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Stability Assessment of the Brick Masonry Veneer Walls of an Existing Reinforced Concrete Building

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Abstract **-** This paper presents a stability assessment of the masonry veneer walls of a recent building, which displayed visible damage in its masonry cladding system. The investigation campaign, conducted on-site, provided valuable data about the structural performance of the veneer walls. The assessment of out-of-plane stability was carried out analytically, in accordance with the Italian Building Code and the recommendations of UNI EN 1996-1-1:2022, which guide the design and analysis of masonry structures. The effects of thermal variations on the veneer walls stability are also assessed. From the results of the investigations and subsequent analyses, the paper identifies the primary causes of the observed damages. To address these issues and ensure compliance with the safety requirements prescribed by the Code, a series of safety interventions are proposed.

Keywords**:** brick masonry veneer walls; out-of-plane displacements; slenderness; thermal variation; deficiencies; failure;

1. Introduction

Brick masonry veneer walls are a typical cladding solution, extensively used to create the external facade of buildings. This system consists of a brick masonry wall separated from the building's structure by an air cavity, typically ranging from 25 to 100 mm in width. This cavity is often partially filled with thermal insulation to allow air ventilation [1]-[2]. The veneer walls transfer their weight to the structural backing at floor levels, supported either directly by the floor slab or by auxiliary elements, such as steel angles anchored to the floors. Stability under out-of-plane lateral loads, induced by wind or seismic actions, is achieved through horizontal ties connecting the masonry veneer walls to the structural system.

Thanks to their economic, durability, and functional benefits, as well as their attractive aesthetic qualities, brick masonry veneer walls have been widely used in a variety of buildings worldwide [3]-[7]. However, these systems frequently exhibit design and construction deficiencies that pose significant safety risks. Recent seismic events have highlighted the vulnerability of brick veneer walls to seismic forces, primarily due to inadequate design of the ties [8].

This paper presents an assessment of the stability of brick masonry veneer walls in a modern Reinforced Concrete (RC) building in Italy, which exhibits visible damage and localized brick collapses. The results of the investigation campaign conducted on the veneer walls to identify their deficiencies are presented. The analysis of out-of-plane stability of the veneer walls is conducted in accordance with the Italian Building Code [9] and its accompanying guidelines [10]. In addition, the effects induced by the thermal variation on the brick masonry veneer walls are examined.

Given the widespread diffusion of brick masonry veneer walls in existing buildings, this study addresses a critical issue of significant importance, offering valuable contributions to the evaluation and enhancement of existing systems, as well as to the safe and efficient design of future constructions.

2. Case Study

The building analysed in this study is a hotel located in Italy, built in 2001. It consists of two units, labelled A and B in Fig. 1, each featuring a floor plan shaped like a circular crown arc. The overall plan of the building complex can be approximated as a circular crown arc with an external radius of 31 m. Unit A is an eight-story structure, reaching a height of 28 m, while Unit B is a ten-story building with a height of 34 m. The two units are separated by a thermal expansion joint, denoted as G-G in Fig. 1.

The brick masonry veneer walls, which form the external envelope of the building, are 10 cm thick and are separated from the RC walls along the building perimeter by an air cavity, which is partially filled with 5 cm thick thermal insulation panels. The air cavity runs continuously through the veneer walls, except for the sections of façades 3 and 5 near the doors (highlighted with red lines in Fig. 1), where the veneer is adhered to the RC walls.

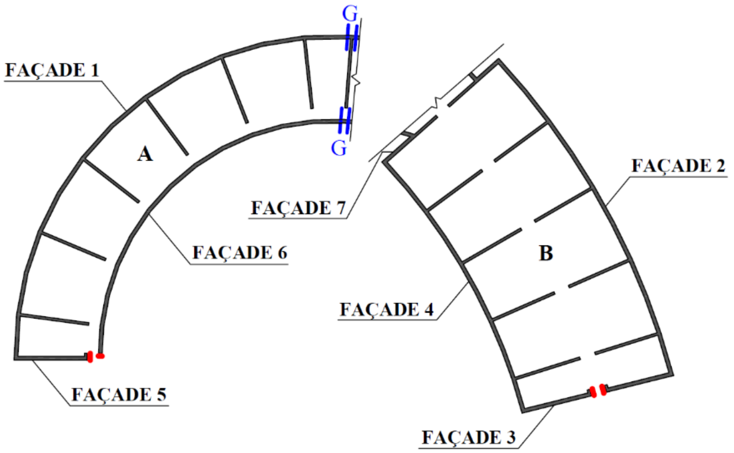

Fig. 1: Schematic representation of the floor plan for building units A and B.

The masonry walls are supported by RC corbels that protrude 14 cm from the floor slabs at levels 2, 4, 6, 8, and 10 (Fig. 2). Due to the curvature of the veneer walls on façades 1, 2, 4, and 6, the support length of the masonry walls on the RC corbels, having flat vertical face, is not uniform along these façades. The vertical face of the corbel is covered with 2.5 cm thick facing bricks, as depicted in Fig. 2.

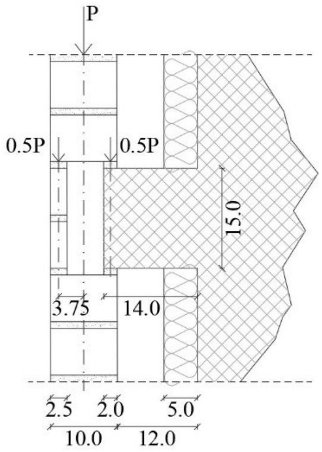

Fig. 2: Cross-section of the brick masonry walls at support on RC corbels (dimensions are in cm).

The self-weight of the veneer panels above the openings is transferred to the RC corbels below via post-installed RC architraves.

Originally, steel ties with a plain surface and a diameter of 4 mm were installed to connect the masonry veneer walls to the RC structure. Since these ties proved ineffective in transferring lateral loads, due to pull-out failures, to resolve this issue, reinforcing steel ties with a rough surface and a diameter of 8 mm were installed on façades 1, 2, 3 and 5 in 2014.

3. In-situ Investigations

3.1. Visual Inspection

On façades 3 and 5, vertical cracks at the interface between the masonry cladding adhered to the RC structure and the ventilated façades were detected on all storeys. These cracks correspond to relative displacements between the masonry walls of façades 3 and 4 and those of façades 5 and 6, observed in both the radial and circumferential directions of the building plan (Fig. 3a). Moreover, detachment of the adhered masonry walls from the RC structure and localized brickwork collapses were observed on façades 3 and 5 (Fig. 3b).

Additionally, on façades 1, 2, 4 and 6, detachments of the masonry walls from the backing structure along the vertical and upper horizontal sides of the windows were observed (Fig. 3c).

(a) (b) (c)

Fig. 3: Damages on the brick masonry veneer walls: (a) cracks and relative displacements, (b) detachment of the adhered masonry walls and localized brickwork collapses and (c) detachment from the backing structure along one vertical edge of a window.

3.2. Pacometric Survey

Pacometric surveys were conducted on façades 1, 2, 3, and 5 (Fig. 1) to identify the location of the 8 mm diameter steel ties and verify the regularity of their installation. The survey covered 56 square areas, each with a side length of 1.8 m, except for those near the building edges, which were smaller in size. Using the survey data, the mean number of ties per unit area (n_t/A), and the mean horizontal (p_h) and vertical (p_v) spacing of the ties were calculated for each façade. The results are shown in Table 1.

Table 1: Mean number of ties per unit area, and mean horizontal and vertical spacing of the ties obtained from pacometric survey.

Façade	**n_t/A (ties/m^2)**	**p_h (cm)**	**p_v (cm)**
1	4.03	70	30
2	1.72	Irregular in most cases. In survey areas with regular arrangement: 80	Irregular in most cases. In survey areas with regular arrangement: 60
3	2.01	70	30/50
5	2.44	Regular in most survey areas: 70	Regular in most survey areas: 50

From Table 1 it can be seen the number of ties per unit area for façade 1 is roughly twice the one for the other façades. It is also observed that the ties are regularly arranged only on façades 1 and 3. On façade 1, the mean horizontal and vertical spacing is 70 cm and 30 cm, respectively. For façade 5, the spacing is 70 cm horizontally and either 30 cm or 50 cm vertically. On façade 5, the ties are regularly arranged in most surveys areas. In the survey areas where the pattern is regular, the mean horizontal and vertical spacing is 80 cm and 60 cm, respectively. In contrast, on façade 2, the ties are irregularly arranged in most surveys areas. In the survey areas where the pattern is regular, the mean horizontal and vertical spacing is 80 cm and 60 cm, respectively.

3.3. Pull-out Test

Four ties were subjected to an increasing tensile axial force, up to a maximum load of 10 kN, the highest force applied during in-situ testing after their installation. The load was applied in 2 kN increments, maintaining the load applied at each step for at least 10 minutes. All ties successfully passed the test without failure.

3.4. Micro-perforations

To measure the distance between the vertical face of the RC corbel and the outer vertical surface of the veneer wall, 8 mm diameter micro-perforations were drilled into the facing bricks covering the corbels. By combining this measurement with the known thickness of the masonry veneer wall, the support length of the masonry wall on the RC corbel, l_s, at the drilling location was determined. Micro-perforations were made in three different portions of the RC corbels. The support length values measured at the micro-perforation locations are summarized in Table 2. These values range between 0 and 3.5 cm. From these data, it is determined that the average support length of the masonry walls on the RC corbels is approximately 2 cm.

Table 2: Support length of the brick masonry walls on RC corbels at the micro-perforation locations.

Survey point ID		l_s (cm)	Survey point ID		l_s (cm)	Survey point ID		l_s (cm)
1	A	-	2	A	2.0	3	A	2.0
	B	-		B	2.0		B	3.5
	C	-		C	2.0		C	3.5
	D	0.5		D	1.5		D	2.5

3.5. Laser Scanning Survey

To detect out-of-plane deformations of the masonry veneer walls on the curved façades, a laser-scanner survey was conducted on façades 1, 2, 4 and 6. The results for façades 1 and 2, which are affected by the largest out-of-plane displacements, are shown in Fig. 4 and Fig. 5, respectively, where the positive sign indicates outward displacements, i.e. from the interior to the exterior of the building. For each façade, the reference vertical surface was determined by vertically extruding the arc of a circle that best fits the base geometry profile of the façade. In Fig. 4 and Fig. 5, the colorimetric displacement scale is accompanied by an orange line representing the percentage of the façade area affected by displacement values within each range.

Fig. 4 and Fig. 5 reveal that out-of-plane deformations affect both the portions of walls between two adjacent vertical alignments of windows, as it can be seen from the vertical blue strips in Fig. 5, and those between two adjacent horizontal alignments, as it can be seen from the horizontal blue and yellow strips in Fig. 4. An analysis of displacement distribution along the height of the façades shows no consistent range of heights across the façades where the largest displacements are concentrated. This indicates variability in deformation behaviour across different sections of the façades.

From Fig. 4 it can be seen that about 30% of façade 1 is affected by out-of-plane displacements, outward or inward, between 1 and 2 cm, and that about 50% of the façade is affected by out-of-plane displacements smaller than 1 cm.

Similarly, from Fig. 5 it can be seen that about 38% of façade 2 is affected by out-of-plane displacements, outward or inward, between 1 and 2 cm, and that 37.4% of the façade is affected by displacements smaller than 1 cm.

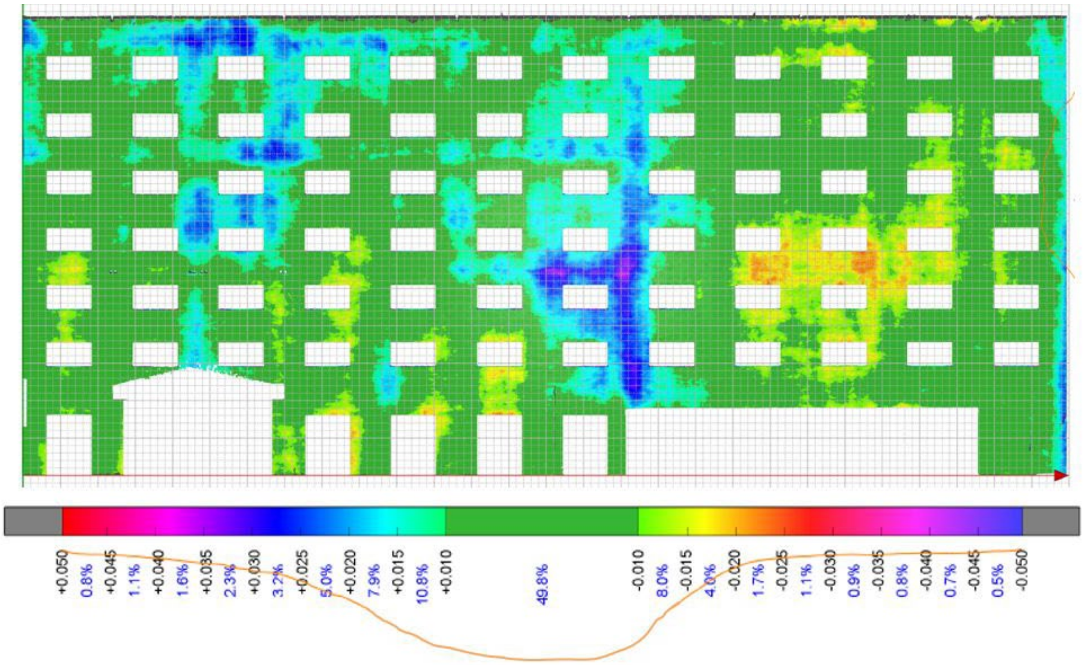

Fig. 4: Colorimetric map of the out-of-plane displacements of façade 1, measured by laser scanning (values in meters).

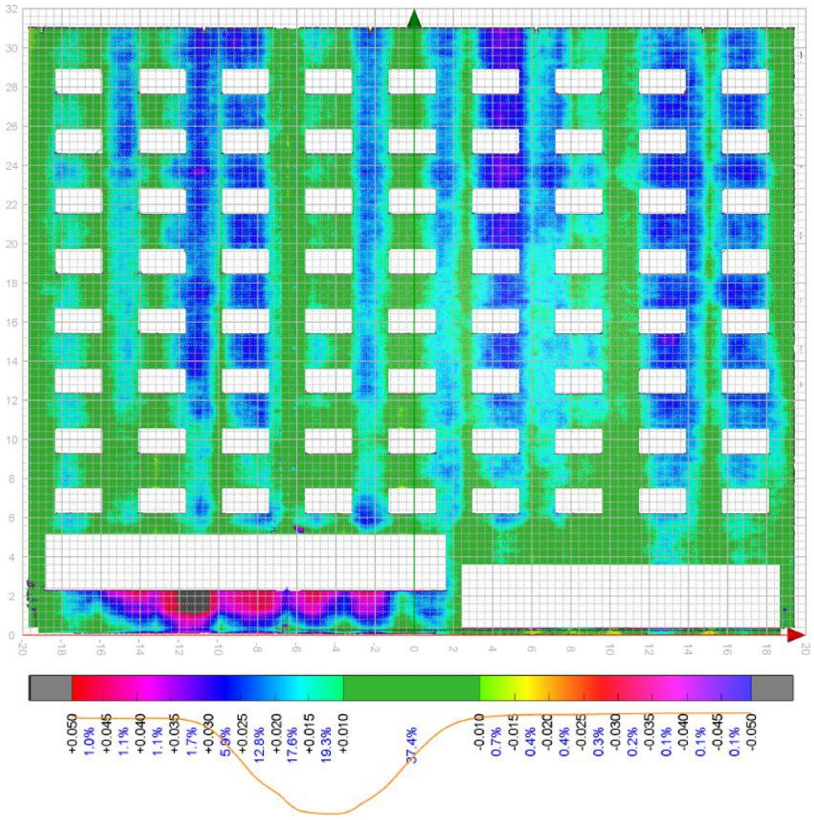

Fig. 5: Colorimetric map of the out-of-plane displacements of façade 1, measured by laser scanning (values in meters).

The out-of-plane displacements observed on façades 4 and 6 are, on average, smaller compared to those recorded on façades 1 and 2.

4. Analysis of Stability of the Masonry Veneer Walls

4.1. Out-of-plane Stability

The analysis of out-of-plane stability is performed analytically following the recommendations of UNI EN 1996-1-1:2022 [11], as permitted by [9]. The analysis is applied to individual masonry panels bounded by two contiguous RC corbels, while also accounting for the structural effects of openings within the panels. The panels are modelled as column elements, with support provided at the bottom end and a restraint at the top end to prevent horizontal displacements. The panels are represented by frame elements with rectangular resisting cross-section of dimensions b_wxt, where b_w is the panel width and t is the panel thickness, equal to 10 cm.

The effect of the ties on the panels is modelled by linear springs. To calculate the axial stiffness of the ties on façades 1 and 2, the out-of-plane displacement of the masonry walls was taken into account. The results obtained from the laser-scanner survey of these façades (Fig. 4 and Fig. 5) show that, for a safe evaluation of the ties contribution to the lateral load, a value of the out-of-plane displacements of the masonry walls equal to 2 cm can be considered.

The axial stiffness of the ties was determined based on their clear length, equal to 14 cm, which was determined accounting for out-of-plane displacements of the masonry walls. Given that the resisting cross-sectional area of the tie is 38.7 mm^2, and the Young's modulus of steel is 206,000 MPa, the axial stiffness of a single tie results approximately 57,000 kN/m.

The loads considered in the analysis are: the self-weight per unit length of the panel, the force transferred to the panel by the facing bricks above along the vertical axis of the bricks, the bending moment resulting from the eccentricity between the application point of this force and the vertical axis of the panel, and the lateral distributed load due to seismic or wind action.

The analysis are performed accounting for second-order geometric effects induced by compression.

The masonry panels subjected to the most severe gravity loads are located on storeys 3 and 4, while those experiencing the highest lateral loads are on storeys 7 and 8 for Unit A, and storeys 9 and 10 for Unit B. Consequently, the analysis focused on the panels at these specific storeys. The dimensions of thede panels, including their width (b_w) and height (h_p), are provided in Table 3.

Table 3: Width and height of the masonry panels considered in the analyses.

Façade	**1**		**2**		**4**		**6**	
Storeys	**3-4**	**7-8**	**3-4**	**9-10**	**3-4**	**9-10**	**3-4**	**7-8**
b_w [m]	2.06	2.06	1.73	1.73	1.02	1.02	3.92	3.92
h_p [m]	7.50	6.00	7.50	6.00	6.00	6.00	6.00	6.00

For the considered case study, the absolute value of the wind load is higher than the seismic load. Additionally, in the seismic design, the seismic load is not amplified by partial factors, whereas the wind load, when acting unfavourably, is increased by a partial factor of 1.5 in the ultimate limit state design. This amplification of the wind load, combined with its higher absolute value, means that the wind action imposes the most severe load conditions on the masonry panels, making it the dominant factor in the design analysis for this case study.

According to [10], a constant value of the wind pressure along the building height, equal to that acting at the building top, is taken. The values of the wind pressures considered in the analysis are provided in Table 4.

For the brick masonry properties, the average values recommended by [10] for existing buildings are taken. A unit weight of 18 kN/m^3, a mean compressive strength of 3.45 MPa and a Young's modulus the values and 1,500 MPa are respectively considered.

Table 4: Wind pressures acting at the top of units A and B in the most unfavourable direction of the wind load (values are in kN/m^2).

Wind direction	**Façade 1**	**Façade 2**	**Façade 4**	**Façade 6**
Windward	1.12	1.17	0.94	0.89
Leeward	-1.67	-1.76	-0.65	-0.68

For the ties, tensile and buckling verifications were carried out. The design value of the ties' pull-out strength is 3 kN.

The results of the strength verifications for the masonry panels indicate that the panels on façades 1 and 2 meet the required standards, whereas those on façades 4 and 6 do not. Therefore, to ensure the adequate stability of the masonry panels on façades 4 and 6 against out-of-plane lateral loads, safety interventions are necessary.

4.2. Effects of Thermal Variations

According to [10], the horizontal length variation of the masonry walls due to thermal variations, Δl, is calculated as

$$\Delta l = \alpha_T \cdot L \cdot \Delta T \tag{1}$$

where α_T is the thermal expansion coefficient of the brick masonry wall, L is the length of the façade and ΔT is the thermal variation. According to [10], for the considered case study $\alpha_T=8\cdot 10^{-6}$ °C^{-1} and $\Delta T=57$ °C. Consequently, for façade 1, which is 51 m long, $\Delta l=2.3$ cm. Assuming that each vertical edge of façade 1 undergoes a displacement of 1.15 cm in the circumferential direction of the building unit, the thermal expansion of façade 1 results in a lateral displacement of 1.15 cm at the vertical edge of façade 5 where it intersects with façade 1. Meanwhile, the other edge of façade 5 remains fixed, being adhered to the RC structure. The strength verification of façade 5, carried out according to [11], reveals that this façade is not able of withstanding the design thermal expansion of façade 1.

Similarly, for façade 6, which is 40 m long, the thermal expansion results in a length variation of 1.8 cm. Façade 6 is connected along one vertical edge to façade 5, which is adhered to the RC structure. As a result, façade 6 is unable to withstand the displacements at the edge caused by the thermal expansion of façade 6.

Regarding façades 2 and 4, they are bounded by infinitely rigid restraints. As a result, these façades are unable to withstand the design thermal variations without the masonry veneer walls experiencing failure.

5. Proposed Safety Interventions

To ensure the brick masonry veneer walls of the considered case study meet the safety requirements prescribed by the Italian Building Code [9], the following interventions are recommended:

1) To enhance the performance of the masonry veneer walls on façades 4 and 6 against lateral loads, the installation of steel ties from the outside is proposed. The out-of-plane stability of the masonry walls can be ensured by using ties with an 8 mm diameter, similar to those used on façades 1 and 2. These ties should be arranged with horizontal spacing of 1 m and vertical spacing of 0.5 m
2) To prevent cracking and local collapses of the veneer wall adhered to the backing structure on façade 5, due to the length variations of façades 1 and 6 caused by thermal changes, two vertical expansion joints, each 2 cm thick, are required on façades 1 and 6 at their intersections with façade 5. Similarly, to prevent damage to façades 3 and 7, 2 cm thick vertical expansion joints should be created at both vertical edges of façades 2 and 4.
3) To restore the veneer walls where brick collapses, cracking, and detachments of the masonry walls from the backing structure have been observed, local repair interventions should be implemented. It is recommended to demolish and rebuild the damaged sections of the wall.
4) Due to the short support length of the brick masonry panels on the RC corbels, a strengthening intervention for the corbels is proposed. Specifically, cement mortar injections should be applied to fill the space between the corbels and the facing bricks. Although this is not an active strengthening measure, the injections will improve the support conditions of the masonry walls on the corbels, enhancing their stability against vertical loads.

6. Conclusion

Brick masonry veneer walls are a typical cladding solution, widely used to create the external facade of buildings. However, brick masonry veneer walls often present deficiencies due to poor execution or inadequate design, which may result in inadequate structural performance of the veneer walls and may constitute a threat for the human life safety.

In this study, the stability of the masonry veneer walls of a recent building with visible damage in the masonry cladding system was assessed. The analysis of the case study highlighted the presence of serious constructional and design deficiencies of the brick masonry veneer walls, which are typical of this cladding system. These deficiencies are:

1) Excessive slenderness of the brick masonry panels, due to the lack of support from RC corbels at every floor level. RC corbels are crucial as they segment the height of veneer walls, increasing their stiffness against out-of-plane bending forces and mitigating second-order geometrical effects.
2) Inadequacy of the ties in transferring out-of-plane lateral loads to the backing structure and in preventing the failure of the masonry walls.
3) Lack of thermal expansion joints, which are necessary to allow the masonry to accommodate the expansion and contraction caused by temperature variations. Without these joints, horizontal length variations can accumulate stress within the walls, leading to cracking, detachment, and potential failure of the veneer, especially where the walls are adhered to the backing structure.

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