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INVESTIGATION OF THE MASONRY PILLARS OF A MODERNIST BUILDING OF HOSPITAL DE SANT PAU, BARCELONA

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Abstract. *The methodology employed and the results obtained from an experimental campaign to determine the compressive strength of a masonry pillar extracted from an early 20th century building are presented. The samples of the pillar were extracted from a structure located in the Hospital de Sant Pau modernist complex. The pillars analyzed are characterized by a circular section of a diameter of 60 cm, and are composed of clay bricks and, instead of the more common lime based mortars, Portland cement as a binder. The pillars show a complex interior morphology including an outer layer of regular masonry in combination with an internal core composed of an irregular mix of mortar and brick portions. The material, geometrical and structural typology of the pillars investigated are fairly representative of the pillars encountered throughout the hospital complex, therefore making the determination of its capacity of wide interest for the structural study of several adjacent buildings.*

The experimental campaign was planned and performed with the purpose of determining the compressive strength and elastic properties the masonry pillar under cyclic and monotonic concentric loading. The campaign included several tests on entire portions of the pillar measuring a height of 100 cm. It also included a detailed characterization of the mechanical properties of the constituent materials and masonry samples including one or more mortar joints.

The ultimate load obtained from the pillar test is compared to the service and design loads. Comparisons are also drawn between the compressive strength obtained from the pillar test and from tests performed on sampled masonry specimens. The effects of existing damage, which is extensive in the pillars, and overall structural arrangement are also discussed.

1 INTRODUCTION

Compression tests on masonry pillars, especially ones extracted from historical structures, are uncommon, although the existing literature includes tests performed on pillars composed of historical clay bricks and new lime mortar [1] or on pillars composed of stone units and mortar [2] or even wall segments extracted from masonry structures [3]. The opportunity to perform such a test on a wholly original structural element arose during investigation and restoration of a building in the Hospital Sant Pau complex in Barcelona. The intervention program exacted involves the replacement of several of the pillars in the structure, therefore a comparison between the service loads and the compressive capacity obtained from the experiment can be used to gauge the safety margin of the remaining structural elements of this typology.

Given the fact that the structural typology and materials found in this building are encountered in several other parts of the hospital complex, the conclusions reached in this campaign may prove useful, at least as a first estimation, concerning the structural behavior and capacity of pillars in this and other buildings.

2 INSPECTION AND PREPARATION OF THE PILLAR

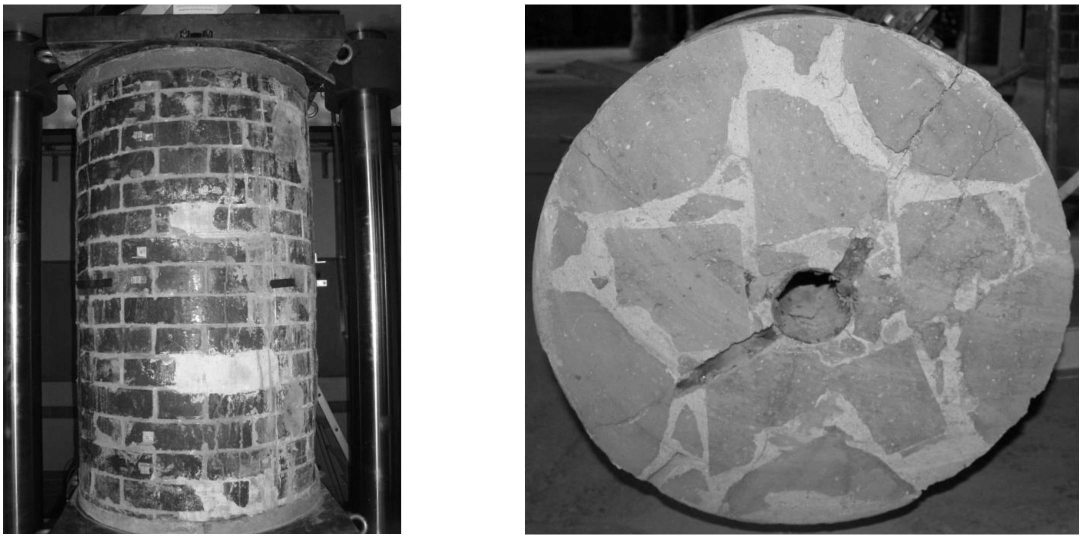
The cylindrical pillar was initially located on the ground floor of the toxicomania department building. Following the removal of a large portion of the pillar, it was placed in a protective steel jacket padded with a neoprene sheet in order to facilitate moving and to avoid damage during transportation.

The total height of the sample was 1600 *mm* and had a diameter of 620 *mm*. A portion with a height of 1000 *mm* was decided to be tested in compression and the remainder to be removed for sample extraction and further material testing. The removal and sectioning of the 600 *mm* portion of the pillar was performed using a diamond thread.

The pillar is composed of solid clay bricks and mortar. The outer structure of the pillar resembles a Flemish bond arrangement of the bricks. Slight variations of the dimensions of the bricks and the pillar are encountered. Taken as arc lengths at the perimeter, the “stretcher” bricks have an average length of roughly 280 *mm*, the “header” bricks 90 *mm* and the “head” joints have a thickness of 5 *mm*. The thickness of the outer leaf, as defined by the thickness of the large stretcher bricks, is roughly 140 *mm.* The full circumference of the pillar is composed of 5 “stretcher” and 5 “header” bricks. The bed joints have a thickness of 7.5 *mm* and the bricks have a height of 60 *mm*. The portion of pillar tested was composed of 16 brick courses and 15 bed joints (Figure 1).

Masonry samples were extracted from the exterior part of the pillar for destructive testing. These consisted of cylindrical couplets composed of two bricks and a single intervening mortar layer. The couplets had a diameter of 75 *mm* and a height of 110 *mm* and were subjected to compressive testing. The tests resulted in an average compressive strength of 15.7 *MPa* and a Young’s modulus of 3654 *MPa*. Infill cylinders of the same diameter and a height of 150 *mm* were also extracted and tested in compression, yielding an average compressive strength of 10.2 *MPa* and a Young’s modulus of 9596 *MPa* [4].

Several distinct damage patterns are visible in the exterior, the most prevalent of which is a set of three large vertical cracks extending to nearly the entire height of the pillar. Several smaller vertical cracks are also present. A large spalling area is also visible near the base which spans several courses in height and a few centimeters in depth. The supports of previously installed timber elements are also visible, having left voids several centimeters in depth.



(a) (b)

Figure 1: (a) External and (b) cross sectional geometry of the pillar.

While the exterior structure presents complete regularity, inspection of the cross sections, made visible by the diamond thread cuts, revealed a somewhat irregular internal structure, in which the “header” bricks are but a few centimeters thick. The “stretcher” bricks have more regular internal dimensions. The infill of the pillar is composed of 5 bricks of moderate dimensions and smaller brick fragments resembling a rubble masonry structure. The mortar, however, appears well compacted, although several voids were found. The center of the pillar is vertically traversed by a drainage pipe with an external diameter of 90 *mm*. The pipe appeared heavily corroded. The large vertical cracks can be seen to extend to the center of the pillar (Figure 1b).

The bounding sections at the base and the bottom, which would serve as the load surfaces in the compression test, were rough and non-parallel. In order to overcome these defects so that good contact could be established with the load plates and in order to avoid premature localized damage during the test, high strength concrete caps were cast directly on the load surfaces. Additionally, 5 *mm* thick neoprene sheets were applied between the concrete caps and the load plates. Finally, a cylindrical steel jacket lined with neoprene padding was used for the transportation of the pillar.

3 LOADING AND INSTRUMENTATION

A large number of several types of instruments were used for the monitoring of the compression test. Considering the rather uncommon nature of the test and the lack of an extensive literature on the subject, it was deemed necessary to attempt to gather as much information as possible. Given the large size, the irregular composition and damaged state of the structure, global measurements of vertical and horizontal deformation were deemed appropriate. However, properly arranged local measurements were not ruled out and may in fact provide insight into the global behavior of the structure.

The global axial stiffness of the pillar was measured using three transducers measuring the vertical displacement along a large portion of the height of the pillar, designated L1, L2 and L3. These transducers were placed one each on every part created by the three large vertical cracks. Therefore, they are not symmetrically distributed on the surface of the pillar. The instruments were attached using small diameter pins attached in drilled holes.

Local vertical displacements were measured using 9 displacement transducers. These were arranged on three height levels and aligned horizontally where possible: T1, T2 and T3 near the top; M1, M2 and M3 at mid height; B1, B2 and B3 near the bottom. The purpose of this arrangement was the measurement of variation in local stiffness according to the position along the height of the pillar. A representative measurement length including two half bricks and one bed joint was adopted. These instruments were too attached on the surface of the pillar using pins.

Four displacement transducers, H1 through H4, were used to measure horizontal movement in four points along the perimeter at the mid height of the pillar. These points were located at 90^0 angle intervals and their measurements could be used to approximate the global radial expansion of the pillar under concentric compression. These instruments were fixed on a perimetric aluminum frame and oriented in a direction normal to the surface of the pillar.

Three strain gauges, G1, G2 and G3 were used in alignment with the long vertical LVDTs. They were attached to the outer surfaces of three intact bricks using an adhesive resin. The intended purpose of the strain gauges was the measurement of the deformation of a single brick in order to estimate its modulus of elasticity.

The arrangement of the instruments is shown in Figure 2, along with the existing damage documented through visual inspection. The distribution of the large vertical cracks and the location of the spalling area divide the pillar in three uneven segments: one part consisting of roughly half the pillar and two parts consisting of roughly a quarter of the pillar each. This fact, along with the superficial damage, dictated the arrangement of the instrumentation.

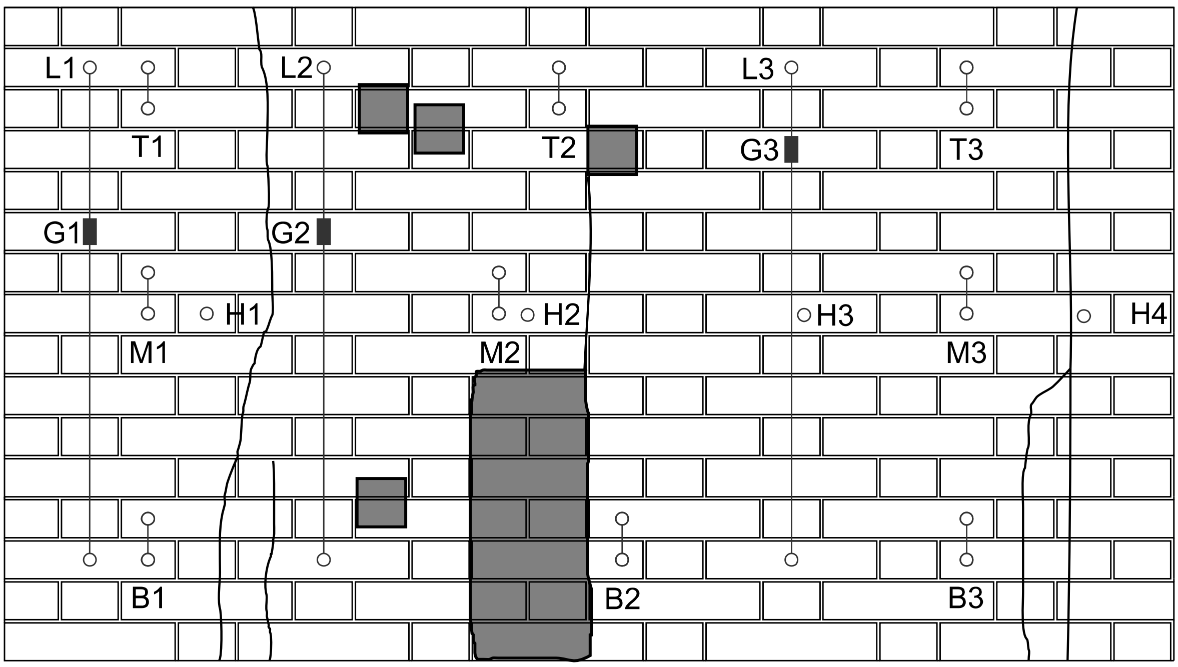


Figure 2: Existing superficial damage and instrument placement. L: large vertical transducers, H: small horizontal transducers, T, M & B: small vertical transducers at the top, middle and bottom, G: strain gauges.

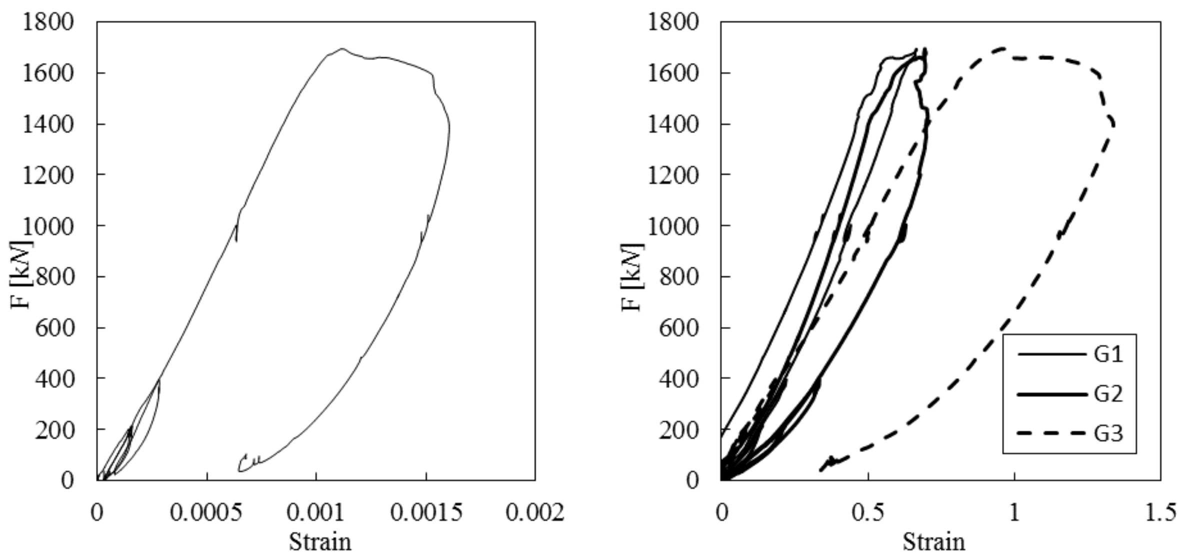
Several load cycles were performed during the test. These consisted of two applications of 200 *kN* at a load and unload rate of 0.2 *mm*/*min* with the maximum load being maintained for 5 minutes. An application of 400 *kN* at a rate of 0.3 *mm*/*min* followed, the maximum load again maintained for 5 minutes. Subsequently, a load of 400 *kN* at a rate of 0.5 *mm*/*min* was again applied, held for 5 minutes at the maximum, and, finally, a steady load rate of 0.2 *mm/min* was applied until failure of the pillar. Following attainment of the peak the pillar was unloaded by lifting the load cell.

Due to the height/diameter ratio of the pillar, equal to roughly 1.6, failure due to buckling can be ruled out. The monolithic behavior of the pillar, however, cannot be easily ascertained due to the presence of large vertical cracks which may, in effect, split the pillar in three independent parts. The concrete caps may assist in preventing or mitigating such a mode of response, but collapse should be governed by both local material failure and global failure mechanisms.

4 RESULTS

The peak force attained was 1694 *kN*, corresponding to 5.6 *MPa* of compressive stress. The elastic modulus of the pillar at 50% of the maximum load was 6075 *MPa*. Throughout the application of the load and before the attainment of the maximum force, the variation of the elastic modulus was very small, owing to the good compaction of the concrete used in the joints. The force-axial strain response curve, the strain having been calculated from the displacement measured at the large vertical transducers, is presented in Figure 3a.

The average compressive stress corresponding to the maximum load is noticeably lower than either the compressive strength of the previously tested outer part couplets and the infill samples. Possible causes for this difference include irregularities in the interior of the pillar and the effect of existing damage.



(a) (b)

Figure 3: Force-axial strain curves: (a) transducers and (b) strain gauges.

Figure 3b illustrates the strain measurements from gauges G1, G2 and G3. According to these readings, the elastic modulus of the bricks is equal to 7320 *MPa*. Given the irregular structure of the pillar and the very short measurement length, it is not certain that the stress in the brick is equal to the average vertical stress at the pillar. Therefore, this value can only be considered as a rough indication of the elastic modulus of the bricks.

The progression of damage was visually monitored during the test. At a load of 1000 *kN* the large preexisting vertical cracks had expanded into the concrete caps and new vertical cracks had appeared on the surface. It is assumed that the preexisting cracks exhibited further opening. Near the maximum load, limited superficial spalling of bricks was registered, while the already large spalling area near the base had degraded, but not significantly.

Localized damage in the joints, such as vertical cracks in the head joints or crushed mortar in the bed joints was not noticed at close visual inspection. Furthermore, superficial damage in the bricks was mostly limited to "header" bricks, which are only a few centimeters thick at most points. Crushed material was not found to have fallen from the pillar in any significant amount from either the bricks or the joints. No cracks or other damage appears to have originated from the pins used for the anchoring of the measurement instruments. The concrete caps also did not appear to bear significant damage except near the edges. Removal of the concrete caps also revealed that no localized damage had been caused near the load surfaces.

This global failure appears to have developed mostly along the preexisting vertical cracks and resulted in separation of the three pillar segments. The new damage identified at the end of the test, along with the preexisting damage, is shown in Figure 4. It is clearly indicated that most new vertical cracks originated near the anchor points of the old timber elements. These too extended to the concrete caps. No evidence of crushing damage was discovered in neither the bricks nor the joints and new vertical cracks were limiter in number and expanse.

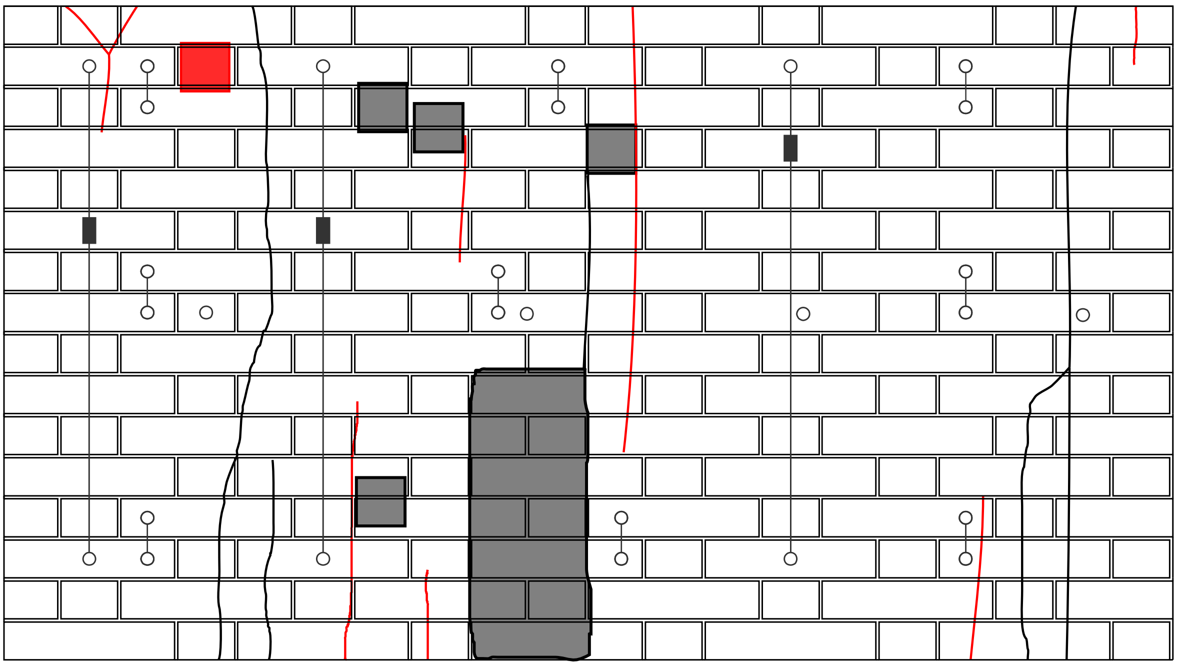


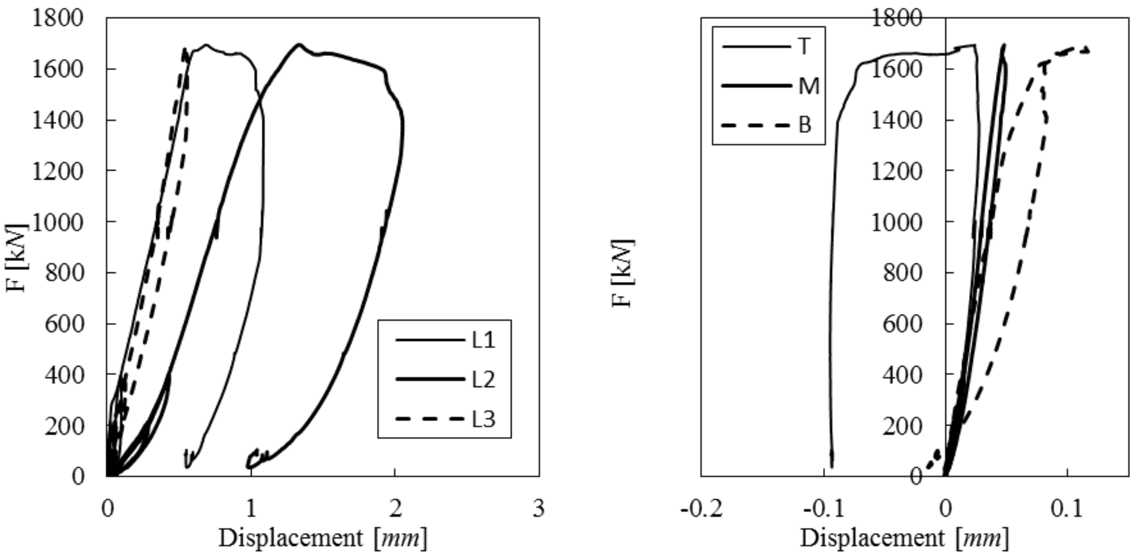
Figure 4: Preexisting (black) and new (red) damage at the end of the test.

Whereas global axial stiffness, defined as the average stiffness derived from the large vertical transducers, was steady until failure, different values of stiffness were registered in each of the three masonry segments. Transducer L2 in particular showed a much smaller stiffness than L1 and L3, especially for low loads and for loads near failure, as can be seen in Figure 5. The L2 transducer was placed near the large spalling area which may account for this behavior. Another discrepancy was found in the behavior registered at different heights by the small vertical transducers, which is also illustrated in Figure 5. The bottom transducers recorded a clearly nonlinear response near the peak, the middle transducers recorded an almost elastic unloading after the peak, as did top transducers following a sudden expansion after the unloading process started. At 50% of the maximum load the top transducers registered a stiffness of 13511 *MPa*, the middle transducers 9196 *MPa* and the bottom transducers 6111 *MPa*.

However, the transducers at each level did not register the same stiffness, especially at the top part, where the maximum stiffness was 20252 *MPa* and the minimum was 7883 *MPa* at T3 and T1 positions respectively. The variation was much smaller for the other two levels.

Horizontal expansion was uneven in the two directions set by transducers H1-H3 and H2-H4. Generally, the displacements were much larger in the H1-H3 direction. Considering the total radial expansion as the average produced by the two directions, the Poisson's ratio of the pillar reaches the value of 0.50 before 50% of the maximum load. The initial ratio for a load level of 300 *kN* is 0.22. The measurements of the horizontal transducers, along with the evolution of the diameter of the pillar at the height of measurement, are illustrated in Figure 6.

Following the complete unloading of the pillar, significant residual displacements were registered for all measurements.



(a) (b)

Figure 5: (a) Force-displacement curves: (a) L1, L2 and L3 transducers and (b) average of top, middle and bottom transducers.

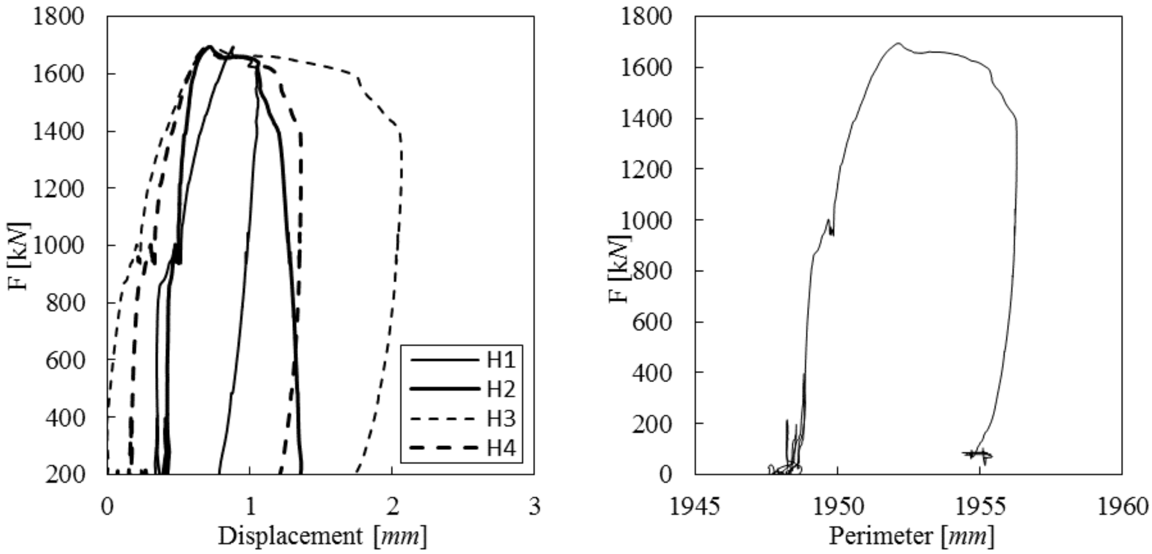
5 CONCLUSIONS

An experimental research has been presented on the strength of a brick masonry pillar of an existing modernist structure built at the beginning of 20^{th} c. The research has included a laboratory test of a large-size pillar specimen extracted from the building investigated. The test has allowed the measurement of the maximum compressive capacity of the specimen.

It has been observed that the maximum compressive force attained in the test is significantly lower than the compressive strength measured on small specimens (couplets) extracted from the same and other similar pillars of the building. The compressive force is also significantly lower than the compressive strength than can be estimated based on the mechanical properties of the materials (bricks and mortar) used in the construction of the pillar.

It is therefore understood that the noticeable preexisting damage possibly has a strong effect on the compressive capacity of the pillars. Irregularities or voids in the interior of the pillar may also have caused this lower than expected capacity. Therefore, the repair, strengthening or replacement of pillars of this typology in the building investigated may be necessary at least in those cases where similar damage patterns are encountered: large vertical cracks extending well into the interior of the pillars.

The difference in the vertical stiffness as measured globally and as measured locally in the outer leaf indicates structural or material irregularities and significant variation in the stiffness of the outer leaf and the infill.



(a) (b)

Figure 6: (a) Horizontal transducer readings and (b) mid height perimeter.

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