Reliability and Economic Aspects of Restoring Interventions

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***Abstract*— In building restoration the last decades have been characterized by a more and more active research of technological solutions that – almost in every case with the support of chemistry – could allow to perform interventions even in the situations where it was more opportune to execute demolitions and reconstructions.**
The lack of a cost-benefit analysis, caused by issues of cultural approach, and the lack of evaluations in terms of reliability of the interventions of restoration executed, due to a lack of management during the period between the restoration intervention and the next failure, are producing situations of performance deficit which are bound to produce consequences not only on the economic balance, but also on the safety of the existing building heritage. A theoretical dissertation is followed by some emblematic examples.

***Index Terms*— reliability, service life, cost, performance, multi-criteria**

I. Introduction

The unstoppable rise of importance of the building restoration, which has culminated in the economic overtaking of the new constructions and still continues as of today, has brought many evident consequences, often very positive.

Considering the intervention typologies, several design solutions were born, in order to solve a quite wide number of pathologies following the slogan "restore at any cost", even when the object of the intervention was an element with no historical-artistic value.

The industry has supported this tendency with an incredibly various range of products, drawing on chemistry as much as possible, in order to offer the most varied possibilities to passivate the oxidized steel profiles, to prevent the capillary rise of water, to provide waterproofing without using bituminous products, to consolidate structures beyond the initial resistance levels even in the most desperate cases.

There have actually been several significant contributions, which have led to the creation of a wide and varied expertise of technical solutions.

Though, the reverse of the coin is in the convincement that there is always a valid solution for the restoration – and that restoration is the most valid solution – without comparing costs and benefits of the projects of restoration with those of reconstruction, that is to say – even when the analysis has been carried over – not to consider at least a medium-term time horizon.

The purpose of this paper is, after a theoretical introduction to the subject, to highlight the most emblematic cases of design solutions where little regard is generally given to this aspect, reporting some images that bring out the criticality of the matter.

II. State of the Art

The industrial products that have supported the building sector in the last decades have ranged in the whole building sector.

In detail, it can be said that they have influenced the main technological sectors: reinforcement of existing structures (reinforced concrete, masonry, wood, steel); concrete additives; structural materials of new generation; humidity; waterproofing; thermo-acoustic insulation; protection from rusting; sealing and elastic bonding.

The industry systematically dealt with the issues coming from the world of employment, providing more than one solution.

In the field of materials, then, the building sector has been literally invaded by a huge choice of products, among which the following can be reported as examples: thixotropic mortars; osmotic mortars; epoxide resins; composite materials; self-compacting concrete; fillers for the mix design of more durable concrete; silicate paint; siloxane paint; insulating panels in glass or rock wool; insulating panels in polystyrene; insulating panels in polyurethane.

The tendency, which in Italy is prescribed by Merloni law since 1994, to a performance approach to design, has led to a great care for the modalities in which the offer was presented, through technical sheet where the objective data, the geometric one, has left more and more space to the data regarding the performance provided.

In a crowd of problems, solutions and products, the 'design by catalogue' – notably supported by the multimedia tools – has caught on more and more, in relation to the performance provided by the component.

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III. Reliability Analysis in Building Constructions

Certainly, today there is still a notable complexity in carrying over reliability analysis on building components, but even more on building systems.

As it is well-known [1][2][3][4][5][6][7][8][9], reliability can be intended as the aptitude of a given component to fulfil a specific function under specific conditions for a given period of time, and can be expressed through the relation:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)\,dt = \int_t^\infty f(t)\,dt \qquad (1)$$

Basically, what matters is the trust that can be attributed to the behavior over time of a given component, under environmental and usage conditions that have to pre-defined and, when possible, codified.

The quantitative determination of reliability can be achieved in three ways:

- *direct survey*, derived from a number of observations according to which, through appropriate statistical methods (methods of statistical inference), the desired information can be acquired, in particular for the components that fulfill the requisites of sameness and repeatability (non-complex components);
- *sample testing*, carried over in laboratories or generically under conditions that simulate the ones that effectively occur in exercise, using the methods of statistical inference in this case as well;
- *theoretical evaluations*, applied to the elementary components in which a more complex one can be divided, making use of the knowledge on reliability obtained through the abovementioned methods.

The study of the failure rate λ is an item of particular interest: it can be defined for a given component in a given time period as the number of failures that occur in the period, and has the following expression:

$$\lambda\,(t_1, t_2) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \lambda(t)\,dt \qquad (2)$$

Analyzing what happens for the building components, it can be affirmed that the failure rate has a particular trend over time, compared – for example – to industrial components.

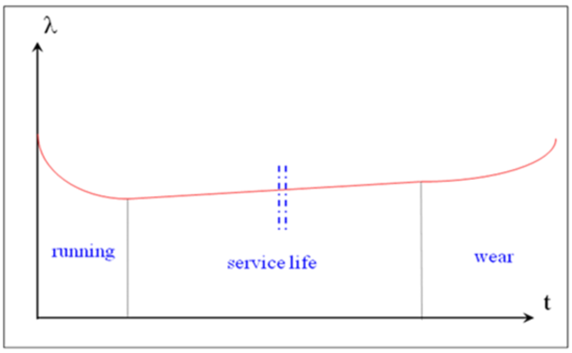

Figure 1 - Trend of failure rate over time for a building component.

In the classic λ/t diagram referred to a technical element of a building, the 'running' or 'infant mortality' is quite limited, or even absent, in most of them, while 'service life' cannot be represented by the horizontal portion of the curve, but it is rather quite increasing, with a trend that depends on the typology of element (Fig. 1).

Because of these characteristics of the λ/t diagram, if it is overlapped with a performance/time diagram, the graphs don't coincide, as the start of service life, according to the failure rate diagram, is not the initial time, while for the performance diagram it is connected to the phase of installation. This can be explained by the variability of the *running* phase, which may exist or not, so the start of service life actually coincides with the start of the *regimen* phase.

The transposition of the concepts and methodologies described above finds concrete possibilities of actuation in the building sector, despite some difficulties and particularizations, in detail:

- the processes of performance decay are very slow and the failure rates are not elevate in so-called period of *service life* of the product;
- most construction elements are not *bi-stable*, in the sense that there is a significant range of performance values between the states of '*functioning*' and '*not-functioning*', and this – as mentioned – embodies one of the main problems in the evaluation methodologies;
- compared to other technological systems, in the building sector the required reliability can assume, in general, less elevate values, as the damage produced by the failures are less severe, as they often don't cause an out-of-service state of the system.

To complete the third point, there are actually some elements or sub-systems which require high values of reliability:

- from the functional point of view: the technical systems (and all the sub-systems and components that influence the conditions of habitability and comfort), the structural sub-systems and the finishing components, such as external coverings, decorative elements, etc. for which failures compromise the requirements of security;
- from the economic point of view: the sub-systems or components with a low degree of accessibility (and so an elevate cost of reparation or substitution) and for which failures unavoidably cause consequent ones in irreversible times and/or terms.

As an example, in order to understand the complexity of the evaluations concerning the performance of the building components [10][11][12][13][14], and in particular that related to the state of '*failure*', it is sufficient to compare the characteristic performance/time diagrams of an industrial component (for example, a light bulb) (Fig. 2) and that of a plaster covering (Fig. 3).

In general, in the building sector it is not easy at all to follow the usual criteria to '*design for reliability*', in order to obtain '*intrinsically reliable*' products, criteria such as:

- adopting an oversizing of the components, that is to say to choose and/or to design components with higher capacities (or resistance to stress) than required, in order to have them work at lower utilization rates (*de-rating* concept);
- improving the environmental conditions of the components, for example by increasing the cooling action on the components that are sensitive to the effects of temperature; adopting better protections from dust; reduce vibrations; etc.;
- making use of redundancies (this measure has to be used with caution as it improves the '*system reliability*', but tends to increase the number of interventions of corrective maintenance);
- minimize the number of components (banal but effective concept: '*what does not exist does not fail*');
- use as much as possible components and/or materials of external supply with '*known reliability*' or '*controlled reliability*' (that is to say, components for which a '*history*' already exists or new components for which the supplier can guarantee a certain level of reliability).

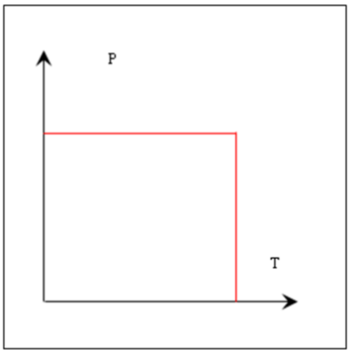

Figure 2 - Performance-time curve of a light bulb.

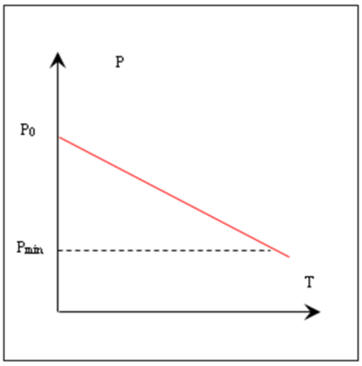

Figure 3 - Performance-time curve of a plaster covering.

It is evident, in general, that the design for reliability is not to be conceived as an effort to achieve infinitely high levels of reliability: this criteria has to be guided first of all by the nature and the characteristics of the component to which we refer, taking into account both the consequences deriving from its failure and the economic implications of the maintenance intervention, both direct (on the component itself) and indirect (on the components that have a technological connection with it) [15].

In building constructions, most of the systems and sub-systems can be schematized as '*sequential*', even though – in many of them – the failure of a component does not always determine a state of out-of-service for the whole system: that is actually because of the *non-bistability* from which the building elements are characterized, and because of the particular bond of technological connection that exist between many of them.

So, considering sub-systems such as top horizontal enclosures and vertical enclosures, it can be noticed that on one hand there are sequential components, respectively:

- floor slab – gradient screed – screed – waterproofing layer – separation and creep layer – bedding screed – floor paving;
- masonry – plaster – paint;

while on the other hand the failure of these components does not always determine by itself an out-of-service state for the system.

Just from the observation of the two exemplified sub-systems, it can be noticed that a certain '*direction*' exist in the connections between the components, in the sense that the out-of-service of the former ones in each system surely brings to the out-of-service of the whole sub-system and then of the others, but this is less true as we consider the others, to the point that a failure of the most superficial layers becomes a potential cause of out-of-service only in particular conditions and in presence of a long-lasting situation of failure with no maintenance interventions.

Basically, it can be said that the components of the building sub-systems only become *potential* causes of failure for the whole sub-system, even if they are displaced sequentially, but in many cases (maybe the most of them) and in ordinary working conditions they can only cause failures, at most, in some of the components they have a technological connection with.

According to one of the possible classifications, it can also be affirmed that systems in building constructions are mainly '*systems with acknowledged performance demand'*, for which, among the various models used in the calculation of probabilities of certain events of failure for the system, the most fitting is the *truth table* (or, space of events in a system): it consists in the list of all the possible states of the system (for which the number is 2^n for a system constituted by n bi-stable elements), establishing whether or not each of them constitutes a state of failure for the system.

The scenery outlined above highlights well the complexity of a reliability analysis in building constructions, and it is evident that this constitutes the main excuse for the lack of proposition and articulation of this kind of evaluation: yet, it has to be made clear that in the field of durability as well, where – after several years of research – a wide literature and data provided from producers are available, a correct culture in the programming of times and modalities for the management of obsolescence through programmed interventions of restoration, has yet to catch on [16][17][18][19].

IV. Economic Aspects

In the evaluation of the '*convenience*' to carry out either an intervention of restoration or one of demolition and reconstruction, the pattern is well-consolidated: the back-discounted cost are compared, overlooking completely the necessity to make use of monitoring activity or new interventions to keep the performance level above the fixed minimum threshold, and often what is considered as '*benefit*' – and tends to prevail – is the aspect linked to the limitation of the discomfort to users which comes from the execution of interventions of restoration, rather than reconstruction.

It is well-known, but too often forgotten, that the curves of the costs of construction and maintenance as a function of reliability have two opposite trends, as shown in Figure 4.

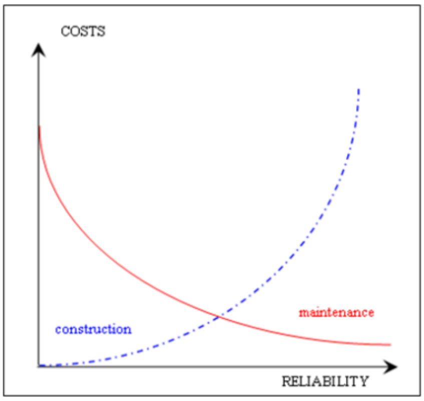

Figure 4 - Trend of construction and maintenance costs in a cost/reliability diagram.

This evaluation of convenience for an intervention of restoration can be performed by comparing the economic utility that derives from the extension of the service life of the component and the cost of the intervention, and this can be realised by obtaining the numerical value corresponding to this utility.

This is possible if we consider the initial cost of construction of a component as the present value, at the year of construction, of *n* constant annuities, where *n* is the duration of service life expressed in years, in absence of maintenance interventions. The formula for the calculation of the present value of the annuities can be equalled to the difference between the initial cost of construction of the component C_0 and the residual value of the component after the end of service life V_r, if present (actually, it is null for almost all the building components), back-discounted for *n* years. The result is the following equation:

$$C_0 - V_r \cdot (1+i)^{-n} = A_v \cdot \frac{1-(1+i)^{-n}}{i} \qquad (3)$$

The second side of the equation can be named *CE (n)*, the value of the *Component Employment* for *n* years. A_v, the annual value of the component, can be easily obtained from it. This value is useful because it can be used to calculate the present value of the annuities that theoretically constitute the service life of the component if the intervention of restoration were executed. So, assuming the intervention is performed in the *l*-th year of life of the component, and that it extends its service life for p years so that $n + p = m$, then the convenience of the intervention can be evaluated by comparing the value of *m* constant annuities, detracting the cost of the intervention of restoration C_r, back-discounted for *l* years, and the first side of the previous equation.
Eventually, an intervention of restoration is convenient if:

$$CE(m) - C_r \cdot (1+i_1)^{-l} > C_0 - V_r \cdot (1+i_2)^{-n} \qquad (4)$$

CE (m) is, as defined before, the value deriving from the employment of the component for *m* years, and is then equal to the present value of *m* constant annuities with A_v as amount.

Of course, since there are several possibilities for each intervention of restoration with different costs of execution and results in terms of residual service, the inequality might be satisfied only by some, or one of them. If no intervention of restoration matches the inequality, it is better to choose demolition and reconstruction at the end of service life instead. It should finally be noticed that the interest rates used in the formula are different as they depend on the year they are referred to.

The issue of evaluating performance is not taken into account, though: it is indeed problematic to evaluate in action – for example – what is the mechanical resistance of a decayed rafter in reinforced concrete which has received an intervention of cortical restoring, to which residual service life is of course tied.

In any case, it is too evident that any comparative evaluation brought on an economic level, cannot overlook the necessity to keep the performance levels above the minimum thresholds.

V. Examples

Some interventions are characterized by their vast diffusion, and by the equally vast tendency of the designers to a very superficial approach, of which the well-consolidated practice and the process documentation of some products of undoubted effectiveness is a major culprit.

The problem, though, is not constituted by the quality of the product, but rather by some lacks, in particular in:

- The evaluation of convenience;
- The evaluation of the performance levels reached after the interventions;
- The evaluation of the duration of the residual service life del component after the intervention, and so of the interventions that have to be programmed for the future.

The simplest (but also most effective) example to suggest is that of the building products in reinforced concrete: the pilasters, beams and the floor slabs, in particular, are being referred to.

The first interventions of cortical restoring were proposed in the ‘80s, then in recent years after being ‘reinforced’ by the diffusion of composite materials that – at last – do not aim to a desperate rescue of the present conditions, but also to a restoration of the mechanical properties.

Unfortunately, some behaviors that can be considered to be quite dangerous are quite diffused as well:

- A consequent verification of the structural elements, which have surely undergone a reduction of the resistant capacity because of the reduction of the section of the steel bars, is not performed;
- A detection of the state of carbonation of the concrete, which may undermine the interventions of passivation – often executed only on the lower surface – as the concrete which is in contact with the upper surface may have become acid, is not implemented;
- The problem of adhesion between pre-existing concrete and thixotropic mortar, which could be solved as well by the products of chemical industry, is overlooked.

The problem reaches troubling dimensions when considering components with particular combinations between environmental stress agents and technological characteristics.

In particular, in reference to the following:

- Roof slabs, connected for a significant length to rainwater streams, in addition to thermal stress, in particular when there is a high construction quality: for example, those – widely spread as often employed in the ‘60s – with rafters embodied in the bricks (Fig. 5), which are characterized by no distribution insole, steel bars often not introduced into concrete, that is a sign of nearly-absent inner face detachment;
- Cantilever balcony insoles, for which the initial lack of waterproofing has often caused damage which cannot be cured by cortical restoring (Fig. 6), and for which the time to make use of reconstructions is presumably close.

Another wide family of pathologies, often wrongly faced, is the one regarding tuff structures (building masonry or retaining walls), subjected to phenomena of humidity by contact or capillary rise.

As it is well-known, the evaporation of water produces in these cases the crystallization of salts with consequent volume increase: efflorescence mainly causes undesired aesthetic effects; subflorescence, in a porous material like tuff, causes deep erosions with loss of notable quantities of matter.

Figure 5 - Steel bars oxidation in a reinforced concrete slab.

Figure 6 - Concrete balcony insole decayed because of rainwater infiltrations.

The observation of the interventions suggested to cure this problem also highlight the following measures:

- filling voids with cinder blocks;
- filling voids with enlarged mortar;
- making use of the technique of ‘*reversal*’, by removing the tuff ashlars and repositioning the eroded part inside.

It is evident that these criteria do not allow any restoration of the resistance that the stone elements and the whole wall have lost, and in presence of structural elements of limited size (in particular, retaining walls often have minimum values of width) determine a significant risk.

VI. Conclusions

Several factors intervene to determine the effectiveness and convenience in the decision of the opportunity of interventions to recover the performance of a building component and – even more – in the choice of the intervention to execute.

In particular, it seems opportune to highlight that three main factors influence the result:

- Performances;
- Costs;
- Interactions with the environment.

Several researchers have investigated the problem through a multi-criteria analysis, reaching very interesting considerations, but, unavoidably, without a definitive response [20][21][22][23]. This is, of course, a result of the fact that these analysis suffer from a quite subjective evaluation, as the weights that are attributed to the influencing factors are set by the evaluator, and may lead to different results when performed by different people.

In any case, offering a decisional tool to those who have to make choices on the restoring interventions represents the most correct approach, because it helps to prevent the ill thinking that leads to favor low costs of realization, with the dangerous result of obtaining a low residual life, higher costs of management and heavier environmental impact.

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