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THE CONSIDERATION OF SERVICE LIFE OF NATURAL STONE CLADDING AS A DESIGN VARIABLE

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ABSTRACT

Durability is an integral part of modern building design. The demands for innovative building techniques and the inclusion of materials and components, with lower life-cycle cost the knowledge and skills of building designers. The pressing need for reliable information about the role of durability in the building design process, has led to the formation of extensive research, which has been carried out on durability of building materials and components. In accordance with the literature, this paper intends to demonstrate the relationship between natural stone claddings' defects and their probable causes, by analysis of 162 samples, inspected in Tehran, Iran, in order to determine the importance of considering of service life, as a design factor.

KEYWORDS: Degradation State, Design Factor, Natural Stone Cladding, Probable Cause, Service Life

INTRODUCTION

Practitioners and researchers from different design disciplines have recognized that concurrency of knowledge and interdisciplinary collaboration during the design process are fundamental conditions for the development of better products (Cavieres et al., 2011). On the other hand, durability would be one of the intrinsic factors when considering service life and the service life would be one of the extrinsic factors when realistic design life is taken into account (Nireki, 1996). Why so, the overwhelming majority of decisions affecting the lifecycle of a product are taken during the design phase, as it is estimated that design decisions will affect more than 75% of final product costs (Hsu & Liu, 2000). Hence, with the lack of appropriate design decisions, cost and time will increase in order to achieve optimal performance in each design problem(Eastman et al., 2011). The design stage is the period when technical and economic optimization is to be carried out by various design factors, but due to inadequate knowledge and experience or defects in designer training, as well as the selection of inadequate technical specifications for materials or failure to provide the correct execution details, causing early damage and reduce the service life of building components (Chew & Tan, 2003).

Building degradation is a complex phenomenon that is affected by many factors and has highly influences on the built heritage. Deterioration begins immediately after the materials and components are installed on site, due to natural aging and the effects of environmental agents (Harris, 2001) which leads to an accelerated loss of building's performance (Haagenrud, 2004). This loss of performance, which manifests itself in ever higher levels over time, expressed by the presence of defects, leads to the inability of the buildings to fulfil the requirements for which they were designed (Chai et al., 2013). Therefore, the knowledge concerning the service life of buildings and their components assumes a very important role in achieving more rational and sustainable solutions (Daniotti et al., 2008; Mateus et al., 2008; Pearce, 2003).

The deterioration of buildings does not occur uniformly: since buildings are composed of various subsystems, which degrade at different rates, it can be assumed that they are composed of several layers of durability, with different service lives, which are distinct from the structure's service life. Façade claddings have a fundamental role in the performance of buildings, functioning as the first and foremost protective layer from environmental degradation agents of the wall and the structure. As a result, the buildings' envelope - sometimes also referred to as the skin of the building - is very prone to defects, with direct consequences on the quality of the urban space, on the comfort of users and in repair and maintenance costs (Kirkham & Boussabaine, 2005). The degradation of the envelope can lead, in some situations, to structural problems to such an extent that the rehabilitation of the built heritage usually always implies the evaluation and monitoring of the external surface of the buildings. Finally, in recent years, due to the use of innovative materials and complex constructive technologies, external surfaces have gained an increased importance, being currently considered and designed as part of the building (Schittich, 2006). More specifically, the construction market sees natural stone cladding as a versatile coating material, a noble natural product of high quality, and a good technical and aesthetic solution. It provides the surfaces on which it is applied with insulation, strength, durability, hygiene, and ample aesthetic value (Winkler, 1994).

A survey conducted by Brisch and Englund (2005), to a group of researchers, standardization committees, universities, manufacturers, associations and consultants related to the construction area revealed that, 63 % of the experts surveyed believe that service life prediction methods are extremely important and only 6 % consider that these models are not relevant. However, when considering the use of these methods, only 40 % use this type of methodologies and 13 % assume that they are totally ignorant on this subject. To make matters worse, data related with the durability and service life of buildings and materials are not even included in the majority of the architecture and construction projects. Therefore, even though the usefulness of the service life prediction methodologies is widely accepted in the scientific community, their application is still incipient.

DURABIITY CONCEPT IN DESIGN

Buildings are composed by different components that reach the end of their service life in different stages of the buildings' life cycle. Various authors (Brand, 1997; Gaspar, 2009; Neto & de Brito, 2011; Slaughter, 2001) subdivide the building in durability layers, i.e. in construction subsystems whose degradation occurs at different rates, among which are the "structure", the "skin", the "systems" and the "interior lay-out and finishes". The façade can be seen as the "skin" of the building, contributing to increase the durability of the structure, protecting it from the environmental agents. Since the cladding is the most exterior layer of the building, and therefore more exposed to agents causing degradation, it is also more prone to defects. In fact, a research carried out by the BRE concluded that façades are the building component most affected by pathological manifestations, representing 20 % of the defects detected in current buildings (Watt, 2007). Façades also present a very important aesthetic function since they represent the public image of the building. Their visual degradation not only affects the quality of urban space and impact on the perception of buildings and – indirectly - of their owners, but is also a major concern for the latter, since in the majority of the cases, maintenance and rehabilitation actions are performed based on the appearance of the building only (Balaras et al., 2005).

The selection of the facade systems, materials and technology in accordance with its performance is considered to be a set of activities undertaken in the process of designing and constructing external building shells that is expected to be carried out at design stage. Previous researches considered the facade design as a cross-disciplinary multi-objective optimization process. Thus, in order to provide a quantitative holistic assessment of alternative facade options, a service life value approach should be implemented (Jin & Overend, 2014a; Lapinskiene & Martinaitis, 2013). With this regard, the facade performance indicators generally fall into three categories: functional, financial, and environmental sustainability, which represent the three principal dimensions of service life value. A facade should achieve the optimal trade-offs between the performance indicators by adopting an appropriate combination of various facade design variables (Jin & Overend, 2014b).

At the design stage, the selection of the stone type and its finishing and application procedures must take into account the physical and mechanical properties suitable for the intended use, the technology available, the surrounding environment, and the expected service life (Casal Moura et al., 2000; Pinto et al., 2006). In fact, before using the protection and maintenance activities, the materials used in the facade should be identified in all directions, since the use of inappropriate materials can activate the mechanisms of deterioration of the stone.

NATURAL STONE CLADDING PATHOLOGY

Cladding systems on external walls are constructive elements that protect built heritage and increase its value (Neto & de Brito, 2011). This is done by providing a proper design based on the specifications and quality of the materials (including the type, color, dimensions and type of surface treatment of the stone), the position of the façade (geographic orientation, the location and height of the stone installation on the facade) and the environmental conditions (building location). In fact, before performing repair and maintenance operations, the specifications and technical characteristics of the materials used by the designers should be examined in order to prevent the utilization of inappropriate materials which activate the deterioration mechanisms of claddings (Urosevic et al., 2010).

The most important causes of anomalies in natural stone claddings are related to the responses of stone to external actions, its mineralogical and physical-mechanical characteristics, the fastening system used, atmospheric agents, design and execution errors, and the care taken after installation (maintenance and cleaning). The difficulty of establishing cause-effect relationships (given the variety of anomalies observed) jeopardizes the determination and evaluation of the anomalies' causes based on their manifestations and consequences. For the sake of systematization and objectivity a classification system is proposed for anomalies and their causes. It is based on the expert literature, the inspections carried out and the experience of the authors, all of which made it possible to class each anomaly in a specific group and then identify its direct and indirect cause(s). This information was the basis for building matrices that provide the degree of correlation between anomalies and their causes (Neto & de Brito, 2012).

Anomaly Classification

The cladding anomalies were defined in accordance with on-site inspections by the writers and relevant literature (Aires-Barros, 2001; Henriques et al., 2005). Defects in the natural stone cladding were classed in 7 families and 18 subfamilies. Within the seven groups identified in the field work there are the anomalies located in the cladding plate, i.e.

related to the stone itself and changes to its characteristics, and three groups related to anomalies in the cladding system, which includes the stone plate, the joints and the fastening elements. The first step under this system is to identify defects. This is done by instant direct visual observation at the inspection site and comparison with Table 1, which shows the groups and subgroups of defects in the proposed system. Even though several defects quite often show up simultaneously, for simplification's sake the defects were designated individually. This must be taken into account in the analysis of their causes.

Table 1: Natural Stone Cladding Defects Classifications

<table>
<tr><th>Location</th><th>Groups</th><th>Sub-Groups</th><th>Description of the Manifestation</th></tr>
<tr><td rowspan="11">Stone plate</td><td rowspan="2">A-A
Color change</td><td>A-A1</td><td>Stain or difference of color shade</td></tr>
<tr><td>A-A2</td><td>Peripheral chromatic change</td></tr>
<tr><td rowspan="2">A-F
Fracture and cracking</td><td>A-F1</td><td>Fracture</td></tr>
<tr><td>A-F2</td><td>Cracking</td></tr>
<tr><td rowspan="3">A-B
Presence of biological or other agents</td><td>A-B1</td><td>Biological colonization</td></tr>
<tr><td>A-B2</td><td>Vegetation</td></tr>
<tr><td>A-B3</td><td>Other organisms/materials</td></tr>
<tr><td rowspan="3">A-P
Loss, volume change or deterioration of the stone</td><td>A-P1</td><td>Volume decrease of the stone (laminar spalling, wear, granular disaggregation, pulverization, pitting, cavities)</td></tr>
<tr><td>A-P2</td><td>Alteration or deposition (surface deposit, efflorescence, film, concretion, crust)</td></tr>
<tr><td>A-P3</td><td>Partial lacuna in the stone</td></tr>
<tr><td colspan="0" style="display:none"></td></tr>
<tr><td rowspan="8">Cladding system</td><td rowspan="3">A-DE
Loss of adherence or loosening of the stone plate</td><td>A-DE1</td><td>Loss of adherence of the stone element (partial or total)</td></tr>
<tr><td>A-DE2</td><td>Loosening of the stone element (partial or total)</td></tr>
<tr><td>A-DE3</td><td>Flatness deficiencies of the cladding surface</td></tr>
<tr><td rowspan="3">A-JU
Joint defects</td><td>A-JU1</td><td>Degradation or loss of joint filling material (partial or total)</td></tr>
<tr><td>A-JU2</td><td>Non-linearity or inappropriate design of the joints</td></tr>
<tr><td>A-JU3</td><td>Cracking or fracture of the stone element near the joints</td></tr>
<tr><td rowspan="2">A-Fi
Defects in the fastening elements</td><td>A-Fi1</td><td>Scaling of the stone near the fastening spots and/or corrosion of the metal fastening elements</td></tr>
<tr><td>A-Fi2</td><td>Bending and rupture of the metal fastening elements</td></tr>
</table>

Probable Causes

The vast array of probable causes for stone deterioration includes the influence of climatic factors (Marini & Bellopede, 2007) and the impact of a building's architectural features (sheltered or non-sheltered exposure and preferential rain pathways), studied by Grossi et al. (2003) and Chew and Tan (2003), respectively, or the choice of unsuitable cleaning procedures, protection treatment or biocide application (Warscheid & Braams, 2000). Moreover, Neto and de Brito (2011) declare that, the factors that lead to defects may be intrinsic, extrinsic, or imposed and may occur at different stages of the NSC life cycle. The classification proposal (Table 2) helps to analyze the defects and to improve construction quality. Causes were ordered chronologically, starting with design errors, followed by execution errors, exterior mechanical actions, environmental actions, maintenance faults, and changes in the conditions initially predicted.

Design Errors

The design stage of the cladding solution is often underestimated and so becomes one of the main contributors to the development of construction pathology. Omissions in the specifications also contribute to anomalous situations at this stage. These situations can lead to inadequate execution options and consequent defects at the in-service stage. Design errors are the easiest ones to analyze and can be detected by examining the project blueprints and specifications and chronologically recreating the sequence design, execution, and utilization.

Table 2: Classification of Probable Causes of Natural Stone Cladding Defects

Group of Causes	Acronym	Name of Causes
Design errors (C-P)	C-P1	Specification of materials with inappropriate or incompatible characteristics, or failure to specify characteristics
	C-P2	Missing/ill-advised/faulty specification of the fixing system
	C-P3	Poor design of the near-the-ground area
	C-P4	Stereotomy unsuited to the substrate characteristics
	C-P5	Areas inaccessible for cleaning operations
	C-P6	Deficient constructive detailing in terms of the substrate and singular spots
	C-P7	Excessive deformation of the substrate
	C-P8	Inadequate design of the stone cladding joints
	C-P9	Cladding drainage inadequate or missing
Execution errors (C-E)	C-E1	Use of materials not prescribed in the design
	C-E2	Noncompliance with the intervals between execution phases
	C-E3	Inappropriate use of materials
	C-E4	Application on irregular substrates or fixing flaws
	C-E5	Application of weak or cracked stone slabs
	C-E6	Noncompliance with the prescribed joint dimensions or application of slabs over the expansion joints of the substrate
	C-E7	Noncompliance with the stereotomy of the stone slabs
Exterior mechanical actions (C-M)	C-M1	Stress concentrations on the substrate (by expansion, flexure, shrinkage or settling)
	C-M2	Structural-related movements of the walls and foundations
	C-M3	Vandalism
	C-M4	Accidental impacts
	C-M5	Splitting of the substrate in expansion or peripheral joints or between stone elements
Environmental actions (C-A)	C-A1	Wet-dry cycles, water action, chemical action of ground materials
	C-A2	Thermal shock, temperature, fire action
	C-A3	Freeze-thaw cycles
	C-A4	Corrosion of the metal fixing elements
	C-A5	Air pollution
	C-A6	Biological or chemical action (through living organisms)
	C-A7	Dirt or solid particle accumulation
	C-A8	Wind
	C-A9	Natural aging
Faulty maintenance (C-F)	C-F1	Cladding not cleaned or cleaned inappropriately
	C-F2	Lack of maintenance of the joints
	C-F3	Corroded or deteriorated fixing elements not replaced quickly enough
Changes in the conditions initially predicted (C-I)	C-I1	Excessive loading in pavements
	C-I2	Application of excessive vertical loads in stone cladding

Execution Errors

Unlike the analysis of design errors, the analysis of execution errors is hindered by the absence of records. Because the cause-effect relationship is not immediate, a long time may elapse before the pathology manifests itself. Execution errors are mostly due to poor workmanship and a lack of specific training in the application of new materials and technologies.

Exterior Mechanical Actions

These causes are difficult to predict or avoid, and therefore it is at the design stage that their consequences can be prevented or minimized by specifying the characteristics of strength and performance required of the natural stone cladding to be used. Examples of defects that may be triggered by these causes are those in group A-F (fractures and cracking).

Environmental Actions

Stone deterioration occurs through weather-related factors (Marini & Bellopede, 2007). Causes related to environmental actions lead to deterioration of the appearance and structure of natural stone. Stones with different characteristics may have very different resistance to environmental actions (e.g., temperature-related factors), as is shown in the specific case of a building with marble cladding that was studied by Royer-Carfagni (1999).

Faulty Maintenance

Faulty cleaning, inadequate maintenance processes or products, and even vandalism may cause the stone slab to deteriorate or cause stains to form. To guarantee the durability of a cladding system, regular preventive maintenance is required for early detection of defects and their subsequent repair. Grossi et al. (2003) state that, if soiling coefficients are established, it may be possible to determine at what intervals cleaning is needed (both from an aesthetic point of view and to prevent stone degradation).

Changes in the Conditions Initially Predicted

These causes include change in natural stone cladding use, change in the type and intensity of the actions initially expected to be exerted on this kind of cladding, the use of excessive loads on pavements, or the application of excessive vertical suspended loads in walls, all of which may lead to wear, fracture, or other defects.

Correlation Matrices

The correlation matrices are designed to facilitate the inspector’s on-site diagnosis. By relating potential defects in natural stone cladding and their probable causes, two matrices, defect-probable cause and interdefect, were compiled. Two more matrices, which correlate the defects with diagnosis methods and repair techniques, are presented later. The preparation of these matrices was based on works by other writers (de Brito et al., 1997; Garcia & De Brito, 2008; Silvestre & de Brito, 2009; Walter et al., 2005). The matrices were validated using the data collected in the 162 inspections

The probable causes of the defects in natural stone cladding were divided into direct (close) causes and indirect (first) causes. Direct causes are those that immediately precede the defect (physical, chemical, or biological natural actions or incidents caused by human intervention), and their effects can be halted by adequate prevention and repair measures. Table 5 exhibits the matrix of defects and causes.

The intersection of each row and column contains 0, 1, or 2 with these meanings

- 0 if there is no correlation between the defect and the cause;
- 1 if there is a weak correlation [an indirect (first) cause of the defect related to the triggering of the deterioration process; the cause is not essential to the development of the deterioration process even though it aggravates its effects]; and
- 2 if there is a strong correlation [a direct (close) cause of the defect associated with the final stages of the deterioration process; the cause is one of the main deterioration factors and is essential to its progress].

This theoretical matrix was adjusted (bolded in Table 3) as a result of the 162 natural stone cladding case study inspections. Numerical criteria were defined (Silvestre & de Brito, 2009) in order to evaluate the compliance of the theoretical and inspection results. Noncompliance cases were the object of a technical analysis to judge the need for adjustment; however, the detailed analysis performed is not presented here.

Table 3: Defect–Probable-Cause Correlation Matrix

C/A	A-A1	A-A2	A-F1	A-F2	A-B1	A-B2	A-B3	A-P1	A-P2	A-P3	A-DE1	A-DE2	A-DE3	A-JU1	A-JU2	A-JU3	A-Fi1	A-Fi2
C-P1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
C-P2	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0	1	1	1
C-P3	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
C-P4	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	1	0	0
C-P5	1	0	0	0	1	0	1	0	1	0	0	0	0	2	0	0	0	0
C-P6	1	0	1	1	1	0	0	0	0	1	1	1	1	0	1	1	0	1
C-P7	0	0	2	1	0	0	0	0	0	0	1	1	1	0	1	1	0	0
C-P8	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0
C-P9	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
C-E1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	0	1	1	1
C-E2	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
C-E3	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	0	0	0
C-E4	0	0	1	1	0	0	0	0	0	0	1	1	2	0	0	1	1	1
C-E5	0	0	2	2	0	0	0	0	0	1	0	2	0	0	0	1	1	0
C-E6	0	0	0	2	0	0	0	0	0	0	0	1	0	0	2	1	0	0
C-E7	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0
C-M1	0	0	2	2	0	0	0	0	0	0	1	0	1	0	1	2	0	0
C-M2	0	0	2	2	0	0	0	0	0	0	1	0	1	0	0	2	0	0
C-M3	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
C-M4	0	0	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0
C-M5	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0
C-A1	2	2	0	1	2	1	0	1	2	0	2	2	0	2	0	0	2	0
C-A2	2	0	1	2	0	0	0	0	0	1	2	2	1	0	0	0	0	0
C-A3	0	0	2	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0
C-A4	2	0	1	2	0	0	0	1	0	1	0	2	0	0	0	1	0	2
C-A5	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
C-A6	2	0	0	0	2	2	0	0	2	0	0	0	0	1	0	0	0	0
C-A7	2	0	0	0	0	0	2	0	2	0	0	1	0	2	0	0	1	0
C-A8	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
C-A9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C-F1	2	0	0	0	0	0	2	2	1	0	0	0	0	1	0	0	1	0
C-F2	1	0	0	0	1	1	1	0	1	0	0	0	0	2	0	0	0	0
C-F3	2	0	1	2	0	0	0	0	0	0	0	2	0	0	0	1	2	0
C-I1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C-I2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

To illustrate the practical use of this matrix, it is concluded that cause C-A1 (wet-dry cycles, water action, chemical action of ground materials) can be an indirect cause of defect A-F2 (cracking of the stone slab). In a real example, Silva et al. (1997) report that the characteristics of granite recently used to clad a building's envelope, together with some of the lower protected areas being constantly damp and located in the shade, led to biological colonization and a decrease in the stone slabs' strength, making them more fracture prone.

DISCUSSIONS

In order to illustrate the impact of each probable cause, on the incidence of the anomalies of the natural stone cladding, and basis on the correlation matrix are shown in Table 5, the following diagrams are presented (Figure 1 to 3). From the Figure 1, it can be seen that, the design errors can be consider the causes of all anomalies of the natural stone cladding. In terms of indirect causes, the graphs show that, design errors (group C-P) and execution errors (group C-E) paly predominant role, which underlines the importance of action at the initial stages, in order to prevent many of the anomalies.

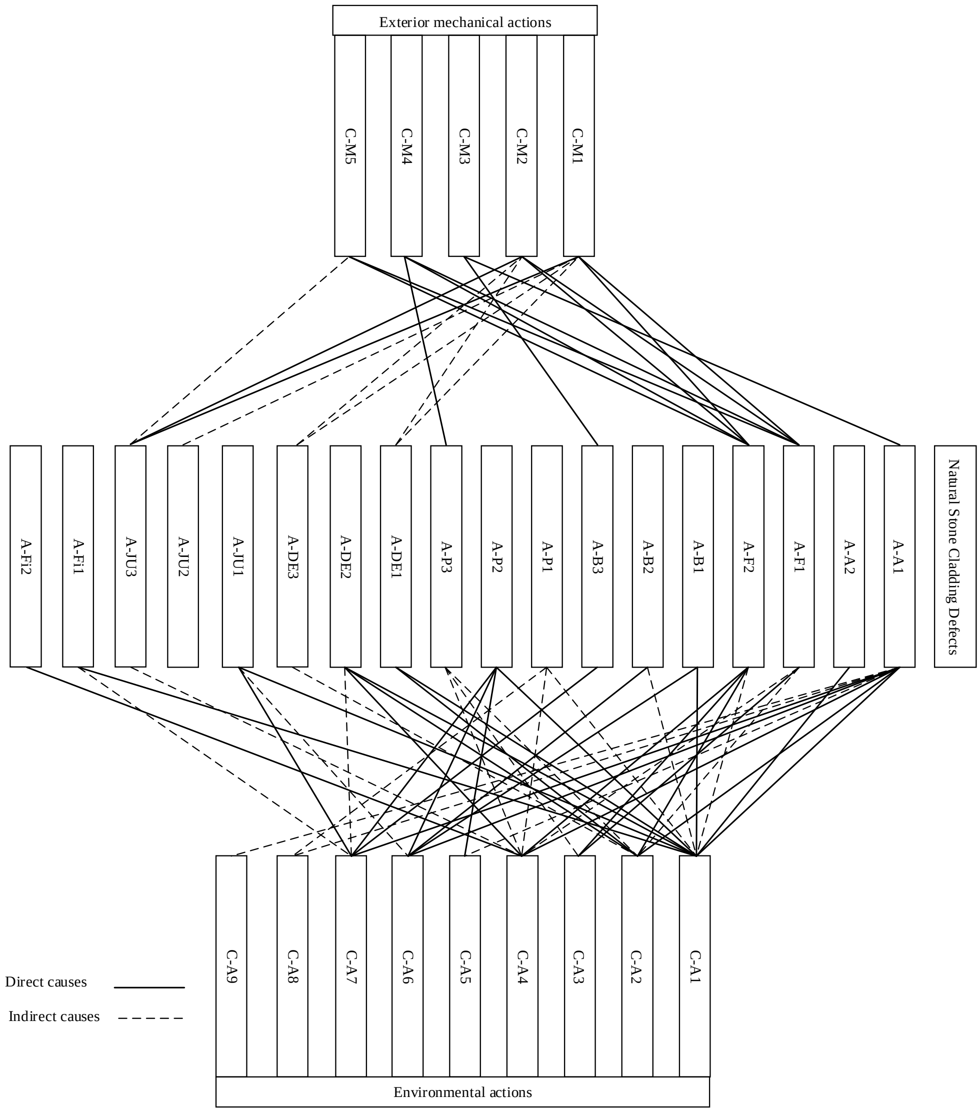

Figure 1: The Connection of Design Errors and Execution Errors to Natural Stone Cladding Defects

With respect to the direct cause of the defects, the diagrams reveal that environmental actions (group C-A) are major direct causes since natural stone cladding are widely exposed to the environment, as expected. They are also very often associated with the final stage of the deterioration process as one of the main causes of degradation. These findings seem to be consistent with other researches (Neto & de Brito, 2012) conducted on stone cladding, which reveal that design errors in 42% of the natural stone cladding under analysis are considered as the most important indirect cause of degradation while in the direct cause environmental agents have the highest frequency of 48%.

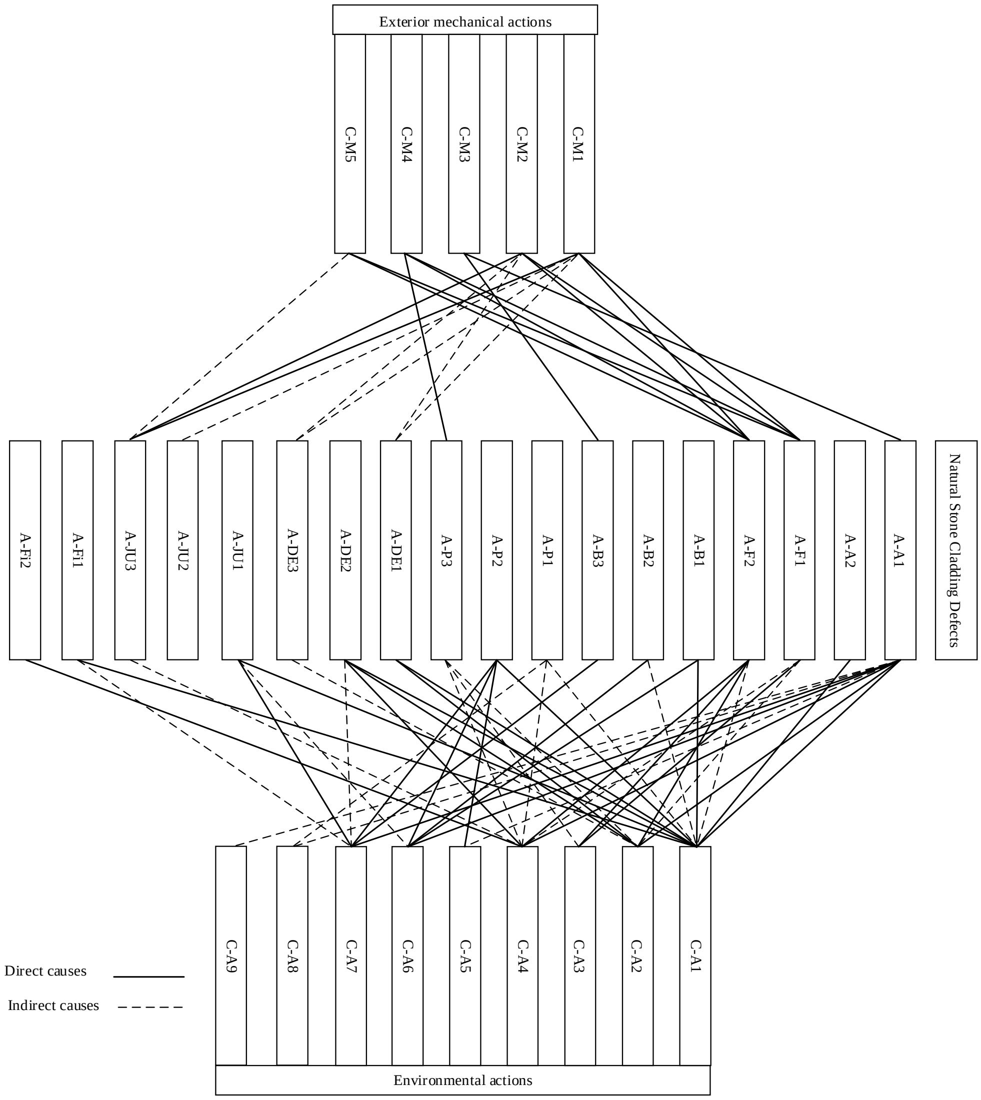

Figure 2: The Connection of Exterior Mechanical Actions and Environmental Actions to Natural Stone Cladding Defects

A final comment on the general frequency of the groups of causes is due. The design deficiencies and the execution defects are very difficult to identify in inspections that occur several years after the cladding has been put into place, as was the case here, and it is rare that the inspector has any information concerning design or execution. Therefore these problems tend to be less conspicuous than the others and that was reflected in the frequencies found. The authors believe that, if there technical documentation were available concerning the design and execution stages, the frequency of the situations where they are associated to natural stone cladding’s pathology would significantly increase.

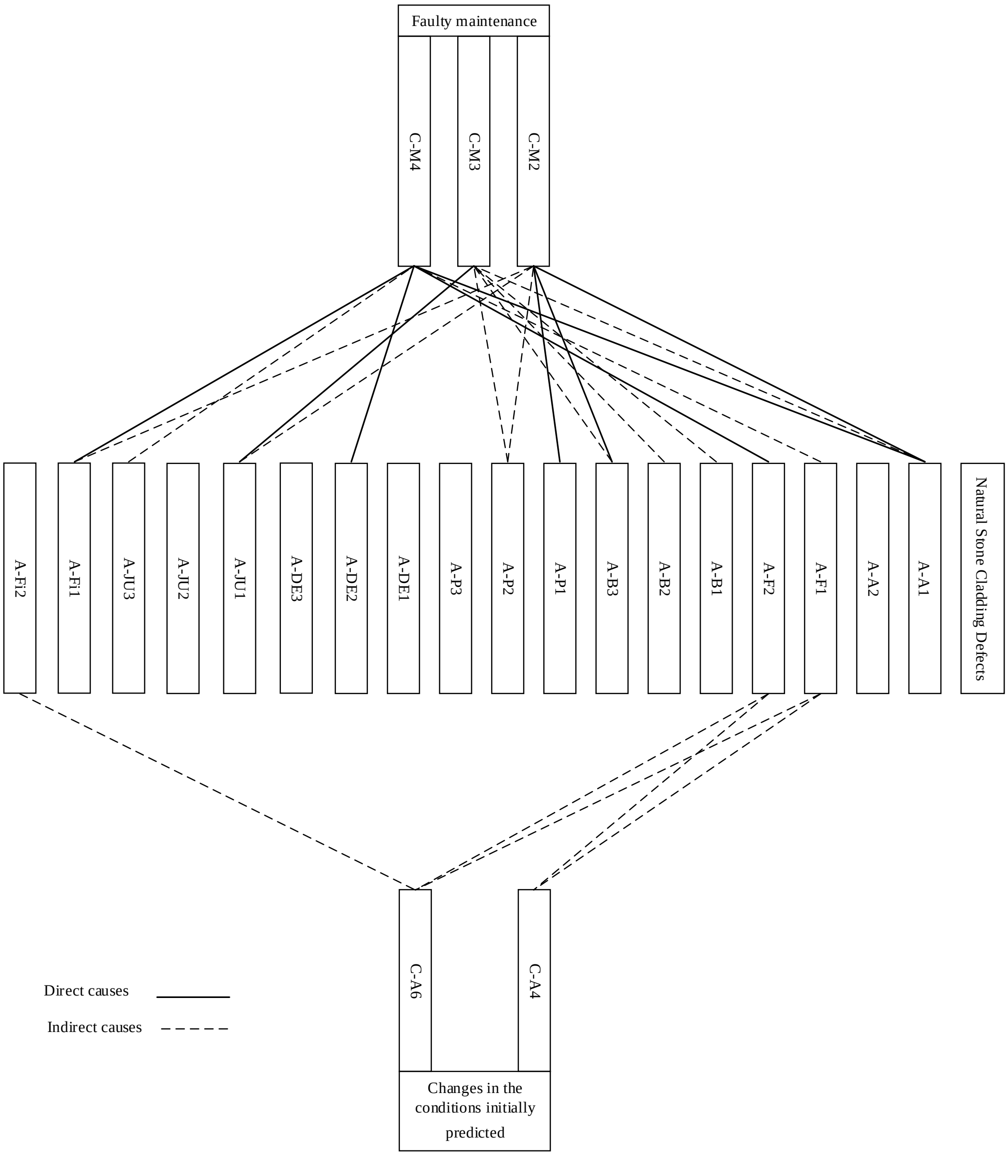

Figure 3: The Connection of Faulty Maintenance and Changes in the Conditions Initially Predicted to Natural Stone Cladding Defects

CONCLUSIONS

In fact, there are many instances, when the stone for exterior cladding is chosen at the design stage for exclusively esthetic reasons, to the detriment of suitability for the location and its resistant or future in-service demands. The poor technical know-how, leads to the early appearance of many anomalies in natural stone claddings, a situation that can easily be prevented by the people responsible. The concept of durability refers to the ability of a building or its components to achieve the best performance in a given environment or location, without having to be subjected to significant corrective measures or to the repair or replacement of its elements. In reality, durability cannot be seen only as an intrinsic quality of a material; simple changes in the construction details may promote a higher protection of a building element against the degradation agents, contributing to the increase of its service life. This study has shown that concerning the service life as one of the design factor gain an increasingly important role in the implementation of durable buildings, which should be designed based on: (i) the knowledge of the performance of the materials over time; (ii) the knowledge regarding the capacity of the material withstanding the degradation mechanisms it will be subjected to, under a given set of environment exposure conditions; (iii) the characteristics of the construction and its context. In the end, the service life and durability of constructions are closely related and necessary to understand the life of buildings; they are therefore relevant concepts in the construction process, either at the design stage or in the use phase, thus allowing reducing the maintenance costs, increasing the comfort of users and the sustainability of the solutions adopted.

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