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CAUSES, DETECTION AND REMEDIATION OF WATER-INDUCED BUILDING DEFECTS: A SYSTEMATIC REVIEW

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ABSTRACT

Water ingress in buildings can considerably impact the building and its occupants by compromising structural integrity, health, safety, and financial stability. While existing research has identified common defects associated with water seepage, a comprehensive framework for systematically documenting these issues and their corresponding solutions is currently needed. This study aims to comprehensively review the means of water ingress, its root causes, associated defects, detection methods, and remediation techniques, using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines. A comprehensive search was conducted on articles related to water ingress-related building defects in the Scopus and Web of Science databases. Content and thematic analysis methods were applied to analyze 66 publications. The study identified seven vulnerable building components: exterior and interior walls, facades, roofs, basements, wet areas, and plumbing systems. It was found that cracks, faulty joints, defective fittings, and inadequate waterproofing lead to water ingress, causing structural, aesthetic, and functional damage. Further, detection methods ranging from visual inspections to advanced technologies like thermography and unmanned aerial vehicles (UAVs) were explored and various remedial actions including repairing, replacing, or reconstructing affected elements were suggested. The framework presented in this study provides design and construction professionals with proactive strategies for detecting and remedying water-related defects, offering practical guidelines for informed decision-making to effectively manage building defects linked to water ingress.

Keywords: *Building Defects; Causes, Diagnosis; Maintenance; Systematic Review; Water Ingress.*

1. INTRODUCTION

In the construction industry, one of the main concerns post-constructions is the manifestation of building defects. This issue carries economic implications (Talib & Sulieman, 2020), affects the builders' reputation (Gurmu et al., 2021) and compromises building quality (Jonsson & Gunnelin, 2019). In Australia, building defects cost around $2.5 billion annually with rectification accounting for 75% of the total cost (The Centre for International Economics, 2021). Defects occur due to poor workmanship, non-

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adherence to building design and standards, low-quality materials, and inadequate maintenance (Chong & Low, 2006). Notably, water-related defects are the most prevalent (Chew & De Silva, 2003b). In Australia, 42% of defects are related to water leaks with exterior water penetration and plumbing faults accounting for 40% and 22%, respectively (PICA, 2021).

Water ingress continues to pose significant structural and economic risks (Chew & De Silva, 2002), and contributes to energy loss (Kirimtat & Krejcar, 2018). Rectification costs for water-related defects are 42% in residential buildings and 31% in commercial buildings (The Centre for International Economics, 2021). Additionally, moisture intrusion promotes mould growth, creating unhealthy living spaces (Coulburn & Miller, 2022). Often latent in nature, these defects appear over time and may be overlooked (Chong & Low, 2006), highlighting the need for better understanding and prevention of water ingress.

The existing literature on building defects and water ingress tends to focus broadly on building defects, with limited emphasis on water or plumbing-related issues (Gurmu & Mudiyanselage, 2023). While previous studies have explored the causes and manifestations of this phenomenon in different building areas (Chew & De Silva, 2003a) as well as methods for detecting water or moisture ingress (De Filippo et al., 2023), the literature remains fragmented. Additionally, existing remediation discussions predominantly address defects in a general context (Sandanayake et al., 2022), lacking a comprehensive framework that integrates the causes, resulting defects and remedial strategies for water ingress. Thus, the research gap identified here is twofold: first, there is a need for focused studies on water and plumbing defects; second, a holistic framework linking water ingress causes with defects and remediation strategies is missing. Addressing these gaps will enhance understanding and inform practical strategies for addressing water-related defects. This study will investigate water ingress and develop a framework linking causes, defects, identification techniques, and remediation strategies.

2. LITERATURE REVIEW

Several studies have explored building defects and their causes. Sandanayake et al. (2022) reviewed residential building defects in Victoria, Australia, and found that poor workmanship was the leading cause, responsible for 90% of rectification costs, with waterproofing and water penetration defects having the highest cost implications. However, their study was limited to residential buildings. Talib and Suleiman (2020) categorized defects into latent and non-latent types, noting that dampness from water ingress was the most common latent defect, also contributing to other non-latent defects.

Recognizing water ingress as a major contributor to building defects, several studies have examined water-related issues. Chew et. al (2004) analyzed defects in wet areas in 56 non-residential high-rise buildings in Singapore, identifying 14 common defects, nine of which were linked to water penetration or moisture. These included water leakage, staining, paint defects, concrete spalling, tile debonding, water ponding, and corrosion, with construction deficiencies being the primary cause (43%). Similarly, Chew & De Silva (2003b) found that ceiling leaks accounted for 36% of defects in residential high-rise buildings, leading to fungi growth and paint deterioration. However, these studies predominantly focus only on wet areas of a building. Later research also highlights internal and ceiling leakages as major defects caused mainly by construction issues (Gurmu et. al., 2025).

Studies on basement water seepage have identified plumbing leaks, poor waterproofing, and groundwater changes as key contributors to below-ground defects, which can compromise structural integrity (Chew & De Silva, 2003a). Gurmu and Mudiyanselage (2023) reviewed residential plumbing system anomalies, identifying leakage, clogging, corrosion, damaged pipes, faulty equipment, and poor installation as common causes, along with diagnostic methods for defect identification. However, these studies focus on specific areas - wet zones, basements, or plumbing - rather than providing a comprehensive review of water-related defects across an entire building.

Studies on inspection methods include Kot et al. (2016), who applied electromagnetic waves to detect water infiltration in concrete flat roofs, enabling early identification of moisture content to prevent critical defects. De Filippo et al. (2023) explored the use of UAVs with AI algorithms for defect detection, although their research focused only on identification without addressing causes or remediation. Chong and Low (2006) examined design-related defects in 74 buildings, attributing failures like plaster cracks, staining, and paint peeling to weather, occupant impacts, load, and moisture from wet areas. They offered strategies on material use and water leakage prevention. Ghani et al. (2023) emphasized the importance of planned maintenance and regular visual inspections to reduce the occurrence and impacts of building defects, including water ingress. Accordingly, the existing literature highlights the significant impact of water ingress-related defects in buildings. However, a comprehensive analysis of their causes, implications, and remediation has not been thoroughly explored. Therefore, further research is necessary to gain a holistic understanding of these defects.

3. RESEARCH METHODOLOGY

This study aimed to comprehensively review existing literature on water ingress in buildings, focusing on the causes and associated defects. A stand-alone review approach was adopted, which is effective for summarizing prior research and providing valuable insights (Templier & Paré, 2015). The research utilized a systematic literature review (SLR), a structured and transparent method that enhances the quality, replicability, reliability, and validity of findings (Xiao & Watson, 2019). Following the SLR guidelines outlined in Xiao and Watson (2019), the study defined its scope, searched and screened relevant literature, extracted and analyzed data, and reported the findings. It focused on building defects and water ingress, using Scopus and Web of Science (WoS) databases, which are widely recognized for comprehensive coverage (Sandanayake et al., 2022). A rigorous review protocol was established, following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework as shown in Figure 1.

The literature search keywords were based on research themes and included commonly used synonyms. The search string for Scopus was TITLE-ABS-KEY ("building*") AND TITLE-ABS-KEY ("defect*") AND TITLE-ABS-KEY ("water") OR TITLE-ABS-KEY ("moisture") AND TITLE-ABS-KEY ("ingress") OR TITLE-ABS-KEY ("leak*") while a similar string was used for WoS as ("building*" AND "defect*" AND ("water" OR "moisture") AND ("ingress" OR "leak*")). The asterisk was used to include all possible variations of relevant search terms.

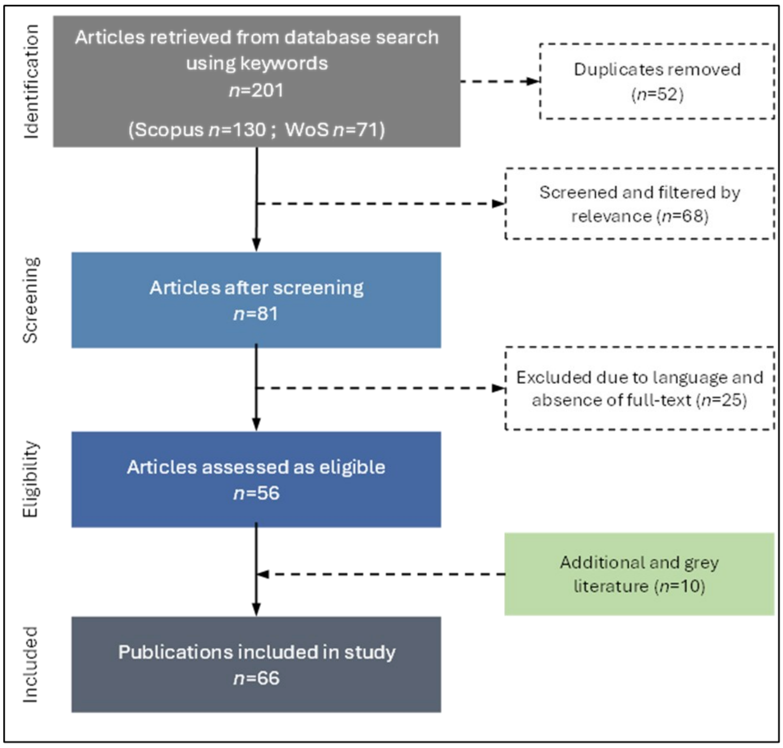

Figure 1: Article screening and eligibility assessment protocol – PRISMA Flowchart

The search focused on scientific publications, including journal papers, conference papers, books, and book chapters. Scopus yielded 130 records, and Web of Science (WoS) provided 71, totalling 201 records as of October 2023. After removing 52 duplicates, titles and abstracts were screened, excluding 68 irrelevant publications. Further, 25 non-English or unavailable full-text papers were removed, leaving 56 eligible for analysis. Additionally, 10 grey literature sources from government and private organizations were included. Ultimately, 66 publications were reviewed, comprising 42 journal articles, 18 conference papers, 1 book section, and 5 reports. The research used content analysis to organize and categorize articles, identifying patterns related to building defects caused by water ingress (Bengtsson, 2016). The literature findings were categorized into five main areas: (1) means of water ingress into buildings, (2) causes of water ingress and associated defects, (3) defects caused by water ingress, (4) methods of detecting water ingress, and (5) remediation techniques.

The research employed thematic analysis to synthesize the data and identify emerging themes (Clarke & Braun, 2017). A defect and cause table was created in Microsoft Excel to analyze the causes, related defects, and remediation for each component, while detection methods were analyzed separately.

4. RESULTS AND DISCUSSIONS

The review of articles identified key themes related to water ingress in buildings, including the most vulnerable building components, associated defects, detection methods, and remediation techniques. The findings highlight the vulnerabilities of these components and discuss the multifaceted nature of water ingress, offering potential remediation strategies for the construction industry. Figure 2 presents the framework developed based on the SLR of existing literature. Detailed discussions of the framework are provided in the subsequent sub-sections.

Figure 2: Framework for water ingress into buildings

4.1 MEANS OF WATER INGRESS

Water ingress in buildings manifests in different forms, affecting structural integrity and indoor air quality. Sahi et al. (2022) categorize water ingress into three types: water penetration/leakage, moisture/dampness, and airborne particles (aerosol). The causes and defects related to these types vary depending on the building component. Studies have identified seven key vulnerable areas where water ingress occurs, including exterior and interior walls, basements, wet areas (ceilings and floors), roofs, building façades, and plumbing systems.

Exterior walls act as a barrier between indoor and outdoor environments, making them vulnerable to water infiltration, especially when construction deficiencies and deteriorating materials create pathways for moisture to enter (Talib & Sulieman, 2021). Similarly, building façades, which include cladding, windows, doors, and balconies, are crucial in preventing water ingress. Inadequate weatherproofing and faulty installation of façade components can lead to water infiltration and allow moisture and airborne particles to enter (Jonsson & Gunnelin, 2019). Interior walls, designed as partitions, can retain moisture if leaks or cracks compromise the building envelope (Yu et al., 2023).

The most common areas in which water ingress in buildings are wet areas, including bathroom, kitchen, and utility room floors and ceilings, due to their frequent exposure to moisture (Chew, 2005). Water penetration in these areas is often linked to structural damage and mould growth (Chong & Low, 2006). Roofs, another key defence against environmental elements, are also prone to water infiltration, leading to leaks and moisture issues (Kot et al., 2016). Basements are at high risk due to groundwater seepage and construction defects, which can severely affect structural integrity (Chew & De Silva, 2003a). The plumbing system, including water supply, drainage, and water tanks, is a major source of water ingress, with leaking pipes and poor drainage contributing to water damage and indoor air quality problems (Gurmu & Mudiyanselage, 2023). The next section will explore the defects and causes linked to these building components.

4.2 DEFECTS THAT CAUSE WATER INGRESS INTO BUILDINGS

Exterior walls often give way to water penetration due to structural defects such as cracks or gaps, faulty building joints, and porosity in the materials used for construction. These defects are commonly induced by structural movements, poor construction practices and material use, while inadequate waterproofing further encourages greater water absorption (Talib & Sulieman, 2021). Defects identified in building facades include anomalies in balconies, windows and door seals which create air and moisture gaps (Crean, 2017). These defects are often attributed to environmental exposure such as high winds, UV radiation and rain, and defective installation and materials (Cladding Safety Victoria, 2023). Similar to exterior walls, interior walls are also susceptible to cracks resulting from structural and construction deficiencies. Additionally, improperly sealed gaps where the wall is penetrated by plumbing or other fixtures highlight the need for meticulous installation practices (Singh et al., 2011). Furthermore, high humidity and condensation due to restricted airflow contribute to moisture retention in indoor spaces which have been linked to the deterioration of wall finishes (Felipo & Charpin, 2022).

While its characterisation implies the presence of water, anomalies such as water leakage from faulty pipes and cracks in the floor or wall joints due to poor workmanship and excessive moisture absorption pose added risks in wet areas (Sahi et al., 2022). Additionally, design defects leading to water ponding, along with inadequate drainage and waterproofing issues, highlight the importance of thorough inspection and repair protocols (Chew & De Silva, 2003b).

The roof presents susceptibility to water ingress through the manifestation of cracks and material deterioration due to high exposure to environmental conditions and construction deficiencies. Inadequate attention to specifications also causes defects in construction joints and drainage resulting in water penetration into the building (Pamera & Gurmu, 2020).

Cracks in the foundation often induced by structural movements or poor construction practices and faulty joints serve as conduits for water and moisture penetration in basements. Additionally, the lack of good airflow in these spaces intensifies moisture retention (Chew & De Silva, 2003a). Similarly, there are several common defects associated with water ingress within the plumbing system. The defects associated with water supply are water leakage due to faulty pipes or fixtures, corrosion of pipes and overflowing tanks (Gurmu & Mudiyanselage, 2023). Pipe leakage was identified as the most commonly occurring defect. The defects related to sanitary drainage include defective water trap seals and sewer backflow resulting from defective installation, which has been linked to the dispersion of contaminated aerosolized particles and the transmission of pathogens, with severe health implications (VBA, 2023). Additionally, the incorrect discharge of stormwater from the roof and defects in swimming pool structures caused by defective design and installation are also identified as contributing to water ingress.

The defects that encourage water ingress in buildings are often physically evident; however, they may not always be visually distinct. Overall, the defects discussed above were identified as commonly associated with issues relating to inadequate design, low-quality material use, poor workmanship and lack of regular maintenance of buildings. The origin of these defects could further be linked to the designers, contractors, material suppliers and maintenance contractors (Chong & Low, 2006). However, similar to the findings by Chew (2005) and Chew and de Silva (2002), most causes were attributed to the construction stage, particularly deficiencies or non-adherence to construction standards and attention to detail. Nevertheless, understanding the root causes of these defects is necessary for implementing effective remediation strategies.

4.3 DEFECTS CAUSED BY WATER INGRESS

Water ingress, caused by defects in building structures, leads to additional issues such as structural, aesthetic, and functional defects. Structural defects are defined as issues that compromise the structural integrity and stability of a building. Water and moisture in buildings have been identified as causing deterioration of building materials and corrosion of structural components leading to the weakening of the overall structure (Singh et al., 2010). Aesthetic defects refer to damages primarily affecting the appearance of the building. Water ingress not immediately visible to the occupants is often first visible through defects in the paint/plaster such as peeling, blistering or flaking on walls and ceilings, discolouration of surfaces and increasing efflorescence. These defects occur as a result of water seepage and excessive moisture absorption on surfaces (particularly those in proximity to wet areas), which also lack sufficient waterproofing (Chew & De Silva, 2002). While they may not directly compromise the structural integrity of a building, they significantly impact its visual appeal and are typically common visual indicators of water damage.

Functional defects impact the usability of the building, affecting the comfort, convenience as well as health and wellbeing of its occupants. Water ingress has been associated with electrical system malfunctions and plumbing defects caused by corroding pipes which are both functional and safety hazards (Law et al., 2021). However, it is more commonly associated with the growth of toxic mould and algae on surfaces exposed to moisture and dampness which is a significant health hazard in most affected buildings (Felipo & Charpin, 2022). Water ingress in indoor spaces, combined with low ventilation can create a suitable environment for fungal growth and once established, could affect material with low moisture content (Talib & Sulieman, 2020). This has been linked to respiratory issues and allergies among exposure to other health risks, leading to 'sick buildings' (Singh et al., 2010). Additionally, the presence of water could also encourage insect infestations and the breeding of mosquitos (Singh et al., 2010). These defects highlight the significance of this issue and the immediate need to address them. Thus, it is important to identify these defects such that the root cause or origin can be addressed to ensure the functionality and structural integrity of the building. The following section discussed methods of detecting water ingress and associated defects.

4.4 DETECTION METHODS

The literature identifies various methods for detecting water ingress or damage, with a focus on non-destructive techniques. These methods differ in the technology used but all aim to identify affected areas and determine the underlying causes of water-related issues. The most traditional method to detect water ingress is through regular visual inspection (Bortolini & Forcada, 2018). This refers to visually examining different components of a building for signs of water leaks, staining, dampness, condensation, mould or algae growth and corrosion (Wahab & Hamid, 2011). It also serves as the initial step in diagnosing potential defects, to guide further investigation or testing, if needed. However, effective inspection and results rely on the expertise and experience of the inspector (Gurmu & Mudiyanselage, 2023). Other traditional testing methods include the use of moisture meters and electrical resistance or conductivity tests, which are both low-cost strategies for measuring moisture in building materials (Phillipson et al., 2007).

Thermography and microwave technology are non-destructive methods that can be used to detect water ingress and related defects that are not visually evident. Thermography detects variations in surface temperature based on thermal properties, which can reveal underlying dampness or water within the structure (Pamera & Gurmu, 2020). Similarly, microwave technology allows areas of leakage due to cracks in concrete structures (Kot et al., 2016). This could be a more effective method if used together with thermography, where the water-ingress areas can be more easily detected due to the specific temperature distribution caused by microwave heating (Barreira et al., 2013). However, the level of moisture content cannot be evaluated with these methods (Phillipson et al., 2007). More recent innovations include the use of UAVs and robotic technology to diagnose defects, particularly on building facades. These methods can provide 3D visual and thermal data and locate points of air or moisture leakage more accurately, thereby, reducing operational costs and safety risks (De Filippo et al., 2023). These methods are most suitable for inspection of high-rise buildings.

In addition to visual inspection, defects in the plumbing system can be diagnosed using specialized equipment and testing methods. Water leaks and faulty pipes could be identified using hydrostatic pressure tests. Additionally, infrared cameras combined with listening devices such as leak detectors and leak loggers can be used to isolate points of ingress, particularly in inaccessible areas, such as underground piping and within walls and slabs (Gurmu & Mudiyanselage, 2023). Water trap seals within the sanitary drainage system have been previously tested using air pressure transient simulation in building drainage and vent systems. This operates similarly to a sonar system, reflecting air pressure waves off drainage boundaries, and revealing defective seals (Swaffield, 2005). The detection of defective water trap seals can be significant in preventing cross-contamination and the spread of infectious diseases.

4.5 REMEDIATION OF WATER-RELATED DEFECTS

The above sections discussed the causes and defects of water ingress in buildings, along with methods for detecting and addressing them. The required remedial actions such as repair, replacement, or management depend on the stage at which the defects are diagnosed. Nevertheless, the foremost step would be to control water ingress at the source or remove the source (Singh et al., 2011). To do this, the results suggest that the most common method is to seal sites of infiltration or repair defects that could lead to water ingress in the future. This includes repair or replacement of defective elements and substandard material (Chong & Low, 2006) and appropriate application of waterproof coatings or sealant. Waterproofing is a key step in the construction process which limits moisture levels on building surfaces, preventing water-related aesthetic and structural damage. It also protects against the growth of toxic moulds. However, if there is existing evidence of dampness or mould, immediate remediation is necessary to minimize health risks to the occupants. The most effective strategy in this instance is cleaning or treating affected surfaces by chemical means and improving ventilation and airflow (Singh et al., 2010). Humidity control and maintenance of HVAC systems could further address issues and defects associated with condensation and moisture retention (Wang & Yin, 2019).

The defects previously discussed also revealed design and construction-related causes due to possible non-compliance with standards and guidelines. Some of these defects may require design improvements or reconstruction of the related elements to rectify the damages. This highlights that many building defects are not merely symptoms of isolated workmanship issues but are indicative of more systemic shortcomings in design decision-making, quality assurance practices, and regulatory enforcement. The identified defects, such as water ingress, concrete cracking, and joint failures, signal a disconnect between design intentions and construction execution. These issues may also reflect a lack of robust feedback mechanisms from post-construction performance data into future design and specification standards. Thus, the findings from this SLR could inform a design-feedback framework, where recurrent defects become catalysts for revising design protocols, detailing practices, and material selections, thereby preventing recurrence in future projects.

Additionally, remediation must be undertaken following the appropriate design and construction specifications (Chong & Low, 2006). Furthermore, building defect investigations often take place following signs of damage that might hinder the functionality of the building, requiring extensive repair which is both time-consuming and costly. This can be avoided by regular inspection and appropriate maintenance of the building (Talib & Sulieman, 2021). Maintenance that is unplanned and occurs following defect diagnosis to rectify the defect and its causes is referred to as corrective maintenance. Conversely, preventive maintenance involves planned strategies to minimize the materialisation of such defects. Of these, preventive maintenance is identified as the most suitable and effective strategy to ensure the long-term structural and functional integrity of the building (Ghani et al., 2023). Thus, it can be noted that preventive maintenance of buildings together with good construction practices could limit water-related defects and the need for defect remediation.

4.6 IMPLICATIONS OF THE STUDY

This research enhances the theoretical understanding of water ingress in buildings by systematically examining its causes, related defects, identification methods, and remediation strategies. It proposes a comprehensive framework that connects these elements, offering a theoretical model for addressing this complex issue and forming a foundation for future research in building maintenance and pathology. By integrating knowledge from engineering, construction management, and materials science, the study strengthens the interdisciplinary foundation related to building defects and water ingress.

The research also offers valuable insights for architects, engineers, and construction professionals by identifying common causes and defects associated with water ingress. The findings support improvements in building design, material selection, and construction techniques to mitigate water intrusion risks. The framework can improve maintenance and inspection processes, enabling early detection and resolution of water ingress issues, thereby extending the building's lifespan. By linking specific causes to effective remediation strategies, the study provides practical guidance for developing cost-effective repair plans to prevent structural and aesthetic damage.

5. CONCLUSION

Water ingress in buildings poses significant challenges to the construction industry, impacting structural integrity, indoor environmental quality, and occupant well-being. This review comprehensively analyzed defects linked to water ingress, highlighting causes, resultant defects, and remediation strategies. Key vulnerable components identified include exterior and interior walls, façades, roofs, basements, wet areas, and plumbing systems. Defects such as cracks, faulty joints, material deterioration, and inadequate waterproofing contribute to water penetration and typically arise from issues in design, workmanship, materials and maintenance. Water ingress leads to structural, aesthetic, and functional problems, affecting building stability and appearance. Detection methods range from visual inspections to technologies like thermography and UAVs. Remediation involves sealing, repairing, replacing, or redesigning affected elements, with preventive maintenance being essential to prevent future defects and maintain a healthy environment. The study emphasizes the need for better design and construction practices and greater awareness of the impacts of poor workmanship and maintenance. Findings can guide contractors, architects, and engineers to prevent water ingress and support building owners and managers in developing proactive maintenance strategies to reduce costs and minimize occupant disruption. Although the study offers a framework for understanding water ingress causes, defects, and remediation, it relies on existing research and may not capture all defects or regional variations. Future research could examine specific building components in greater depth and contribute to improved construction standards and diagnostic tools.

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