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Inspection and diagnosis system for rendered walls

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Abstract

This paper presents an inspection and diagnosis system customized for rendered walls, both interior and external. It classifies all anomalies capable of affecting renderings and most of the likeliest corresponding causes and is supplemented by anomaly-cause and inter-anomaly correlation matrices. In addition, the diagnosis, repair and maintenance techniques suitable for these anomalies are classified. Examples of the files that contain the exhaustive characterization of the anomalies and diagnosis, repair and maintenance techniques are also presented.

The system is the result of an intense literature review, which allowed collecting and organizing the information available on pathology of renders. Next it was validated by mathematical manipulation of the data collected from standard inspections of 55 buildings, in which 150 renderings (100 exterior and 50 interior) were examined.

The system proposed may be included in a proactive maintenance strategy, since it is robust, reliable and has been statistically validated. The systematic structure of this system is innovative and can help the inspector by making his/her work more objective and standardizing procedures.

Anomalies in wall renderings may be prevented/minimized if buildings are properly managed by developing and implementing proactive maintenance plans that cover the following areas: technology (adequate maintenance and repair solutions, including the selection of materials and execution techniques), economy (minimizing running costs) and functionality (appropriate use).

Keywords: *Inspection and diagnosis system, Rendering, Anomalies, Causes, Diagnosis, Rehabilitation.*

1. Introduction

Renderings are essentially inorganic wall coatings and they have proved invaluable since ancient times for smoothing finishing masonry and protecting it against attack by climatic agents. The performance of rendering depends on the nature and state of the substrate, the characteristics of the component materials, the way the render is prepared and applied and the surrounding environmental conditions. Rendering should meet certain requirements to guarantee its quality. The most important are: aesthetics; workability and consistency; water retention; water vapour permeability; adherence to and compatibility with the substrate; mechanical, shock and cracking resistance, and durability.

According to the Census performed in 2001, renderings are the type of coating most widely used in Portugal, especially on the outside of buildings. Their economic importance to construction is indicated by the fact that 13% to 17% of all construction added value is accounted for by masonry works with coatings. Only concrete structures exceed this figure. The impact of coating anomalies on people and their welfare is also emphasized. The condition of the rendering directly influences the health of a building, user comfort, expenditure on energy for thermal insulation and the aesthetics of the built heritage, which has enormous bearing on the economic and social value of the neighbouring area.

This paper concerns interior and exterior renderings of the traditional and non-traditional/single-layer types.

Traditional rendering is here taken to consist of render that is prepared and proportioned on site using traditional techniques and technologies (manual preparation, mixed mechanically and applied manually) and whose components are cement, lime (slaked or hydraulic), sand (siliceous, calcareous, silica-calcareous or clayish) and perhaps some admixtures or fillers. This type of coating is applied in three layers of different thickness, composition and dosage, which are (from the innermost to the outermost): an adhering layer, a base layer, and a finishing layer. There are five stages in their application:

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preparation, application, evening out, levelling, and smoothing.

Non-traditional/single-layer rendering is here taken to be that which is premixed at the factory and usually applied in a single layer projected onto the wall in one or more applications. The composition of this render is similar to the traditional type and is ready after mechanically mixing water with the bagged pre-dosed mixture produced at the factory.

The pathology of renderings is a well-studied subject, but information is scattered in various papers and inspections need to be performed by a specialist on this matter. This paper intends to present the systemization of data, through the creation of an inspection and diagnosis system for wall renderings that can be incorporated into a similar wider-ranging system for buildings as a whole.

The system proposed presents an organised approach to classifying anomalies, their most probable causes, and their diagnosis, repair and maintenance techniques, consisting on an innovative tool that can decrease the need for expert inspectors, provide standard reports and simplify the decision process on wall render pathology.

2. Method

The development of the inspection and diagnosis system of rendered walls presented in this paper is the result of an intense study of their pathology, followed by a field work application of the current knowledge, providing more accurate data.

Therefore, the method of development of this system may be divided in three stages: bibliographic research, fieldwork data collection and validation. This method has been used by other authors, although applied to different non-structural elements of buildings, such as ceramic tiling [1], stone cladding [2], gypsum plasters [3, 4], and external insulation systems [5], among others.

2.1. Bibliographic research

In a first stage, references on pathology of renders were searched for and studied, covering the state of the art in order to characterize the element [6, 7, 8], its durability, service life estimation and degradation models [9, 10]. Subsequently the most common anomalies [11], their effects and probable causes [11 - 14], diagnosis techniques applicable to this particular type of coating [15-17] and repair solutions and maintenance plans [18-22] were studied.

With the data gathered, a theoretical system was developed, in which the four main variables concerning pathology (anomalies, causes, diagnosis techniques and repair techniques) were listed, grouped and classified in classes and subclasses.

After the classification, other tools were created to rationalize the use of the system, namely: correlation matrices (anomaly-cause, inter-anomaly, anomaly-diagnosis techniques and anomaly-repair techniques) and standard files for anomalies, diagnosis methods and repair methods.

a) Classification of anomalies

The classification of anomalies follows visual criteria, since the first approach of the inspector is by means of naked eye analysis. The main goal of this approach is to allow the identification of anomalies easily and correctly during inspection and guarantee that such identification is unequivocal.

As shown in Table 1, anomalies are organized in three groups: aesthetic anomalies (A-E), anomalies associated with humidity (A-H), and mechanically-related anomalies (A-M) (Table 1). Aesthetic anomalies (A-E) can be described as those that do not jeopardize the integrity of the rendering but do affect its aesthetics, and strongly affect its appearance. Anomalies associated with humidity (A-H) are caused by the presence of moisture on the surface of or within the rendering. Besides being unaesthetic, they affect the rendering's integrity and are viewed with great concern in interior coatings where evaporation and drying conditions are poor. Mechanically-related anomalies (A-M) are associated with forces or stress that lead to the rendering's degradation through the physical destruction of the bonds between its constituent particles. These forces/stresses can originate from static actions (e.g. loading), dynamic actions (e.g. strikes or shocks), imposed displacements (e.g. settlements) or other causes.

Table 1 Classification of the anomalies in wall renderings

A-E - aesthetic anomalies	
A-E1 graffiti	**A-E3** corrosion stains
A-E2 dirt/deposits of particles	**A-E4** colour change/discolouration
A-H - anomalies associated with humidity	
A-H1 infiltrations/dampness stains	**A-H4** efflorescence/cryptoflorescence
A-H2 biological colonization	**A-H5** carbonation
A-H3 vegetation growth	
A-M - mechanically-related anomalies	
A-M1 adherence loss/detachment	**A-M4** map cracking
A-M2 cohesion loss/crumbling	**A-M5** scratches/grooves
A-M3 linear cracking	

b) Classification of causes

This classification system stems from the need to have a tool to help decide on the best way of controlling and repairing anomalies. It divides causes into five categories, using their origin as the criterion and ordering them chronologically: design errors (C-C); execution errors (C-E); environmental actions (C-M); mechanical actions (C-A), and wear and maintenance faults (C-U), as shown in Table 2.

The grouping of causes varies with the timeline of the renders life with the aim of best identifying where most mistakes are made, in order to avoid those errors in the future.

Table 2 Classification of the causes of the anomalies in wall renderings

C-C - DESIGN ERRORS
C-C1 faulty application of regulations and tenders
C-C2 faulty design or lack of detailing
C-C3 faulty design or lack of gutters or water drainage systems
C-C4 faulty design or lack of heat insulation in walls
C-C5 faulty design or lack of reinforcement systems for protection against mechanical action
C-C6 faulty specification of the products applied
C-E - EXECUTION ERRORS
C-E1 use of inexperienced/unqualified workmanship
C-E2 lack of conformity to design and/or building and construction specifications
C-E3 use of dirty tools during construction (contamination)
C-E4 presence of water-soluble salts in moisture or in the materials employed
C-E5 inappropriate mortar composition
C-E6 excessive fines content
C-E7 excess water/moisture in construction (mortar and/or supporting walls)
C-E8 corrosion in metal elements (embedded in the rendering or attached to its surface)
C-E9 heterogeneity of supporting walls
C-E10 faulty preparation of supporting walls (cleaning, roughness, wetness)
C-E11 rendering applied under adverse weather conditions
C-E12 inadequate rendering thickness
C-E13 inadequate rendering texture
C-E14 lack of follow-up of the rendering during curing
C-E15 lack of sufficient water vapour permeability in rendering or painting
C-E16 use of dark colours on exterior walls
C-M - environmental actions
C-M1 air-borne dirt particles
C-M2 solar radiation/temperature action
C-M3 wind and/or rainwater action
C-M4 presence of water/water vapour
C-M5 high relative humidity (RH > 70%)
C-M6 poor ventilation
C-M7 reduced natural lighting/sun exposure or lack thereof
C-M8 natural wear and tear
C-A - mechanical actions
C-A1 abrasion
C-A2 shocks/bumping
C-A3 wall cracking (propagation to the rendering)
C-A4 supporting wall shrinkage
C-A5 rendering shrinkage
C-A6 structural movement (settlement and deformation)
C-A7 stress concentration
C-U - wear and maintenance faults
C-U1 irregular cleaning/washing
C-U2 irregular repainting
C-U3 poorly executed maintenance /small repair works
C-U4 haphazard actions related to user occupation, traffic and wear
C-U5 lack of fittings (piping, drains, gutters, rainwater vertical piping)
C-U6 vandalism

c) Diagnosis techniques

Diagnosis techniques are essential for correctly identifying anomalies, determining their extent and helping to establish their probable causes. On-site visual inspection and macroscopic analysis are important diagnosis methods and are always the first choice when checking for anomalies. They may not be enough for complete diagnosis, however. Quite often additional means are needed to collect more detailed and quantitative data on the anomalies. These means are based on in situ and laboratory tests. The first are usually preferred as they are less complex, the results are gathered more swiftly and they are cheaper. The most important factors for choosing a diagnosis method are cost, test procedure, intrusion level, the need for specialized workmanship, reliability, time needed, ease of interpretation of the results and the type of data it provides relative to those needed.

The diagnosis techniques in the system are limited to in situ tests for they allow faster and simpler diagnosis. They may be classified as destructive and non-destructive and their grouping was made according to the aspect one wants to study: preliminary diagnosis (D-I); moisture diagnosis (D-H); permeability diagnosis (D-P); salts diagnosis (D-S); cracking diagnosis (D-F); resistance diagnosis (D-R); adherence diagnosis (D-A); diagnosis of discontinuities and hidden anomalies (D-D); and detection of metal elements (D-M), as shown in Table 3. The choice of the method to be used depends on its appropriateness to the relevant circumstances and is based on a series of specialized references [15-17].

Table 3 Classification of the diagnosis techniques for wall renderings

D-I - Preliminary diagnosis	
D-I1 visual inspection and macroscopic analysis (non-destructive test)	
D-H - Moisture diagnosis	
D-H1 thermometer (non-destructive test)	**D-H3** humidity meter (non-destructive test)
D-H2 hygrometer (non-destructive test)	**D-H4** speedy moisture tester (destructive test)
D-P - Permeability diagnosis	
D-P1 Karsten-tube penetration test (non-destructive test)	
D-S - Salts diagnosis	
D-S1 colour comparison test strip (non-destructive test)	**D-S3** colour analysis (non-destructive test)
D-S2 titrimetric analysis (non-destructive test)	**D-S4** phenolphthalein indicator (non-destructive test)

D-F - Cracking diagnosis	
D-F1 crack comparison chart (non-destructive test)	**D-F3** testimony testing (non-destructive test)
D-F2 optical crack meter (non-destructive test)	**D-F4** crack meter (non-destructive test)
D-R- Resistance diagnosis	
D-R1 sphere shock test (destructive test)	**D-R5** pendulum sclerometer (destructive test)
D-R2 grid testing (destructive test)	**D-R6** micro-perforation (destructive test)
D-R3 scratch test (destructive test)	**D-R7** controlled penetration (non-destructive test)
D-R4 abrasion test (destructive test)	
D-A- Adherence diagnosis	
D-A1 pull-off test (destructive test)	
D-D - Diagnosis of discontinuities and hidden anomalies	
D-D1 ultrasound test (non-destructive test)	
D-D2 percussion test (non-destructive test)	
D-D3 infrared thermography (non-destructive test)	
D-M - Detection of metal elements	
D-M1 magnetometer (non-destructive test)	

d) Repair techniques

The importance of rehabilitating built heritage has been recognized because of the progressive scarcity of space for new constructions and the growing demand for interventions as existing buildings grow older. Therefore the need to systemize the repair and maintenance techniques of the various types of coatings, in particular wall renderings, is a priority.

The classification system considers three types of techniques: restoration (rc), prevention (rp) and maintenance (m). The first ones eliminate, repair or hide the anomaly; the second ones are interventions needed to eliminate the causes of the anomaly even if they do not directly treat the anomaly itself; the third ones aim at preventing or correcting slight degradations of the renderings on a regular basis.

The grouping of repair techniques depends on the layer of the walls where the intervention must take place (Table 4): involving the rendering's surface (R-A Rendering surface); affecting the finishing layer (R-B Finishing layer); highly intrusive, implying changing or reconstructing the rendering (R-C Rendering system); and related to the envelope of the coating (R-D Envelope).

Table 4 Classification of the repair techniques for wall renderings

R-A Rendering surface	
R-A1 cleaning **R-A2** protection of salient corners	**R-A3** application of surface protection
R-B Finishing layer	
R-B1 filling and elimination of cracks	**R-B3** application of new finishing over existing rendering
R-B2 full/partial replacement of the finish (top or finishing layer)	**R-B4** application of a moisture barrier to interior wall faces **R-B5** creation of joints over live cracks
R-C Rendering system	
R-C1 full/partial replacement of the rendering	**R-C4** execution of a reinforced rendering coating independently of the supporting wall
R-C2 application of a reinforced rendering	**R-C5** application of a new render coating over the existing rendering
R-C3 execution of an External Thermal Insulation Compound System (ETICS)	**R-C6** application of a higher thermal performance grade rendering **R-C7** application of drainage or corrective rendering
R-D Envelope	
R-D1 correction of geometric construction features	**R-D2** maintenance/removal of corroded metal elements

e) Correlation matrix: anomalies - causes

By relating anomalies and their possible causes through a matrix, a correlation degree identifies the extent to which each cause may affect each anomaly, and vice-versa. Each possible cause of each anomaly is classified by 0, 1 or 2 according to its degree of correlation [1]: 0 - no correlation - there is no relationship whatsoever (direct or indirect) between the anomaly and the cause; 1 - low correlation - indirect (first) cause of the anomaly related to the initial stage of the degradation process or secondary cause not fundamental to the degradation process; 2 - high correlation - direct (close) cause of the anomaly associated with the final stage of the degradation process which, when it does occur, is one of the main factors in the degradation process and is essential to its development. Each line of the correlation matrix corresponds to an anomaly in renderings and each column to a possible cause of the anomalies.

f) Correlation matrix: inter-anomalies

An anomaly may occur in a localized area or it may affect the whole rendered surface. Furthermore it may occur by itself or be associated with other anomalies. With this in mind a correlation index between anomalies, in percentage, was established showing which other anomalies could occur when a given anomaly is detected.

g) Correlation matrix: anomaly-diagnosis technique

The "anomaly-diagnosis method" correlation matrix is design to help the inspector by indicating how useful each test is for evaluating the severity and extent of each anomaly.

After the detection or suspicion of the existence of a given anomaly, this correlation matrix allows choosing the most appropriate diagnosis technique(s) for its correct identification and characterization.

Each index (the intersection of a line representing an anomaly and a column representing a diagnosis technique) corresponds to a figure with the following meaning [1]: 0 - no correlation (there is no relation between the anomaly and the diagnosis technique); 1 - low correlation (method suitable for characterizing the anomaly even though it is limited in terms of technical procedures or its costs reduces its scope of application); 2 - high correlation (method suitable for characterizing the anomaly and also involving a technically undemanding procedure and using accessible (or no) equipment, thus widening its application scope).

h) Correlation matrix: anomaly-repair techniques

This correlation matrix represents the degree of suitability of each repair technique to each anomaly. The correspondence is measured by an index of 0, 1 or 2, representing a no correlation, a small or a large correlation between technique and anomaly, respectively.

2.2. Field work data collection

The validation of this theoretical system resulted from a field work consisting on the standardized inspection of 55 buildings, amounting to a total of 150 renderings (100 exterior and 50 interior), in Portugal.

Onsite, anomalies were visually identified, probable causes were assigned, diagnosis tests prescribed and repair techniques registered. Every wall (both interior and exterior) was characterized, registering the surrounding conditions, age, location and type of exposure, among other influential aspects. Within the inspection programme implemented, diagnosis and repair techniques were prescribed (but not fully applied) according to the anomalies identified onsite. Nevertheless, the integrity of the system to classify repair and maintenance techniques and their interdependence with the anomalies is not jeopardised by this factor, since the analysis corresponds to actual case files.

Some of the choices in terms of repair (maintenance) were influenced by the fact that the system was devised to be applied to current buildings whose historic/architectonic value is not overly relevant.

2.3. Validation

After gathering all the data from practical inspections, the results were numerically manipulated and compared with the theoretical data, leading to an adjustment of the tools. A statistical analysis of the results collected from the inspection program was also developed, specifying the sensibilities of wall renders. However that study is beyond the scope of this paper and may be found in another reference [24].

Classification lists were reanalysed, with the purpose of examining if any parameter was missing or, alternatively, unnecessary.

Subsequently, a mathematical manipulation of the data collected allowed the comparison between matrices obtained theoretically and practically, for each one:

a) Correlation matrix: anomalies - causes

Onsite, for every anomaly, an analysis of the surrounding conditions was made and determined the probable direct and indirect causes. They were then translated into a matrix by applying the following algorithm:

$$(f_1 + f_2) \leq \frac{1}{3} \rightarrow C_{ac} = 0$$
$$(f_2 > f_1) \wedge \left(f_2 > \frac{1}{3}\right) \rightarrow C_{ac} = 2$$
$$remaining\ cases \rightarrow C_{ac} = 1$$

In which f_1 is the frequency with which cause is identified onsite as an indirect cause of a given detected anomaly, f_2 is the frequency with which the same cause is identified onsite as a direct cause of the same given anomaly, and C_{ac} is the correlation index between the cause and the anomaly [5].

When the practical matrix was obtained, it was compared to the previous theoretical matrix and their discrepancies were analyzed, considering a Mild discrepancy when the index values differ by 1, and an Outstanding discrepancy when the values differ by 2. For every discrepancy an individual critical analysis was performed and the final matrix built based on the adjustments made to the onsite matrix.

b) Correlation matrix: inter-anomaly

The correlation matrix of inter-anomaly is built based on the anomalies-causes matrix. Being "k" and "j" two different anomalies, their correlation is determined based on the following:

$$CI_{kj} = \sum_{i=1}^{N} c_{ki} c_{ji}$$

Where "N" is the overall number of causes and "c_{ki}" and "c_{ji}" are the correspondent cell values of the "anomaly-cause" matrix [5].

To obtain a percentage result ($CI_{\%kj}$), is applied the following formula:

$$CI_{\%kj} = \frac{CI_{kj}}{IM_k} \times 100$$

Where I_{Mk} is the maximum theoretical value of the correlation index for each anomaly "k":

$$IM_k = \sum_{i=1}^{N} 2c_{ki}$$

The matrix presented in Table 6 represents the probability of anomaly j (column j) occurring when anomaly i (line i) is found.

c) Correlation matrixes: anomaly-diagnosis method and anomaly- repair techniques

In both matrixes, columns represent anomalies and rows represent techniques. In both cases, the following method was used: correlations were adjusted on the basis of the frequency of recommendation of each technique relative to the overall number of occurrences of each detected anomaly. For each cell an agreement/disagreement analysis was made between the theoretical values (0, 1 or 2) and the recommendation frequencies according to the following criteria [5]:

- Agreement: $0 \geq 17\%$; $2 \leq 33\%$; $17\% \leq 1 \leq 50\%$;
- Slight disagreement: $17\% \leq 2 < 33\%$; $1 > 50\%$ or $1 < 17\%$; $17\% < 0 \leq 33\%$;
- Complete disagreement: $2 < 17\ \%$; $0 > 33\%$.

When discrepancies were found, the cells were individually analysed and adjusted in order to obtain the final version of each matrix.

3. Results

During the inspection campaign, 476 anomalies in rendered walls were identified and 1277 causes detected (887 direct and 390 indirect), making up an average of 2.7 causes combined for each anomaly. Both anomaly and causes classification lists were revised (Tables 1 and 2, respectively) considering the results, and no alterations were made between the literature and practical case studies.

For diagnosis techniques, 908 tests were recommended for the total of identified anomalies, either to characterize the extent of the anomaly or its cause. The analysis of practical data confirmed the initial classification list based on the literature (Table 3).

As for the classification list of repair techniques, was also confirmed by the data gather onsite, which consisted on 1731 repair techniques for the anomalies identified (Table 4). This value is influenced by the possibility of alternative techniques for the repair of one anomaly.

The validation of "anomalies-causes" matrix, applying the previously described method of comparison reached 7% as for Outstanding discrepancy and 30% for Mild discrepancy. Each case of Outstanding discrepancy was closely reviewed, as were the Mild discrepancy cases when the literature indicated a null correlation and onside data indicated otherwise, or vice-versa. The revised matrix is presented in Table 5.

Entries in white show the changes to the initial figures based on the thorough literature review that resulted from the inspections and results obtained when validating the system.

Considering the adjustment of the anomaly-causes matrix, the inter-anomaly matrix was also revised, reaching a 5% adjustment from the original matrix. The final matrix is presented in Table 6.

Table 5 Anomaly-cause correlation matrix for wall renderings

	C-C1	C-C2	C-C3	C-C4	C-C5	C-C6	C-E1	C-E2	C-E3	C-E4	C-E5	C-E6	C-E7	C-E8	C-E9	C-E10	C-E11	C-E12	C-E13	C-E14	C-E15	C-E16
A-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A-E2	1	2	2	1	0	1	1	1	0	0	0	0	0	0	2	0	0	1	1	0	0	0
A-E3	0	1	1	0	0	1	1	1	0	1	1	0	1	2	0	0	1	1	0	0	0	0
A-E4	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
A-H1	1	2	2	1	0	1	1	1	0	0	1	0	2	1	0	1	1	0	0	1	0	0
A-H2	1	1	1	1	0	1	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0
A-H3	1	2	1	1	0	1	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0
A-H4	1	1	1	0	0	1	1	1	1	2	1	0	1	0	0	1	1	0	0	0	2	0
A-H5	1	1	1	0	0	1	1	1	0	0	1	0	1	0	0	1	1	0	0	0	0	0
A-M1	1	1	1	0	1	1	1	1	1	1	2	2	1	2	2	2	1	2	0	2	2	0
A-M2	1	1	1	0	1	1	1	1	0	1	1	1	0	1	0	1	1	0	0	1	0	0
A-M3	1	0	0	0	2	1	1	1	0	0	1	0	0	0	2	0	0	1	0	0	0	0
A-M4	1	0	0	0	0	1	1	1	0	1	2	1	2	0	0	0	2	2	0	2	0	0
A-M5	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	C-M1	C-M2	C-M3	C-M4	C-M5	C-M6	C-M7	C-M8	C-A1	C-A2	C-A3	C-A4	C-A5	C-A6	C-A7	C-U1	C-U2	C-U3	C-U4	C-U5	C-U6	C-M1
A-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0
A-E2	2	1	2	1	2	1	1	0	0	0	0	0	0	0	0	1	1	0	0	2	0	2
A-E3	0	0	2	2	1	1	1	1	0	0	0	0	0	0	0	1	1	0	0	1	0	0
A-E4	0	2	1	0	0	0	0	2	0	0	0	0	0	0	0	0	1	2	0	0	0	0
A-H1	0	0	2	2	2	1	1	1	0	1	1	1	1	1	1	0	1	1	0	2	0	0
A-H2	1	0	1	2	2	1	1	1	0	0	0	0	0	0	0	1	0	0	0	2	0	1
A-H3	1	1	1	2	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	1
A-H4	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
A-H5	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
A-M1	0	0	0	2	2	0	0	1	0	1	2	1	2	1	1	0	0	2	0	1	0	0
A-M2	0	0	2	1	1	0	0	1	2	2	1	0	1	1	1	0	0	1	2	1	2	0
A-M3	0	2	0	0	0	0	0	1	0	2	2	2	0	2	2	0	0	1	0	0	0	0
A-M4	0	1	0	0	0	0	0	1	0	0	0	0	2	0	0	0	1	1	0	1	0	0
A-M5	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	1	0	2	0	2	0

Table 6 Percentile inter-anomaly correlation matrix for wall renderings

	A-E1	A-E2	A-E3	A-E4	A-H1	A-H2	A-H3	A-H4	A-H5	A-M1	A-M2	A-M3	A-M4	A-M5
A-E1		25%	25%	13%	13%	13%	13%	13%	13%	0%	50%	0%	13%	63%
A-E2	4%		41%	13%	56%	48%	44%	31%	31%	41%	31%	20%	19%	4%
A-E3	4%	48%		15%	63%	43%	39%	41%	37%	52%	41%	13%	33%	2%
A-E4	5%	32%	32%		41%	23%	32%	14%	14%	36%	36%	45%	41%	5%
A-H1	1%	43%	41%	13%		40%	36%	33%	33%	57%	44%	24%	30%	6%
A-H2	2%	62%	48%	12%	67%		55%	40%	40%	43%	36%	10%	24%	2%
A-H3	3%	60%	45%	18%	63%	58%		40%	40%	40%	35%	15%	25%	3%
A-H4	2%	40%	45%	7%	55%	40%	38%		43%	62%	40%	12%	31%	2%
A-H5	3%	53%	53%	9%	72%	53%	50%	56%		59%	47%	16%	34%	3%
A-M1	0%	26%	28%	9%	47%	21%	19%	30%	22%		41%	34%	36%	5%
A-M2	6%	26%	29%	12%	47%	23%	21%	26%	23%	53%		29%	26%	27%
A-M3	0%	23%	13%	21%	35%	8%	13%	10%	10%	60%	40%		25%	15%
A-M4	2%	22%	33%	20%	46%	22%	22%	28%	24%	67%	37%	26%		4%
A-M5	23%	9%	5%	5%	18%	5%	5%	5%	5%	18%	82%	32%	9%	

The analysis of the correlation matrix between anomalies and diagnosis techniques reached a 3% value of total disagreement and 16% of slight disagreement. Total disagreement cases were verified individually and, considering the results, the matrix was adjusted, as presented in Table 7.

For the correlation between repair techniques and anomalies, 2.5% of the cells were in total disagreement and 9.7% in slight disagreement. As for the other matrixes, total disagreement cases were revised and the final matrix is presented in Table 8.

Table 7 Anomaly-diagnosis techniques correlation matrix for wall renderings

	D-I1	**D-H1**	**D-H2**	**D-H3**	**D-H4**	**D-P1**	**D-S1**	**D-S2**	**D-S3**	**D-S4**	**D-F1**	**D-F2**	**D-F3**	**D-F4**	**D-R1**	**D-R2**	**D-R3**	**D-R4**	**D-R5**	**D-R6**	**D-R7**	**D-A1**	**D-D1**	**D-D2**	**D-D3**	**D-M1**
A-E1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A-E2	2	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
A-E3	2	0	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
A-E4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
A-H1	2	1	1	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
A-H2	2	1	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
A-H3	2	1	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
A-H4	2	1	1	1	1	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
A-H5	2	1	1	2	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A-M1	2	0	1	1	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	2	1	2	1	1
A-M2	2	0	1	1	1	0	1	1	1	0	0	0	0	0	1	2	1	2	1	1	2	0	0	0	1	0
A-M3	2	0	0	1	0	1	0	0	0	0	2	1	1	1	0	0	0	0	0	0	0	0	1	0	1	0
A-M4	2	0	0	1	0	1	0	1	1	0	1	2	0	0	0	0	0	0	0	0	0	0	1	0	0	1
A-M5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	1	1	1	1	0	0	0	0	0

Table 8 Anomaly-repair techniques correlation matrix for wall renderings

A\R	**R-A1**	**R-A2**	**R-A3**	**R-B1**	**R-B2**	**R-B3**	**R-B4**	**R-B5**	**R-C1**	**R-C2**	**R-C3**	**R-C4**	**R-C5**	**R-C6**	**R-C7**	**R-D1**	**R-D2**
A-E1	2	0	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0
A-E2	2	0	1	0	2	2	0	0	0	0	1	0	0	1	0	2	0
A-E3	2	0	0	0	2	2	0	0	1	0	0	0	0	0	0	2	2
A-E4	0	0	0	0	2	2	0	0	1	0	0	0	0	0	0	0	0
A-H1	2	0	2	0	2	0	1	0	2	0	0	0	0	0	1	2	0
A-H2	2	0	2	0	2	0	0	0	2	0	0	0	0	0	0	1	0
A-H3	2	0	2	0	2	0	0	0	2	0	0	0	0	0	0	2	0
A-H4	2	0	0	0	1	0	0	0	2	0	0	1	0	0	1	0	0
A-H5	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
A-M1	0	0	0	0	2	0	0	0	2	1	0	0	0	0	0	0	0
A-M2	0	0	0	0	2	0	0	0	2	2	0	0	0	0	1	0	0
A-M3	0	0	0	2	1	1	0	2	2	0	0	0	0	0	0	0	1
A-M4	0	0	0	2	2	0	0	0	2	2	0	0	1	0	0	0	0
A-M5	2	2	0	0	1	2	0	0	1	0	0	0	2	0	0	0	0

All the data resulting from the classification and characterization of anomalies in wall renderings and their causes, and from the relationships established between them, was compiled in individual anomaly files. The architecture and content of these files are based on other works by this research team [1-5] and consist of the following fields: heading with the name and code of the anomaly, according to Table 1; a representative picture of a case study; a succinct description of the pathological manifestations characteristic of the anomaly; probable causes of the anomaly (in accordance with the respective correlation matrix, Table 5) identified by a brief description and its code designation, as in Table 2 (direct causes are underlined); possible consequences of the anomaly that themselves may become new anomalies; aspects to be inspected (characteristics related to the anomaly detected that may be useful for its diagnosis, or again be anomalies themselves); tests recommended *in situ* in accordance with Table 3 (in order to characterize the anomaly in terms of extent, gravity and evolution stage and in accordance with the anomaly-diagnosis techniques correlation matrix presented in Table 7; first-choice techniques are underlined); rating parameters (results from *in situ* tests or other data that help calculate the gravity level of the anomaly); level of gravity/intervention urgency (0 - immediate action needed - maximum 6 months; 1 - need to intervene in the medium-term - maximum 1 year; 2 - need to monitor the evolution of the anomaly, i.e. in the next inspection).

Table 9 shows an example of an anomaly file for anomaly A-E1 (*graffiti*).

The classification and characterization of the diagnosis techniques for wall renderings enabled the development of individual files of these tests/methods. These compiled files contained the following fields: technique code (according to Table 3); illustrative figure; type of test (destructive/non-destructive); objectives of the test; equipment needed; description of the method; advantages; limitations. Table 10 shows such a file, for technique D-I1 (visual inspection and macroscopic analysis).

Table 9 Anomaly file A-E1 - *graffiti*

Anomaly file A-E1	
Name: *Graffiti* **Description:** Paintings or markings on the wall's surface that are absorbed due to the rendering's porosity	
Probable causes: - Irregular cleaning/washing (C-U1) - Irregular repainting (C-U2) - <u>Vandalism (C-U6)</u>	
Possible consequences: - Aesthetics affected - Degradation of the visual quality of the rendering	
Aspects to be inspected: - Near schools or other locations with young crowds (Y/N) - Ease of access to the location (near the ground/elevated spot) - Type of graffiti (paint/spray/markers) - Percentage of area affected: (…) %	
Recommended tests: - <u>Visual inspection and macroscopic analysis (D-I1)</u>	
Rating parameters: - Aesthetic value of the areas affected (H-high/M-medium/L-low) - Conditions for repetition of the phenomenon (Y/N) - Percentage of area affected: (…) %	
Level of gravity/intervention urgency: 0 - building aesthetics seriously affected or high probability that the phenomenon will occur again and area affected over 20%; 1 - all other cases	

Table 10 Diagnosis technique file D-I1 - visual inspection and macroscopic analysis

Diagnosis file D-I1	
Name: Visual inspection and macroscopic analysis **Destructive (d) / non-destructive (nd):** ND **Objectives:** <u>Preliminary diagnosis:</u> - Initial identification of the anomalies on the rendering surface, of the most affected areas, the probable causes and the extent of the anomalies **Equipment needed:** Magnifying glass, binoculars, spatula, brush, extensible rods with mirror, compass, levelling device, ruler, wire plummet, tape, clinometer and strain gauge	

Description of the method:

1 - Observation of the surfaces under analysis; **2** - Use of auxiliary devices such as magnifying glass or binoculars; **3** - Inspection of the surface by touch/palpation, brush, spatula; **4** - Use of compass, spirit level, ruler, tape, wire plummet, tape, clinometer and strain gauge to collect some quantitative data to reinforce visual observation; **5** - Use of extensible rods with mirror to inspect less accessible locations

Advantages:

- Swift and economic
- Suitable for diagnosis of any anomaly that develops on the surface of the rendering

Limitations:

- Very subjective
- Dependent on the opinion, experience and skill of the inspector
- Leads generally to qualitative data
- Not suitable to evaluate the state of deep layers of the rendering or the substrate

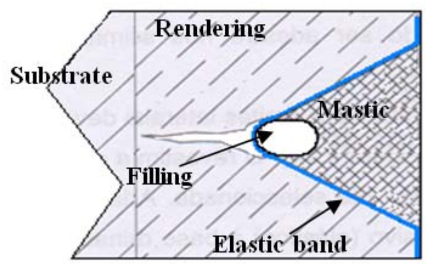
Repair technique files were also devised, so as to summarize the repair techniques from Table 4, and compile the main data concerning them. The files contain the following data: technique code and name (according to Table 4); list of the main anomalies for which the technique is appropriate; illustrative picture or figure; list of the main materials used by the technique; list of the equipment needed; requirements of the substrate to maximize the technique's efficiency; short step-by-step description of the procedure; workmanship and its degree of specialization and estimated execution time; estimate of the unit cost; expected results in terms of anomaly's repair, cause's elimination and improved performance; general or specific recommendations and special care for applying the technique and its limitations.

Table 11 shows an example of a repair file for technique R-B5 (creation of joints over live cracks).

Table 11 Repair technique file R-B5 (creation of joints over live cracks)

Repair file R-B5

Name:	**C**reation of joints over live cracks **(rc) / (rp)**
Element:	Rendering
Anomalies repaired:	**A-H1** infiltrations/dampness stains; **A-M1** loss of adherence/detachment; **A-M2** loss of cohesion/crumbling; **A-M3** linear cracking; **A-M4** map cracking.



Materials used:

Elastic band, polyethylene or polyurethane foam roll (filling), polyurethane or special polymers mastic, coating material similar to the existing one.

Equipment needed:

Hammer, chisel, grinder, compressed air pistol, spatula, manual or pneumatic pistol and brush or roll.

Substrate preparation:

The intervention area must be clean, dry and free of loose particles and debris or contaminated elements that may jeopardize the adherence of the products to be applied.

Description of the technique:

All repair techniques must be implemented only after the elimination of the causes of the relevant anomalies.

1 - Widening of the cracks to be repaired, leading preferably to "V" sections 5-10 mm deep and 5-25 mm wide; **2** - Cleaning and elimination of all debris or contaminated elements that may jeopardize the adherence of the products to be applied; **3** - Application of an elastic band over the crack that must be fixed only at the limits of the crack; **4** - Application of a polyethylene or polyurethane foam roll, usually called a filling. This roll must be applied in order to stay compressed between the sides of the crack; **5** - Application of a polyurethane or special polymer mastic using a spatula or a manual or pneumatic gun; **6** - Application of the coating, which must be elastic and preferably reinforced with a grid, and executed keeping the desired aesthetic finishing in mind.

Workmanship and estimated execution time:

1 mason + 1 helper (0.12 to 0.14 m/h).

Estimated cost[1]:

12 to 16 €/m^2 according to the maker and depth of the materials.

(1) This figure must be increased by the cost of scaffolding, whenever needed.

Recommendations and special care:

Fix the elastic band only at the ends of the crack. Apply to non-stabilized cracks with a regular outline and no abrupt changes in width.

Limitations:

Relatively complex execution procedure, open to mistakes. The creation of a joint where there was none is mandatory, and this may have aesthetic consequences.

4. Discussion

The adjustments resulting from the comparison between the literature review and onsite inspections were minor, confirming that the knowledge of pathology in renders is a well-studied field. Nevertheless, the present system serves as an organized compilation tool of the scattered information, allowing for the simplification of the inspection procedure and decision-making.

Tests and diagnosis techniques were not actually performed, which may influence the final result on a small scale, meaning that the correlations could slightly change. However, the discrepancy is hardly concerning since the recommendations were made specifically for each anomaly and after deep study.

The system is intended to facilitate inspections, minimizing the need of an expert. Nevertheless, the good judgment and observation skills of the inspector are essential to correct diagnosis and intervention.

6. Conclusion

This paper presents a proposal for an expert inspection and diagnosis system for wall renderings that was meticulously validated through an inspection programme. Its main objective is to be a tool to guide inspection procedures. The main anomalies, their most probable causes, diagnosis techniques and repair techniques were classified and relationships were established between these items in order to simplify the on-site work of inspectors. The inspection sample (55 buildings comprising 150 renderings, 100 of which were exterior surfaces) enabled the consistent calibration and validation of the proposed classification systems and correlation matrices. Data on the system are summarized in anomaly, diagnosis and repair files, which are fundamental tools to back up on-site work.

During inspection, conclusions are drawn about the type, importance, extent and causes of the anomalies and consequently on the solutions to be implemented to eliminate their causes and repair them.

The system proposed may be included in a proactive maintenance strategy, since it is robust, reliable and has been statistically validated. The systematic structure of this system is innovative and can help the inspector by making his/her work more objective and standardizing procedures.

Anomalies in wall renderings may be prevented/minimized if buildings are properly managed by developing and implementing proactive maintenance plans that cover the following areas: technology (adequate maintenance and repair solutions, including the selection of materials and execution techniques), economy (minimizing running costs) and functionality (appropriate use).

Finally there is a need to develop specific software to compile data on the various construction elements in order to systemize the whole inspection process.

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