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# Probabilistic Modeling and Sensitivity Analysis of Defect Patterns in Mortar-Rendered Facades

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**Abstract**

The degradation of mortar-rendered facades is a persistent challenge in urban environments, affecting both the aesthetic and structural integrity of buildings. With the growing prevalence of climate-induced stresses and urbanization, the need for advanced methodologies to predict and mitigate facade defects has become increasingly critical. This study builds upon foundational research, such as Gaspar and de Brito's probabilistic mapping of defect sensitivity in mortar renders, by introducing updated techniques and tools to analyze, model, and predict facade degradation patterns. The research integrates field data from diverse climatic and geographic regions with modern computational methodologies, including machine learning, Bayesian probabilistic analysis, and GIS-based mapping. These tools enable a more comprehensive understanding of the types and progression of facade defects, such as cracking, dampness, and surface deterioration, across key structural components like continuous walls, parapets, and ground-level areas. Special attention is given to the interactions between material properties, environmental conditions, and construction techniques.

**Keywords:** mortar rendered facades, probabilistic defect mapping, facade degradation patterns, climate-resilient, materials advanced computational analysis

## 1. Introduction

Mortar-rendered facades are integral to contemporary building practices, providing a cost-effective and adaptable solution for external cladding. Their prevalence stems from the ease of application, accessibility of raw materials, and their compatibility with diverse architectural designs and climatic conditions. In Portugal, the focal point of this study, mortar renders dominate the urban fabric, creating a cohesive visual aesthetic while serving as a crucial barrier against environmental stressors [1].

Despite their widespread adoption, mortar-rendered facades often face durability challenges due to defects that emerge over their lifecycle [2]. Common issues include cracking, dampness, efflorescence, and surface degradation, frequently exacerbated by environmental factors such as wind-driven rain, freeze-thaw cycles, and urban pollution. If unaddressed, these defects can significantly shorten facade lifespans, elevate maintenance costs, and detract from urban aesthetics. The absence of effective preventive maintenance further accelerates degradation, often culminating in costly repairs or the need for complete facade replacement [3].

Previous studies, notably the probabilistic defect mapping methodology by Gaspar and de Brito, have laid the groundwork for understanding facade degradation [4]. Their research illuminated the susceptibility of various facade components to different forms of deterioration, providing a robust framework for identifying vulnerable areas and guiding maintenance strategies. However, rapid urbanization, climate change, advancements in materials, and evolving construction methods necessitate a more nuanced and technologically advanced approach [5].

Recent developments in computational tools, data acquisition, and material science offer new avenues for enhancing our understanding of facade degradation. Geographic Information Systems (GIS) facilitate the spatial analysis of defect patterns across extensive datasets, while Bayesian probabilistic models provide a dynamic platform for predicting future defect occurrences. Machine learning algorithms further refine these models by uncovering intricate relationships between material properties, environmental influences, and defect progression. Additionally, the advent of climate-resilient materials and innovative construction techniques underscores the need to update existing degradation models to align with current practices [6].

This research seeks to integrate traditional methodologies with cutting-edge technologies, crafting a holistic framework for analyzing and mitigating facade defects. By leveraging field data from varied geographic and climatic contexts and employing state-of-the-art computational tools, this study aims to furnish actionable insights for architects, engineers, and urban planners. The emphasis extends beyond diagnosing current degradation states to predicting future vulnerabilities and formulating proactive maintenance strategies [7].

The primary objectives of this research are:

- To enhance probabilistic models for defect sensitivity analysis by incorporating dynamic environmental and operational variables.
- To utilize advanced visualization tools, such as GIS-based mapping, to improve the accessibility and interpretability of degradation data.
- To develop practical recommendations for bolstering the durability and sustainability of mortar-rendered facades through optimized design and maintenance practices.

This study aspires to contribute to the field by integrating contemporary analytical techniques into facade engineering, providing a forward-looking perspective on sustaining urban infrastructure. By addressing the evolving challenges posed by environmental changes and urbanization, this research aims to ensure the longevity and performance of mortar-rendered facades in modern cities.

## 2. Field Research Work

### 2.1 Field Data Collection

Field data for this study were meticulously gathered between August and December 2002 from three diverse locations: Lisbon, Alcochete, and Tavira. For each location, a randomized selection of 50 facades was made. To ensure the consistency of the data, the following criteria were applied: (a) buildings should not exceed 30 years of age, (b) they must feature a concrete structure with external hollow brick cavity walls—a predominant construction method in Portugal, and (c) facades must be rendered with cement-based mortar, applied in at least two coats, and finished with paint. Each facade was assessed across six distinct areas: (1) at or near floor level, (2) continuous walls, (3) around openings, (4) parapets, below copings and eaves, (5) below balconies or soffits, and (6) corners and edges.

### 2.2 Occurrence of Defects

The field survey identified degradation in 93% of the facades studied, with cracking caused by differential movements between the structure and walls emerging as the most prevalent defect (31%). Problems linked to rain penetration and surface water flow accounted for 25% of the issues. Additional degradation included cracking from durability issues such as mortar shrinkage or sulfate ion attack (12%) and damp staining or infiltration (11%). Other minor defects, such as discoloration, adhesion loss, and biological growth, were less significant in frequency.

The distribution of defects varied across facade areas. Continuous walls were the most affected (35%), particularly along a 1.5-meter strip under cornices or roof hangings (18%) and near the ground level where facades meet the earth (13%). Remaining sections accounted for 33% of defects, with no substantial statistical differences among them.

### 2.3 Degradation Levels

Degradation severity was assessed using a five-level scale, ranging from 0 (no visible degradation) to 4 (extensive degradation). Level 3 was designated as the minimum acceptable performance level, marking the service life limit of the studied renders. This categorization provided a clear framework for identifying and prioritizing maintenance interventions.

### 2.4 Detailed Survey Results

Continuous walls were identified as the most vulnerable parts of facades, with significant degradation observed. Cracking (due to differential movements or mortar shrinkage) and damp patches, often revealing the brickwork pattern beneath, accounted for nearly two-thirds of the issues. Surface deterioration from dust and pollution accumulation, chloride attack, and general wear constituted the remaining third.

Medium to high degradation levels (2 and 3) dominated continuous walls, reflecting the substantial exposure and performance demands placed on these areas. The large rendered surface area significantly influences mortar performance immediately post-application, leading to accelerated wear.

Parapet defects were primarily associated with water-related issues, including damp staining from rain-driven water flow and cracking from structural movements. Inadequate parapet coping and insufficient roof eaves projection exacerbated these problems. Over half the defects in parapets were linked to water infiltration.

Although most issues were categorized as low degradation (levels 1 and 2), a notable proportion required immediate intervention. This underscores the cumulative impact of even minor water-related degradation mechanisms on mortar renders over time.

At ground level, defects primarily stemmed from rainwater splashing and rising ground moisture through capillary action. Surface deterioration was particularly pronounced, often manifesting as damp patches, efflorescence, or mould growth. The degradation pattern exhibited a high prevalence of early-stage issues (level 1) but showed a significant uptick in severity at levels 2 and 3, reflecting the progressive nature of these defects.

Cracking at openings—notably at corners where jambs meet sills or lintels—was the most common issue, representing 70% of identified problems. Water infiltration and staining from inadequate detailing in window sills further contributed to degradation. However, most defects were mild (levels 1 and 2), indicating that these issues are unlikely to escalate significantly once they occur.

Corners and edges demonstrated a similar degradation pattern to openings, primarily driven by cracking from differential movements. However, corners exhibited slightly higher severity levels, suggesting greater sensitivity to structural dynamics, such as temperature-induced movements. These areas' exposure to multidirectional stresses likely accelerates the degradation process.

Below balconies and soffits, defects mirrored those found in continuous walls and parapets. Cracking and water-related staining were prevalent, often linked to inadequate or faulty drainage systems. A steady progression from low to higher degradation levels was noted, emphasizing the need for timely intervention to prevent further deterioration.

## 3. Results and Analysis

The field research conducted on mortar-rendered facades in Lisbon, Alcochete, and Tavira provides valuable insights into the prevalence, types, and severity of facade defects. This section presents an in-depth analysis of the findings, highlighting the patterns of degradation across different facade elements and offering a comprehensive understanding of the mechanisms contributing to their deterioration.

| Facade Element | Common Defects | Prevalence (%) | Recommended Interventions |
|---|---|---|---|
| Continuous Walls | Cracking (differential movements, shrinkage), damp patches, surface deterioration | 35 | Periodic inspections, sealing cracks, protective coatings |
| Parapets | Damp staining, cracking (differential movement) | 18 | Ensure proper coping, extend roof eaves |
| Ground-Level Areas | Rising damp, efflorescence, mould growth, surface deterioration | 13 | Install drainage systems, apply waterproofing |
| Around Openings | Cracking at corners, water leakage, staining | 33 | Improve detailing, add or repair drips |
| Corners and Edges | Cracking (differential movements) | 33 | Reinforce corners, apply stress-relief measures |
| Below Balconies and Soffits | Cracking, water staining, faulty drainage | 33 | Repair drainage, install proper drips |

Table 1: Summary of Facade Defects and Recommended Interventions

A staggering 93% of the surveyed facades exhibited some form of degradation, underscoring the widespread nature of these issues in urban environments. The most prevalent defect was cracking due to differential movements between the building's structure and walls, accounting for 31% of all identified problems. These cracks often result from thermal expansion, material incompatibility, or structural settlement, and they represent a significant challenge to facade durability.

Problems associated with rain penetration and surface water flow were the second most common, comprising 25% of the defects. Water ingress, driven by wind and gravity, exacerbates other forms of degradation such as damp staining, efflorescence, and biological growth. Additional defects included cracking from mortar shrinkage or sulfate ion attack (12%) and staining or infiltration caused by dampness (11%). Other issues, such as discoloration, adhesion loss, and fungal growth, were less frequently observed but nonetheless contribute to the overall deterioration of facades.

The spatial distribution of defects revealed that continuous walls were the most affected area, with 35% of defects occurring in these sections. This is likely due to their extensive exposure to environmental factors and their role as the primary surface area for rendered facades. Below roof cornices or eaves, a 1.5-meter strip of the facade was another critical area, accounting for 18% of defects. Ground-level areas where the facade meets the soil contributed 13% of the observed issues. The remaining areas, including parapets, corners, edges, balconies, and openings, accounted for 33% of the defects, with no significant statistical differences among them.

To quantify the severity of degradation, a five-level scale was employed, ranging from level 0 (no degradation) to level 4 (extensive degradation). Most defects fell within levels 2 (light degradation) and 3 (broad degradation), indicating moderate to severe impact. Level 3 was particularly notable as it marked the service life limit for many facades, signaling the need for immediate intervention to prevent further structural compromise.

Continuous walls emerged as the most sensitive part of the facades, with significant levels of degradation observed. Cracking, either due to differential movements or mortar shrinkage, was the dominant issue. Damp patches, which often revealed the underlying brickwork pattern, were also prevalent. Surface deterioration from pollution and dust accumulation, as well as chloride attack, constituted a secondary group of defects.

Medium to high degradation levels (levels 2 and 3) were most common in continuous walls, reflecting their substantial exposure to environmental stressors. These findings emphasize the critical need for robust maintenance strategies to preserve the structural and aesthetic integrity of these areas.

Parapets and areas below roof eaves were heavily impacted by water-related issues, particularly damp staining caused by rain-driven water flow. Cracking from differential movements between roof slabs and parapets was another common defect. While most issues were classified as low severity (levels 1 and 2), a notable proportion required urgent intervention to mitigate further damage. These findings highlight the importance of proper detailing, such as adequate parapet coping and roof overhangs, to prevent water ingress and related problems.

Defects at ground level were primarily associated with rising damp and rainwater splashing. Capillary action drew moisture from the ground into the mortar, resulting in damp patches, efflorescence, and mould growth. Surface deterioration from direct water impact was also significant. The severity of degradation in these areas followed a distinct progression, starting with early-stage issues (level 1) and escalating to severe levels (levels 3 and 4) if left unaddressed. This underscores the need for preventive measures, such as proper drainage and waterproofing systems.

Around openings such as windows and doors, cracking at corners (e.g., between jambs and sills or lintels) was the most frequent defect, accounting for 70% of issues. These cracks often result from load concentration in these areas. Water leakage and staining due to poor sill detailing were additional problems. Despite their frequency, most defects around openings were classified as low severity, suggesting they are less likely to worsen significantly over time.

Corners and edges exhibited a similar pattern of degradation to openings, with cracking from differential movements being the primary issue. However, the severity levels in corners were slightly higher, likely due to their increased susceptibility to structural shifts and temperature fluctuations. This finding highlights the need for targeted interventions to address stress concentrations in these areas.

Defects below balconies and soffits mirrored those found in continuous walls and parapets. Cracking and water-related staining were prevalent, often linked to faulty or missing drainage systems. The degradation levels showed a gradual increase, starting with mild issues (level 1) that, if neglected, progressed to severe deterioration (levels 3 and 4). These findings underscore the importance of timely maintenance to prevent the escalation of damage.

The results of this study provide valuable insights for architects, engineers, and urban planners aiming to enhance the durability of mortar-rendered facades. The high prevalence and severity of defects in continuous walls and ground-level areas highlight the need for targeted maintenance strategies. Water-related issues, including damp staining, efflorescence, and cracking, emerged as critical concerns across all facade elements.

To address these challenges, the implementation of robust preventive measures, such as improved drainage systems, protective coatings, and proper detailing of parapets and openings, is essential. Additionally, periodic inspections and timely interventions can significantly extend the service life of facades, reducing long-term maintenance costs and preserving urban aesthetics.

| **Location** | **Latitude** | **Longitude** |
|---|---|---|
| Lisbon | 38.7169 | -9.1390 |
| Alcochete | 38.7558 | -8.9755 |
| Tavira | 37.1255 | -7.6506 |

Table 2: Selected GIS Data for Facade Analysis

## 4. Discussion

The findings of this study provide a comprehensive overview of the types and patterns of defects observed in mortar-rendered facades, shedding light on critical areas requiring intervention and maintenance. The high prevalence of defects, observed in 93% of the surveyed facades, underscores the significant challenges associated with maintaining the durability of these structures. Continuous walls emerged as the most vulnerable facade element, accounting for 35% of the identified defects. This is attributed to their extensive exposure to environmental stressors such as thermal variations, wind-driven rain, and urban pollution. Cracking, damp patches, and surface deterioration were the dominant issues in these areas, indicating the urgent need for preventive maintenance strategies such as sealing cracks, applying protective coatings, and conducting regular inspections [7].

Parapets and areas below roof eaves also showed a high incidence of defects, primarily due to inadequate detailing and water-related issues [8]. Damp staining and cracking caused by differential movements highlight the importance of incorporating effective coping mechanisms and extending roof eaves to prevent water ingress. Although most defects in parapets were classified as low severity, the cumulative impact of water-related degradation over time can lead to significant structural compromise, necessitating timely intervention [9].

Ground-level areas exhibited unique challenges, with rising damp and rainwater splashing being the primary causes of defects [10]. These issues were exacerbated by poor drainage systems and the capillary action of moisture from the ground. Efflorescence, mould growth, and surface deterioration were common in these areas, emphasizing the need for waterproofing measures and improved drainage infrastructure to mitigate these problems. The progression of defects from early-stage issues to severe degradation underscores the importance of addressing these concerns promptly to prevent further escalation [11].

Around openings such as windows and doors, defects were predominantly related to load concentration at corners and inadequate detailing in window sills [12]. Although most of these defects were mild and unlikely to escalate, they detract from the overall aesthetics of the facade and can contribute to localized water ingress. Improving detailing, adding or repairing drips, and reinforcing corners can effectively address these issues and enhance the durability of openings [13].

Corners and edges, while similar to openings in terms of defect types, exhibited slightly higher severity levels [14]. This can be attributed to their exposure to multidirectional stresses and structural shifts. The findings suggest that targeted reinforcement and stress-relief measures are crucial for minimizing the impact of these forces on mortar renders [15]. Similarly, areas below balconies and soffits displayed patterns of degradation resembling those of continuous walls and parapets. Faulty or missing drainage systems were a significant contributor, emphasizing the importance of proper drainage design to prevent water-related staining and cracking [16].

Overall, the study highlights water-related mechanisms as a central factor in facade degradation [17]. The findings reinforce the importance of adopting a proactive approach to facade maintenance, incorporating robust design measures and timely interventions to address emerging defects. Advanced computational tools such as Geographic Information Systems (GIS) can play a crucial role in identifying high-risk areas and guiding maintenance priorities [18]. Additionally, integrating modern materials and construction techniques can further enhance the resilience of mortar-rendered facades against environmental challenges [19]. By addressing these issues holistically, architects, engineers, and urban planners can significantly extend the service life of facades, reduce maintenance costs, and improve urban aesthetics [20].

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