Heritage Science

REVIEW

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A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles

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Abstract

Architectural heritage is vulnerable to disasters. Digital technologies can fight destruction and can ensure integrity by monitoring, managing and protecting architectural heritage from disasters. In this paper, we clarify the relationship between disasters, digitalization and architectural heritage conservation for the sustainability of cultural heritage. This study used the PRISMA process, and bibliometric tools VOSviewer and Citespace to explore the potential of digital technologies in the protection of architectural heritage—especially during disaster cycles, from the perspectives of both universal and typicality; the results revealed that digital twins, deep learning, and preventive conservation are currently hot topics in digital preservation research (especially that research which relates to disaster cycles). On this basis, this paper summarizes the relevant technologies involved in architectural heritage preservation from the perspective of the disaster cycle and the digital phase, and proposes three future research directions: accurate prediction of multi-disasters, automatic early warning of structural damages, and intelligent monitoring of human–computer interaction. This paper constructs a new research frame for digital preservation of architectural heritage during disasters, providing theoretical reference and practical guidance for architectural heritage conversation.

Keywords Disaster cycles, Digital technology, Architectural heritage, Bibliometric analysis, PRISMA

Introduction

Architectural heritage is a carrier of history and culture, a medium for historical transmission, and a foundation for future development. In 1996, the concept of "Digital Preservation" was first introduced by the World Intellectual Property Organization (WIPO), which refers to a series of management activities utilized to ensure continuous access to digital materials over time [1]. In 2003, the United Nations Educational, Scientific and Cultural Organization (UNESCO) issued the Charter on the Preservation of Digital Heritage, which defines digital preservation as the process of using digital technologies (DTech) to record, preserve and access the cultural and historical values of historic buildings and sites [2]. Digital preservation involves methods of recording, analyzing, displaying and disseminating information about architectural heritage in a comprehensive, accurate and efficient manner using DTech such as three-dimensional (3D) scanning, modeling, visualization and virtual reality (VR). Digital preservation has three characteristics: firstly, non-destructiveness, which means that digital methods do not cause any physical damage to the architectural heritage, but rather improve its accessibility and visibility and facilitate its monitoring and maintenance [3]. Secondly, digital preservation involves convenient operation, which means that digital methods are used to record, monitor, analyze, and restore architectural heritage simply, quickly

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and accurately, while overcoming the limitations of traditional methods [4]. Thirdly, digital preservation allows for authenticity, which means that digital methods ensure that architectural heritage retains original aspects of form, structure, materials, and decoration, and is used to assess the reliability, accuracy, and validity of the data [5]. Digital preservation provides technical support for architectural heritage conservation. Preservation refers to the complete upkeep and maintenance of an old building in relation to its original state. Conservation refers more to the uses of architecture within broader social, cultural and political systems [6]. DTech can overcome the shortcomings of traditional historic building conservation methods by enabling the non-destructive monitoring of architectural heritage [7], real-time monitoring [8], data sharing [9], and virtual-real interaction [10]. These methods not only increase public awareness and appreciation of architectural heritage, but also facilitate non-destructive restoration and conservation while effectively maintaining its authenticity.

Disasters pose a serious threat to the value and sustainability of architectural heritage. A full lifecycle conservation approach can help reduce losses by employing different strategies before, during and after a disaster. This approach follows the concept of the disaster cycle, which was first introduced by Baird et al. [11] (1975) and later refined by Khan et al. [12] into three phases: pre-disaster, mid-disaster and post-disaster. Each phase has different needs, challenges, tools, strategies and resources. In 1989, European universities jointly organized a symposium on "Protecting Architectural Heritage from Natural Disasters", highlighting the need to address hazards in heritage conservation [13]. In 2015, the United Nations adopted the Sustainable Development Goals (SDGs), which recognized the risks and challenges of climate change for architectural heritage conservation and placed cultural heritage at the core of sustainable development policies [14].

DTech is one of the effective means to protect architectural heritage from various threats caused by natural and man-made disasters (including climate change events) by using laser scanning, drones, digital photography, Geographic Information System (GIS), Artificial Intelligence (AI), and other technologies. With the development and popularity of DTech, some countries carried out research and developed practices in relation to the digital preservation of architectural heritage. For example, Italy incorporated heritage conservation in its constitution in 1948, whereby conservationists defined and disseminated the concept of "cultural heritage" through the Franceschini Commission in 1964, and initiated a pilot program for preventive conservation of Umbrian cultural heritage in 1976 [15]. In recent years, Italy actively participated in international heritage initiatives and forums, such as the G7 Cultural Summit in 2017 and the Comité International de Photogrammétrie Architecturale (CIPA) conference in 2023, and advocated for increased digital cooperation and participation among countries. China has been exploring "Digital Preservation" since 1993, with the launch of the "Digital Dunhuang" project [16]. It has developed various DTech, such as a LIDAR-based survey of the Great Wall [17], a drone-based inspection of ancient temples [18], and AI-based identification of cultural relics. The United States (US), one of the pioneers in the digital preservation of architectural heritage, adopted the Historic Preservation Act (NHPA) in 1966 to establish a national policy for the preservation of heritage [19]. The United Kingdom (UK), one of the cradles of Western architectural heritage conservation, launched its own movement in the nineteenth century (through John Ruskin, William Morris and SPAB) and established legal provisions for the hierarchical protection of its architectural heritage [20]. In 2008, the UK proposed the Heritage Conservation Act to streamline and strengthen its architectural heritage conservation system [21]. In 1985, Spain enacted the Law of the Spanish Historical Heritage, which established the legal concept of archaeological heritage [22]. The Ministry of Culture and Sport of Spain, in its *National Plan for the Conservation of cultural Heritage of the 20th Century* also proposes the use of digital technology for the preservation of cultural heritage [23]. Australia focuses on the sustainability of architectural heritage and issued the policy document "Australian Heritage Strategy" in 2015, hoping to use DTech such as Building Information Modeling (BIM), VR and AR (Augmented Reality) to improve the sustainability and value of its architectural heritage [24].

Previous studies have also proposed some ideas for investigations on the digital preservation of architectural heritage. For example, Trillo et al.[25] compared the applications and effects of digital platforms in architectural heritage conservation, and proposed that appropriate DTech and methods can be selected based on the characteristics and needs of architectural heritage. Li et al. [26] reviewed research on LiDAR technology in architectural heritage from 2012 to 2021, and clarified the current research hotspots, methods, and discussion. Ramón [27] reviewed the acquisition, processing and application of thermal point clouds, proposing their use for detecting thermal properties, identifying structures and materials, and assessing conservation status of architectural heritage. Zhao [28] analyzed the research related to BIM technology from 2005 to 2016, listing the combination of BIM technology and other DTech such as laser scanning, 3D modeling, cloud computing and 4D-CAD. Wang et al. [29] reviewed the applications and status of

BIM and GIS technologies in construction project management from 1990 to 2018. Pan et al. [30] performed a bibliometric and scientometric analysis of the literature on BIM and AI integration from 2000 to 2021, and presented the current state and future directions of BIM full-cycle integration with AI technology. Orimoloye et al. [31] explored the evolutionary trajectory of disaster risk reduction research over a period from 2000 to 2019, emphasizing the innovative role of DTech in disaster risk reduction. Sesana et al. [32] analyzed the impact of climate change on cultural heritage from 1990 to 2020 and explored the use of DTech to monitor and analyze the status of heritage, pointing out the limitations of the study and while offering future directions. Munawar [33] scanned the literature from 2000 to 2020 and explored ways to build smart cities, while exploiting the potential of disruptive technologies in urban construction; Munawar also pointed to ways to improve post-disaster management.

Throughout the previous reviews related to the conservation of architectural heritage, scholars review or look forward to the research direction of heritage architecture conservation from the perspectives of policy, management, cognition, and value interpretation. Our literature review reveals that DTech can go some way to enhancing the conservation of architectural heritage, although frequent disasters pose a major challenge to architectural heritage. However, the existing literature lacks a comprehensive perspective and neglects the necessity and feasibility of the digital preservation of architectural heritage within disaster cycles. This paper systematically conducts a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) analysis of the relevant articles, aiming to accelerate the conservation process, so as to help scholars understand the causes of damage so that they can adopt digital methods of preservation.

Research methods

Method

This study used the PRISMA process to investigate previous studies. Following the PRISMA guidelines, this study specifies a minimum number of items to be reported, and assesses the effectiveness of interventions of systematic reviews and meta-analyses. This method improves the transparency, rigor and credibility of this study [34].

Questions and aims

This study aims to review the current literature on the digital preservation of architectural heritage under the disaster cycle, to explore the interplay of disasters, DTech, and architectural heritage, and to propose future research directions and methods for preserving architectural heritage. To achieve this aim, the study addresses the following questions:

Q1: Which countries, journals, and institutions are the most active and influential in the field of digital preservation of architectural heritage within disaster cycles, and what are the current research trends and challenges?
Q2: What is the potential for digital conservation of architectural heritage in the disaster cycle?
Q3: How is digital technology applied in architectural heritage conservation?
Q4: How do disasters, DTech, and architectural heritage interact with each other?
Q5: What are the future opportunities and directions for the digital preservation of architectural heritage?

Data collection

During the data collection phase, Web of Science (WOS) literature data was used to set the search strategy based on three keywords: disaster, architectural heritage, and digitalization (and their synonyms) as TS = (Heritage) AND TS = ("Build" OR "Building" OR "Architectural" OR "Architecture") AND TS = (Digital) AND TS = ("Preservation" OR "Conservation" OR "Protection") OR TS = (Heritage) AND TS = ("Build" OR "Building" OR "Buildings" OR "Builds" OR "Architecture") AND TS = ("Disaster" OR "Hazard"). The screening process consisted of two parts (Fig. 1): The first part was a universal analysis, which screened the papers by title relevance, inclusion criteria (paper source, time frame, paper type and abstract match) and content relevance, and obtained a total of 866 relevant papers as the sample. The second part was a typical analysis. Based on 866 papers, 257 articles involving architectural heritage, disasters and digital technology were screened through literature reading.

Bibliometric analysis

Data acquisition

This paper employs Vosviewer and Citespace software to analyze the literature from January 2012 to December 2022, and visualizes the network structure and clustering of four dimensions: country, journal, discipline and co-citation. On this basis, this study tracks hot research topics, constructs a multidimensional relationship structure, and provides a comprehensive overview of the research trends and development of digital preservation of architectural heritage within disaster cycles [35]. The research on these themes shows an upward trend from 2012 to the present. As shown in Fig. 2a, "architectural heritage" and "disaster" are involved in 205 papers (23.4% of the total sample). "digitalization preservation" and "architectural

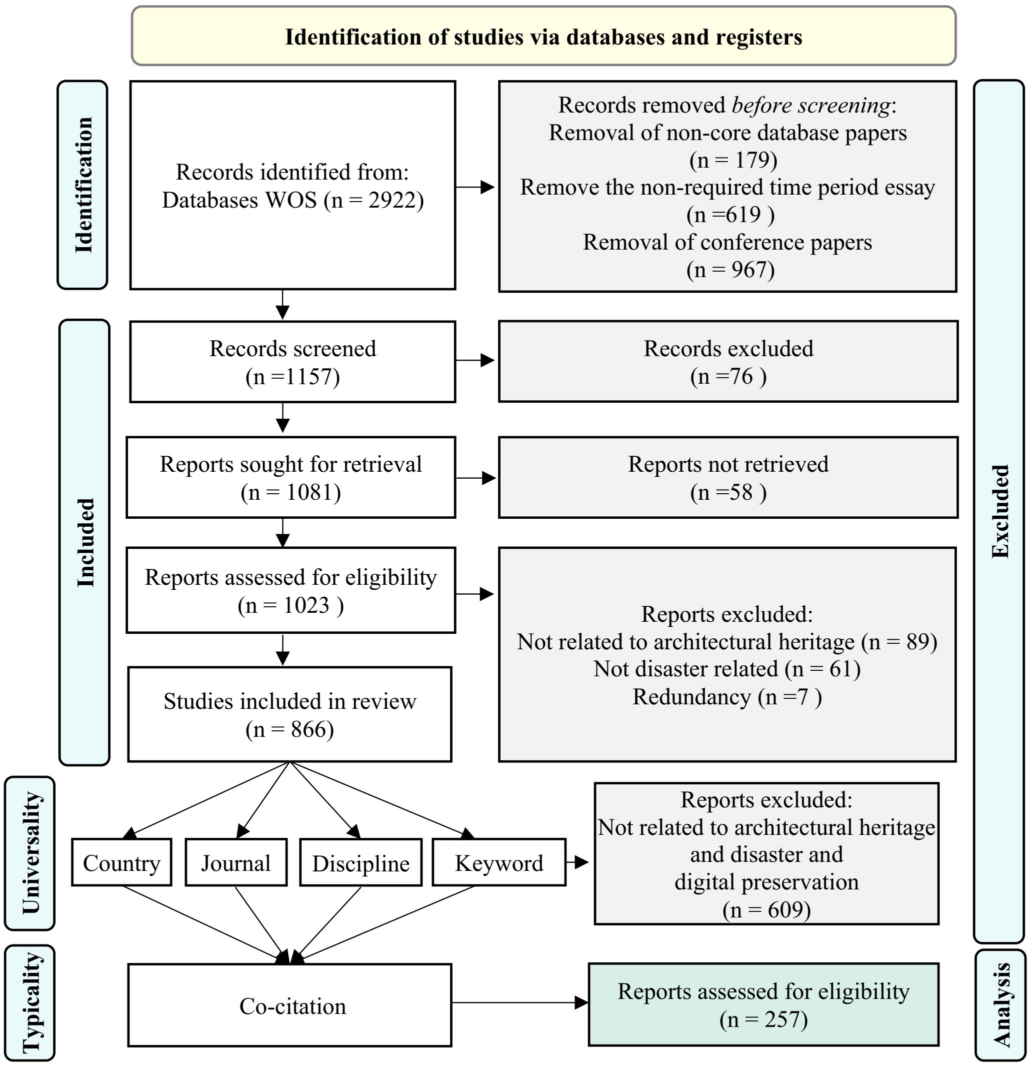


Fig.1 PRISMA flow diagram of literature search and review

heritage" are involved in 743 papers (85.8% of the total sample). "digitalization preservation", "architectural heritage" and "disaster" are involved in 866 papers. These two combinations have similar fluctuation trends: indeed, there is an increase after 2016 which then levels off from 2012 to 2022.

In comparison, the combination of "architectural heritage" and "disaster" produces a relatively low number of papers. While there is less research on the way in which disasters cause damage to architectural heritage, the frequency of papers demonstrates that DTech is the main research direction for architectural heritage conservation. In terms of development trends, the curve in Fig. 2b is fitted with the Gompertz function, and an R^2 value of 0.839 is obtained at the 95% confidence level. The number of publications shows a trend of slow growth at the beginning and then gradual acceleration, and in 2022 is 8.5 times higher than in 2012. It is suggested that research on the digital preservation of architectural heritage in a disaster cycle is growing continuously and has some potential for development, and is likely to become a hot topic in academia.

Universal analysis

(1) Country/region analysis

A bibliometric analysis of the publications in each region was conducted to explore the research status, collaboration network, and impact of digital preservation of architectural heritage in a disaster cycle across different countries. Figure 3 depicts the collaborations and the number of publications in this field by country. Italy leads the field with 158 articles, accounting for 18.2% of

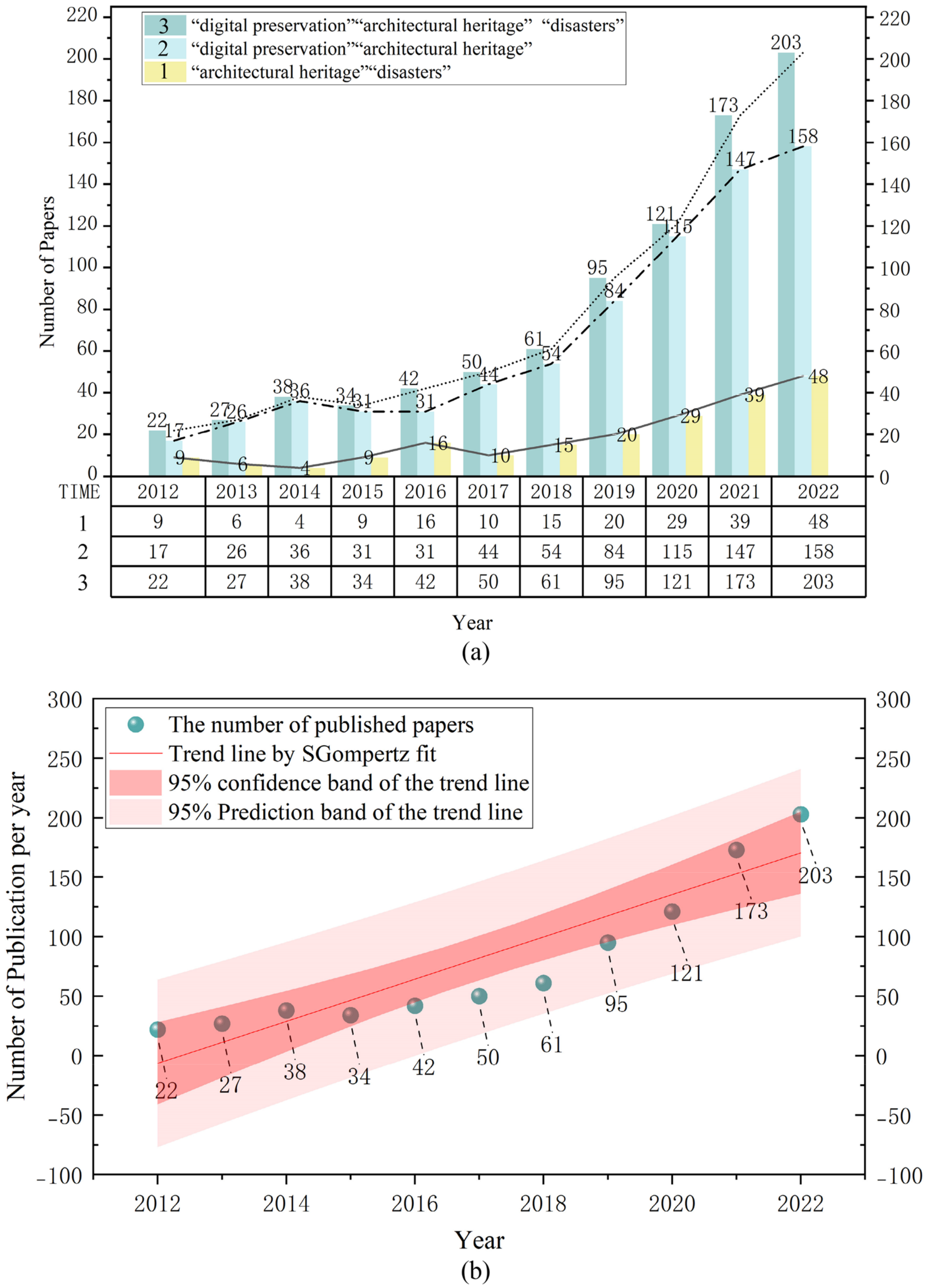


Fig. 2 Variation of publication number per year during 2012–2022

the total literature, followed by China with 119 articles (13.7%) and the US ranks third with 94 articles (10.9%). According to UNESCO data as of July 2021, Italy has 58 World Heritage sites and plans to use Historic Digital Twins (HDT) in museum complexes for heritage maintenance and preservation [36]. China, with its long history and cultural diversity, has 56 cultural heritage sites, ranking second in the world. To effectively protect and preserve its precious cultural heritage, China has established the largest cultural heritage conservation

The number of papers	Proportion
Italy (158 articles)	18.2 %
China (119 articles)	13.7 %
USA (94 articles)	10.9 %
Spain (82 articles)	9.5 %
United Kingdom (78 articles)	9.0 %
Germany (42 articles)	4.8 %
Australia (33 articles)	3.8 %
France (32 articles)	3.7 %
Portugal (30 articles)	3.5 %
Japan (28 articles)	3.2 %

Fig. 3 Regional distribution and Countries with the largest number of publications and citations

system in the world and continues to enhance its efforts to preserve cultural heritage [37]. The US, with 25 cultural and 12 natural heritage sites, has developed multiple digital tools and platforms to record, monitor, and disseminate information about its heritage resources [38]. While confronting common challenges and opportunities, this survey demonstrates that different countries have different priorities and strengths in the digital preservation of architectural heritage during the disaster cycle. In addition, a noteworthy observation is that the number of publications is positively correlated with the amount of cultural heritage possessed by each country.

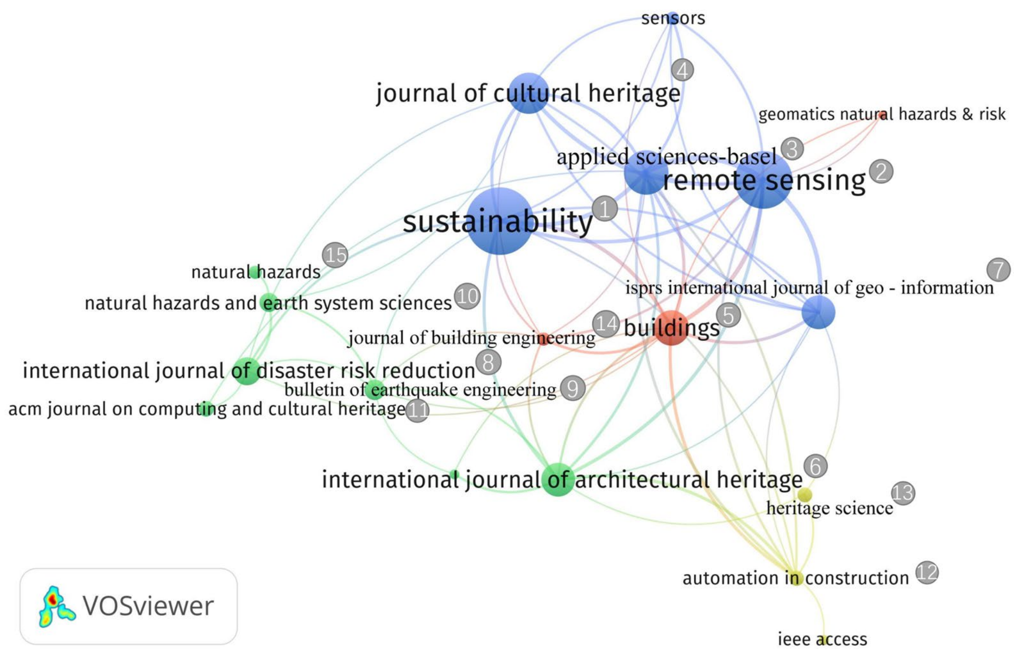
(2) Analysis of publication sources

As various countries pay more attention to architectural heritage conservation, the number of publications on these topics has steadily increased. Figure 4 shows the top fifteen journals in this field and their number of articles and impact factors (IF) in 2021: *Sustainability* (46 articles, 3.89), *Remote Sensing* (39 articles, 5.35), *Applied Sciences-Basel* (30 articles, 2.84) and the *Journal of Cultural Heritage* (28 articles, 3.23). These journals share a common topic in that they use remote sensing (RS) techniques and sustainable development principles to protect cultural heritage from natural disasters and climate change. Meanwhile, they also have different focuses. For instance, *Sustainability* explores the environmental, cultural, economic and social aspects of human development and natural heritage, while *Remote Sensing* specializes in the use of RS techniques for the protection of architectural heritage. *Applied Sciences-Basel* involves the application of natural sciences, and the *Journal of Cultural Heritage* is a multidisciplinary journal that covers all aspects of cultural heritage. These journals provide rich resources for researchers in this field. Based on keyword clustering analysis, they can be divided into four categories (Fig. 4): blue journals apply RS techniques to architectural heritage conservation in earth science and engineering research; green journals are related to natural sciences and study disaster prevention and mitigation; red journals focus on engineering aspects of architectural design, construction and maintenance; and yellow journals implement data collection, model establishment, information management and data application in DTech.

(3) Discipline analysis

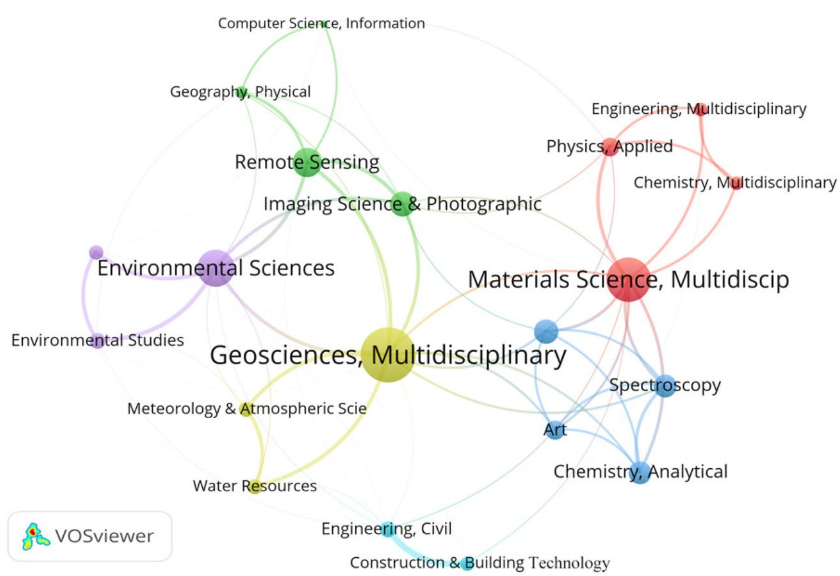
The digital preservation of architectural heritage is a multidisciplinary and comprehensive research field that covers various topics. According to Fig. 5, the main disciplines involved in this field are Geoscience, Materials Science, and Environmental Science.

This implies that to protect architectural heritage from disasters, it is necessary to: (1) apply knowledge and methods from earth science, material science, and environmental science to analyze the geographical location, structural characteristics, and environmental impacts of



Ranking	IF
1	3.89
2	5.35
3	2.84
4	3.23
5	3.32
6	3.00
7	3.10
8	4.84
9	4.58
10	2.05
11	10.52
12	2.84
13	4.61
14	7.14
15	3.16

Fig. 4 The top 15 journals in this field and their number of articles and IF in 2021



Subjects	classification
Geosciences	Earth Science
Meteorology	
Water resources	
Materials Science	Natural Science
Chemistry	
Physics	
Engineering	
Environmental Sciences	Environmental
Environmental Studies	
Remote sensing	Information Science
Imaging Science	
Geography	
Computer Science	
Spectroscopy	Humanities and Natural Science
Art	
Chemistry	
Engineering, civil	Engineering Technology
Construction	
Building technology	

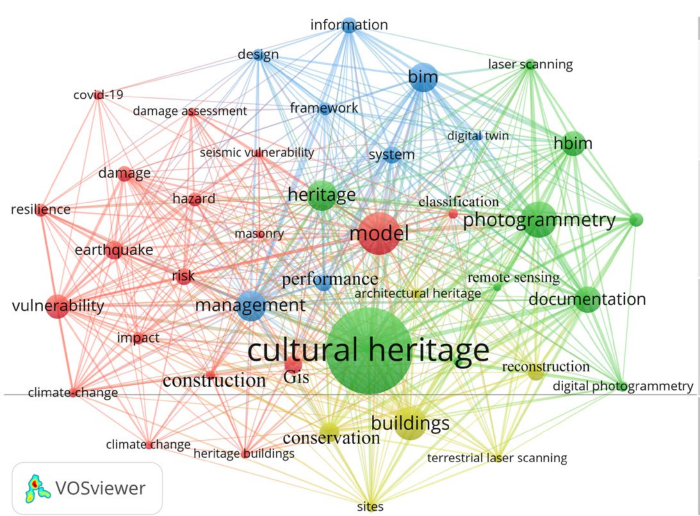
Fig. 5 Distribution and topic clustering of academic disciplines based on keywords

architectural heritage so as to develop appropriate digital preservation plans; (2) understand the value of information science in the digital preservation of architectural heritage and select suitable DTech according to the degree and type of damage so as to record, preserve and apply data, thereby reducing the threat of disasters; (3) integrate knowledge from humanities, engineering, history, archaeology, culture, architecture and related fields to fully comprehend and express the various values and meanings of architectural heritage [39].

(4) Keywords analysis

Using VOSviewer software with modularity optimization and smart local moving algorithms, this paper retrieved 4180 keywords from the literature on the digital preservation of architectural heritage in the disaster cycle and selected 42 keywords with a minimum frequency of 13 to generate a keyword clustering map with 42 nodes, 477 links, and a total link strength of 1341. Among them, the co-occurrence frequency indicates the association between keywords, and the modularity optimization and smart local moving algorithms so as to assign keywords to different topics that then optimize the network layout. The color and size of the nodes are determined by the keywords, and the lines represent the distance and connection strength between the nodes, showing the relationships, differences, and development trends among different topics, as shown in Fig. 6 [40]. According to the keyword clustering, four topics are identified: Model, Cultural heritage, Management, and Buildings. These keywords represent different aspects of architectural heritage conservation, such as disaster analysis, spatial modeling, data management, and heritage conservation. Cluster 1 (red) uses the keyword "Model", which discusses the impact of disaster types on architectural heritage and the application of corresponding DTech. Cluster 2 (green) uses the keyword "Cultural heritage", which focuses on architectural heritage as the core object and explores spatial models, data management, and reality technologies. Cluster 3 (blue) uses the keyword "Management", which is oriented towards information systems and related aspects, and studies the protection management of architectural heritage. Cluster 4 (yellow) utilizes the keyword "Buildings", which uses types of architectural heritage as the scale range and discusses the role of DTech in architectural heritage conservation and restoration. From an overall perspective of the clusters, the most frequent keywords are mainly related to architectural heritage and digitalization, among which "Cultural Heritage" ranks highest, with a frequency of 130 times and a total link strength of 236 times. This suggests that architectural heritage is the main theme, and covers aspects such as disasters, DTech, management, etc. Moreover, DTech runs through the whole process of architectural heritage conservation and is therefore an important core technology.

Using keyword burst analysis in CiteSpace, this paper investigated the research trends of the digital preservation of architectural heritage in a disaster cycle. This method detects keywords with a surge in citation frequency within a certain period, revealing research hotspots and frontiers. It also produces a timeline graph that displays keyword clusters and theme transitions across different years, visually depicting the evolution of keywords [41]. Figure 7 shows that the high-frequency citation keywords are grouped into three periods by every 3 years. In the first-period keywords such as accuracy, calibration, and algorithm reflect the technical demands for the restoration and reconstruction of architectural heritage. For instance, Santagati [42] suggested using photographs to rapidly create 3D models of architectural heritage and examined the limits and potentials of the image-based modeling techniques of accuracy and algorithm. The second-period keywords such as vulnerability, aerial image, reconstruction, and architecture heritage mark the onset of the digital era in architectural heritage conservation. For example, Gabellone [43] employed LiDAR and satellite multispectral data to extract architectural archaeological features, so as to analyze urban morphology, reconstruct historical scenes, and increase public interest and involvement in architectural heritage. The third-period keywords such as resilience, terrestrial



Cluster	Subjects	Occurrence	Total link strength
Cluster 1	Model	64	154
	Vulnerability	37	79
	Earthquake	28	51
	Gis	27	36
	Damage	23	53
Cluster 2	Culture Heritage	130	236
	Photogrammetry	55	180
	Heritage	46	96
	Documentation	41	168
	Hbim	38	119
Cluster 3	Management	46	135
	Bim	44	142
	Performance	26	38
	Information	24	51
	System	26	62
Cluster 4	Buildings	50	141
	Conservation	30	80
	Reconstruction	25	55
	Sites	16	54
	Laser Scanning	17	53

Fig. 6 Keyword clustering

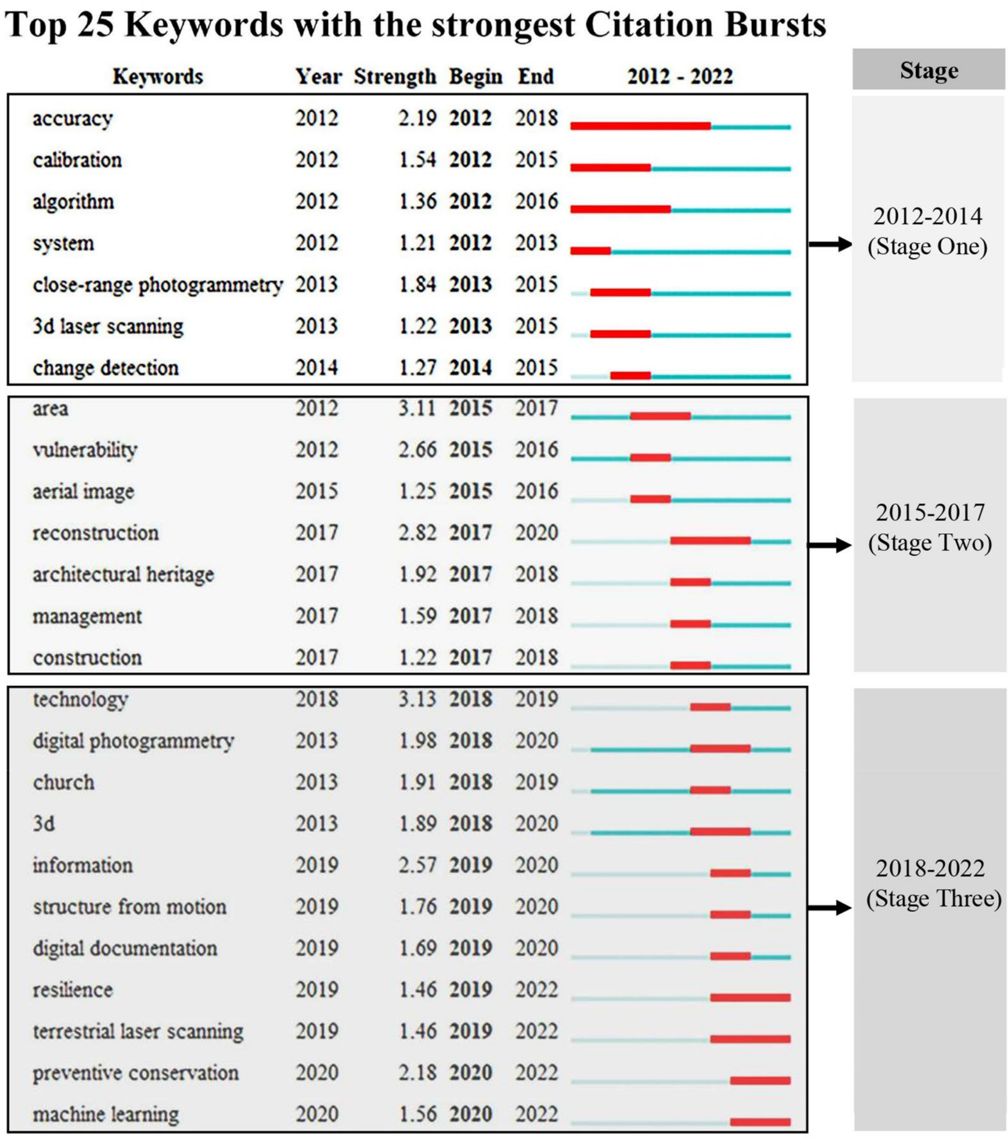


Fig. 7 Top keywords with the most frequent occurrence

laser scanning (TLS), preventive conservation, and machine learning (ML) indicate the close integration of AI and digital preservation in architectural heritage.

Typical analysis

Universal analyses reveal the current state of research, collaborative networks, and impact of the field, providing a comprehensive context for understanding its distribution, publication outlets, interdisciplinarity, and transdisciplinarity. Typical analyses explore the core themes, key technologies, and future challenges of the field. Document co-citation analysis (DCA) is a methodology for overcoming academic isolation, facilitating knowledge integration, and establishing interdisciplinary coherence [44]. By combining DCA and typicality analysis, the 275 papers screened by PRISMA were used to identify the research hot topics and the representative papers in the field (Table 1). For example, Yastikli [45] utilized digital close-range photogrammetry to generate 3D point files of architectural heritage surfaces for conservation purposes. Murphy [46] described three phases of design, methodology and results of heritage building information modeling (HBIM). Remondino [47] analyzed 3D modeling technology from four aspects: limitations, potential, norms and requirements, and proposed a combination

Table 1 Ranking of literature and reviews with the highest citation

	Title	First Author	Method	Co-citation frequency
1	Documentation of cultural heritage using digital photogrammetry and laser scanning	Naci Yastikli	Digital photogrammetry laser scanning	20
2	Historic building information modeling (HBIM)	Maurice Murphy	HBIM	19
3	Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning	Fabio Remondino	Photogrammetry 3D Scanning	19
4	A method of Registration of 3D Shapes	Paul J. Besl	The iterative closest point	14
5	An Efficient Pipeline to Obtain 3D Model for HBIM and Structural Analysis Purposes from 3D Point Clouds	Massimiliano Pepe	HBIM	14
6	Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans	Luigi Barazzetti	Cloud point BIM、FEM	12
7	Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—The Basilica di Collemaggio (L'Aquila)	R. Brumana	laser scanning photogrammetry HBIM	11
8	Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management	Silvana Bruno	DA-HBIMM	11
9	Historic Building Information Modelling – Adding intelligence to laser and image based surveys of European classical architecture	Maurice Murphy	HBIM	11
10	Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila)	Daniela Oreni	HBIM	10

of heritage building protection and visualization technology. Besl [48] proposed a method for registering 3D shapes using the Iterative Closest Point (ICP) algorithm, which was beneficial to capture and compare the geometric shapes and conditions of architectural heritage before and after disasters. Pepe [49] presented a method for creating accurate and reliable HBIM and FEM models from laser scan data and demonstrated its application in architectural heritage conservation.

The citation analysis shows that DTech has a wide range of applications and prospects in the protection of architectural heritage. Among them, the literature on HBIM model construction received the most attention, followed by exploratory research on earthquake damage to architectural heritage. This literature reflects the important role of digital preservation of architectural heritage in disaster cycles, in line with the SDGs formulated in 2015 to protect the world's cultural and natural heritage. These goals include Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable; and Goal 13: Take urgent action to combat climate change and its impacts [14]. The impact of climate change on built heritage also informs and guides DTech strategies to achieve SDGs for built heritage. These citation levels support that DTech can effectively support information management, risk mitigation, and damage recovery of built heritage, while also enhancing the resilience and sustainability of built heritage in disaster settings.

The potential of digital preservation of architectural heritage in the disaster cycle

DTech is essential for conserving architectural heritage in the face of disasters. Based on the disaster cycle, digital preservation can be categorized into three phases: pre-disaster, mid-disaster and post-disaster. This phased approach can lower maintenance costs and enable the application of suitable DTech for different disaster phases, achieving the conservation objectives of batching, stratification and classification. The keywords in the literature reflect the relevance of digital preservation for architectural heritage throughout the disaster cycle. These keywords are divided into four clusters according to the disaster cycle (Fig. 6): cluster 1 focuses on the analysis of the type of disaster; cluster 2 deals with the maintenance of architectural heritage before the disaster; cluster 3 addresses the management and maintenance of architectural heritage during and after the disaster (mainly for emergency relief and restoration of its function and structure); and cluster 4 covers the reconstruction and conservation of architectural heritage after the disaster, mainly to recreate its form and style and to ensure its sustainable development.

Pre-disaster: preventive "maintenance"

Pre-disaster, DTech can help predict and prevent disasters affecting heritage buildings and protect architectural heritage. Preventive measures can protect buildings from deterioration and threats of sudden and chronic disasters.

DTech can be used to determine the time and type of disaster [50], monitor changes in building structures [51], identify vulnerable buildings [52], map disaster scenarios [53], and collect data [54] to plan in disaster-prone areas, so as to ensure the integrity of architectural heritage.

Mid-disaster: corrective "repairs"

Mid-disaster, DTech are mainly used for emergency salvage and real-time monitoring of architectural heritage to assess disaster impacts and to prevent further damage and loss, and to propose corrective maintenance strategies to prolong the life of architectural heritage. For example, drones can capture real-time images of fire scenes and can scan damaged building parts for disaster damage assessments [55]. TLS can record disaster phenomena such as landslides, cracks, and displacements on the ground [56]. Infrared scanners can quickly obtain the temperature distribution on the surface of the disaster area, can reflect potential structural defects, cracks, and landslides, and can propose repair solutions [57]. GIS can provide location information and can create disaster zone maps for locating, inventorying, managing, and protecting architectural heritage by providing accurate visual spatial data to develop disaster response strategies [58]. Microbial isolation techniques can assess damage to buildings and can mitigate the onset of deterioration [59].

Post-disaster: recovery "sustainable"

Post-Disaster, DTech provides effective means for the restorative maintenance of architectural heritage, ensuring its sustainable conservation. Various techniques can be employed to reconstruct and restore damaged buildings, while assessing the impacts of disaster; these techniques can also allow for the development of mitigation strategies. For instance, 3D methods and aerial photogrammetry can generate realistic models of architectural heritage which also interpret their features [60]. The earthquake vulnerability index can evaluate the extent of post-earthquake damage and can identify the vulnerable parts of buildings [61]. 3D-GIS technology can facilitate 3D modeling and information management of architectural heritage, and can provide data support for post-disaster conservation and restoration [62]. Landsat-8 and Sentinel-2 can compare pre-earthquake and post-earthquake images to devise evacuation and rescue plans [63].

Based on the above observations of the disaster cycle. In the pre-disaster phase, DTech can predict and prevent the impact of disasters by recording, preserving and applying data technologies such as GIS, HBIM, Finite Element Method (FEM), etc., to achieve a preventive conservation approach to the architectural heritage. In the mid-disaster phase, DTech can support emergency response and real-time monitoring by using structural health monitoring (SHM) systems, drones and satellite imagery, etc., to achieve emergency conservation of architectural heritage. In the post-disaster phase, DTech can facilitate the recovery and reconstruction of architectural heritage by using data management and data application, etc., to achieve restorative conservation of architectural heritage. Furthermore, disasters can be classified into three types: natural disasters, human-induced disasters and climate change events. Different types of disasters cause different degrees and kinds of damage to architectural heritage. DTech can provide different data technologies and solutions according to the stage and type of damage caused by disasters, to maintain, monitor or sustain architectural heritage, achieving comprehensive conservation of architectural heritage. As shown in Fig. 8, natural disasters, such as earthquakes, landslides, pests and diseases, require accurate and timely data collection and analysis to reduce uncertainty and risk. Borri [64] used 3D laser scanning and photogrammetry techniques to analyze the damage process of different buildings after the 2016 Central Italian earthquake, providing a basis for conservation and safety issues. Earthquake sensors, SHM systems, and finite element analysis can also be used to assess and mitigate damage to buildings. Human-induced disasters, such as war, urbanization, tourism, etc., require the security and transparency of data protection and sharing to prevent data abuse and loss. For example, Trillo [65] took the traditional city of As-Salt near Amman in Jordan as a case study, analyzing the threats posed by urbanization, disorderly growth, and environmental problems to architectural heritage, and proposed using BIM technology to record and evaluate the damage of architectural heritage (so as to develop effective conservation measures). Satellite imagery, drones, and blockchain technology can also prevent and track attacks on heritage sites. Climate change events, such as floods, droughts, sea level rise, etc., can cause damage to heritage structures by changing environmental conditions and can increase natural disasters. For example, Anderson et al. [66] used RS and GIS technologies to monitor and predict the impact of sea level rise on heritage structures, and proposed sampling, grading, and mitigation methods. RS, GIS and hydrological models can also be used to monitor and predict the impact of climate change on heritage structures, providing data, information and tools for coping with changing environmental conditions.

Application of DTech in architectural heritage conservation

The results of VOSviewer and Citespace software indicate that the research field of the digital preservation of architectural heritage in a disaster cycle consists of four

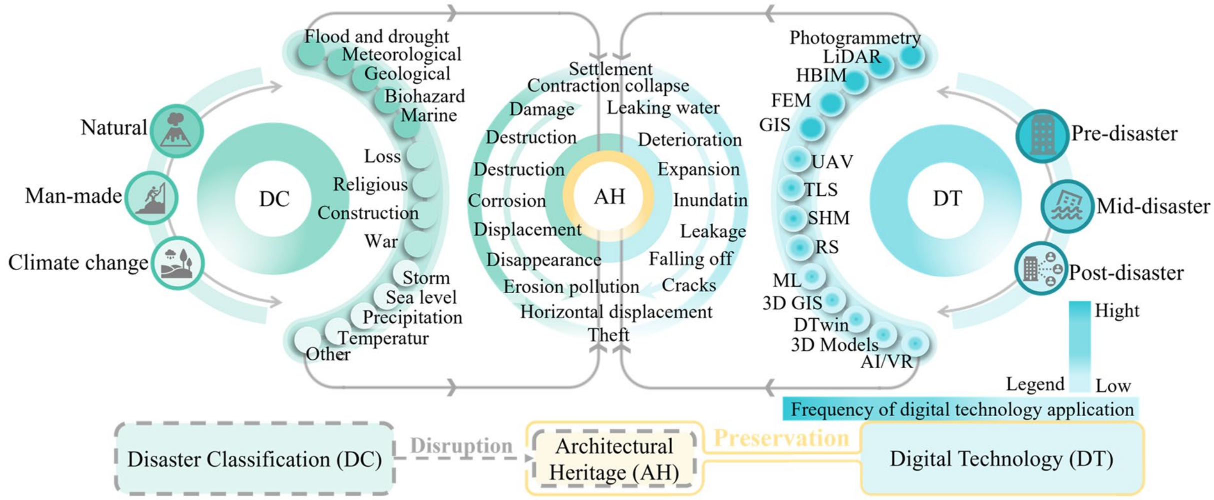


Fig. 8 A flowchart of digital technology for architectural heritage protection under different disaster types

clusters: Modeling, Cultural Heritage, Management and Architecture. These clusters cover different aspects of architectural heritage conservation, such as disaster analysis, modeling, data management, and heritage conservation, and illustrate the application of DTech in various stages of architectural heritage conservation under disaster conditions, which involve digital recording, digital preservation and digital applications (Fig. 9).

Digital recording

The purpose of data recording is to obtain, process and analyze relevant data on architectural heritage, and to construct digital models. Data recording can effectively capture the current characteristics of architectural heritage, can identify potential threat factors, and can formulate reasonable conservation measures. Data recording is an essential task of architectural heritage conservation, which involves both data collection and morphological modeling.

Data collection plays a fundamental part in the construction of digital preservation, archiving and the management of architectural heritage. Non-destructive, accurate and efficient methods such as surveying techniques can better enable the recording, recall and use of data to meet the challenges under the disaster cycle [67]. Data collection methods include historical data, photogrammetry, laser point clouds, LiDAR and other digital techniques. For example, Dlesk et al. [68] used photogrammetry to collect data for changes in the different life cycles of the Padis Monastery in Estonia. Khalid A. [69] summarizes the conservation challenges and existing digital conservation methods of Pakistan's architectural heritage, and proposes the adoption of photogrammetry as an urgent and effective digital conservation solution. Masciotta et al. [70] used laser scanning and imaging to digitally model the New Manueline Church in Portugal. Affek et al. [71] combined field research and historical archives, and used LiDAR to collect pre- and post-war heritage-built environments and images. Prus et al. [72] used LiDAR-DTM, digital photographs, and historical maps, and analyzed the layout of rural heritage buildings to obtain information on historical structures, new settlements, cultural contexts and spatial landmarks.

Morphological modeling is a key aspect of digital preservation that creates realistic 3D models by processing images with data, which includes coded images, image sequences from low-cost digital cameras, laser scanning, and point cloud techniques. These models reflect the geometry, location, material degradation and the alteration of the buildings. For instance, Kadhim et al. [73] used coded images to capture the external geometry and location of buildings. Dimen et al. [74] used laser scanning and image monitoring to propose a non-destructive technique that quantified the physical characteristics and flatness of mural surfaces. Pepe [75] used laser scanning to construct architectural heritage models that were managed and displayed in a 3D-GIS environment. Moreno et al. [76] used GIS software and expert opinion to analyze architectural heritage information, to identify damage to architectural heritage, and to assess heritage architectural vulnerability.

Digital preservation

Digital preservation is an important step in the conservation of architectural heritage; by using DTech, which covers both digital archiving and data management, digital preservation aims to manage digital information on

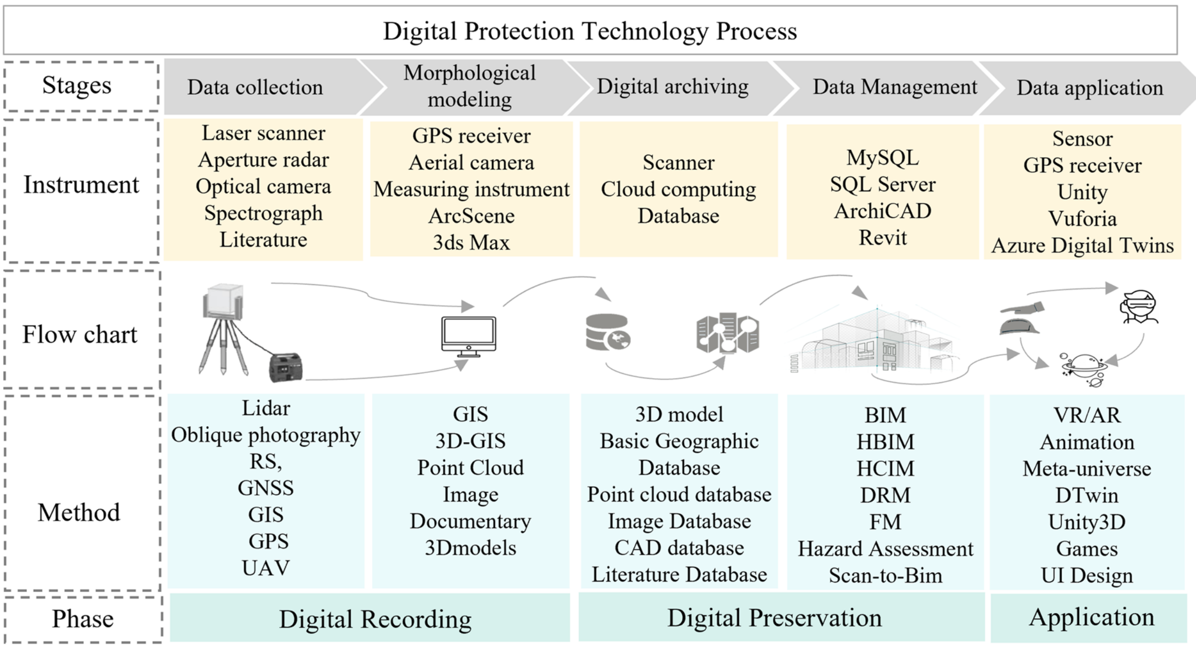


Fig. 9 Flow chart of the digital preservation of architectural heritage

architectural heritage so as to enable rapid retrieval and access to information. Digital preservation preserves and transmits the value of architectural heritage and enables the sharing of data, which increases the resilience of architectural heritage in disasters.

Digital archiving is a crucial aspect of digital preservation, systematically constructing databases and reconstructing data by building digital models of architectural heritage which reflect the geometry, location, material degradation and alteration of the buildings [77]. For example, Crisnapati et al. [78] used the volcanic eruption in Bali as a context to build a 3D digital library for the digital preservation of the architectural heritage of Besaki. Koutsoudis et al. [79] used visible and infrared spectroscopy of drones to segment building materials which then enabled them to form a model database to visualize fire propagation and crowd movement. Bent et al. [80] used Orsanmichele's church as a case study, using a LiDAR scanner to obtain a 3D database of the building's interior and exterior to form a highly accurate virtual reconstruction mode. Youn et al. [81] used laser scanning and image inspection data to construct a Rhino 3D model to construct a timber frame building information platform to analyze deformation and damage between timber joints. Saura et al. [82] proposed an intervention method using 3D software and LiDAR technology to control and document changes in architectural details of the 16th-century Colegio Diocesano Santo Domingo.

Digital management is an optimized aspect of digital preservation, enabling data to be viewed, analyzed, shared and interacted with through platforms such as GIS and BIM, providing a dynamic and operational system for the digital preservation of architectural heritage [83]. In 1975, Chuck Eastman proposed the concept of BIM. In 2009, Murphy et al. [84] proposed the concept of HBIM for embedding heritage building data into a 3D computer model throughout the preservation lifecycle. This study on digital management was divided into two parts: the framework establishment and the information collection process. For framework establishment, BIM technology is combined with other technologies to form new BIM frameworks to facilitate data exchange and interoperability in HBIM. For example, Bruno et al. [85] proposed the 4D-BIMM concept, which integrates historical digital archival documentation, survey data, diagnosis and monitoring to achieve a monitoring and management knowledge framework. Lindner et al. [86] described the components of the disaster risk management (DRM) framework, highlighting the positive impact of DRM on heritage buildings against climate change and natural disasters. Nieto-Julián [87] proposed the HBIM+Common Data Environment (CDE) framework and workflow to ensure data interoperability by creating a geometric cloud of data for the classification of architectural heritage. Ostwegel et al. [88] proposed the openBIM approach to address the accessibility of BIM data through an Information Delivery Manual (IDM). For information collection, BIM technology is used for digital management, and different methods are used to access and collect relevant data and information. For example, Moyano et al. [89] used Autodesk Revit, ArchiCAD, and BIM software to establish a database of heritage building elements to manage architectural heritage information. Rodrigues et al. [90] used convolutional neural networks to scan heritage buildings; these networks also automatically recorded anomalous images into BIM software to establish architectural heritage pathological shapes. Bazan et al. [91] used BIM to manage the damage, historical restoration information, and maintenance costs of public heritage (HCIM) to improve its sustainability and efficiency. Khan et al. [92] proposed an architectural heritage management information base combining HBIM and facility management (FM), which contained semantic information, maintenance information, and restoration planning. These studies demonstrate that digital management provides a platform for the storage, communication, and application of architectural heritage conservation, and is of great significance in the preservation and transmission of architectural heritage.

Digital application

Data application is a presentation aspect of digital preservation. Digital presentation of architectural heritage affects value interpretation, virtual-real interaction, simulation and dynamic preservation. To better present architectural heritage, several researchers have constructed different technological tools. For example, Bugalia et al. [93] propose a mixed reality (MR) based interactive system that combines computer graphics and VR technologies for real-time monitoring of architectural heritage, which allows users to experience and interact with cultural heritage. Stroscio et al.[94] create thematic maps and analyze data on the properties and decay forms of building material loss to monitor material degradation, building loss and restoration information; the thematic maps also allow Stroscio et al. to query damage information in a parametric way.

As research in architectural heritage preservation gradually moves towards high fidelity and dynamic digital models, digital twin technology also shows great potential within this field. Francoe et al. [95] established a digital twin system through photogrammetry to build a digital preservation system for architectural heritage with databases, meta-universes, VR and gamification methods; as they have suggested their digital twin system should enhance users' auditory and visual experiences and can improve the perception of architectural heritage preservation. Ma et al. [96] took Taiwan's historical buildings as an example and applied the Unity3D platform to build an interactive old city neighborhood information model, which provides dynamic VR simulation of interactive buildings and environments. These technological tools not only enrich the presentation and content of architectural heritage, but also increase public participation and awareness of architectural heritage.

Based on the analysis of the potential of digital preservation of architectural heritage in the disaster cycle and the application of DTech in architectural heritage conservation, it is found that the preservation of architectural heritage follows the frame of "identifying problems—analyzing problems—solving problems", which can be specifically classified into the three steps of disaster pattern identification, architectural heritage awareness and digital preservation. As shown in Fig. 10, architectural heritage is vulnerable to disaster attacks and damages, DTech is like a protective shell to protect architectural heritage under the cycle of disasters by adopting vulnerability assessment, sustainability, resource allocation, model archive, and restoration through three phases of digital recording, digital preservation, and digital application. Our idea aims to identify architectural heritage risks and damage according to different types of disasters, to perceive architectural heritage value and significance, and to select suitable DTech for measures such as prevention, restoration and rehabilitation; by taking this approach, we believe that our idea should achieve the objective of protecting heritage architecture within disasters cycles and moreover, we hope that our idea should offer future research guidance within further investigations.

Future research avenues

This paper explores the applications and challenges of DTech in architectural heritage preservation from a disaster cycle perspective. The literature review shows that architectural heritage preservation is a central topic in several countries and that the integration of multiple disciplines provides an effective means of improving conservation approaches. Digital documentation, sustainable development, preventive preservation and ML are popular topics of research and investigation, while methods such as accurate prediction, AI, human–machine collaboration and Digital Twins (DTwin) will also lead future research trends. However, digital preservation within the context of disasters still faces many challenges.

Accurate prediction of multiple disasters

Architectural heritage is threatened by multiple disasters, including natural, human-induced and climate change-related events, which may occur individually or jointly, resulting in different levels of damage or even loss of architectural heritage. To effectively protect architectural heritage, the accurate prediction of multiple disasters is necessary to assess their vulnerability and risks, devise

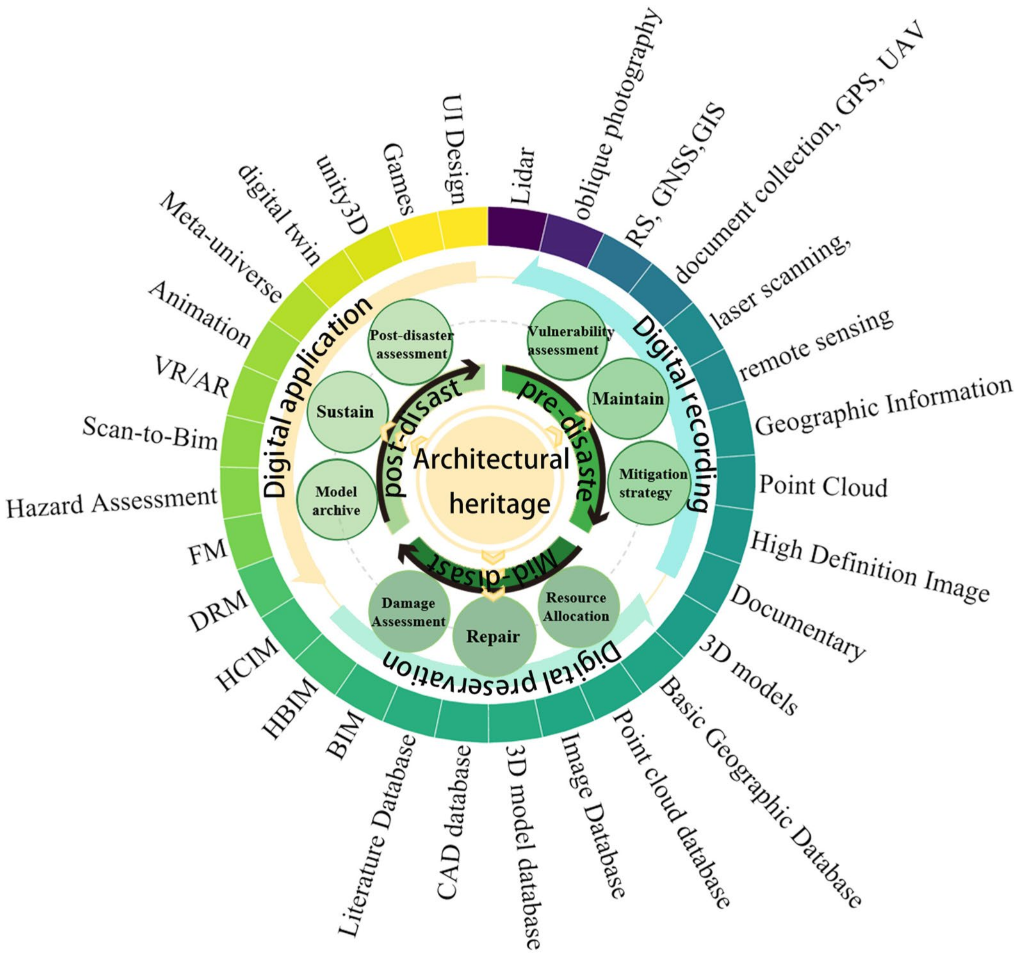


Fig. 10 The application of the digital preservation of architectural heritage under the disaster cycle

preparedness and response strategies, and reduce disaster losses and impacts. DTech offers great advantages in this regard, as it enables the use of big data, AI and the Internet of Things (IoT) to collect and analyze various types of disaster data; establish disaster simulation and early warning systems to achieve dynamic monitoring and accurate prediction of the condition and risk of architectural heritage; and use drone scanning and convolutional neural networks to examine damage to built heritage, shorten the time of manual monitoring, and improve efficiency.

Automatic early warning of building damage

Active measures such as LiDAR, tilt photography, unmanned aerial vehicle (UAV) photogrammetry, Global Positioning System (GPS), GIS, and 3D laser scanning are commonly used to monitor architectural heritage damage, but they cannot provide automatic early warnings. The integration of DTech has the potential to enable automatic early warning systems in terms of building damage and DTech can create a self-aware, self-determined and self-executing system for architectural heritage conservation. Disaster information can be collected and stored through IoT and BIM platforms, and real-time monitoring can be performed using structural monitoring systems and AI technology to provide timely feedback on architectural heritage; Radio Frequency Identification (RFID) technology can be used in conjunction with 5G mobile devices to identify architectural heritage and read/write relevant data using radio wave signals, combined it with real-time photos uploaded by tourists on social media platforms to actively capture damaged areas for increased safety and traceability. indeed, these systems will be able to provide early warning information and can reduce or minimize damage.

Intelligent monitoring with human–machine integration

Architectural heritage preservation can employ technologies that combine virtual reality to create immersive environments for architectural heritage, enabling human–environment interaction and enhancing the public's awareness of the value of architectural heritage. For example, Banfi [97] developed VR and AR environments based on visual programming language (VPL) and BIM to guide the public to interact with the environment and to increase the public's understanding of architectural heritage. Guido [98] introduced a new communication paradigm to build models of architectural heritage using 3D models to give viewers an immersive experience (which enhances participation). Rajcic [99] used the heritage building of the Tesla Museum in Zagreb as an example of an architectural and structural model based on BIM, and proposed the use of reinforced structures for seismic resistance and VR immersive environments to optimize the building and its structure. Chotchaicharin [100] proposed the use of AR and VR within architectural space technology to simulate earthquake scenarios and used AR screen shaking technology to allow participants to experience disaster scenarios. In summary, VR/AR technologies in architectural heritage conservation can provide immersive experiences for participants. With the development of technology, human–machine integration monitoring allows the public to interact with architectural heritage and particularly this technology allows for sensory elements such as sight, sound, touch, smell, and others. Simulating architectural heritage conservation in a multi-dimensional digital model allows for context-aware risk management with architectural heritage information modelling and VR, which in turn enables the digital restoration of architectural heritage using virtual technology.

Limitation

This study has some limitations regarding the data sources and analysis, which are mainly shown in the following two aspects:

First, there are limitations to the data sources. This article uses WOS, the most authoritative and highly influential academic journal database in the world, but Scopus and China national knowledge infrastructure (CNKI) also provide academic literature databases. Therefore, the samples in this article may not fully reflect the whole picture of the field, and in the future, it can be considered to import data from other databases or custom data sources for supplementation.

Second, the analysis software lacks novelty. Vosviewer and Citespace analysis software are widely used, but with the development of digital technology, technologies such as ML and data programming can present more intelligent and accurate data analysis. Therefore, the analysis method in this paper may not be able to make full use of the potential of the data, and it may be considered to develop or use more advanced analysis software for optimization and improvement in the future.

Conclusion

Disasters are one of the main causes of damage to architectural heritage, and DTech is one of the effective means to preserve architectural heritage. A comprehensive understanding of the impact of disasters and the application of DTech is essential to achieve comprehensive preservation of architectural heritage. Based on the PRISMA flowchart, this study reviewed the articles from 2012 to 2022 on the digital preservation of architectural heritage under the disaster cycle, and specifically, we analyzed the hot research topics and development trends of multidisciplinary intersections in terms of universality and typicality. According to the literature analysis, this study proposes a research frame that integrates disaster cycle, DTech and heritage preservation, and explores possible future research directions. The main results of this paper are:

(1) VOSviewer and Citespace software analyzed the papers screened by PRISMA. The analysis revealed that Italy, China, and the US are the main countries for research on the digital preservation of architectural heritage (during disaster cycles), with different emphases on disasters and DTech.The most prolific journals in this field are Sustainability, RS and Applied Science-Basel. The main disciplines involved in this field are Geoscience, Materials Science and Environmental Science. The citation analysis indicated that HBIM modeling is highly regarded and that earthquakes are one of the major threats to the conservation of built heritage. From this it follows that disaster is the driver, architectural heritage is the central object, and DTech is a key tool for digital preservation.

(2) The potential of the digital preservation of architectural heritage within disaster cycles is discussed. The preservation strategies of preventive "maintenance" before disasters, corrective "repair" during disasters, and restorative "sustainable" after disasters are explored. Moreover, based on the keywords, the practical cases of digital preservation of architectural heritage under disasters on different stages of digital preservation were illustrated. It was emphasized that using appropriate DTech according to the different phases of a disaster can lower maintenance costs and achieve the conservation objectives of batching, stratification and classification.

(3) Digital technology can be divided into three stages: digital recording, digital preservation and digital

application. Digital recording can acquire data and characteristics of architectural heritage, identify disaster threats and formulate protection measures. Digital preservation can preserve the information and value of architectural heritage, improve disaster resilience and provide reference for restoration and reconstruction. Digital applications can demonstrate the originality, diversity and sustainability of architectural heritage, achieve multiple effects and enhance public participation. According to the stage of digital technology, choosing the appropriate means of protection of disaster-affected architectural heritage can reduce maintenance costs and prevent unnecessary damage to architectural heritage.

(4) Three potential research directions, namely, (a) accurate prediction of multiple disasters; (b) automatic early warning of building damage and (c) intelligent monitoring with human–machine integration, provide references and insights for future technological innovations and applications to address the remaining challenges of architectural heritage conservation.

Architectural heritage conservation is an important mission and challenge to continue the history of human civilization, a key link between the past, present and future, and an important way to achieve sustainable development. The contribution of this paper is to propose an integrated research idea consisting of disaster pattern recognition, architectural heritage awareness and digital model management, aiming at applying new technologies, methods and concepts to solve the multi-disaster problems of heritage buildings. This will help researchers to quickly identify problems, effectively apply digital technology, save time, energy and money, and provide ideas for architectural heritage research.

Abbreviations

WIPO	The World Intellectual Property Organization
UNESCO	United Nations Educational, Scientific and Cultural Organization
CIPA	The Comité International de Photogrammétrie Architecturale
NHPA	Historic Preservation Act
UK	United Kingdom
BIM	Building Information Modeling
VR	Virtual reality
AR	Augmented reality
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RQ	Research Question
WOS	Web of Science
HDT	Historical Digital Twin
IF	Impact factor
DCA	Literature Co-Citation Analysis
SDGs	Sustainable development goals
TLS	Terrestrial laser scanning
GIS	Geographic information system
FEM	Finite Element Method
DRM	Disaster risk management
IDM	Information Delivery Manual
HCIM	Historical Restoration Information and Maintenance Costs of Public Heritage
FM	Facility management
MR	Mixed Reality
DTech	Digital technology/digital technologies
DTwin	Digital Twins
3D	Three-dimensional
AI	Artificial Intelligence
VPL	Visual programming language
UAV	Unmanned aerial vehicle
CSIC	Spanish Scientific Committee
HBIM	Heritage building information modeling
CDE	Common Data Environment
GPS	Global Positioning System
IoT	Internet of Things
ML	Machine learning
SHM	Structural health monitoring
ICP	Iterative closest point
CNKI	China national knowledge infrastructure
HDT	Historic Digital Twins
DCA	Document co-citation analysis

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Author contributions
LY: conceptualization, methodology, funding acquisition; DY: data curation, writing—original draft; YM: formal analysis, writing—original draft; Lj: methodology, writing—reviewing & editing BH: writing—reviewing & editing. LR: writing—reviewing & editing. AL: reviewing, language and editing. All authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The authors declare no competing interests.

Consent for publication
Not applicable.

Competing interests
The authors declare no conflict of interest.

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