Façade Assessment Procedure for the Evaluation of Durability of Existing Buildings

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Abstract

The aim of the research is the development and application of a method for the assessment of durability and environmental impacts in the context of sustainable construction with regard to existing buildings. The method is based on the evaluation of the residual service life which, carried out through non-destructive surveys and laboratory tests, assesses the damage of the buildings envelope and its energy efficiency, correlating the level of degradation to residual performances. This analysis will be followed by maintenance planning and life cycle assessment concerning sustainability. In the case of historical buildings the analysis, together with specific surveys and documentation, allow to design a preventive preservation plan in order to avoid further damage and risk factors.

The method has a direct experimental application within the project "Città Studi: Sustainable Campus", which has the aim to transform the university quarter in Milan into an exemplar campus with respect to life quality and environmental sustainability. In particular the paper will report about the recovery-requalification of existing buildings of Politecnico di Milano at Leonardo Campus, which are nowadays under investigation/study through visual inspections, imaging diagnostic, and especially, IR Thermography. The case study deals with both the issue of repairing and increasing energy efficiency, considering durability and management of buildings, and the cultural issue of preserving masterpieces of the contemporary architecture, since many of the buildings under investigation have the famous architect Giò Ponti as author.

Keywords: sustainability, diagnostic, durability, IR Thermography, planned conservation

1. Introduction

The integration of environmental balances, within the processes of assessment and definition of the design choices, is essential towards the goals of a *sustainable* intervention; the *life cycle* approach is fundamental in order to determine the performances criteria which are necessary for an environmental critical analysis of the whole building. The search of a

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methodological formulation is unavoidable from a consideration of *durability* aspects, based on service life data of components, which represents the starting point for the development of an *analytical method*, to be applied on a representative sample of buildings.

As part of a project dedicated to the identification and enhancement of the application of service life information in the context of sustainable constructions, this paper focuses on the first part of the research, i.e. the determination of the present damage state necessary for the evaluation of *residual service life* of components belonging to the external envelope of existing buildings, including the listed ones. Within the standards framework, the ISO 15686 – Buildings and constructed assets. Service life planning – defines *service life* as the period of time after installation during which a building or its parts meets or exceeds the performances requirements upper or equal to the accepted limits [1] [2].

For existing buildings and components must be taken into account the *residual service life,* defined as the service life remaining after a certain moment of consideration. To assess residual service life of an inspected building or component is important to know its history, i.e. data on the original performance values, information on the installation, maintenance, trend of deterioration, etc., which can involve several difficulties to be obtained. During the process of assessment of the residual service life of the existing building/component, must be planned that during the remaining service life the performance levels will be maintained equal or higher to accepted limits, taking into account *sustainability* aspects and *maintenance plans* [3].

In the case of monuments, life-cycle assessment offers a holistic method for comparing the costs of renovation against maintenance and in the case of historic buildings the economic advantages of conserving existing finishing, support also the planned conservation strategy [4].

As case studies, the research takes into account some buildings inside Campus Leonardo of Politecnico di Milano, where nowadays it’s in progress a project of revitalization and transformation of the university quarter Città Studi into an exemplar campus with respect to life quality and environmental sustainability. As a matter of fact since 2010 an articulate and widespread research has been developing at Politecnico of Milano and State University of Milan, titled “Sustainable Campus Leonardo”. Focus of the research is to involve the scientists employed at Politecnico and at State University of Milan on the study, analysis, survey, assessment, management, repair, enhancement of the university’s campus in the eastern area of Milano.

The buildings under study are characterized by the presence of cladding systems with ceramic tiles, popular practice in Italy since the 50-60s, due to their good wear resistance, high temperatures stability, hardness, tenacity and inertia. Besides the durability of the ceramic materials, their low cost, stainless and apparently low sensitivity to the effects of pollution and finally the low requirement for maintenance are some of the reasons of their diffused application in the middle-southern region of Europe, as an effective alternative to brick faced masonry, timber cladding and stucco [5]. Nowadays, after 50 years of usage, the façades present degradations problems on materials and systems, such as detachments, missing tiles and discoloration, due to the action of atmospheric agents, to the loss of adherence between the support and the tile or among the layers of the support, to the absence of a correct maintenance [6].

Among these research lines, the authors developed a methodology to assess the state of conservation of the facades, especially ceramic finishing [7]. In the paper it's shown the improvement in the field of diagnostic and preliminary tests, in particular non-destructive surveys through IR Thermography, based on the solution of the mathematical model of heat transfer in the ceramic medium. The preliminary tests had their validation by softly hammering both the detached area and the "safe" one: the different sounds of hammering revealed the detachment of the finishing.

The experimental application has been performed on historical buildings among which some were designed by one of the most famous architect of 50-80's, Gio' Ponti, who realized these buildings with contemporary techniques and materials. For this reason the assessment of façades in Campus Leonardo is an important issue both for economical aspects related to the costs of maintenance and usage of the most advanced techniques, and for the project of repair that deals with contemporary buildings having high historical-artistic value.

From this side, the critical point is to preserve the authenticity of a building. It is unanimously accepted in the current debate on restoration of historical building that the repair should be clearly identified, although it should not affect the aesthetical unit of the work of art, and that a "mimetic" solution, with the substitution of materials and elements with new ones "a l'identique" is a banned practice since the third decade of the 20° century. Therefore it rises up the need to limit as much as possible the substitution, preventing the damage by reducing the risk factors (environment, building techniques, use, lack of maintenance, etc.) and by means of a plan of conservation. This is inevitably linked with a life cycle assessment of the building which keeps into account the durability aspects aimed at the evaluation of proper maintenance plans.

2. Description of buildings and diagnostic

2.1 Buildings description

In the research were taken into account three different types of tiles belonging to three buildings inside Campus Leonardo.

Building 12 - whose tiles are in grès, flamed at high temperature, produced by the Italian Society of Grès, now acquired by Italcementi spa. These tiles are no longer under production. The paste of the material is compact and the superficial layer has the typical glazed structure obtained through a partial melting while burning, whose thickness varies between 50 µm for plane/linear tiles and 150 µm for corner tiles *(fig. 1.a).*

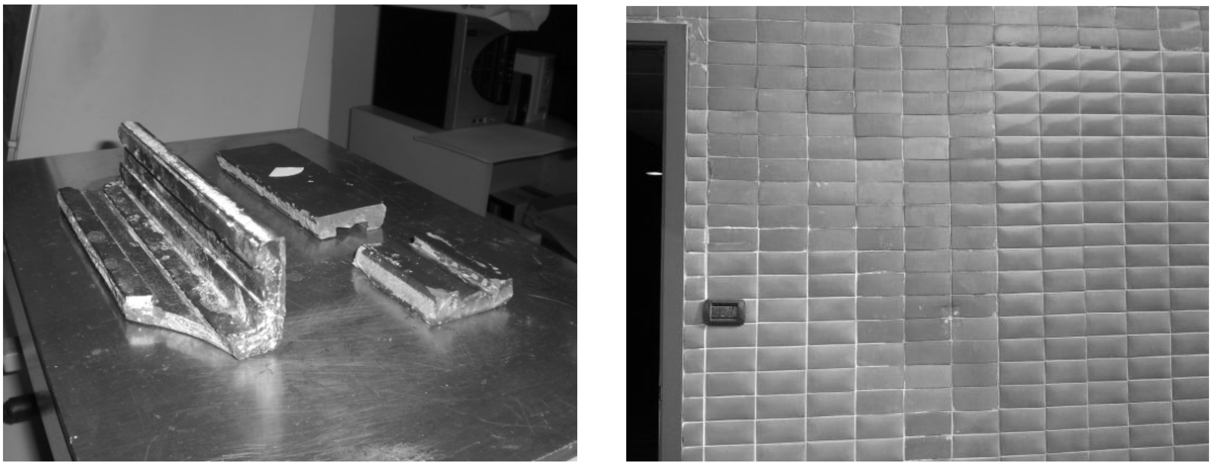


Figure 1: a. Building 12 – tiles details, b. Building 14 – original and new tiles

Building 14 “La Nave” – presents grey clinker tiles placed on a finishing of mortar (2,5 cm thick). On the façades it’s possible to recognize two different types of tiles: Giò Ponti original tiles and new ones, after maintenance interventions. The new series of tiles have flat and smooth surface while the original has rounded polyhedral surface *(fig. 1.b)*.

Building 15, has grey clinker tiles with a vitrified layer on the surface. The tiles are characterized by a small projection 1 cm thick, placed with different inclination in order to create effects of light and shade *(fig. 2)*.

Figure 2: Building 15 – tiles details

2.2 Inspection, diagnostic and laboratory test

The first step to assess the residual service life was to analyze the present state of damage of the external cladding system of the façades. This was performed testing the buildings through visual inspections, non-destructive surveys (IR thermography and hammering) and laboratory tests (emissivity and heat conduction tests).

The thermographic survey and the consequent thermal analysis has been developed through alternative methodologies based on the identification of reference temperatures; these let the optimization of the phase of defects mapping and allow to underline their geometric localization on the façades. The use of this innovative technology allowed to obtain more accurate results avoiding manual and punctual analysis of single areas [7].

2.2.1 The investigation Procedure of the thermographic survey

The following procedure has been used in the phase of analysis of thermograms to evaluate the presence of possible detachment problems in adhered cladding systems, consisting of clinker tiles placed on a substrate by means of mortar.

The thermographic survey was achieved under passive technique: this means the measurements were done at ambient conditions without artificial sources of heat.

The investigation procedure, aimed at detecting delamination problems, was performed in transient conditions since this type of defect is in these conditions more reliable. During the heating phase, the heat is transmitted by conduction to the inner layers of the material according to its heat capacity. If within it, the voids are formed, the layers of air interposed between the heated surface and the substrate prevent the linear propagation of the heat, causing a differential heating of the surface: the defect appears as a warmer area when the net heat flux is entering the building [8].

The proceeding consisting of three steps provides plausible results with a probability of check-up that can reach 80%. This probability value is influenced by different reasons: it does not reach 100% because at the state of the art there are still unknown aspects due to uncertainties regarding the methods of heat transfer and boundary conditions. Moreover the discoloration and the different reflectance of the surface can influence the results and therefore decrease the security of check-up of the pathology.

Thermal images were acquired after heating by solar irradiation for 2 hours. This time window has been determined to obtain the better contrast between delaminated areas and adhered ones. The factors that play a prominent role in the heat diffusion in the cladding system are its thickness and thermal characteristics, the supposed depth of the defect, the environmental conditions (temperature of the air, wind speed, humidity), and the season (consequently the inclination of solar rays).

The first phase of the analysis (performed by IRT Analyzer) is based on the identification of the temperature gradient which characterizes the presence of detachment defects. This was obtained by manually selecting small homogeneous areas representing safe and detached areas and comparing their temperatures. In the second phase, the previous results have been compared with the outcomes of the analysis of the thermograms performed by ArcGIS, in which the low and high isotherm has been set up by means of the values previously identified and characterising respectively the “safe” and detached areas. Through this analysis were systematically individualized the areas which can be more probable seat of detachment defects. In the third phase the previous results have been inspected through hammering. In addition, laboratory tests have been performed for the evaluation of heat transmission and emissivity.

2.2.2 The application on study cases of the thermographic survey for the

3.a

determination of possible detachments

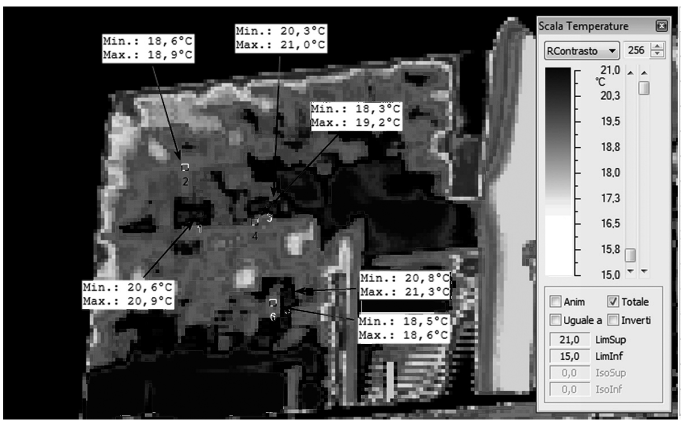
Figure 3: a. Building 12, South façade; b. Building 14 "La Nave" North façade

These two case studies have been presented in order to show the application of the methodology and to study the effects of the different orientation and therefore solar exposition of the façades in the thermographic analysis. In the picture on the left it's possible to notice areas interested by missing tiles and it's visible the presence of mortar on detached tiles above the window. The picture on the right represents a portion of the North facade of building "La Nave" where the tiles look intact by visual examination. From the pict 3.b s possible to see moisture stains caused by percolation below the window sills.

During the thermographic analysis, it's important to take into consideration the different colour and reflectance of the tiles or the presence of stains in order to avoid misidentification. In the first part of the analysis has been determined the emissivity value through laboratory tests on angular and linear tiles. In the case of Building 12 the value has been set equal to 0.95; for "La Nave" the value is 0.9 [9] [10].

Phase 1 - Identification of the characteristic gradient of temperature through IRT Analyzer

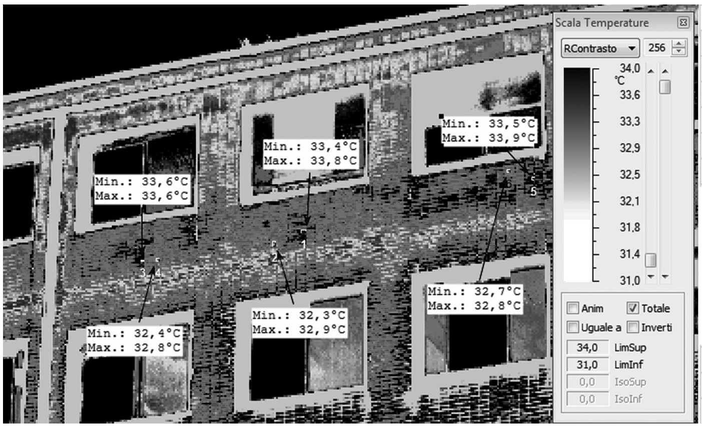
The following pictures show the analysis of the thermogram, in which the characteristic gradient of probable detachment has been identified through the selection of small adjacent areas having different temperatures. In particular for the Building 12 a gradient around 2°C has been evaluated as characteristic of the pathology while in the case of "La Nave" it is equal to 1°C. This difference is due to the orientation of the façade under study which in the case of North side receive less solar irradiation.



Area	Min. °C	Max. °C	Med °C
1	20,6	20,9	20,7
2	18,6	18,9	18,7
3	20,3	21	20,7
4	18,3	19,2	18,7
5	20,8	21,3	21
6	18,5	18,6	18,5
1_2	2	2	2
3_4	2	1,8	2
5_6	2,3	2,7	2,5

POSSIBLE DETACHMENTS

Figure 4: Building 12, South façade, 5th floor – characteristic thermal gradient identification



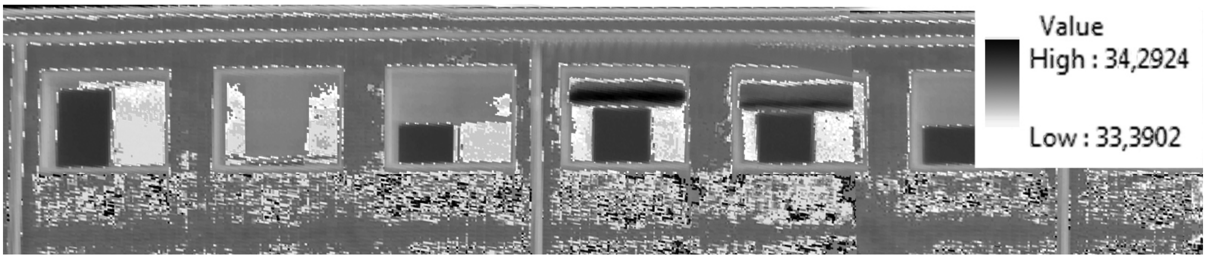
Area	Min. °C	Max. °C	Med °C
1	34,1	34,5	34,3
2	32,9	33,5	33,3
3	34,3	34,3	34,3
4	33,1	33,5	33,3
5	34,2	34,7	34,4
6	33,4	33,5	33,4
1_2	1,2	1	**1**
3_4	1,2	0,8	**1**
5_6	0,8	1,2	**1**

POSSIBLE DETACHMENTS

Figure 5: Building 14 North façade, 6th floor – characteristic thermal gradient identification

Phase 2 - Insertion of the isotherms and analysis by ArcGIS

Figure 6: Building 12, South façade, 5th floor – areas with possible detachments (in



black) and adherent ones (in white)

Figure 7: Building 14 North façade, 6th floor – areas with possible detachments (in black) and adherent ones (in white)

The temperature difference between the surface with possible detachment (in black) and the adherent ones (in white) is respectively 2°C for Building 12 and 1°C for "La Nave". The areas characterized by higher temperatures but affected by gaps or by the presence of different materials are to be identified through a rigorous comparison with the picture of the visible and omitted. In the case of Building 14 can be observed that once evaluated the characteristic thermal gradient it's possible through ArcGIS to analyze the whole mosaic of the façade. In the third phase the areas have been subjected to hammering and, after having checked the correspondence of the thermografic information, a probability of detachment has been assigned.

As example, the following figure shows the outcomes of the process through the map of the possible tiles detachments as regard the East façade of Building 12, for which has been evaluated a characteristic gradient around 3°C, due to high solar irradiation. The areas in which the thermal anomalies are representative of detachments are represented with boxes: the areas with higher probability of detachment (80%) are highlighted in black, in white the ones with medium probability (50%). The areas with white border indicate probable detachments of single tiles diffuse along a certain surface.

Figure 8: Example of application: Building 12 East façade, possible detachments of cladding tiles

These results will be used in the next phase of the research with the aim to construct fault trees and consequently to evaluate the residual service life of the components.

3. Results analysis

3.1 Anomalies and their probable causes classification

As a result of the surveys phase a series of pathological failures have been listed and classified according to the gravity associated (possible danger and therefore repair intervention):

1. detachment and missing tiles

2. cracking of the cladding system

3. discoloration and chromatic alteration

The most important damage tallied is represented by detachments, since they represent a source of danger for people (in particular for the case of a public building as it is university) and they imply the necessity of a timely intervention in order to guarantee safety [11]. The detachment is expressed in terms of lack of adhesion and the corresponding degradation level has been divided in low, medium and high according to the entity, the probability and the superficial extension (localized or diffuse) of the pathology. A large extension is linked to the possibility of fractures which can imply the collapse of the element: this is associated to a high degradation level. These three level of damage are associated to the probabilities of check-up previously explained and have been fixed in order to quickly and intuitively localize the areas more affected by the pathology and therefore to plan possible interventions aimed at flanking and reinforcing the fragile element.

The main causes have been listed according to the classification proposed by Silvestre & de Brito (2011) [12] *(fig. 9)* in design errors, execution errors, accidental actions, environmental actions, lack of maintenance, changes from initially predicted conditions.

DESIGN ERRORS
Incompatible, omitted or unsuitable choice of materials
Texture inconsistent with the background characteristics
Prescription of single bedding instead of double
Incorrect design of the ACT joints
Non-existence of peripheral, quartering or construction joints
ACT areas inaccessible to cleaning
Deficient care in detailing singularities of the ACT
Non-existence or defect in peripheral elements
Excessive background deformations
Rising damp

EXECUTION ERRORS
Use of non-prescribed and/or incompatible materials
Application in extreme environmental conditions
Disregard of the settling time between the stages of execution
Application in dirty, powdery or non-regular backgrounds
Disregard of the adhesive pot-life
Inadequate thickness of the tile bed
Incomplete contact between tile and tile bed
Tiles laid over structural joints
Single bedding instead of double
Use of tile bed or grout with high shrinkage
Filling of unclean joints
Joints of insufficient width or depth/missing joints
Incomplete filling of the joints
Disregard of the ACT's texture
Inlaid metal accessories unprotected at the joints

ACCIDENTAL ACTIONS
Impacts against the ACT
Vandalism/graffiti
Stress concentration in the background
Deformation of the background

ENVIRONMENTAL ACTIONS
Wind
Solar radiation
Reduced solar exposure
Thermal shock
Leaching of ACT materials that contain cement
Damp within ACT
Biological action
Air pollution
Crypto-efflorescence
Natural ageing

LACK OF MAINTENANCE
Lack of cleaning of the ACT and surrounding areas
Incorrect cleaning of the ACT

Figure 9: Classification of the causes of failure of cladding systems façades according to Silvestre & de Brito (2011)

3.2 Case studies: relations between degradations and their possible causes

In the examples under study, in the majority of cases of detachments and missing tiles, design and execution errors are supposed to be probable causes. Design errors are mainly localized close to windows: the loss of adherence could have been caused by water infiltration due to percolation from the sill and the mullions, in the point of junction between the wall and the window frame. Besides, as regard the upper part of the window, rainwater stops there causing the corrosion of the steel frame placed over it, since on that part of window it's not present a slope to let the water slide away.

Execution errors are mainly referred to the mortar used to place the tiles, which often having high thickness (around 40 mm) and being placed on several layers, creates various contact surfaces which are not always adherent among them.

Also the cases of cracking are supposed to be related mainly to design and execution errors: in this case they are due to the creation of excessive shear stresses between tiles and support, due to absence of expansion joints, to the wrong choice and laying of the adhesive and substrate.

As regards problems of discoloration and chromatic alteration, in the majority of cases, they are probably caused by environmental actions and lack of a proper maintenance.

4. Conclusion

The described research which has direct experimental application on the buildings inside Leonardo Campus of Politecnico di Milano, has been useful to assess the present conditions of the state of damage; it's now possible to evaluate the residual service life correlating the level of degradation to residual performances.

This analysis will be carried out through the *performance limits method*, which ties the estimated service life of component to its performances. The aim is to intervene by changing the boundary conditions and therefore by removing the risk factors or by flanking and reinforcing the fragile element (e.g. possible protective coatings for the mortar) so that to slow down the degradation growth and elongate the permanence of the element guaranteeing a proper level of performance.

In this specific case, the performance requirement is expressed in terms of the adhesion level of the cladding system and therefore the performance decay (and consequently the degradation growth) is evaluated in terms of tiles detachments.

In the following image it's possible to see a qualitative representation of the performance decay and degradation growth for adhered cladding systems, expressed as a function of time. The degradation level is divided in low, medium and high according to the entity, the probability and the superficial extension of the pathology. The graph provide useful information for the evaluation of the residual service life (and residual performance) of the component in order to plan maintenance interventions taking into account sustainability aspects along the whole life cycle of the building.

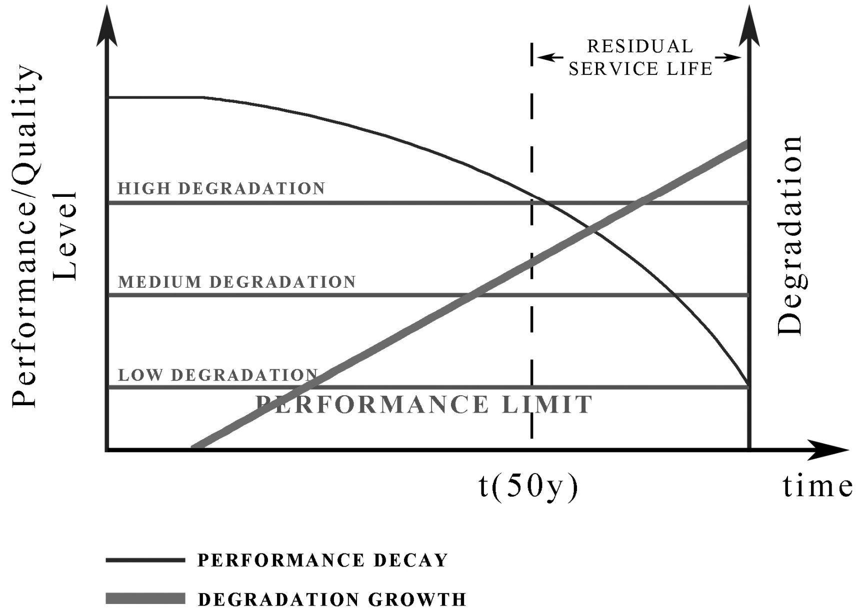


Figure 10: Qualitative representation of performance decay and degradation growth as a function of time

The next step of the research will be based on the development of a method for the evaluation of durability with the aim to identify and improve the application of the information on service life, keeping into account sustainability aspects. In addition, laboratory and in-situ tests will be performed in order to obtain further information as regards the initial performance and the performance decay trend during time [13].

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