Methodology	Main conclusions	Type of structure	Reference
● Ground penetrating radar ● Ultrasonic testing ● Visual inspection test	Image Fusion (IF)	The multi-model NDT approach enabled the precise localization of the corridor and the determination of its geometry.	Masonry structure	[78]
● Rebound hammer test ● Ultrasonic pulse velocity test ● Half-cell potential measurement ● Electrical resistivity test	The sigmoid function	Correlate the data from the Rebound Hammer, Electrical Resistivity, and Ultrasonic Pulse Velocity NDT tests in the introduction of the bridge Quality Index, considering the effectiveness of the test results and their interdependency.	Concrete structure	[79]
● Resistivity Measurement ● Ultrasonic Rayleigh Wave Technique	Integration assessment	Investigate the capacity of each method to detect, localize, and characterize the induced crack pattern, i.e., its width and depth.	Concrete structure	[80]
● Ground penetrating radar ● Close range photogrammetry	Integration modelling	Develop a novel methodology that consists of integrating two methods for constructing 3D models of masonry vaults.	Masonry structure	[81]

6. Future trends

Extensive research has been conducted in the field of hidden damage detection in building structures. The development of non-destructive testing (NDT) technology has facilitated the efficiency of detecting and assessing hidden damage. As a result, the field of testing has evolved towards artificial intelligence. Future improvements in detecting hidden damage in masonry structures may be achieved through the following methods:

(1) To address the issue of the limited accuracy of a single damage detection method, it is possible to envision a future where a combination of multiple detection methods could be utilized to offer a comprehensive assessment of the damage to a structure. For example, ground-penetrating radar (GPR), infrared thermography, and ultrasonic methods are discussed in this paper, collectively addressing the limitations of each technique. This approach can facilitate the detection of hidden damage to masonry structures, offering a comprehensive assessment from the local to the global scale.

(2) To address the issue of the correlation between damage detection results and mechanical property damage, it would be beneficial to focus on the integrating of damage detection technology with finite element models in the future. This would allow for the development of a damage assessment method that incorporates both mechanical property information and damage detection information. A structural finite element model should be constructed based on the acquired damage conditions and locations. The damage results should then be mapped onto the finite element model, with a mapping mechanism established to achieve quantitative judgement of structural performance.

(3) To address the issue of limited datasets, it would be solved in two ways. On the one hand, the construction industry datasets and the development of industry macro-models represent the fundamental basis for the resolution of problems. Conversely, techniques such as transfer learning are employed to enhance the generalization capabilities of algorithms.

7. Conclusion

A great deal of research has been conducted on the topic of hidden damage detection in building structures. However, the test results are subject to the influence of environmental factors, which may affect the accuracy of the results. In light of the aforementioned considerations, it is possible to employ integrated testing methodologies and propose optimization algorithms for noise reduction. in order to offset the inherent limitations of individual testing approaches and to achieve a synthesis of local testing and overall assessment of the damage. This establishes a foundation for integrating damage detection outcomes with mechanical damage modelling or finite element modelling, thereby enabling the prediction of structural performance.

The field of intelligent damage detection has been the subject of extensive research. This approach offers a significant enhancement in the efficiency of damage detection compared to traditional methods. The potential for developing intelligent hidden damage detection in masonry structures warrants further investigation.

Conflicts of interests

The authors declare that they have no conflicts of interest in this paper.

Authors' contribution

Dilidaer Dilixiati: formal analysis; writing; **Na Yang**: funding acquisition; resources; supervision; conceptualization; **Peng Chang**: funding acquisition; resources; supervision.

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