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Durability of masonry and steel elements in building's envelope exposed to coastal and marine environment

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Abstract

Buildings in urbanized areas exposed to coastal and marine environment are subjected to aggressive agents that particularly affect masonry and steel elements, which usually correspond to a significant presence in the building's envelope.

Among other environmental predicted risks, the projected impacts of climate change, the probable increase in hurricane wind speed, linked to the rising sea temperatures, are expected to lead to heavier floods and storms in some densely urbanized areas located around costal line, with the consequent threat to their population and increase of building stock damage.

In this paper, relevant durability aspects of masonry and steel elements in the envelope of recent buildings exposed to coastal and marine environment are generally discussed. The analysis will be centered, especially, around the coastal or marine environmental conditions that could lead these elements, during service life, to a degradation process usually related with moisture effects that cause material deterioration, as well as to a decrease of performance level, with influence on respective service life. Also, important issues about service life prediction of masonry and steel elements in building's envelope near coastal line and marine environment are briefly described. Finally, general considerations are made about preventive and maintenance actions envisaged for buildings subjected to the coastal and marine environmental negative impact, in order to sustain the deterioration of materials and decrease of building envelope performance, along with the improvement of the construction sustainability.

Keywords: building, masonry, steel, walls, environment, durability, service life.

1 Introduction

The conservation state of the buildings in urbanized areas subjected to coastal and marine environment (C.M.E.), namely in terms of their physical degradation, strongly influences the quality of life, sense of security, and satisfaction of the society. The global tendency for increased urbanized areas near costal line (C.L.) makes urgent a particular focus on the constructed assets in order to guarantee that an adequate life planning is assured and a suitable environmentally friendly approach is pursuit.

The projected impacts of climate change, particularly in terms of global temperature change (with their almost certain increase), can lead in the next decades to the disappearance of small mountain glaciers and a consequent sea rise level. That can directly threatens some major cities close to the C.L., and force to a displacement of several people living nearby C.L. areas all over the world, and especially will increase the risk for several coastal cities with large population. Furthermore, the probable increase in hurricane wind speed, linked to rising sea temperatures, is expected to lead to heavier floods and to the increase of the annual damage costs in some major cities located around C.L., constraining their competitiveness and development. The probability of occurrence of these damages and their effects can be minimized with the adoption of design, construction and maintenance practices appropriate to flood hazard areas.

Nowadays, it is a rather complex task the optimization of building process, in terms of useful period of use without unexpected economical and environmental costs, and particularly the design of buildings for living effectively as it was previously planned due, among others factors, to the uncertainty associated with the estimation of the long-term performance of the building and its parts, and to unpredicted extreme events like storms, earthquakes, etc. Besides that, the design life of buildings is a multifaceted job, considering that it has to deal with different subjects like lifecycle costing, durability, maintenance, etc.

Buildings in urbanized areas exposed to C.M.E are subjected to aggressive agents above referred and mainly related with their corrosive atmosphere, that particularly affect masonry and steel elements, which usually correspond to a significant presence in the building's envelope. Steel elements can, for example, consist on studs, sheets, and cold-formed profiles, most of them used for structural purposes; and on cladding, ancillary components for masonry (wall ties, brackets, etc.) and accessories for supporting other materials.

Building service life dependence from the performance of the exterior masonry walls and of steel elements in their envelope is well recognized, and the option, in what concern these elements, of appropriate materials, detailed design, correct execution in the works, and good maintenance, generally, confers considerable durability characteristics to the building envelope, particularly to face coastal and marine environmental harmful effects. Besides that, adequate building envelope durability reduces the environmental costs (waste) that result from early failure and premature removal of components of that envelope, hence contributing for the sustainability of the construction (Jernberg *et al.* 2004).

In this paper, relevant durability aspects of masonry and steel elements in the envelope of recent buildings (constructed after the middle of XX century), exposed to C.M.E, are generally discussed. The analysis will be centered, especially, around the coastal or marine environmental conditions that could lead these elements, during service life, to a degradation process usually related with moisture effects that cause material deterioration, as well as to a decrease of performance level, with influence on respective service life. Also, important issues about service life prediction of masonry and steel elements in building's envelope subjected to coastal and marine environment are briefly described. Finally, general considerations are made about preventive and maintenance actions envisaged for buildings subjected to the coastal and marine environmental negative impact, in order to sustain the deterioration of materials and decrease of building envelope performance, along with the improvement of the construction sustainability.

2 Masonry and metallic elements exposed to marine and coastal environment

2.1 – Main degrading environmental actions

Degradation effects on building envelope, mainly vertical enclosure and roof, are brought about by different agents (figure 1) including mechanical, hygrothermal, chemical and biological agents (Lacasse 2003, Haagenrud 2004). For example: chemical agents in the form of moisture (liquid water and water vapour) are responsible for corrosion in metals, and the efflorescence of salt compounds from porous materials like those of masonry; hygrothermal agents can cause dimensional change in all materials, (promoting cracking of masonry), and subject porous materials to the effects of damp and freeze-thaw action (e.g., brick masonry, mortar); biological agents in the atmosphere can result in the formation of fungi or moulds on the surfaces of certain masonry elements; and mechanical agents can result in structural dead loads (gravity), and wind loads (kinetic energy).

The experience of observation reveals that the risk of intensive rain driven by strong winds and/or flooding associated with the overflow of water from ocean can particularly affect buildings in the areas near C.L., and the resulting damage extent on building envelope, amid other factors, strongly depends on local topography, general building characteristics (shape, dimensions, orientation) and hydraulic/hydrologic conditions. Particularly, flooding can severely damage buildings and their contents through the: direct damage as a result of inundation, high velocity flow, erosion, sedimentation and flood generated debris; and degradation of building materials, either during the flood and after the flood, together with the contamination of the building due to flood generated substances or mould.

Under wind-driven rain, considerable sediment transport on coastal line can occur (from dunes and beaches), due to a joint action of wind and raindrop impact causing splash of sand particles, which consequently transports these particles in such a way that a significant mass distribution with height of these particles can hit buildings close to that coastal line, and particularly impair their envelope, with their persistent action along service life. Other environmental agent to be considered in the coastal line is also the fog, common near coastal line, and consisting essentially of droplets suspended in the air and transported by mean wind and turbulence, which can increase the presence of moisture in the building's envelope. For these and other aggressive agents linked to the marine and coastal environment, it is important to estimate the approximate influence area affected in a considerable mode; the distance of buildings in coastal line, from the mean high-water mark should be, clearly, a conditioning factor.

Buildings located in a flood hazard area of the coastal line, are particularly at a risk of severe damage caused by flood waters (FEMA 1993), mainly in case it is unenviable to make a simple and straightforward cleanup, due to the reduced or null incorporation on it of flood-resistant building materials (building materials are considered flood-resistant if they can resist to direct contact with flood waters for at least 72 hours without being considerably damaged).

Essential climatic factors, with influence on wetting or drying of building elements, are temperature (mean temperature range and extremes), atmospheric moisture, wind (wind pressures) and precipitation (rainfall intensity and annual average rainfall). Especially these last two factors can give an important clue of the buildings wetting potential in the affected areas, due to considerable effect of wind-driven rain on the building envelope; atmospheric moisture, outdoor temperature, and wind have a great influence on the risk of condensation on inside wall surfaces (Lacasse 2003). The drying potential depends mainly on the atmospheric moisture, and the evaporative drying potential for climates of coastal regions is generally lower than the warmer and drier regions, so the capability to dry of the masonry and steel elements in building's envelope is comparatively lesser in those coastal regions. Moreover, C.M.E has distinctly higher wetting potential compared to other zones.

In coastal areas, wind loads, water leakage, excessive humidity or condensation can severally damage masonry and steel elements of building's envelope along service life. As examples of metallic elements to be particularly referred are: steel framing buildings, where the excessive humidity and salt attack can accelerate the corrosion of zinc coated materials; curved self-weighted metallic and galvanized roof (high spans) in coastal areas which are subjected to wind and rain effects, as well as to corrosion, due to aggressive marine environment.

In marine and coastal environment, chlorides (whose major sources are sea water), sea-salt (inland transported), and other agents of corrosion (which include air contaminants such as sulphur dioxide and carbon dioxide; acid rain; and warm temperature) had been recognized as contributors to atmospheric corrosion and as a negative influence on durability of building materials.

Therefore, it is important to classify the corrosivity of an atmosphere based on measurements of time of wetness, and pollution categories (sulphur dioxide and airborne chlorides). Environments that can cause corrosion can be classified in different categories according to their corrosivity; the classification could be based on standard ISO 9223 (ISO 9223:1992. Corrosion of metals and alloys - Corrosivity of atmospheres - Classification), which categorizes environments on the basis of wet time, as well as sulphur dioxide and chloride contents.

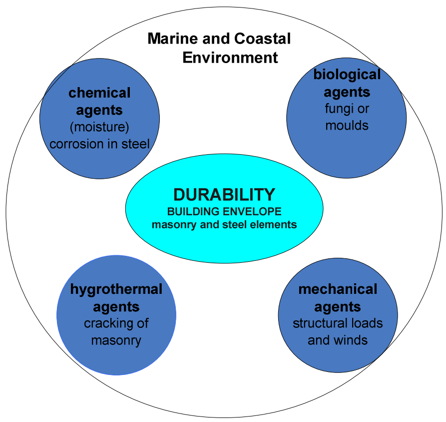

Figure 1 – Scheme of the process of decrease of performance of masonry and steel elements of building's envelope

2.2 Basic properties of masonry and steel elements and their degradation under moisture and thermal changes

The degree of deterioration of masonry and steel elements are dependent on the mechanism of deterioration (e.g., corrosion, heat aging, freeze-thaw action), the expected response of materials to specific service loads and the magnitude and duration of the load effect (EOTA 1999, Haagenrud 2004). Nevertheless, masonry and steel material should have adequate characteristics to face the different aggressive exposure conditions, and to maintain the performance of the corresponding elements in the building envelope; explicitly, it has to face the corrosive character of the sites located near coastal line and its environment, so to avoid, for example, rusting steel elements and spalling of bricks, as a result of salt attack.

In aggressive marine and coastal environment, chemical and physical decay of porous materials, like brick, cement blocks and mortar, and their deterioration process are greatly dependent on quite a few parameters whose variation is difficult to determine, to some extent owing to their intrinsic random character. Climatic conditions, associated with daily or seasonal changes in moisture coupled with temperature variations, can be correlated with volume changes in these materials (Grimm 1986, Miranda Dias Nov. 2002); the associated deformations due to these moisture and thermal effects sometimes can generate considerable cracking of masonry walls (Miranda Dias Set. 2002).

An important trace of characteristic behaviour of brickwork, after their construction and during the use and exposition to degrading agents, is the reversible expansion and shrinkage to which it is subjected, due to wetting and drying, and, superimposed on that movement, also the irreversible expansion that takes place over a long period of time (Grimm 1986). Usually, brickwork is subject to degrading agents such as solar radiation, wind, sea spray, rain, etc. Important degrading mechanism is related to the sulphate and chloride salts, which are soluble in water, and when present in the brickwork can affect bricks and mortar and reduce their durability. Moreover, the penetration of water in the masonry wall can be a result of a capillary transfer of humidity through the pores of bricks and mortar, with negative effect in terms of damp patches on the cavity face of the outer leaf (Newman 1984).

Subjected to the environment, corrosion products are induced in steel elements through a process characterized by electro-chemical reactions, which take place at the surface of the steel (Fontinha, I. R.; Salta, M. 2003, Deacon, D. H. 2006). For marine environment, it is more important to refer the wet corrosion, which takes place when relative humidity is high; time of wetness is, in atmospheric corrosion, one of the most important factors, as corrosion generally occurs while the material is covered by a film of water.

The relationship between the corrosion or deterioration rate and the levels or loads of pollutants in combination with climatic parameters is called “dose-response function”. Throughout the use of the dose-response function, which relates corrosion rate to pollutant and climate exposure, it is possible to calculate the acceptable pollution level, considering a permissible corrosion rate. The dose-response functions, available for some construction materials (Vladimir Kucera et all 2007, NOAH’S ARK 2006), are essentially based on measurement of climatic parameters (temperature, relative humidity, time of wetness, and sunshine radiation), gaseous pollutants (sulphur dioxide (SO2), nitrogen dioxide (NO2) and ozone (O3)) and precipitation (total amount, conductivity and concentration of the ions, among them the Cl^- with interest for carbon steel).

2.3 Decrease of performance level and durability of masonry and metallic elements in building’s envelope due to the effects of marine and coastal environment

The observed effects of environmental loads on these elements, namely those linked with the typical hygrothermal effects in coastal line areas, can show the importance of moisture and temperature variations as one of the major source of deterioration problems in the building’s envelope. Masonry and steel elements deteriorate at different rates when subjected to degradation agents. Their performance level decreases to a limit at which maintenance is no longer practical or possible and replacement is unavoidable.

The durability of masonry and steel elements can not be considered as an intrinsic material property (Jernberg 2004); it is a concept that is based on an indication of expected long-term performance in service and subjected to environmental conditions; and is connected closely to the function of masonry and steel elements in building's envelope and their performance requirements. To study, the deterioration and decrease of performance of masonry and steel elements, during building use and till the end of their service life, it is essential to examine the different possible types of damage, implement maintenance operations and check their effectiveness, in terms of enhanced performance.

The performance of the envelope relies on the performance of different parts, in particular the masonry and steel elements, because the long-term performance is highly dependent on functional performance of the weak points of the envelope, such as the connection of masonry walls with windows. The durability of masonry and metallic elements in building envelope depend strongly on its interrelation with the surrounding environment. But, other factors affecting durability that can be also present together with environmental effects are: inaccurate and bad detailing; differential settlements of foundations; excessive deflection of supporting structure; defective materials; sub-standard workmanship; lack of quality control; lack of maintenance.

For buildings in the coastal line, it is probable the penetration of water, mainly wind driven rain, into the masonry cavity walls due to brick/mortar poor bond, inadequate tooling, unfilled cavities with mortar obstructions and dirty or wrongly sloping ties. However, leakage of water is more possible through cracks present in bricks or blocks and mortar of cavity walls, or in the interface between them (bed and perpend joints), and can result in a fair accumulation of water flowing down the cavity face of the outer leaf (Newman 1984). That humidity presence in cavity walls can be a cause for stain in the internal face of inner leaf, and a reduction of walls thermal insulation, which of course affects building envelope performance.

Rain penetration through cavity walls depends on factors related, largely, with external conditions (local climatic conditions) such as the quantity of rainfall incident on the building and the drying conditions; diurnal temperature cycling; and the type of exposure of their envelope. But, that rain penetration depends also on the intrinsic properties of the walls (Newman 1984), mainly on: the ability of the outer leaf to resist penetration into the cavity; and the efficacy of the cavity, open or insulated, as a barrier to water penetration.

Structural steel elements are usually protected with a coat of paint during building construction, which in some cases is considered a sufficient protection, because they are enclosed by walls. But corrosion may still occur when an element is not conveniently protected and is exposed to a damp environment. Thus, in some cases, where steel elements may require a durable protective coating to ensure their long term performance, these elements should have galvanizing coatings (A.I.S.I. 2006), and steel sections used for connections in wall construction should be hot dipped galvanized to prevent corrosion.

Corrosion of wall ties in external masonry normally occurs, first, in the mortar joint because it is usually the wettest component to which the tie is exposed (Maurenbrecher, 1997). Mortar initially provides an alkaline environment, which leads to the development of a protective oxide layer on the case of mild steel. However, carbonation reduces the alkalinity of mortars, and the presence in the mortar of chlorides from the marine environment, may increase the rate of corrosion.

Potential corrosion of steel ties for lateral support for masonry cladding, in building's envelope, could be favored in cases of: buildings of coastal line placed in strong driving-rain zones, especially those placed in the upper parts of the buildings (parapets and corners); incidence of chlorides from marine spray source, which may be present as an additive to the mortar, and intensify corrosion; presence of salts in leaked water which may allow corrosion to occur; leakage of humid indoor air through the wall in winter, which can be a source of moisture if the air barrier system is inadequate (Maurenbrecher, 1997).

If different metals with considerable electrochemical potential differences are in contact with one another, in the presence of moisture, corrosion may occur (Fontinha, I. R.; Salta, M. 2003), which could be the case of shelf angles for masonry cladding, where mild steel bolts are used together with stainless steel shelf angles.

To prevent early corrosion in injection anchors consisting of a threaded rod, deformed reinforced bar, internal threaded socket, and the mortar (anchor placed into drilled holes in masonry and anchored by bonding the metal part to the sides of the drilled hole by means of mortar and by mechanical interlock – EOTA: ETAG 025: Guideline for European Technical Approval. Metal injection anchors for use in masonry, March 2007 – under approval), stainless steel material in metal parts should be used when subjected to particularly aggressive conditions such as permanent or alternate immersion in seawater or the splash zone of seawater.

3 Service lives of masonry and steel elements in building's envelope near coastal line

In fact, after building construction, and during their use, follows a continuous process of deterioration with discontinuous improvement of performance level through maintenance operations, until a limit condition is reached, where the performance of one or more elements are no longer acceptable, and that (or these) element(s) should be substituted, or refurbished.

To analyze the long-term performance of masonry and metallic elements of the building envelope, subjected to the effects of marine and coastal environment, it is of relevant interest to verify if the basic performance requirements, regarding the intended use and desired indoor conditions, are fulfilled. Clearly, the performance and service life of the entire building when subjected to environmental exposure will depend on each individual of these elements, although the failure or severe impairment of essential requirements, such as health and safety could depend on few of them. At European level, the "Construction Product Directive" (CPD – Directive 89/106/CEE of 21 de December 1988) has defined the essential requirements together with correspondent "Interpretative Documents" for construction works, which consider the main relevant performance requirements for products or components, performance criteria and methods of verification, and assessment of working life. And, the matter of service life planning regarding buildings and constructed assets is treated in detail in ISO 15686: 2001 (International Organization for Standardization, "Building and constructed assets – Service life planning, ISO 15686 - Part 1: General principles, 2000, ISO 15686-1; Part 2: Service life prediction procedures, 2001, ISO 15686-2).

The building performance is expressed in terms of several parameters; for example, in order to satisfy the essential requirement ER1 (CPD - mechanical resistance and stability), adequate structural performance of the building is essential, and thus frame structure elements, particularly in their envelope, shall be capable of supporting the wind loads with adequate safety against structural collapse and inadmissible deformations; and to satisfy ER3 (CPD - hygiene, health and the environment), it is required a satisfactory level of performance of building envelope related with vapour permeability and moisture resistance (to limit interstitial and surface condensation of moisture which may cause unacceptable growth of micro-organisms or affect the indoor climate) and with watertightness (to prevent leakage of water from rain into the building). The satisfaction of performance requirements may be affected differently along the period of working life, depending on the events, especially the extreme ones that can impact the costal line and surrounding areas (flooding, excessive heat or rain, strong wind and "tsunami" effects due to seismic actions), and consequently impair the performance related to the original intended use. For example, as long as buildings remain exposed to flooding, they are likely to be damaged, even when using flood-resistant materials, because these materials do not fully protect buildings from other flood hazards, such as the impact of debris resulting from flooding, although it can reduce the amount and severity of water damage, while requiring usually some amount of cleanup and cosmetic repair.

Also, a need of up-grading performance, fixed at national level, to provide or enhance coastal protection, or even a significant change of use at a certain level (for example: change from fishing zone to residential, tourist, or sportive zone), can modify the context of the performance requirements. The wide variation in climatic conditions of different coastal line regions and user conditions will make it necessary to restrict the usage of many construction products to defined situations in order to reach the predicted service life.

Establishing categories for service life could be possible by means of a process of specification of the product or its protection, either as rendering of walls, galvanizing and final organic coating protection of steel, that results from a careful combination of: different exposure classes based upon environmental actions (degree of the risk of corrosion or attack (freeze-thaw attack; chemical attack, etc.)); intended service life under the anticipated maintenance actions (ex.: short (< 25 years), intermediate, and long (> 100 years)); and global performance level of the elements (low, normal, high) based on functional critical properties (ex.: level of protective performance of the external envelope to avoid the presence of damp in parts of the building or on surfaces within the building; and the ability of envelope to shield structural frame from environmental actions). Results obtained from natural exposure of construction products either under service conditions or under defined exposure conditions can give important information about their durability characteristics.

4 Preventive actions and maintenance

The importance of masonry walls and steel elements maintenance costs in terms of overall building conservation expenditures is well recognized, and the essential target is prevent construction defects at the design and execution stage and to support maintenance effective operations while minimizing their costs. Namely, it is advisable to consider all environmental factors and projected service life before deciding on the degree of protection of masonry and steel elements.

Brickwork is considered as durable and versatile building material due to an appropriate performance achieved when a there is: right design and detailing; proper selection of the brick for the site conditions; accurate mortar mixing; adequate installation of connections to adjacent building materials and components.

In steel framing buildings, exterior walls can minimize the exposure to the marine environment associated with moisture effects; special care should be given to the use of any steel studs or joists that are exposed to extended periods of high humidity or aggressive industrial or marine environments. For good durability, cold-formed steel framing needs proper corrosion protection by a galvanized coating, taken in account that his service life is determined by the exposure conditions and is proportional to its thickness (A.I.S.I. 2006).

To prevent the corrosion of wall ties the following measures can be adopted (Maurenbrecher, 1997): control rain penetration into walls by detailing the joints in the cladding to minimize the entry of rain water and by draining and venting the cavity walls; avoid placing dissimilar metals in direct contact with one another; protect mild steel with a durable coating such as galvanizing; use corrosion resistant materials such as stainless steel.

The protection of buildings from flooding can involve a variety of actions, from inspecting and maintaining of buildings to installing protective devices. Flood-resistant materials should be used for the envelope and other parts of a building that are below the flood level, and where flood proofing is permitted; areas of a building that are below the flood level should be used only for parking, storage, and access. And the risk of flooding can be minimized, essentially, through the control of rainwater entry, and the adoption of the following approaches in the design and in building stage: elevating as much of the building as possible above the design flood level; design assemblies to easily dry when they get wet.

In what concerns maintenance and repair of masonry elements, the choice of surface treatments must take in due account quite a few conditions such as, water penetration through the wall, treatments durability characteristics, etc.

5 Conclusions

Among other environmental predicted risks, the projected impacts of climate change, the probable increase in hurricane wind speed, linked to the rising sea temperatures, and the incessant rains with gusty winds, are expected to lead to heavier floods and storms and to havoc in some densely urbanized areas located around costal line, with the consequent threat to their population and increase of building stock damage, and therefore pressuring for preventive measures in order to especially provide coastal line protection.

A qualitative evaluation was performed of the effects of climate parameters, associated to C.M.E, on the degradation of masonry and steel materials. Amid the environment agents that can affect markedly the durability and service life of these building elements, moisture was recognized as one of the major agent of deterioration in buildings, since its presence increases the risk of efflorescence of salt compounds from masonry and their dimensional changes, as well as the corrosion of metals.

The exploration and use of the building after the end of the construction is based on the assumption that it has, at that time, a performance that is, at least, greater than the level required for the satisfaction of the essential requirements, and that will gradually decrease during the service life, in absence of maintenance or rehabilitation.

Essentially, it is crucial to know the environmental factors to which the building's envelope will be subjected, and particularly it is essential to design in order to minimize water penetration into the masonry wall and to confer adequate protection to the steel elements.

Finally, it is recognized that durability of masonry and steel elements in building's envelope deals with different aspects related with, performance, service life, cost of repair and renovation; environmental impact; and sustainability.

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