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Applicability of the Pull-Off Test: Teachings from a Large Sample of I*n Situ* Tests

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ABSTRACT

The Pull-off test is a very popular way of evaluating the adhesion strength of renderings or ceramic revetments. Several standards frame the application of this test and its results interpretation. The Laboratory of Building Physics (LFC-FEUP) has used the pull-off test results in several cases to support the diagnosis of causes for building anomalies.

In this article, 56 case studies based on in situ tests are analysed. The sample was retrieved from 16 test reports conducted by LFC-FEUP. In each of these reports different situations were analysed in terms of wall components, expected hygrothermal loads, and in testing procedures followed. This large number of tests support a discussion on two subjects: the applicability of the pull-off test and the parameters that can influence the results observed in this sample.

The first subject, the applicability of the pull-off test, was observed for different systems, including ceramic tiles applied with cement based adhesives, cement based renderings and ETICS. Difficulties and opportunities of the test are analysed for each material.

In the second subject, the variability observed in each case study was used in different correlations revealing patterns that can be expected when applying this test. These results support a discussion on uncertainty appraisal of the pull-off test.

KEYWORDS

Pull-off test; Adhesion strength; Finishing materials.

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1 INTRODUCTION

The adhesive bonding of exterior revetments applied on façades is an important factor to ensure the safety and durability of the building. The failure of adhesive bonding has imediate consequences and therefore is a common concern for the building industry and building owners. The Pull-off test, classified as a near-to-surface, partially destructive method, is a classic way of evaluating the adhesion strength of renderings or ceramic revetments. Several standards frame the application of this test and its results interpretation. The Laboratory of Building Physics (LFC-FEUP) has used the pull-off test results in several cases to support the diagnosis of causes for building anomalies. In this article, 56 case studies are analysed. The sample was retrieved from 16 reports of in situ inspections conducted by LFC-FEUP.

The objective of this article is to sinthetize the information that resulted from the large number of pull-off test results available at LFC. The average bonding strength and variability for each situation were statistically analysed, allowing for the definition of patterns and correlations of involved parameters, namely substrate, revetment, test procedure and façade exposure.

2 APPLICATION OF THE PULL-OFF TEST

The LFC-FEUP test reports revealed that the pull-off test can be usefully applied for the test of different finishing systems. The test method and its specificities for each application are described in this chapter.

2.1 Test method

The adhesive strength is determined as the maximum tensile strength applied by a direct load perpendicular to the surface being tested. The tensile load is applied by means of a defined pull-head plate glued to the test area. The adhesive strength is the quocient between the failure load and the test area.

On all the tests described in this paper, the test area was pre-cut in situ, fitting the size of the pull-head plates. These could be square metallic plates of 50 mm x 50 mm or circular metallic plates with diameter of 50 mm.

The test machine for direct direct pull tensile force test is in accordance with standard requirements, with the additional feature of automatic control of the applied force provided by an attached electrical engine, as presented in Fig. 1.

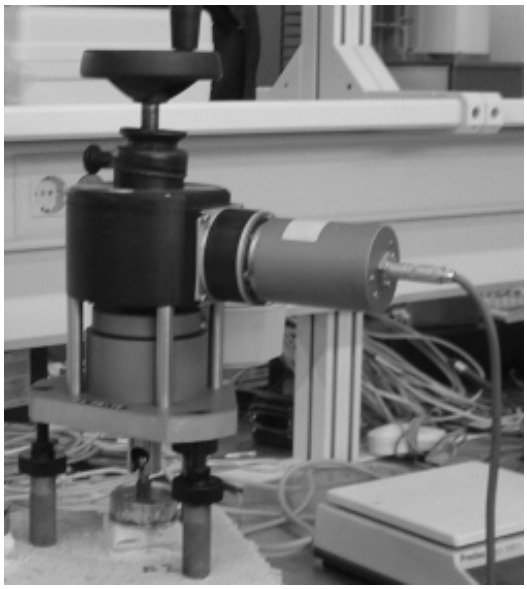

Figure 1. Pull-off test machine.

2.2 Studied systems

Façade cladding systems in Portuguese buildings are frequently composed of ceramic tiles bonded to substrates by means of adhesive. Adhesive bonding strength, both in tension and in shear, plays an important role on the tile bonding strength. Several standard testing methods have been established to measure and evaluate tile bonding strength (see EN 1348 [2007]). One of the difficulties of the implementation of this test in situ is to perform a low disturbance pre-cut of each specimen. Usually, square specimens are preferred, as they are easier to produce. Another aspect is where to take the pre-

cut. If it is performed deep in a render that's acting as subtrate for the adhesive mortar, the failure will probably occur in the substrate, resulting in a false low result. It can however be interpreted as a performance indicator of the substrate and not of the adhesive.

Cement based renderings are also very common in Portuguese façades. The application of the pull-off test in this case is described in several standards (see EN 1015-12 [2000]). A specific analysis must be performed after the test, since a rendering can be produced in one or several layers and, therefore, interpretatiorn is done based on the failure mode which can be cohesive inside a layer or adhesive in an interface between two layers.

Another popular application of the pull-off test is the evaluation of ETICS (External Thermal Insulation Systems) components proposed, for instance, in ETAG 004 [2000]. Again, an adequate pre-cut is essential for the test success. Since insulation is often not fixed continuously to the substrate, testing the thin rendering behaviour implies that the pre-cut must not go too deep into the insulation core.

Although standards exist, supporting the application of the pull-off test to the refered finishing systems, they are meant for laboratory tests and not in situ and therefore chareful adptation has to be made of the proposed methodologies. The RILEM [2004] recomendation is meant for in situ tests of renderings.

The pre-cut on the the three different systems application of the pull-off test is presented in Fig. 2.

Figure 2. Pre-cut a) ceramic tiles, b) rendering, c) ETICS

3 EXPERIMENTAL STUDY

This experimental study is based on data retrieved from inspections of buildings on operation phase. This implies that several factors conditioned the behaviour of the tested components such as the initial quality of the materials, their actual application conditions, substrate, façade exposure, age of the buildings and maintenance operations. The results of these tests cannot be directly compared since the conditions that lead to each set of results are unique.

The available data, however, presented an interesting opportunity to develop a statistical portrait of the adhesive strength that can actually be measured in revetments of building façades. The focus of the study is not only on the average values found but, more importantly, the spread of those values and the factors that influence it. The sample originated by the available data is random as it resulted from the study of buildings whose owners asked for inspections due to façade anomalies.
The results from 16 different in-situ inpections were analysed. In each inspection, different zones in the building were tested, characterized by different components and/or different exposure. The data was therefore grouped by zones of identical conditions, allowing isolating more accurately the

variables that contributed to the measured adhesion strength. The selected studies focused on claddings and cement based renderings as they were the ones with more data available.
Hence, the studied sample includes 213 valid measurements grouped in 56 case studies. All the invalid measurements were discarded from this analysis resulting, for some case studies, in a rather low number of measuremets. Table 1 presents the relation between the different tests and the original inspection report. Table 2 presents the variables that were isolated in this study.

Table 1. Inspection reports and connected case studies.

Inspection report	*Case studies*	*Measurements*
1	5+4+4	13
2	2+3+3+3	11
3	10+10	20
4	5+3	8
5	4+4+5	13
6	2+5+2+7	16
7	3+3	6
8	3+3+3+3+3+2	17
9	5+5	10
10	2+3+3	8
11	3+3+3+3	12
12	3+3+3+6+3+3	21
13	5+5+4	14
14	2+1	3
15	5+5+5+5+5+5	30
16	3+6+2	11

Table 2. Variables considered in this study.

Variable	*Cathegories*	*Frequency*	*%*
Tested Material	Cement based adhesive	97	45.5
	Rendering	116	54.5
Substrate	Concrete	15	7.0
	Stone masonry	35	16.4
	Brick masonry	160	75.1
	Wood-cement panels	3	1.4
Pre-cut	Circular	75	35.2
	Square	138	64.8
Failure mode	Adhesive	81	38.0
	Cohesive	70	32.9
	Plate detachement	21	29.1

The sample is apparently in line with the typicall Portuguse buildings characteristics. A study by Paes Afonso [2003], based on Censos 2001, revealed that rendering has the highest incidence in Portuguese buildings and the sample includes 54.4% of cases where rendering was the tested material. Regarding substrates, concrete and brick masonry are typical solutions for buildings of the last decades while stone masonery is common for older buildings. The only example of a non traditional solution included in this study was the application of ceramic tiles on wood-cement panels. Regarding substrate, there's a clear predominance in these tests of brick masonry, which corresponds to the Portuguese reality.

4 RESULTS

An overview of the results retrieved from the 56 case studies is presented in Figs. 3 and 4, divided between rendering and cement based adhesives. Each case study is represented by the mean value and standard deviation. The graphs also include a reference values for each material, namely 0.3 MPa for renderings and 0.5 MPa for cement based adhesives. The latter value is adopted as reference although an adequate and safe result would be above 1.0 MPa. It can be observed that the mean values for adhesive strength of renderings were typycally low and frequently below the recommended value of 0.3 MPa. The tested cement based adhesives exhibited higher strength and were frequently above the reference value of 0.5 MPa and even above 1.0 MPa. On both types of tested materials, significant variations of the standard deviations could be found. The low values observed, especially for renderings, could be related to the fact that these inspections were done in façades where anomalies could be observed.

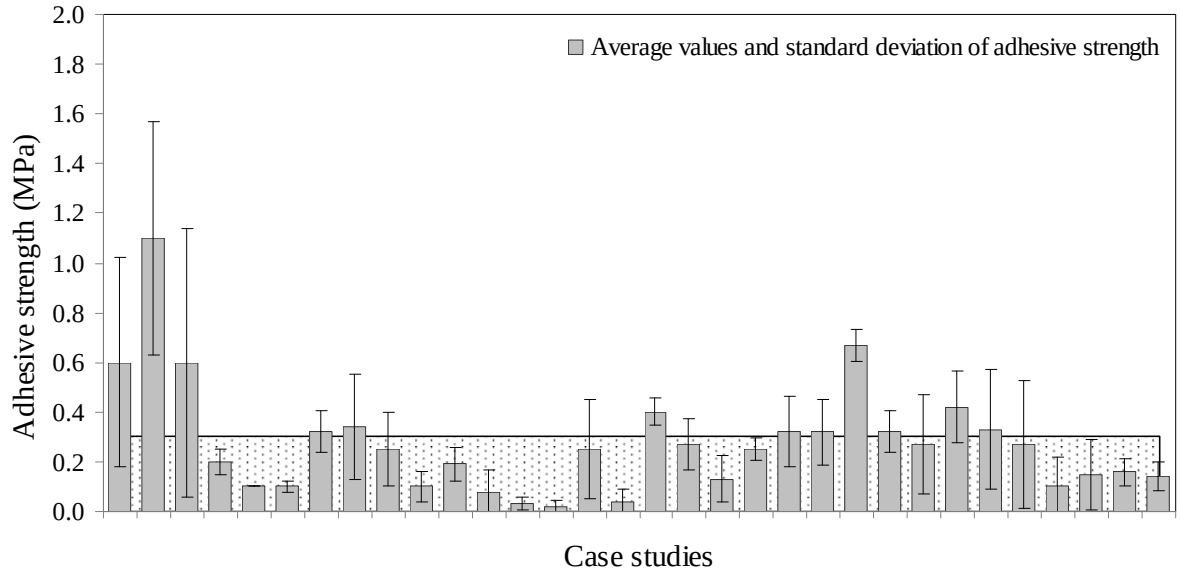

Figure 3. Average values and standard deviation for rendering case studies

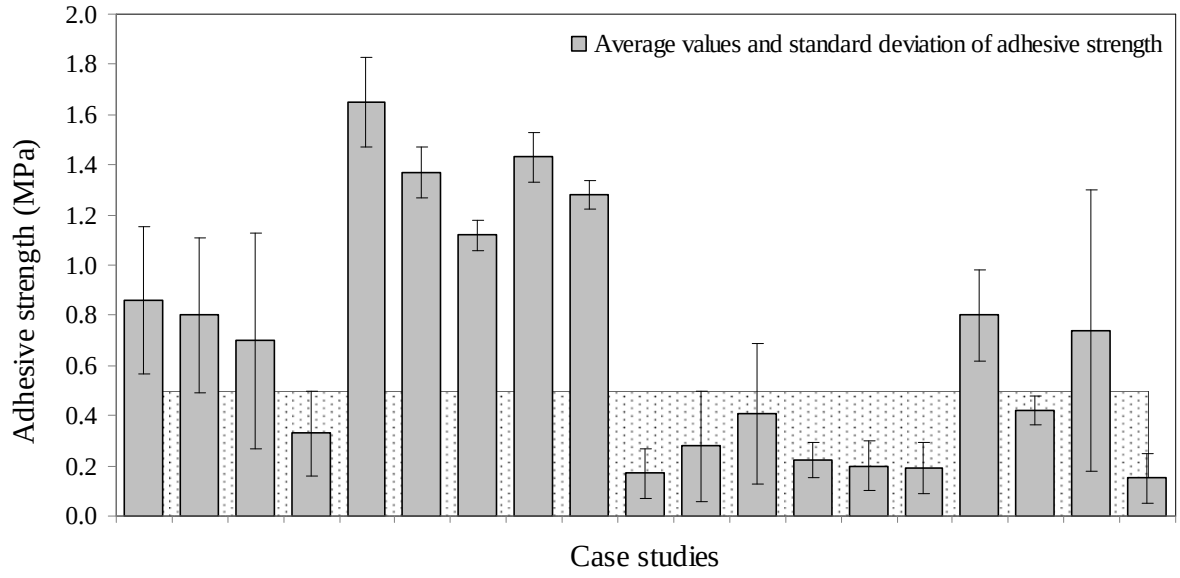

Figure 4. Average values and standard deviation for cement based adhesives case studies

5 ANALISYS

A deeper analysis of the adhesive strength found for renderings and cement based adhesives is presented in Figs. 5 and 6. The distributions found for each tested material were significantly different. While renderings presented a log-type distribution with predominant results below 0.3 MPa, cement based adhesives no theoretical model could be easily assigned. The mean was found above the reference value of 0.5 MPa. The box-plots for each material confirm this observation since, for cement based adhesives, no outliers were defined while for renderings, several values were defined as outliers, all corresponding to high resistance values.

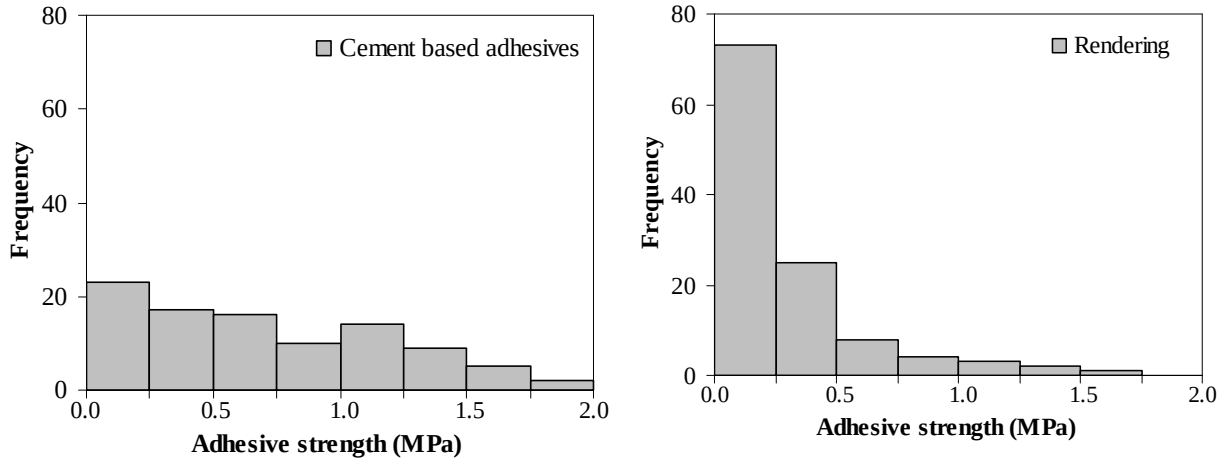

Figure 5. Adhesion strength distribution for the tested materials

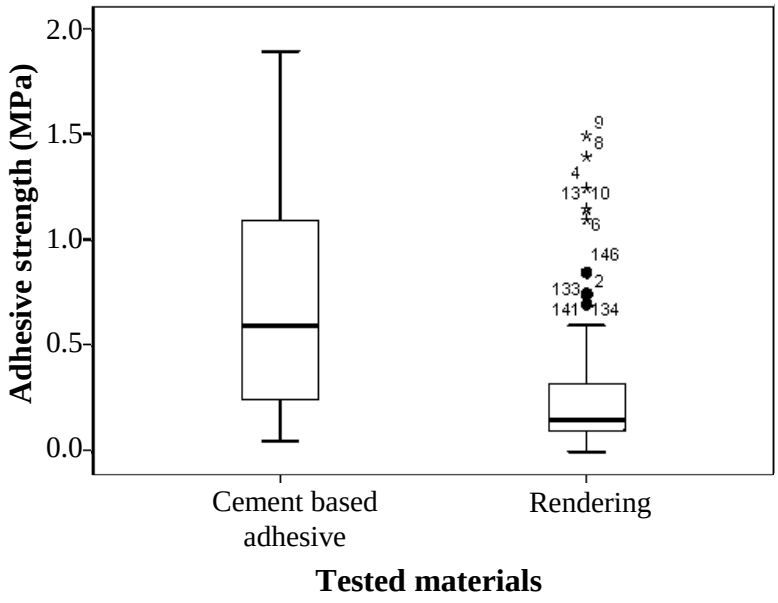

Figure 6. Adhesive strength box-plots for tested materials.

The correlation between solar exposure and mean adhesive strength was tested for renderings. The results are presented in Fig. 7. The results weren't totally conclusive but still it could be observed that the values found on the East oriented façades were higher than the ones found on South and West oriented façades. Surprisingly, the North oriented façades had the lowest values. Except for this orientation, a correlation between surface temperature in summer could almost be derived from these tests. The behaviour of the North façade may implie that other factors, such as wind driven rain or moisture accumulation would have to be taken into consideration. But for the exposure variable the

sample is quite reduced for each cathegory implying that no actual correlations can be strongly supported.

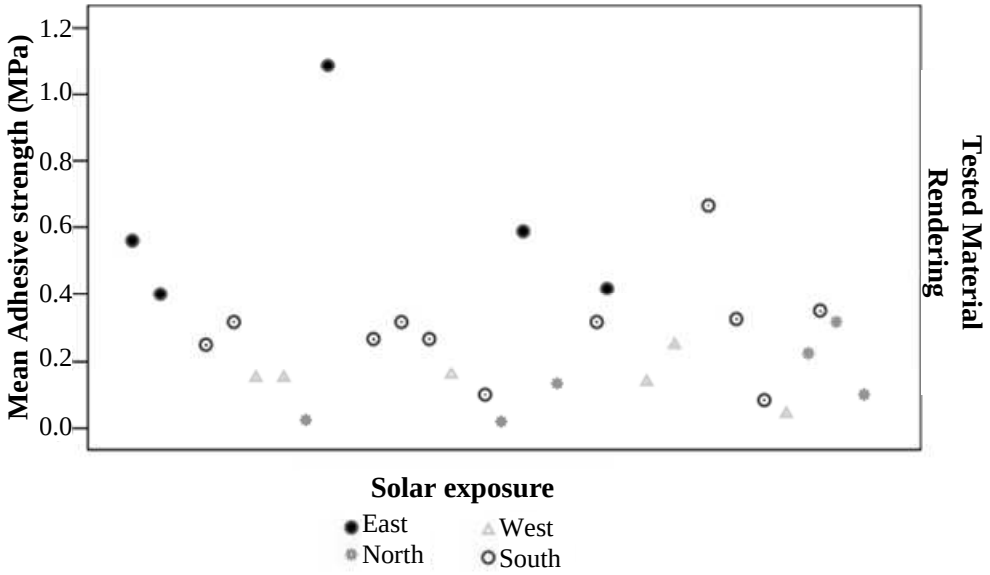

Figure 7. Mean adhesive strength for renderings correlated to solar exposure.

The analysis of the number of measurements influence on the variability of results is presented in Fig. 8. It can be observed that the average variation coefficient is very high and the actual variation can, in a specific test, range from almost 0 to 100%. It can also be observed that the cases where the variation coefficient was very low correspond to tests where a low number of valid pull-offs was performed. The correlation with the number of valid measurements, therefore, seems to indicate that the greater the number of valid pull-offs the greater the probability of not missing the actual variability of adhesive strength under evaluation. The eventual lack of trust in a method that results in such high variability is controlled by standards as minimum values are imposed for single valid tests and not only to the mean value. The problem of in situ tests is that often the adequate number of valid tests is not achieved due to the obvious difficulties in repeating the tests.

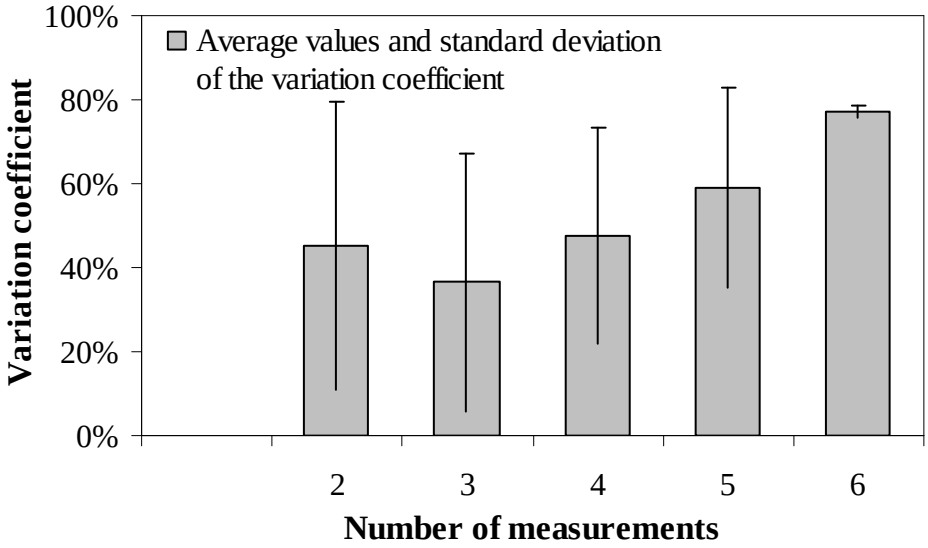

Figure 8. Variation coefficient correlation with the number of measurements per case study.

6 CONCLUSIONS

The analysis of case studies of in situ pull-off test applications to adhesion strength evaluation retrieved from inspections to Portuguese buildings resulted on the following conclusions:

- Pull-off test is used frequently as a decision support tool for building pathology studies;
- Adhesion strength can be measured for different systems and components according to international standards. These standards are however focused on laboratory tests. Documents for in situ measurements are scarse and not adapted to the entire range of components applied on façades;
- Although pull-off tests were applied by LFC-FEUP to different types of components, including ETICS, cement based renderings and cement adhesives used on ceramic tiles, only the tests related to the latter two were explored in a statistical study;
- The adhesion strength distribution found for renderings was logarithmic, presenting many values below recommended resistance while for cement based adhesives no theoretical distribution could be assigned and the mean value corresponded to an acceptable resistance;
- Regarding the influence of façade exposure on renderings adhesive strength, a tendency was found. But the number of cases per orientation is too low to retrieve a definitive conclusion on this subject;
- The variability found in these tests was usually very high, corresponding to variation coefficients ranging from 40% to 100%.

Although a large statistical sample was studied, the number of cases correlated to certain variables weren't sufficiently high to support definitive conclusions. Nevertheless, certain patterns were identified and the variabillity found for adhesive strength in situ tests inspires a cautious interpretation of results and a need for standards adapted to this specific subject.

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