Behaviour of a Façade Anchor System under Simulated Seismic Action

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October 2017

Abstract

In the past years a lot of improvement has been made on earthquake safety of buildings, however, although the loss of life has been minimized due to structural collapses, damage of non-structural elements is still an important topic. Such damage has major social or economical impact, particularly in critical buildings. Being the safety of these elements under seismic load attained by designing them for the forces transferred due to the element's inertia, security depends on the proper anchoring into the structural element. Hence, it is essential to safely design the connection for the expected actions during an earthquake event. Thus, the analysis of a façade cladding system is done using data stemming from tests performed on both single fasteners and on a test frame allowing an investigation of the behaviour of the system under a simulated dynamic load. This analysis is made for inplane movement which is expected to be the higher amplified vibration mode. Under a simplified dynamic analysis, a comparison between experimental data and code prescriptions is attained. It is shown that a behaviour factor of 1.5 may be more suitable for close to resonance states. Moreover, a study of the behaviour of anchors working in a group is made, allowing the conclusion that 50% of forces' redistribution is a reasonable estimation, for two fasteners with a stiffness ratio over 65%. It is also shown that for inplane vibration this redistribution may be negligible on the systems natural frequency.
Keywords: Non-Structural Element, Post-installed Anchors, Seismic Load, Façade Cladding System, Dynamic Analysis.

1. Introduction

This paper represents an extended abstract built from a master thesis [1] developed under a double degree program in collaboration between two universities: Politécnico di Milano, in Italy, and Instituto Superior Técnico, in Portugal. It was based on a research project performed in a partnership between Politécnico di Milano (PoliMI) and Centre Scientifique et Technique du Bâtiment (CSTB), which goal was to evaluate the behaviour of plastic anchors for fixing façade claddings through angle brackets, in masonry and concrete, under seismic action.

The purpose of this study was to evaluate not only the behaviour of the anchorage systems but also the seismic design of this type of non-structural systems. The analysis was supported by test protocols, performed in both research centres, that allow a better understanding on this elements' behaviour under cyclic load, as well as, to establish a relation between experimental data and the current European code prescriptions.

According to Vijaynaraynan,et al.(2012)[2] in the past years a lot of improvement has been made in certain countries with advanced practices of earthquake safety, however although the loss of life has been minimized due to structural collapses, the economic set back due to lack of safety of non-structural elements (NSEs) is still large. Such damage have major social or economical impact, particularly in critical buildings, like hospitals or commercial buildings. Even in urban buildings earthquake losses due to the failure of NSEs are on the rise, in fact, according to Miranda and Taghavi(2003)[3] NSEs are a major part of the total investment in the United States as seen in figure 1. Moreover, Filiatrault, et al. (2014) [4] state that damage to NSE occurs at seismic intensities much lower than the ones requires to produce structural damage.

Several difficulties arise when seeking to safely design NSEs under seismic loading. First, earthquake loads are generally not acting directly on these elements. This means that, it is vital to understand how the load propagates from the SEs to the non--structural ones. Because the load is transferred between different components, it is important to understand the amplification of the response of non-structural components depending on the action subjected to the structural component. To this matter, dynamic analysis tools may be valuable to predict their response.

Nevertheless, in structural engineering a wide

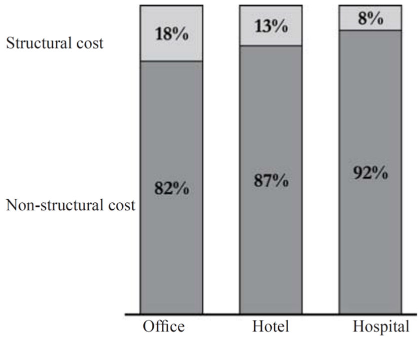

Figure 1: Relative investments in typical buildings [3]

range of NSEs can be found. Besides the fact that these elements have remarkably different functions and characteristics, making it difficult to systematize their design, experimental testing may be expensive and time consuming. Consequently, the knowledge on the behaviour of these systems is a topic to be developed.

Apart from the estimation of the actions on these elements, also the behaviour of the anchoring system needs to be studied. Recently, research on the behaviour of anchors under seismic loading has been made, however, most of these investigations are focused on metal anchors placed in concrete supports. Hence, behaviour on different base materials, like masonry, and made of different materials, such as plastic anchors, is still to be further developed. Furthermore, there are only standardized tests for metal anchor in concrete, consequently, it may be difficult to compare results on differently performed analysis.

In the present report a more detailed look will be made on specific testing protocols used for the system studied in this analysis - façade cladding systems. The study was composed by two groups of tests: the first regarding tests on a framed wall under dynamic loading and the second consisting on single fasteners' tests.

2. Experimental Tests

The present document describes an analysis executed with fundamental data that stem from an experimental analysis performed in a collaboration between Politécnico di Milano and CSTB which goal was to establish an evaluation method for the resistance of the façade anchor system under seismic loading.

With this goal in mind, static, cyclic and dynamic tests were performed on the anchor based on different test layouts. The tests can be divided into two big groups: the first regards tests on a real scale wall under dynamic loading, while the second consists on tests on a single fastener, both cyclic and static.

These experimental results come from a combination between protocols prescribed by CTSB [5] and alternative protocols developed for this study.

2.1. Test Layout

For this project special attention was made on the results attained from real scale wall tests, being the singles fastener tests mainly used to estimate the fastener characteristics such as stiffness and capacity. The dynamic tests on a wall were carried out in a layout that involved a system composed of several elements, connected to the concrete or masonry wall through six anchors as shown in figure 2.

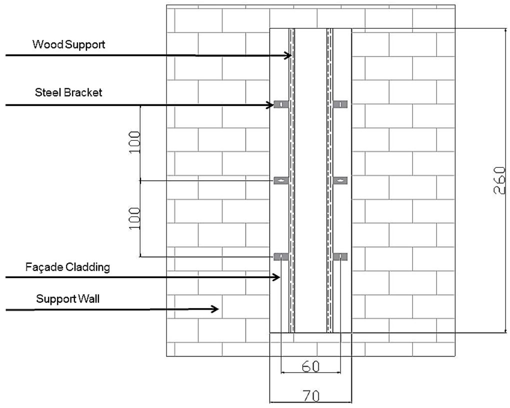

Figure 2: Tested Cladding Layout: Front view

- A bracket ensuring the connection between the wall and a wooden vertical element;
- Wooden supports fixed to the façade element and to the steel brackets. These supports were in epicea timber and presented a section of $65 \times 50mm^2$ and a length of 2.6 m and were fixed to the brackets with one $\phi 10$ and two $\phi 8$ bolts.
- Façade elements with a surface of $0.7 \times 2.6m^2$, TRESPA METEON DUO model, connected to the wooden supports using 5 bolts on each side

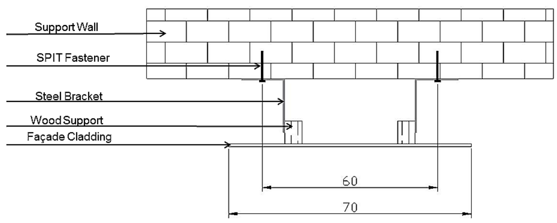

Figure 3: Tested Cladding Layout: Top view

Special attention was made on the design of the steel brackets. As stated on PoliMI's technical report [6], on the first tests a designed bracket was used (from here forward named ideal bracket), in order to avoid the yielding on the bracket and evaluate the performance of the fasteners on linear elastic behaviour conditions, later, a commercial bracket was introduced in order to access the behaviour of the anchors in a real configuration scheme. The main differences between the ideal and the commercial fastener is the thickness and the length of the flange.

The first is related to the fact that yielding of the fastener was to be avoided, in this way, it is ensured an elastic behaviour of the bracket for any value of applied acceleration throughout the frame test. The increase length of the flange of the steel bracket was prescribed in order to reduce the axial force on the fastener, by increasing the lever arm, the resisting moment can be attained with a lower force on the fastener avoiding pull-out failure of this element. The brackets' dimensions can be observed in figure 4.

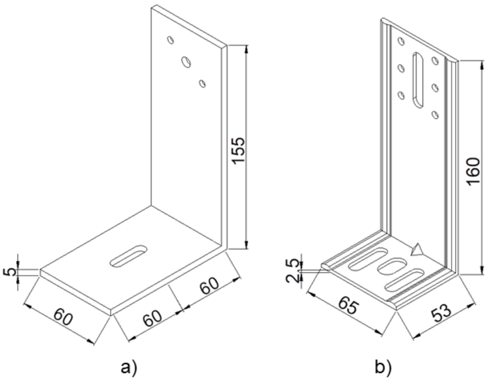

Figure 4: Brackets Geometry: a) Ideal angle bracket b) Simpson ABC strong tie 160x2.5

During the experimental test the acceleration and displacement of both the supporting wall and the façade were measured as well as the forces acting on the seismic resisting fixtures.

2.2. Test Protocol

Because there is no standard European experimental protocol for the evaluation of the seismic behaviour of façade systems, the protocol proposed by CSTB [5] was adopted. This protocol is meant to test the stability of façade cladding systems in seismic areas and was adopted to analyse the behaviour of their anchorage system.

The protocol rests on tests performed on a real scale framed wall solicited in its own plane by imposing a cyclic displacement, as schematically shown in figure 5. It begins by determining the natural frequency of the system by experimentally applying six shock tests where the structure is subjected to a single displacement impulse, allowing it to reach its stationary state.

Once the natural frequency of the system is

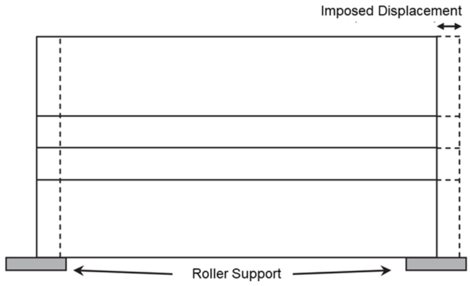

Figure 5: Dynamic test mechanism (adapted from CSTB (2013)[5])

known, two different paths can be followed depending on whether this parameter is higher or lower than 15 Hz. In the present study the natural frequency of the system was always estimated above 15 Hz, consequently, the model was subjected to 8 successive test phases of increasing acceleration, being each phase constituted by three sequences of 20 cycles of increasing frequency.

2.3. Test Program

In order to access the behaviour of the fastener distinct tests with different elements were performed. The test program can then be divided into three groups of tests:

1. Tests on concrete wall with ideal brackets;

2. Tests on masonry wall with ideal brackets;

3. Tests on masonry wall with Simpson brackets.

For each group, two tests were performed using a cladding made by one and four panels. In this way it is possible to grasp the influence of mass on a system of this kind. In each test the protocol prescribed by CSTB [5] for the study of façades under seismic loading was performed. Shock tests were made to obtain the natural frequency of the structure and the dynamic test consisted on the eight phases described on the previous chapter. For some, post-dynamic shock tests where performed as a way of diagnose some damage due to the dynamic loading.

Additionally to the dynamic tests on real scale wall, also residual axial tests were performed on the fasteners after the dynamic loading. Also static and cyclic tests on single fastener were performed, for both concrete and masonry base materials, as well as bending tests on the steel angle brackets.

2.4. Test Results

Test results are extensively presented on the technical reports developed by PoliMI [6] and CSTB [7] as well as on the full thesis document [1]. It was possible to compare the measured forces on the seismic resisting fasteners with the expected theoretical values. For the estimation of the theoretical values it is crucial to define the seismic load acting on the façade. The estimation of this force can be done assuming Eurocode or CSTB formulation. Apart from the coefficients used to account for the uncertainties, the main difference between these formulations is that while CSTB assumes a constant amplification factor, for Eurocode this amplification is dependent on the relation between the acting frequency and the natural frequency of the façade system. This difference is shown in figure 6 for masonry wall with 4 cladding and ideal brackets.

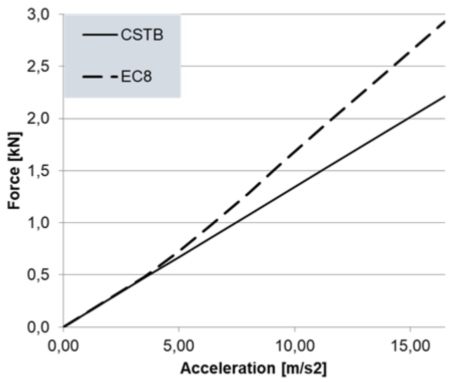

Figure 6: Expected forces on fasteners: constant vs variable amplification

It was possible to observe that a non-constant amplification may be more suitable to represent the loads on the fasteners. Therefore, the analysis was performed using Eurocode 8 formulation, using the systems natural frequency estimation from the shock tests.

Moreover, according to CSTB[5] the expected force on the fastener should take into account uncertainties on the distribution of forces due to fastener's installation and displacements, this is attained through the coefficient K_{alea} that considers a maximum redistribution of 50%. In this way, an upper and lower boundary can be obtained for the predicted forces on the fasteners related to the redistribution of forces on these elements, as shown in figure 7 for concrete wall with 1 cladding.

Test results show that, in fact, the forces are not equally distributed on the fasteners. Therefore, this phenomenon should be taken into account when designing an anchoring system. Moreover, the 50% redistribution limits are coherent with the experimental forces acting on the fastener, which validates the 1.5 coefficient adopted by CSTB [5].

It is important to notice that, for the 4 cladding test with commercial brackets on masonry wall, yielding of the bracket is expected. In this situation, the dynamic load will no longer be transferred

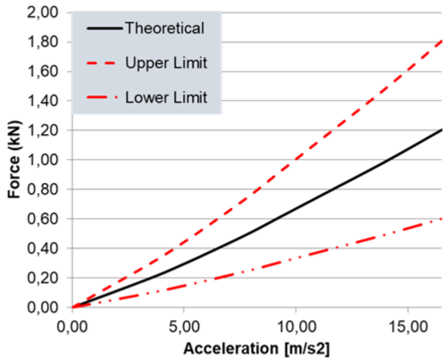

Figure 7: Theoretical values of axial force on fasteners

to the anchors and so, the maximum force acting on the fasteners will be the one computed for the resistance of the bracket, as shown in figure 8. From experimental results, it can be seen that, as expected, once the bracket fails, the load on the anchors remains approximately constant, leading to a design based on fastener protection. Moreover, even in this case, the maximum 50 % redistribution of forces is a good estimate.

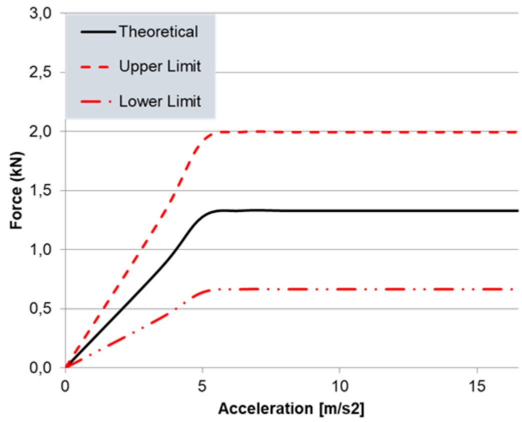

Figure 8: Theoretical values of axial force on fasteners: bracket failure

For the test configurations where structural damage was not observed, post-dynamic shock tests were performed. In this way it was possible to estimate the eigen frequency after the dynamic loading in order to analyse a possible change in the structure's stiffness and consequently the damaged imposed by this dynamic loading. The results coming from these tests showed no significant damage of the structure, in view of the fact that there was no significant decrease in the system's natural frequency and consequently no decline of its stiffness.

However, when comparing the static tests with the residual axial tests on the wall's fastener it was observed that, even tough there was a negligible variation on the fastener's capacity, a considerable decrease on its initial tangential stiffness occurred. This seems to imply that, for this range of stiffness variation, the façade system is not significantly affected.

3. Dynamic Analysis

In order to better understand the behaviour of the tested system, a dynamic analysis was performed. This study was based on a simplified single degree of freedom system, as well as, on the computation and analysis of experimental frequency response functions.

3.1. Simplified Dynamic Model

The single degree of freedom model was built assuming a lumped mass system. In this sense the model was designed to represent two of the four fasteners assuming that the mass was equally distributed amongst them and therefore using a tributary area equal to half of the façade, as seen in figure 9.

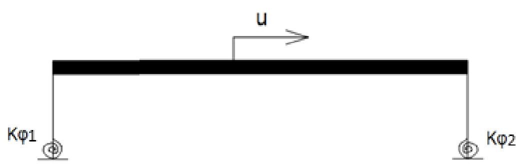

Figure 9: Model with 2 rotational Springs

The following hypothesis were used when performing the dynamic analysis of the simplified model:

1. Rigid supporting wall;
2. Rigid façade panel;
3. Elastic behaviour of the steel brackets;
4. Elastic behaviour of the fastener;
5. Uniform distribution of mass;
6. Negligible damping.

The systems' behaviour was defined assuming that the action of bolts could be portrait as a rotational spring at the bottom of the angle brackets as seen in figure 10. Following this reasoning, this fictional spring stiffness - K_φ - is obviously dependent on the axial stiffness of the fastener - k_{fast} - as shown in expression 1.

$$K_\varphi = k_{fast}\frac{a^2}{2} \quad (1)$$

In order to estimate the validity of the 1.5 redistribution coefficient, based on the simplified model, a relation between the ratio of stiffness of the fasteners and the ratio between the forces acting on

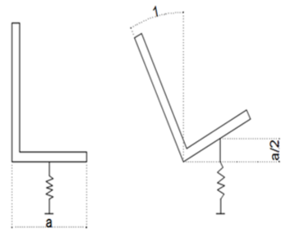

Figure 10: Estimation of the rotational stiffness

them was built. With this study it was possible to determine a maximum stiffness ratio for which the 50% redistribution limit is valid 65%, as shown in figure 11. Notice that this model assumes only a horizontal distribution. However, when compared with the experimental results it was possible to observe that the models results were coherent with the real redistribution of forces.

Because the study of the acting seismic force is dependent on the eigen frequency of the system, a study on how this redistribution of forces affects this parameter was done. It was shown that the redistribution of forces does not influence significantly the expected natural frequency of the system as shown in plot 12, where the reference frequency is attained for $k_1 = k_2$. In other words, even though the forces on the fasteners are dependent on the relation between the real stiffness of the fasteners, the overall stiffness of the system is not affect by this.

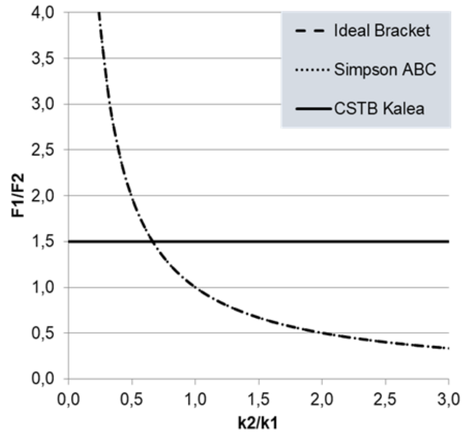

Figure 11: Estimation of Redistribution Factor

3.2. Frequency Domain Analysis

Besides the study on the force redistribution, also a study on the acceleration amplification of the façade cladding system was performed. This analysis was based on the computation of frequency response function obtained from the shock tests performed on the real scale wall.

In order to estimate the forces on the fasteners it is crucial to estimate the seismic force acting on

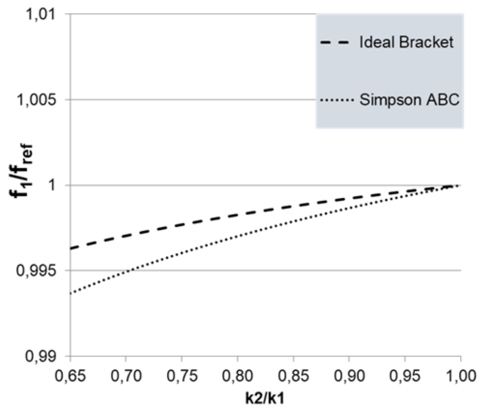

Figure 12: Natural frequency for redistribution factor bellow 1.5

the façade. To this matter several prescriptions are used to compute the acceleration amplification.

Both Eurocode 8 [8] design (equation 2) as well as the commonly used Calvi [9] definition (expression 3) were studied for tests on concrete wall.

The main difference between the two formulations is that, while EC8 takes into account the natural frequency of the system, Calvi also considers the damping coefficient on the estimation of the amplification - α.

$$\alpha_{EC8} = \frac{1}{q_a}\left(\frac{6}{1+\left(1-\frac{f_1}{f_a}\right)^2} - 0.5\right) \tag{2}$$

where,

q_a : Behaviour factor for non-structural elements;

f_a : Fundamental period of the non-structural element;

f_1 : Fundamental period of the building.

$$\alpha_{Calvi} = \frac{1}{\sqrt{\left(1-\frac{1}{\beta}\right)^2 + \xi}} \tag{3}$$

where,

β : Ratio between the natural period of the element and the natural period of the supporting structure

ξ : Damping ratio

The theoretical expressions were compared to the experimental acceleration transfer function computed for tests on concrete wall as shown in figure 13 and 14. It is visible that for the prescribed behaviour factor of 2, Eurocode may underestimate the amplification experienced by the façade. Calvi however, presents a more conservative prediction that is set between the two limit values for Eurocode.

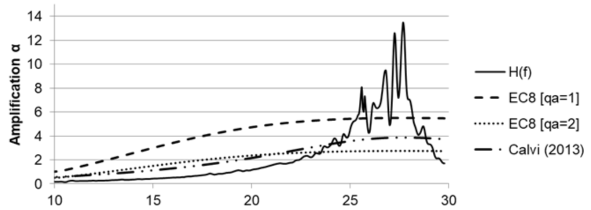

Figure 13: Amplification Factor: Code comparison - 1 cladding

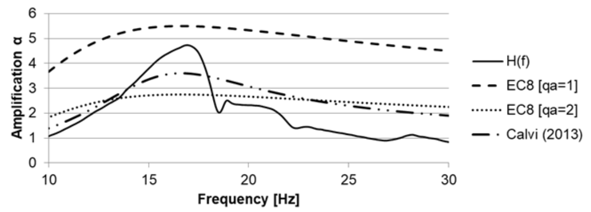

Figure 14: Amplification Factor: Code comparison - 4 cladding

It was important to understand if the system sustained a linear behaviour throughout all the test phases, in other words, independently from the tested frequencies. In this sense the acceleration transfer function was computed for the first two phases with lower acceleration and frequencies and for the last two phases with higher acceleration and frequencies. It was possible to estimate in this way the natural frequency of the system. It was shown that for the test on concrete wall with 4 cladding, for higher phases a peak on the frequency response function could be observed around 12 Hz, while for the first phases the eigen frequency was estimated higher than 15 Hz as shown in figure 15.

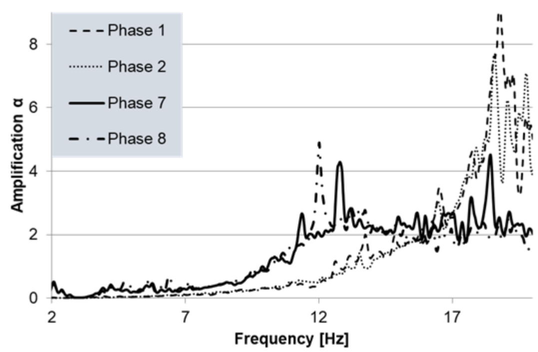

Figure 15: Transfer Function: Test on concrete wall with 4 cladding

Besides showing some non-linear behaviour of the system this also allowed the conclusion that on phase 6, under 13 Hz frequency, a resonant state should be expected, leading to a higher amplification of the response acceleration. With this in mind the experimental amplification computed from the acceleration measured during the test was compared with the estimated amplification arising from the frequency response function. It was shown that an amplification of around 5.3 was observed during the resonant phase.

In fact, when analysing the rest results for phase 6 it was noticed that a peak value for the fasteners forces was reached, unlike what was expected - maximum force on the last phase. This validated the previous results for high acceleration phases.

It is important to understand the cause of this non-linear behaviour of the system. Two main aspects could cause the non-linearity on the system's behaviour: the fastener or the angle bracket. It was proven at the beginning of this dynamic analysis that the change of fastener's stiffness on the range of scope for this study had a negligible effect on the eigen frequency, consequently the behaviour of the bracket for this test was inspected.

Because the real load-displacement behaviour of the bracket is known, through CSTB's bending test, it can be checked if the accelerations from the dynamic test caused any non-linearity of this element. From the measured forces on fasteners it is possible to estimate the force acting on the bracket, it was shown that the range of computed forces acting on the bracket were close to the yielding plateau, in other words, the brackets were no longer on their linear elastic range.

This means that, the initial stiffness no longer characterizes these elements. Actually, the real stiffness throughout these phases is lower than the initial tangent stiffness. This result is in agreement with the lower natural frequencies obtained for the higher acceleration phases.

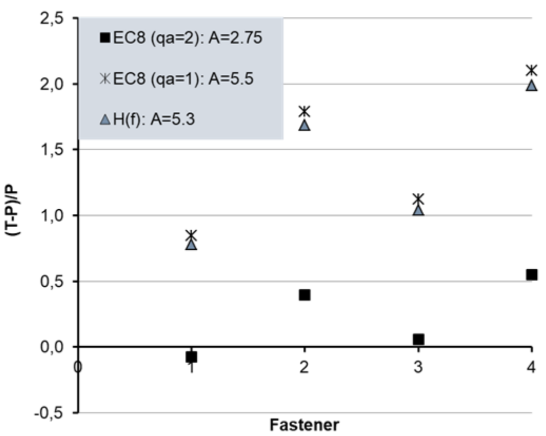

Figure 16: Comparison between theoretical and experimental forces on fasteners

With this in mind it was possible to compare the real forces acting on the fasteners under resonance with the predicted ones from theoretical computations. The relation between experimental and theoretical results can be seen in figure 16 plot. It can be seen that the prescribed behaviour factor of 2 may lead to results that may not be on the safe side, while a behaviour factor of 1 overestimated the forces acting on the fasteners. Consequently, a behaviour factor of 1.5 may be more advisable for systems, with excitations close to the resonant state.

3.3. Higher Vibration Modes

Before this section, only the first vibration mode of the system was studied. However, in order to better understand the behaviour of the system a simplified dynamic model was build to consider also out of plane vibrations. The model was built as a three degree of freedom system, based on the previously explained model allowing out of plane motion, as shown in figure 17.

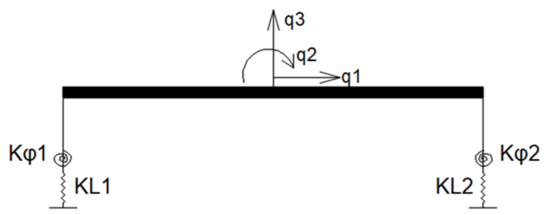

Figure 17: Simplified three degrees of freedom model

The influence of the anchoring system is portrait as a combination of a linear and rotational spring at the base of the angle brackets. Once again, the fact that the fasteners may have different properties is taken into account.

A modal analysis was performed, to this sense, the eigen values and eigen vectors of the system were computed. It was possible to observe from the first computations that, if both fasteners have the same stiffness, the second mode of vibration is linked with the third degree of freedom, however, from experimental testing it was possible to observe that fastener pull out was related with the torsional displacement. Additionally, the residual tests on fasteners showed that the stiffness was not equal for both anchors, and therefore, it is important to understand the consequences of this uncertainty on the higher vibration modes.

Moreover, it can be seen that, even tough the fastener stiffness does not represent a significant influence on the natural frequency of the system, it clearly influences its second eigen frequency.

4. Conclusions

First, it is crucial to understand the behaviour of fasteners in a group. In fact, it was shown from the experimental results, there is some uncertainty on the distribution of the seismic force through the fasteners. An advisable way to deal with this uncertainty on these systems can be to consider a 1.5 factor when designing the anchoring system. The fact that this coefficient is valid for stiffness ratios up to 65% also allows some safety on the installation of the fasteners.

Moreover, the previous results show that, generally, the design of the studied façade cladding systems can be done independently from the choice of the fasteners. In the same way, the assessment of fasteners' behaviour can be done simply with single fastener testing. In fact, when designing the system's anchorage system two paths can be followed. If the design is meant to protect the fasteners, then the prediction of forces acting on the anchorage system can be obtained simply by considering the resisting moment of the angle brackets. On the other hand, if the systems intent is to protect the angle brackets, the forces on the fasteners can be estimated through European codes. Nonetheless, in this case, for systems where resonance can be expected, the lower boundary assuming a behaviour factor of 2 may not be on the safe side. In other words, for these situations a factor of 1.5 may be more advisable.

In conclusion, this work is a very initial study on a topic that is relevant on structural engineering. However, considering the safety and economical importance of these systems a deeper study should be made. It may be important in the future to expand the study of these elements leading to more detailed and practical prescriptions on European codes, not only for the design of these systems but also for their technical assessment.

Acknowledgements

First and foremost, the author would like to express her sincere gratitude to SPIT for allowing access to the data used on this research. This work would not be viable without their contribution together with *Laboratorio Prove Materiali, Strutture e Costruzione (LPMSC)* at Politécnico di Milano and *Centre Scientifique et Technique du Bâtiment* that performed all the test protocols included in this study.

Furthermore, the author wishes to express her utmost appreciation to Professor Giovanni Muciaccia, from Politécnico di Milano, and Professor Luís Guerreiro, from Instituto Superior Técnico, that were crucial for this project, not only for this opportunity, but also for their contribution and availability. Additionally, special gratitude is due to Eng. Giuseppe Di Nunzio that followed and helped with every step of the analysis.

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