Predictive maintenance for monitoring performance decay of plaster coverings according to the criteria of ISO 15686-7 code

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Abstract. The aim of the present work is the construction of the performance/time curve that characterizes and defines the aging of plaster coverings on tuff masonry, a widely used technical solution in the building stock of the city of Naples. 53 sample building were tested; these were selected according to a criteria of homogeneity of the technological characteristics of the support and covering material (tuff masonry + lime-cement plaster + acrylic paint). The year of construction of the buildings, as well as any problem occurred during the work realization, was acknowledged.
The described objective represents a result of indubitable utility and practical consequence, as it allows:
- the evaluation of the residual service life at the moment of the execution of field tests with fixed methodologies;
- the definition of the time thresholds for the execution of the most appropriate interventions, determined in a maintenance plan, in which predictive maintenance of course plays a fundamental role. The chosen methodology for the evaluation of performances, considering the indications of ISO 15686-7, is the infrared thermographic camera test, combined with close-up visual inspections and percussion tests.
The activities were carried out through the following main phases:
- defining the task;
- planning;
- examination;
- evaluation;
- reporting.
The results showed the possibility to create curves like the one represented in the annex B of the already quoted ISO 15686-7 and hence to define the decay with 5 performance degrees (no symptoms – slight symptoms – medium – strong symptoms – totally unacceptable, including collapse and malfunction), corresponding to an accurate quantification of the conditions of conservation, and that is mainly possible thanks to the output of the thermographic camera.
In relation to the results, different scenarios of planned maintenance for a period of 30 years have been hypothesized.

Introduction

The Italian building stock is made up by a significant percentage of ancient buildings (around 1/3), dating back to the period before World War I; they mostly are in poor conditions of conservation. This situation derives from a number of combined factors, such as:

- limited availability of economical resources;

- little knowledge on decay prevention;
- difficulty or incapacity to foresee the dynamics of performance decay for the most important building components, and so to schedule the necessary maintenance interventions

Aside from the problem linked to the general culture of programmed maintenance, for sure the knowledge of the modality and the period of aging of components such as structural ones in general, and also external coverings, would allow to avoid, at least partially, events like the one occurred two years ago, when a 14-year-old boy lost his life, in the city of Naples, because of the fall of a big piece of plaster from the facade of a historical building, as important as poorly maintained. The observation of the significant homogeneity – in groups – of the building stock pushed some years ago a team of researchers in Naples to sample a significant number (about 100) belonging to two different classes (buildings in masonry and buildings in reinforced concrete), in order to understand whether it was possible to realize a model of prediction of failure for painted plasters, which constitute the most widespread solution on the territory.

The experimentation, carried out from 1988 to 2000 (later extended to 2016 with the present experimentation), ended with the finalization of the model for the evaluation of the duration of painted plasters, which has been illustrated in code UNI 11156-3. It was, in fact, a methodology of direct observation, in accordance with the approach suggested by code ISO 15686-7, and supported by the possibility to carry out the following activities:

- in-depth observation of the initial conditions at the beginning of the experimentation, in some cases by visual inspection, and in other with the support of a thermographic camera;
- documentation of the maintenance activities executed during the early years;
- observation of the evolution of the conditions of conservation in the following period, with inspections mainly carried out via thermographic camera.

While in that occasion the main focus was on the performance associated to a state of failure, in the present work the aim has been the construction of performance/time curves, which on the one hand describe the progressive and tendential decay of performances, and on the other hand have significant practical consequences, such as the evaluation of the residual service life at the moment of the execution of field tests with fixed methodologies, and the definition of the time thresholds for the execution of the most appropriate interventions, determined in a maintenance plan, in which predictive maintenance of course plays a fundamental role.

Characteristics of the sample buildings

The buildings that were the object of sampling had in common the following characteristics:

- period of construction between late ‘800 and early ‘900;
- structure in tuff masonry;
- coating in painted common mortar plaster, smooth (in the top) and/or bossed (in the bottom);

Also, they were all subjected to decay anomalies in the first period of survey (between 1988 and the early years of the successive decade).

Fig. 1-2 and Fig. 3-4, for example, show an overview of the situation occurring before the interventions, with a building subjected to the following typologies of decay:

a. chromatic alteration, as a consequence of physical aging;

b. exfoliation of the finishing layer, as a consequence of rainwater infiltration;

c. diffuse cracks, due to the vibrations caused by the excavation works for the realization of the subway in the adjacent underground;

d. detachment of plaster from the surfaces of the facade, both because of phenomena of obsolescence and because of pathologies of static character, and – again - because of infiltrations;

e. detachment of plaster and concrete from the structures of balconies, making protection systems necessary (see Fig. 3).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Monitoring methodology and results

As anticipated above, a monitoring at different time steps (at least three for each building) has been executed, in order to verify the evolution the evolution of the conditions of conservation over time, mainly via inspections with thermographic camera.[1]

In order to individuate phases and activities in the performance assessment protocol, the sequential procedure suggested in code ISO 15686-7 has been followed, though revised and corrected according to the specific conditions of the case, as reported in Table 1 below.

MAIN PHASES	ACTIVITY/CONTENT	EXAMPLES/ELABORATION
Defining the task	Purpose	Planning of maintenance, diagnosis, evaluation of damage and residual service life
	Extent/level	Building, construction work, components
Planning	Basic materials	Performance documentation
	Registration scheme	Systematic
	Plan	Examination, inspection, meetings information, access
Examination	Recording of age, in-use conditions, and performance	Symptoms, in-use conditions
	Performance degree	Description of performances via pictures and thermographic measurements
	Documentation	Photographs, thermographic frames
Evaluation	In-use conditions	Critical properties and performance requirements / prediction of service life and/or residual service life
	Performance control	Requirements set by authorities/client requirements
Reporting	Introduction	Purpose, identification of the items, main structure, construction age, extend of level, time of survey, client and contractor, other parties involved
	Executive summary	Main conclusion, summary, performance, recommended actions, costs, economy, recommendations for further progress
	Main report	Definitions, reference level, registrations, inspections, evaluations, recommendations, costs
	Enclosure	Basic and supplementary material, photographs, thermographic frames

Table 1

In the examination phase, the in-use condition was classified in according with the ISO 15686-7 Annex B, and also keeping in mind the UNI EN ISO 4628-1 recommendations.

So, the definitions of the performance degree were the ones reported in the table 2 below:

[1] For the reading of the thermographical images, it has to be considered that they have been "shot" on facades exposed to direct sunlight, in the morning. In this situation the air, if present, between the plaster and the background (in case of detachment) has the function of thermal insulator in the transmission of heat from the plaster to the background itself.
For this reason, the detached plaster shows itself at higher temperatures in comparison to those of the adjacent zones; in fact, in the latter situation the layer of plaster transmits part of the heat to the background.
According to the scale of temperatures chosen, the zone that is closer to red/orange/yellow (hotter) corresponds to a more detached zone. As time passes, the red/orange/yellow zone increases and the blue/purple zone gets decreases.

DEGREE	TYPE OF SYMPTOMS	IN-USE CONDITION FOR THE PLASTER COVERINGS
1	no symptoms	no performance decay
2	slight symptoms	incipient exfoliations and air bubbles – evident chromatic alterations
3	medium	accentuated exfoliations and air bubbles – microcracks or incipient detachment extended to less than 30% of the surface
4	strong symptoms	accentuated exfoliations and air bubbles – microcracks or incipient detachment extended to more than 30% of the surface
5	totally unacceptable	partial/total collapse

Table 2

It is possible to associate a typology of maintenance intervention to each of the listed performances, and to identify the time threshold at which the performance level is reached. In fact, biunivocal bonds exist between each of these three terms, as shown in Fig. 5:

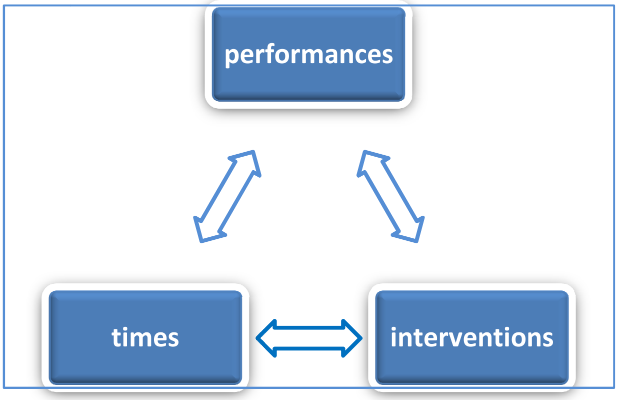

Fig. 5

So, it is possible to associate a typology of intervention to each of the decay levels (in-use conditions, to each of which different performance degrees correspond) listed in Table 2, according to the following table of correspondences:

IN-USE CONDITIONS FOR PLASTER COVERINGS	MAINTENANCE INTERVENTIONS
No performance decay	None
Incipient exfoliations and air bubbles – evident chromatic alterations	Partial grouting + painting
Accentuated exfoliations and air bubbles – microcracks or incipient detachment extended to less than 30% of the surface	Smoothing + painting
Accentuated exfoliations and air bubbles – microcracks or incipient detachment extended to more than 30% of the surface	Partial makeover of the plaster + smoothing + painting
Partial/total collapse	Total makeover of the plaster + smoothing + painting

Table 3

In conclusion, thanks to the outputs of the thermographic inspections, it is possible to build performance/time curves like those in Figures 6, 7, 8, 9 (which respectively refer to the buildings in Piazzetta del Nilo 7, Via V. Colonna 4, Via V. Gemito 5 and Via G. Martucci 10), and then, associating to the performances the related interventions, it is possible to realize reliable maintenance programs for each, after choosing the maintenance strategy to adopt.

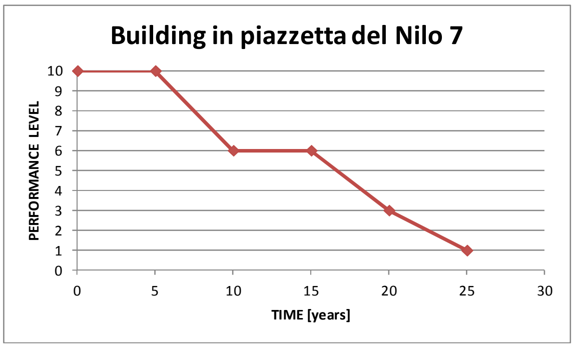

Fig. 6

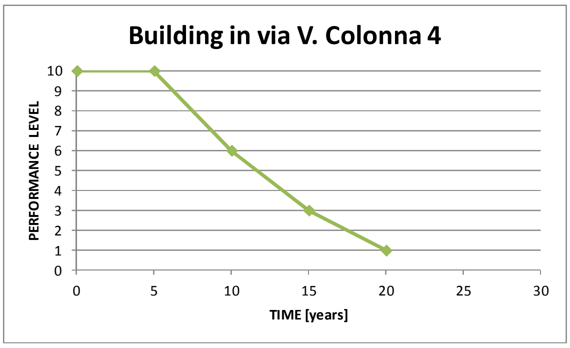

Fig. 7

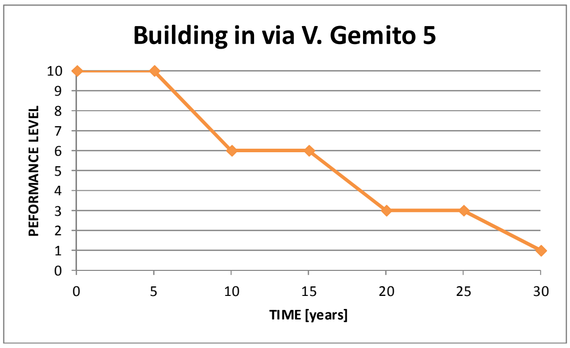

Fig. 8

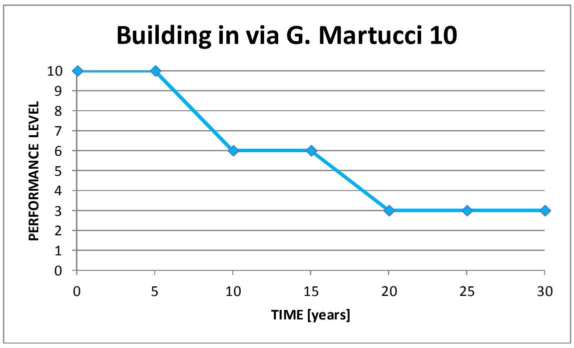

Fig. 9

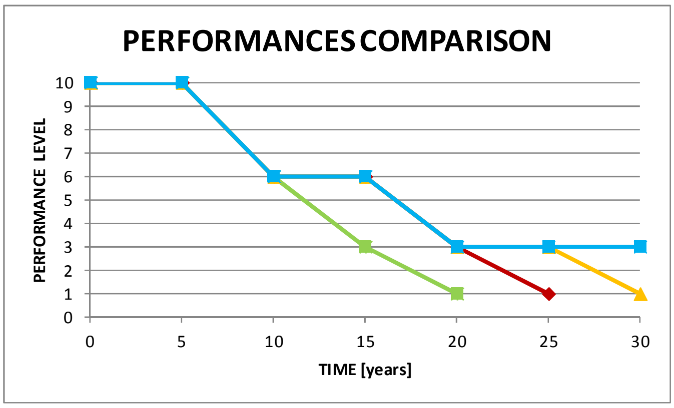

Fig. 10

In this aim, it seems opportune to highlight which are the parameters that lead this choice:

- the general characteristics of the building (historical-architectonical value, collocation, constructive technology) and the security degree to provide;
- the available budget;
- the consequences of possible failures;
- the limits for the execution of maintenance works (such as in the case of schools, theatres, etc.);
- the requirement of particular performance degrees from the client (as for esthetical, hygiene, thermo-hygrometrical performances).

It seems necessary to make it clear that, for the construction of performance/time curves, the performance degrees considered were the significant ones (10, 6, 3, 1, 0), which can be associated to the description of the conditions of conservation defined in Table 2 (respectively 1, 2, 3, 4, 5) with a quantification – in a decimal ratio, as it expresses a percentage – that derives from economical evaluations which estimate the costs of maintenance interventions.

In order to extend the evaluation to the desired time period (30 years), extrapolations other than the direct observation were made, thanks to the acquisition of the documentation of the maintenance history of the buildings (reports, photographical items, accounting), relatively to the period in which inspections could not be executed.

Eventually, Figure 10 shows the four curves overlapped, highlighting a good convergence of the data, and therefore a sufficient reliability of the method.

The four sheets reported in the annex synthesize, for as many buildings among the sampled ones, the progression of performance decay, with 3 thermographic frames referred to consecutive times.

Economical aspects

The economical parameter deserves a stand-alone mention, both because it is more objective, and because it represents a consistent reason behind this kind of choices.

By executing different typologies of maintenance interventions in a given period of time, as a consequence of maintenance strategies, it is possible to compare the consequences on the expense in the mid-long period, overlooking – of course – other factors, despite having influence, as they would require a multicriteria analysis to be taken into account. For the determination of the total cost, the expenses in the different periods have been discounted and summed.

The maintenance scenarios taken into account for the economical comparison are those reported in Table 4, in which the total costs are reported as well, deriving from the application of the unitary costs found in the Official Price list of Campania region – 2016 edition to a surface of 2000 mq, considered as a mean value for the sampled buildings.

SCENARIO	MAINTENANCE INTERVENTIONS	N° OF INTERVENTIONS IN 30 YEARS	UNIT COST [€]	TOTAL COST [€]	TOTAL DISCOUNTED COST [€]
1	total makeover of the plaster + smoothing + painting	1 1	27,98 18,50	141.880	141.880
2	partial makeover of the plaster smoothing + painting	2 2	13,99 18,50	118.960	258.375
3	smoothing + painting partial makeover of the plaster	2 1	18,50 13,99	81.978	211.646
4	partial grouting + painting partial makeover of the plaster smoothing + painting	2 1 1	14,10 13,99 18,50	216.814	314.003
Note: the evaluation of costs took into account the use of the scaffolding, when necessary, and the preliminary works of plaster demolition. The partial reconstructions were evaluated considering the 50% of the total surface.					

Table 4

The first scenario corresponds to a strategy based on the "consumption" of the performance of the component during its whole life cycle, with the total absence of maintenance interventions.

The second scenario considers the possibility of partial reconstructions (2 in a period of 30 years), with finishing works extended to the whole surface in order to provide a sufficient esthetic performance degree.

The third scenario is based on the criterion of defending plaster from the atmospherical agents by renovating the finishing layers, then proceeding to its – partial - reconstruction as late as possible.

The fourth and last scenario, is the one with the lowest intensity of interventions, and aims to the removal of the located anomalies with more frequent superficial interventions, until the reconstruction, partial as in the case above, of the plaster.

Conclusions

The values shown in Table 4 seem to demonstrate that the maintenance strategy characterized by an infrequency of the interventions represents in any case, in the long term as well, the choice with the lowest economical expense (€ 141.880), though the single interventions have the highest cost.

The strategy involving interventions of lower cost, yet more frequent in the period considered, is not too convenient (it must be noted that this consideration is purely economical), in fact the total reaches twice the total of the first scenario (€ 314.003). It would be interesting, as forementioned above, to extend the evaluation to other aspects such as the security and the quality; also, other topics linked to the increase of the costs when chained failures take place, might lead to partially different results, though not decisive for the final outcome of the comparative evaluation.

The results of the thermographical inspections also seem to suggest an optimal periodicity of 5 years for the monitoring, in order to have sufficient control of the aging, as no significant variations of the performances were noticed in smaller time periods.

On the side of the possibilities to make use of the criteria of predictive maintenance in the building engineering in general, the experimentation apparently demonstrates that the construction of the performance/time curves and their substantial convergence around a curve of tendential decay of performances, may allow the evaluation of the residual service life with satisfying reliability, also thanks to the employment of a instrumentation that measures the performances in an objective way, that can be expressed in physical-technical units. This possibility, in particular, represents a concrete element of evaluation for the choice of the maintenance strategy, also taking into account – through the reading of the outputs of the thermographical inspections – the estimation of the times at which an insufficient degree of security will be reached.

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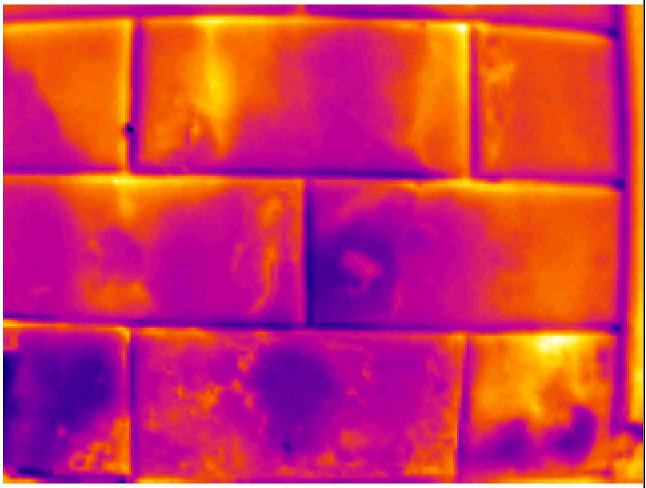
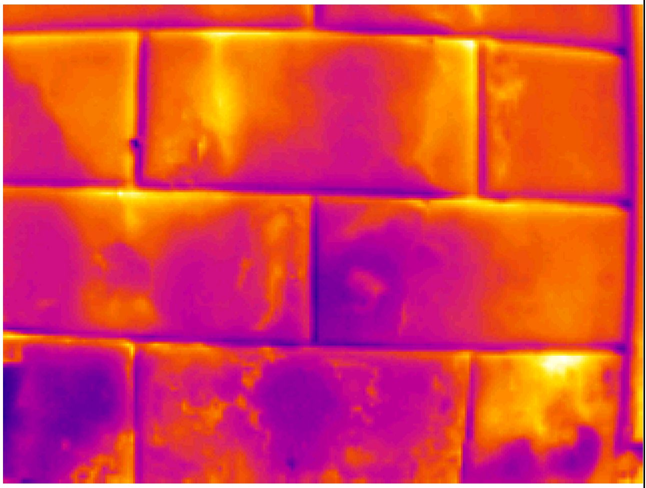
A	Building in Naples (Italy) - Via Riviera di Chiaia, 270

A.1



A.2

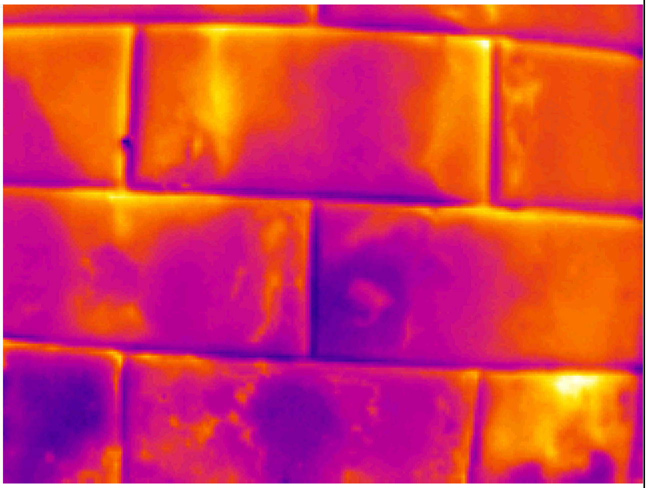


NOTES:

The building, dating back to ‘800, has been object of maintenance interventions on the external facade in the end of ‘90s: some years later phenomena of exfoliation of the finishing in the smooth plaster have started, while the bossed part began to show a more and more evident detachment.

Currently, the phenomena involving the smooth plaster have significantly worsened, while the detachment of the bosses from the wall seems constant, but instable.

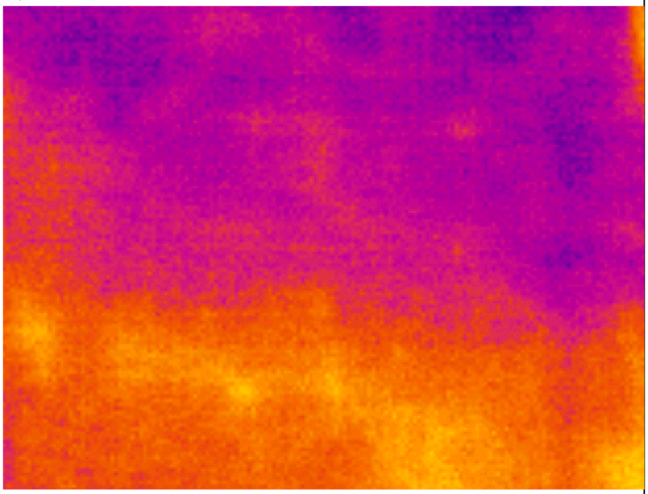
A.3



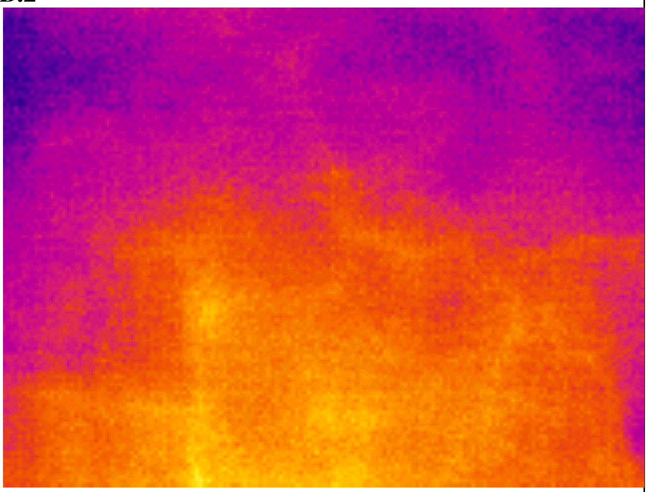
A.1	Date: 1998
A.2	Date: 2006
A.3	Date: 2010

B	Building in Naples (Italy) - Via Riviera di Chiaia, 267

B.1



B.2

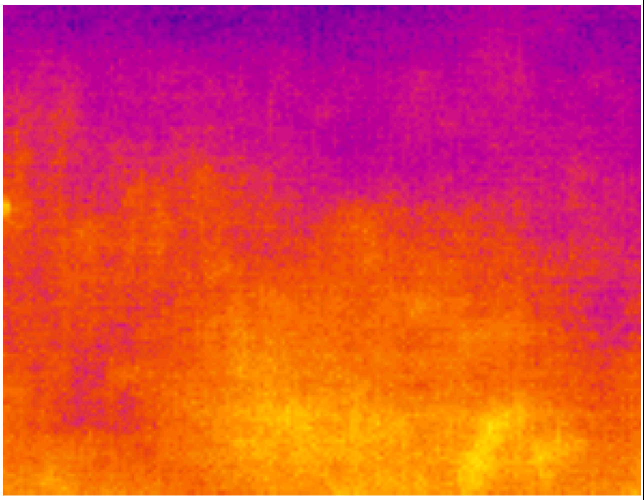


NOTES:

The building is characterized by the simplicity of finishings, quite anomalous if compared to the period of construction (1800).

Maintenance interventions have recently been executed, leading to a cancellation of some of the situations that can be rilevated in the thermographic frames reported in the right, which show a little but constant worsening of the lack of adhesion of the plaster from the background.

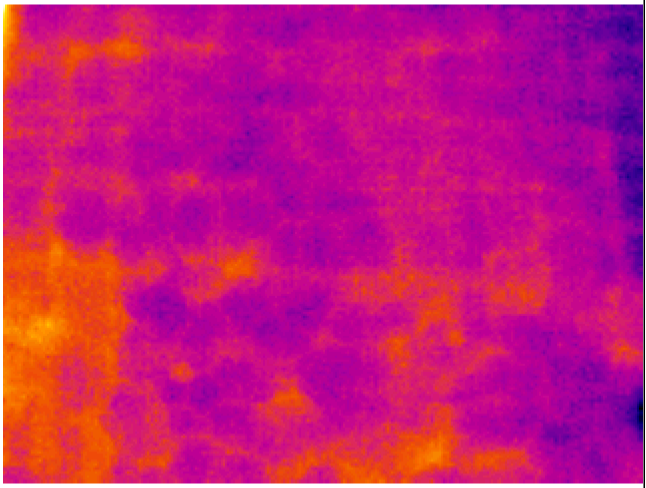
B.3



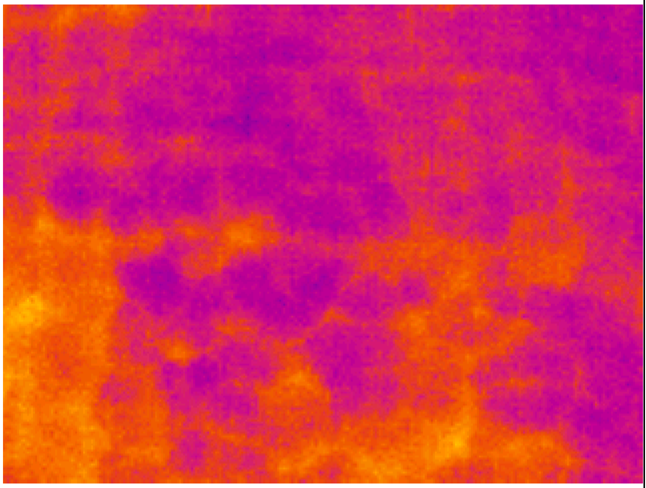
B.1	Date: 1998
B.2	Date: 2006
B.3	Date: 2010

C	Building in Naples (Italy) - Via Riviera di Chiaia, 257

C.1



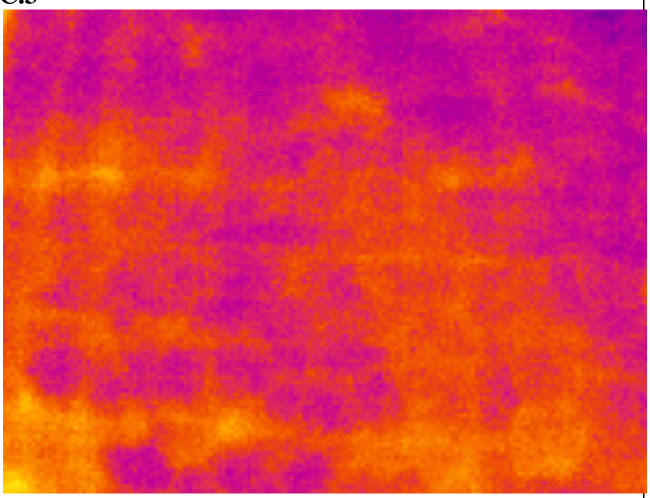
C.2



NOTES:

The building was subjected to maintenance interventions in 2010. Before these works, a slow and progressive worsening of the conditions of adhesion of the external plasters on the side of via Riviera di Chiaia, characterized by an aggressive climate (city environment with intense traffic and sea atmosphere) was noted. The thermographic frames refer, in particular, to the bottom of the prospect, which suffers the most from the vibrations caused by the passage of the vehicles.

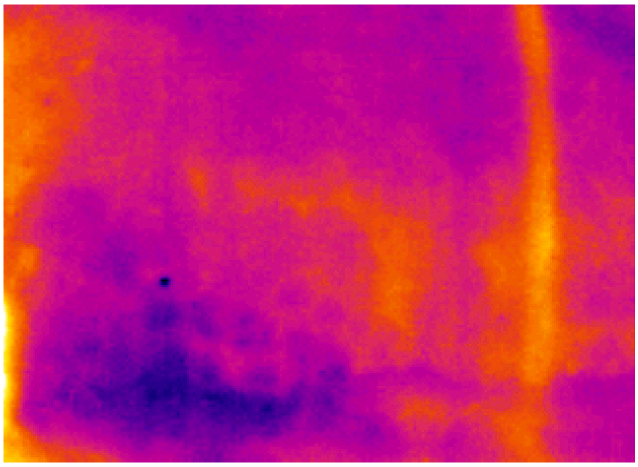
C.3



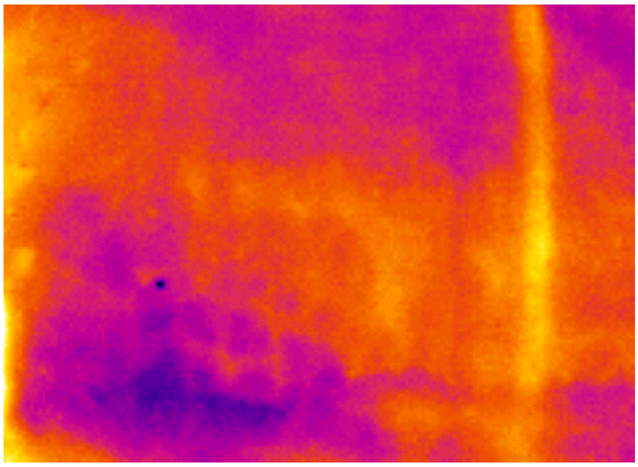
C.1	Date: 1998
C.2	Date: 2006
C.3	Date: 2010

D	Building in Naples (Italy) - Via Enrico Alvino, 37

D.1



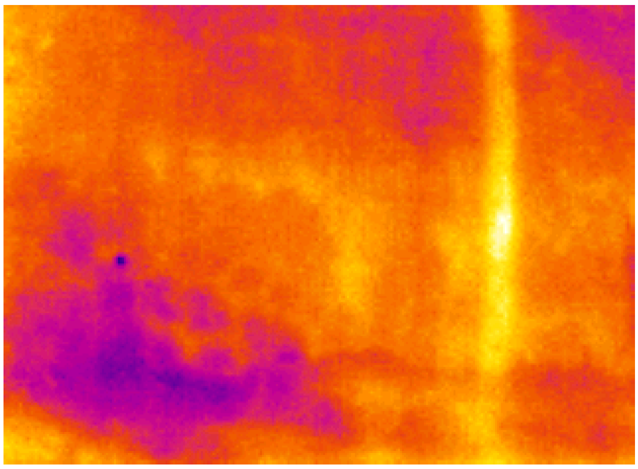
D.2



NOTES:

The building dates back to early ‘900. In 2003 significant interventions of maintenance were executed, including the total reconstruction of external plasters. The thermographics envise a substantial absence of repetition of the phenomena of performance decay, which had previously occurred with the detachment of wide areas from the background. It must be noted that during the last 10 years the streets surrounding the building have been closed to traffic, removing the stress from vehicles.

D.3



D.1	Date: 2000
D.2	Date: 2006
D.3	Date: 2016