XII DBMC
International Conference on Durability of Building Materials and Components
PORTO - PORTUGAL, April 12th-15th, 2011

Ventilated Stone Veneer: Mechanical Behaviour, Calculation Methodologies, Major Pathologies and Existing Tests

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ABSTRACT

The increase of building pathologies related to the use of stone materials and the use of ventilated stone veneers, requires the reformulation of design concepts in building façades and also the reformulation of the architectural project.

The aim of this paper is to identify, analyze and evaluate synthetically building pathologies in stone ventilated façades in order to obtain the main technical conditions to be considered in the architectural design, by interpreting its mechanical behavior and capabilities to prevent such pathologies and to ensure the proper features during the building lifetime.

The methodology is based on both laboratory stone tests and in situ tests about construction systems, by analyzing physical and mechanical behavior of the outer layer in relation to other building requirements.

The results imply the need of proper sizing, specific quality control and practical application of calculation methods, to control high concentration pressures in ventilated façades by reaching appropriate project solutions.

In conclusion, the research about different pathologies of stone ventilated façades, the study of their mechanical behavior, their anchorage and their connection with their constructive aspects, will help to improve the construction quality of the stone ventilated façade in buildings and to enhance the use of natural stone in modern architecture.

KEYWORDS

Ventilated stone veneer, mechanical behavior, measurement, stone pathology, testing.

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1 INTRODUCTION

The traditional use of stone in architecture (with a massive character as a building element independent from the façade and the structure), has turned into a use as a coating material and in the case of ventilated façades is designed as a floating sheet in a constructive sub-system.

This evolution in the use of stone materials and ventilated façade systems in buildings involves a radical transformation of the concept of stone façade. Design and constructive implementation of building façades should be considered from the project to avoid preconceived architectural ideas, to prevent sizing errors in the project or in the material execution and to provide complex technical solutions without generating construction deficiencies.

The aim of this paper is to identify, analyze and evaluate synthetically the main technical factors considered in the construction process that influence the design of ventilated stone façades, by interpreting their specific characteristics and their particular mechanical behaviour.
It should be considered that the ventilated stone cladding differs from the traditional stone wall cladding or from the adhered veneer due to its capability to bear higher efforts with the minimum material and important mechanical requirements due to its geometric features and its constructive configuration in a separate and independent sheet.

These intrinsic characteristics of the stone ventilated veneer involves new formal and constructive conditions to analyze and evaluate:

- The resistant element should be a substructure capable of transmitting the building loads that affect the coating to the structure, by concrete walls, massive or perforated brick walls, concrete block walls or auxiliary metal substructures. Hollow brick wall does not provide a sufficiently homogeneous and strong resistant element for the high stresses transmitted by the anchorages and that´s why it is unacceptable to use it as a resistant element for ventilated façades.
- Anchorage must be able to combine differential deformations and dimensional tolerances between the stone cladding and the resistant element. They must allow some adjustment of distance and the differential movements between the resistant element and the plate, absorbing the rheological and thermal deformation (contraction-expansion) but also resist to electrochemical corrosion, being stable against gravitational actions as the weight of the plates, the wind, impacts, earthquakes and fires. The size and choice of anchorages must take into account not only the loads to be transmitted, but also the characteristic strength of the resistant element.
- An air gap does not prevent direct sunlight (the stone does) it doest reduce heat transmission (with a quite low efficiency) and enhance moisture diffusion, but reducing condensation risk.For this, it is very important to ensure an adequate ventilation by avoiding bottlenecks and by sizing some chamber holes to let the air in and out, especially at the base and at the coronation of the façade to facilitate the flow ascension of hot air and to reduce the vapor pressure inside the chamber.
  Also, it is essential to ensure a proper drainage at the bottom of the camera by providing evacuation to the outside of the condensed water, coming from rain or humidity absorbed by capillary action by any of the component materials of the building system.
- The stone veneer joints must be designed not only based on formal criteria but also on a distribution respecting the structural and expansion joints of the building structure, allowing the movement of expansion and contraction of the stone cladding due to the significant temperature changes experienced.

The lack of consideration of the issues outlined above provoques most of the damages detected in ventilated stone facades. Injuries can be summarized mainly in the following list:

- Broken stone plates by bending efforts due to the pressures and suctions produced by wind action, impacts or thermal movements of the cladding or the resistant element.
- Broken stone plates by pulling out between the anchorage and the veneer in the attachment points due to wind, impact, thermal based efforts or seismic action.

- Stone element collapse by pulling out between anchorage and the resistant element due to overloading because of the existance of an insufficient number and distribution of anchorages (over-dimensioning of the plates or the distance between anchorages) or poor resistance to transmit loads by the anchorage.

Moreover, the low thickness of the stone cladding in a ventilated façade increases the importance of the factors affecting the durability of the veneer, both intrinsic factors (physical and chemical properties of the stone) and environmental factors (temperature changes, wind erosion or ocean spray action) that generate problems that can be summarized mainly in the following list:

- Anchorage breaking due to resistant section decreasing by the presence of voids or internal cracks which reduce the resistance of the stone plate.
- Stone breaking due to cutting force or flexion effort by the lack of homogeneity or insufficient molecular cohesion.
- Aesthetic and resistant transformations by the presence of ferrous salts in aggresive environments.
- Stone cracking by freezing action due to excessive porosity and lack of resistance in aggressive environments.

Due to the obvious increase in the optimization of the stone building solutions because of the ventilated façade, it is pertinent to consider the need to incorporate methods for calculating the correct sizing of the plates and anchoring systems.
In order to increase accuracy in the sizing of stone cladding in the project and its execution control, we propose the practical application of computational methods and quality control for the stone materials and the construction system.

The methodology is based on both laboratory tests of selected stone and tests of the construction system executed on site, analyzing the physical and mechanical behavior of the façade related to the actions and building demands. These calculation methods applied to ventilated facades are substantially simpler than those used for the dimensioning of steel structures or concrete but also they have new characteristics and specific conditions which we proceed to determine by the experimental work described below.

2 MATERIALS AND METHODS

2.1 General

For the correct sizing of a ventilated stone façade is necessary the use of an experimental design and modeling allowing both the verification of the resistance of natural stone plates to bending and pulling testing between the stone and the anchorage, and the calculation of pullout resistance between the anchorage and the anchorage and the resistant element.

Trying to find this aim, we have conducted laboratory tests using natural stone and also in situ testing of the construction system executed on site, by analyzing both physical and mechanical behavior of the cladding related to the most important requirements suffered once the building's façade is constructed. Therefore, on the one hand we first made bending tests to stone plates in laboratory and we found breaking patterns of the stone anchorage used. On the other hand, we also made in situ pullout tests in existing buildings between the anchorage and the resistant element.

2.2 Materials and Methods

To be able to compare both results, in the laboratory tests we used natural stone slabs with the same dimensions and weight as those analyzed in the existent façade.

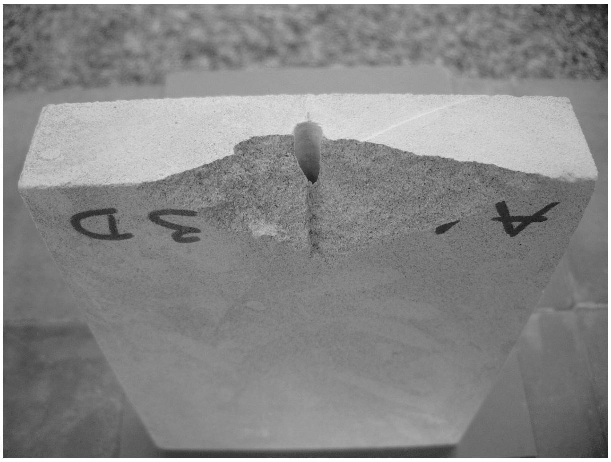

Figure 1. Test pullout (anchorage-plate).

In situ tests were carried out by pullout tests anchorage-resistant element, using a pressure plunger and an hydraulic pump (Enerpac) applied to the anchorage tested.

Figure 2. Test pullout (anchorage-resistant element).

Actions referred to the stone cladding are based on the height of the façade crowning on the building, related to the wind zone of the building location and the type of exposure depending of the legislation, as well as the degree of seismic intensity and the seismic coefficient for the location, according to DB SE-AE, the NTE-CVD and the seismic legislation PDS-1/1974 because of being more restrictive than the current legislation.

3 RESULTS

Results show high tensions and stresses in natural stone plates and anchorages considering usual actions in these constructive elements as part of a ventilated façade, exceeding the breaking strength and causing a cladding falling.

Table 1. Results of tests and calculations.

Breaking study	**Testing results**	**Calculated loads and stresses**	
Cladding breaking	(laboratory) pullout stone-anchorage *Qadm1=42,78 Kp (average)* *Qadm2=31,94 Kp (minimum)*	Fh wind *Fh's =30,38 Kp <Qadm2<Qadm1*	Suitable
		Fh seismic *Fh's =3,50 Kp <Qadm2<Qadm1*	Suitable
	(laboratory) flexion and traction test *σ adm=1,31 Mpa*	Wind flexion *σ max = 0,25 Mpa < σ adm*	Suitable
		Seismic flexion *σ max = 0,058 Mpa < σ adm*	Suitable
Anchorage-resistant element breaking	(in situ test) Pullout anchorage-resistant element *Qadm1=44,83 Kp (average)* *Qadm2=26,89 Kp (minimum)*	Fh wind *Fh's =30,38Kp <Qadm1 >Qadm2*	NO Suitable
		Fh seismic *Fh's =3,50 Kp <Qadm2<Qadm1*	Suitable

It´s important to consider the high tensions caused by the suction wind effect on the areas near the corners of the façade perpendicular to the faces more exposed to wind. Data show that the falling of the veneer in many cases is due to insufficient resistance to pullout from the anchorage and the resistant element, andnot due to stone breaking. Calculations also show that wind action on a ventilated stone cladding is much more damaging than seismic action because of being a large area exposed to horizontal wind action.

Moreover, it should be noted that the results of the tests reflect the wide variation in the values of breaking according to the nature of the stone, the resistant element and the type of anchorage and it´s necessary to establish higher safety factors than those used in the structural design of reinforced concrete or steel. In the same sense, we can find regulations as the ASTM C 1242-96 b or the probabilistic methods of calculation of the UNI 32045130 proposing two hypotheses of safety factors depending on the degree of knowledge about the veneer by previous tests.

Also, modeling allows the calculation of the anchorage resistance on a ventilated stone facade and presents significant problems to establish rigorous behavior hypothesis due to the wide variety of sizes of plates used in a façade design, the distance between anchorages, the different thicknesses of stone used and the size of the holes drilled in situ.

The cost and difficulty of making a high number of breaking or pullout tests in stones used buildings, and the high variability of the results obtained due to the nature of a natural stone material make necessary to increase the safety factor for absorbing the risk of incidents such as variations of loads and stresses or changes in the strength of the material because of its heterogeneity, alterations of resistant sections for cladding, physical or chemical changes over time or other material weaknesses in the implementation of the work.

From the characteristics of the mechanical behavior of the ventilated stone façade, its modeling, testing and the results obtained, it can be deduced:

- The need to choose the adequate type of stone to be used not only in terms of aesthetic factors but also because of its mechanical resistance to pulling, bending and impact, and therefore also because of its homogeneity and lack of cracks or voids, its resistance to humidity and frost changes, its risk of exfoliation or its content on ferrous salts.
- The suitability of evaluating the mechanical behavior of the union resistant element-anchorage and anchorage-cladding based on the expected solicitations, to make a correct dimensioning of the thickness of the cladding, the distances between anchorages and the anchorage type.
- The need to reduce potential weaknesses in material construction through the resolution and definition on design by distributing the adequate anchorage for the plates and the resistant elements and also by carrying out the holes in the edges of the plates in the workshop or using drilling templates on site.
- The need to increase quality control of the work by laboratory testing of physical and chemical characteristics of the stone used and by pullout testing of the anchorage system in situ.

4 CONCLUSION

Nowadays, the traditional massive character of the use of natural stone in the stone ventilated façade in architecture has been transformed into a thin skin exposed to high features within a set of functionally specialized layers. Differences between ventilated façade and adhered veneer are relevant, essentially those related to mechanical behavior and to anchorage, making necessary the domain of their major design features, the calculation methodologies and the appropiate testing to ensure the construction quality and durability.

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