Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems – Zingoni (ed.)

Reconnaissance survey of historic monumental unreinforced masonry building by visual inspection: A case study of senate hall building of Allahabad University, India

A. Kumar
Civil Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India

K. Pallav
Department of Civil Engineering and Surveying, Cape Peninsula University of Technology, Bellville, South Africa

ABSTRACT: The Indo-Saracenic style of architecture reconnaissance survey is presented in the present work. The Senate Hall building is 106 years old unreinforced masonry of Allahabad University, India, built-in 1915. It was designed from Hindu (Stone Columns, Windows), Muslim (Domes, arches) architecture with British plans (inner rooms) like large halls, wide openings, porches, and facades. The building has been survived two major earthquakes, *viz.*, Bihar Nepal (1934) and Nepal (2015). Masonry walls were constructed from cellular wall patterns ranging from 1.07m to 0.61m (thickness) from the ground floor to the first-floor level. Most buildings have observed major cracks and damages in masonry walls, connections, arches, and porches. The construction materials (binder and plaster) have continuously deteriorated due to environmental factors like atmospheric conditions, seepage, and moisture. This work is focused on developing a digital model of the SH building using visual inspection for future preservation.

Keywords: Historical structure, masonry buildings, visual inspection, structural geometry, damages

1 INTRODUCTION

Masonry constructions are one of the important practices in most ancient buildings around the world. The construction of such a building has been started around 1000BC and was made up of stone or brick masonry. It is a simple combination of bricks/stone, mortar, and joint interface units. The bricks are mainly made up of unfired, dried mud (adobe) to fired clay, baked brick, whereas the stone material is commonly in the ordinary form such as rubble/fieldstone and handmade artificial shape. It was mainly the preferred material in constructing different structures in ancient times. The material has a unique quality for construction aesthetics, permanence, workability, and accessibility. Rounded stones have been designed the heavy structures as these stones are used for filling the gap between different stones. They are most durable in all weather and were widely used for old buildings and now in the new buildings of the rural areas.

Allahabad city is rich in old buildings constructed during the 16^{th} - 19^{th} century, and the Senate hall building is one of the oldest masonry structures of Allahabad University. It was constructed in the physics department of old Katra, Allahabad. The building is an amalgamation of Hindu, Muslim and British constructions such as large halls, wide openings and verandah, porches and facades, columns and arches, towers and domes. The architecture of the SH building is one of the unique examples of the Indo-Saracenic style of architecture. In a survey of the building, much evidence has been collected, such as existing plans, construction techniques, architecture style, materials, cracks and damages. This work has been focused on developing a digital model for preserved 106 years old SH building. This study calculates the covered area (floors, masonry walls,

Figure 1. Structural view of Senate hall building, Allahabad University, India.

DOI: 10.1201/9781003348443-322

Printed by: kumarpallav23@gmail.com. Printing is for personal, private use only. No part of this book may be reproduced or transmitted without publisher's prior permission. Violators will be prosecuted.

openings) for future reference if the building is damaged/collapsed by earthquakes and other atmospheric conditions.

2 CONDITION SURVEY

The current condition of the old unreinforced masonry SH building has been performed to assess its state viz., construction techniques, architecture style, structural materials, cracking patterns, material deterioration, damages and failures. Figure2 shows the actual spalling of materials, damages, and failure of its components of the SH building. The geometrical plan and elevation drawing is prepared during the building's continuous survey. The cracks, deterioration and damages of the building are noted and marked.

Figure 2. Major cracks and material deterioration of SH building.

3 GENERAL CRITERIA

The typology of the structure should be identified (churches, buildings, towers, bridges, temples, etc.) and whether the building is isolated or a combination of masonry and stone. The building is a combination of stone and brick masonry in the present case. These details provide a base level of knowledge for the structure. The geology of Allahabad city is similar across the district, consisting of Pleistocene clays and gravels.

3.1 *Visual observation criteria*

The two-storey building is built upon a 1.07m thick plinth level with a load-bearing wall of cellular wall arrangement. The building supports large halls, wide verandah, naves, and a jack arch roof. The entire SH building was built up to the second-floor level, and only towers are built up to higher levels. The SH building is symmetrical at the ground and first-floor level. The building comprises thick walls, arches, towers, columns, vaults, and domes. The three large halls are built on the ground floor level *viz., Meeting hall (ME), Examination Hall (EH)* and *central hall* (*CH*). The geometrical dimensions of the *ME* and *EH* are the same, and they are situated on both sides of *CH*. *CH* is large among all three halls. The CH is spacious with twelve doors, and sixteen windows are situated at North, South, East, and West masonry walls on the ground floor level. It is used for meetings, examination, convocation, conferences, social and cultural activities. The brick masonry is coloured yellow, and the stone materials are red. In visual inspection, major cracks and damages have been observed on the entire building. The decorating and plaster material has deteriorated on masonry walls, stone arches, roofs. The major cracks have visible on the connections and crown of the arches. The masonry wall is overturned through the ground floor to the second floor of the south entrance porch gate shown in Figure 3.

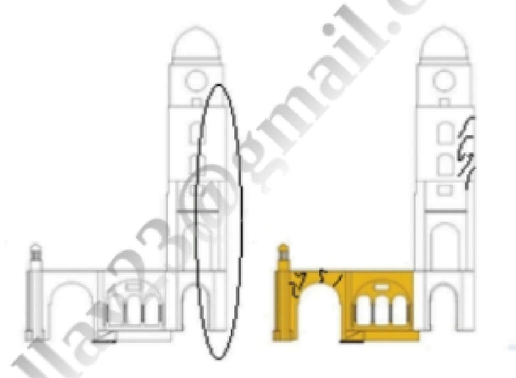

Figure 3. Minor cracks visible in clock tower and arches of front porch.

3.2 *Condition survey of Senate Hall building*

The architectural and structural form of the building should be documented, and photographs of the building must be preserved from time to time. Site observations can be recorded, and preliminary analysis and assessment can be established. The layout of the building is a cellular type with varying wall thickness. The length and breadth of the SH building are ~112.78m and ~54.25m, respectively, with a height of ~18.3m up to the second floor. The height of the tower is not considered, and they are treated as separate units of the SH building.

The basement walls are 1.5m thick, whereas the ground floor facade walls are approximately 0.76m thick, whilst the load-bearing internal walls are approximately 1.07m thick. The thickness of the wall on the first floor and the second floor is 0.61m. On the internal wall 25mm, thick plaster is applied. The partition walls of 0.46m thick are used to form the rooms and passages in the building. The building is covered with a 3.85m wide outer verandah. There are three entrance gates, the same dimension in the building. They are situated at the front gate (East side) and two on the north and south sides. Altogether, eleven towers of different cross-sectional dimensions and heights are situated all around the building. The Clock Tower (CT) is the highest masonry tower (30.48m), situated at the front entrance gate of the SH building. The remaining towers are positioned on the corners, middle and sides of the SH building. A plan of the building, which is on the scale of 1/20, is presented in Figure 4. The building indicates the voids, wall layout, and typology (Structural plan and components).

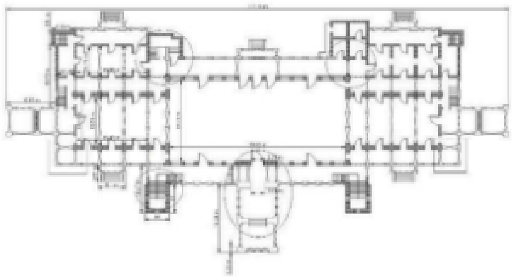

Figure 4 . Minor cracks visible in masonry wall through the ground floor to second-floor level.

4 HISTORIC CONDITION

A detailed survey is shown for all the components in the subsequent section.

4.1 *Visual obtained data*

Walls: There does not appear to be any structural damage at any level. The ground level is maintained compared to other floors of the building. Most algae formation and water seepage appear at points susceptible to rainwater, such as the terrace level walls; other algae and water damage results from rainwater falling freely over sloping shades, walls, and floors of the SH building.

External wall conditions: The outer perimeter comprises stone masonry arches and pillars, while the walls are brick. The corners interior wall extends to form plaster pillars that mirror the symmetry of corridor stone pillars. The stone surface has been whitewashed to yield uniform colour. The walls exhibit an excessive coat of limewash, which are reneging at various places due to age, seepage and algae formation.

Internal wall conditions: The walls are coated with an aged lime plaster, which flakes at various places due to age, seepage and algae formation. Cracks in the wall plaster are also visible. Some area of the university offices has been renovated using modern materials.

Baradari: Baradari, also Bara Dari, is a building or pavilion with twelve doors designed to allow free flow of air. The structure has three doorways on every side of the square-shaped structure. The stone pillars supporting stone lintels appear structurally sound; however, the pillars, walls, and dome are damped, and the algae formation on the exterior allows the water on the inside walls to show signs of damage.

Ceiling: The central hall employs a truss roof system on the second floor, covered by a false ceiling. The remaining areas have jack arch roof systems, and some of the smaller areas employ reinforced brick slabs.

Flooring: Most cement or red IPS (Indian Pattern Stone). Cracks permeate the length of walls along the edges of the floor. All junctions between separate areas have stone flooring.

Parapet walls and baradari: The low parapet walls are in bad shape, as algae formation has damaged the top of the parapet. Though the stone pillars and arches appear to be structurally sound, the collapsed dome of one baradari is observed. The visible cracking is also observed at various points. The stone jali of the parapet is broken at several places and worn away in other places. Baradaris need cleaning and repair.

Doors/window/ventilators: All appear to be made up of teak wood and need fresh polish. The main entrance wooden door has provided in the centre of the east entrance masonry wall of the senate hall with different dimensions to other entries shown in Figure 5. New woodwork is required primarily at first and second floor levels. Only central halls' of second-floor windows retain their original stained glass. Almost all other glasses are replaced. The clock and inside the clock tower need new glass on all four faces.

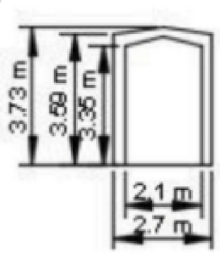

Figure. 5. Main entrance wooden door on the ground floor level of the central hall, Senate hall building.

Ground Floor (GF): Exclusively made of red IPS flooring with black borders along the walls, and the floor has a diagonal square pattern. The central hall and verandahs exhibit minor mosaic patterns, while the committee room has been newly tiled. It is observed that an Inch-wide crack exits along the floor's lines, making repair work extremely difficult shown in Figure 6.

First Floor (FF): The floor is similar to the ground floor with plane cement floor and red IPS borders.

Second Floor (SF): Lime concrete has been replaced recently with a graded concrete floor.

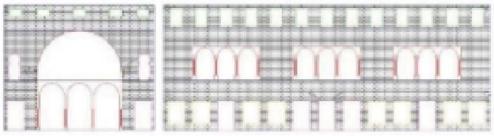

Figure 6. Minor cracks visible in Masonry wall on the ground floor and first floor.

Stone shades: The connection between stones has been corroded due to rainwater seepage and algae formation on the shades. During the survey, many replacements work is required to protect. The shades have mainly been provided in balcony and towers element through each floor level. The major cracks and material deterioration has been visible in decorating elements (towers, arches and porches) of the building shown in Figure 7 and Figure 8. Most portions have been renovated from new materials through the ground floor to the second floor.

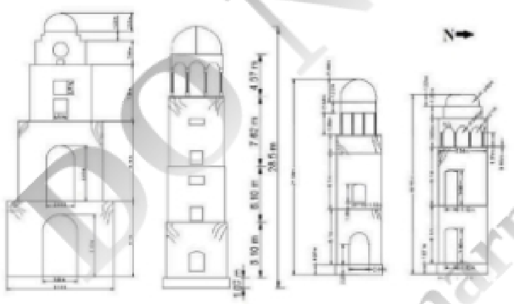

Figure 7. Minor cracks visible in stone material of towers element.

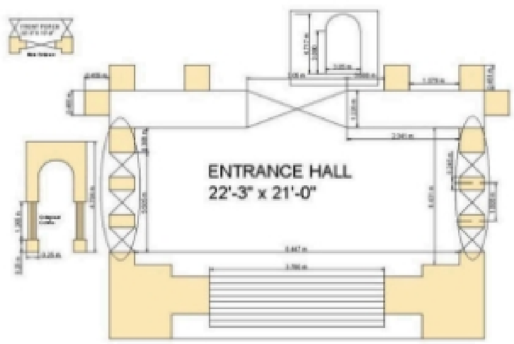

Figure 8. Cracks and material deteriorated in east entrance stone porch of the building.

Tile roof: The tile roof over the main hall of the senate hall building has recently been repaired.

The roof continues to leak during the rainy season. It is required to re-laid tile.

5 COVERED AREA OF THE BUILDING

The building has symmetrical patterns on the ground and first floor levels. Three major halls have been constructed on ground floor level height going up to the second floor. In the building, eleven towers have construed from the combination of brick masonry and stone in different locations. The geometrical plan of the entire building is shown in Figure 9. In the visual inspection of the building, entire dimensions have been measured for each structural element and room, masonry walls, openings on each respected floor level. The graphical representations of each floor are shown in Figure 10 to Figure 13. In the preservation of the building, the covered area has been calculated for each floor level, masonry walls, and openings. This calculation may be beneficial in reconstructing the structural elements and each portion of the senate hall building for future damages by the earthquake, seepage, and atmospheric conditions.

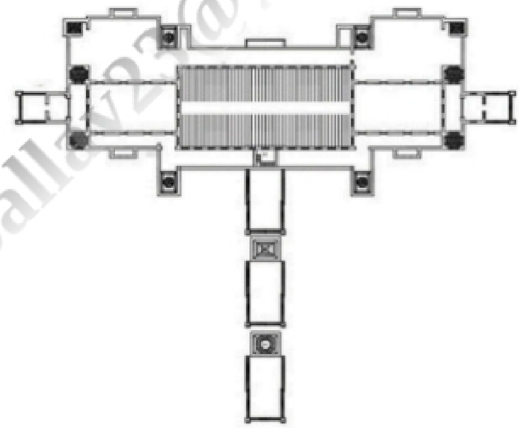

Figure 9. Geometrical plan of the senate hall building.

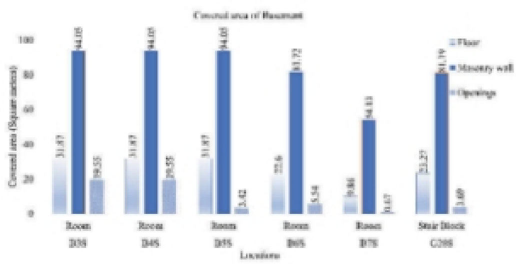

Figure 10. Covered area locations of the basement in senate hall building.

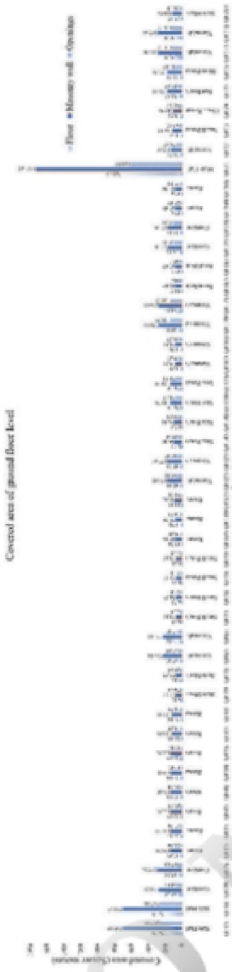

Figure 11. Covered area locations of the ground floor level of the senate hall building

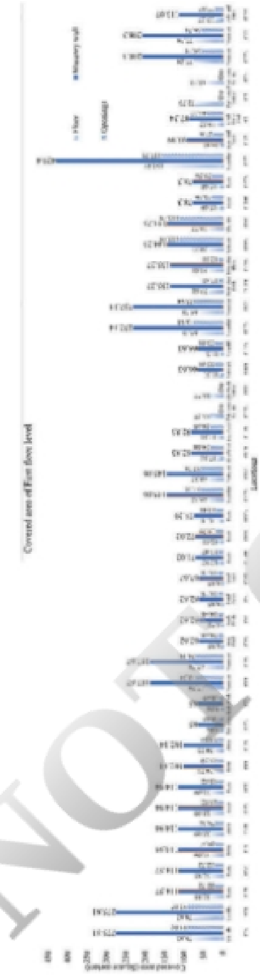

Figure 12. Covered area locations of the first floor level of the senate hall building

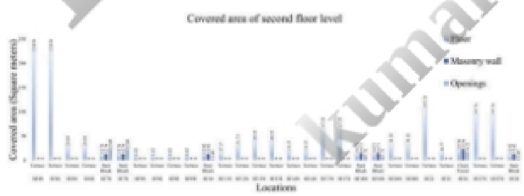

Figure 13. Covered area locations of the second floor level of the senate hall building

6 EXPLANATORY RESULTS

The destructive 2015 Nepal earthquake has made engineers and researchers to focus on the structural behaviour of the senate hall building. The building actual conditions, architectural style, geometrical assessment, a structural element

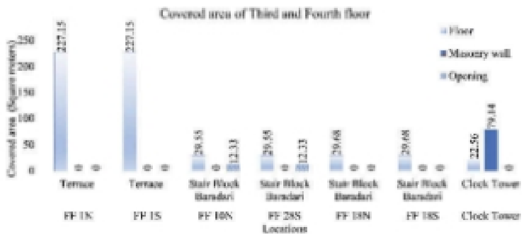

Figure 14. Covered area locations of the third and fourth floor level of the senate hall building

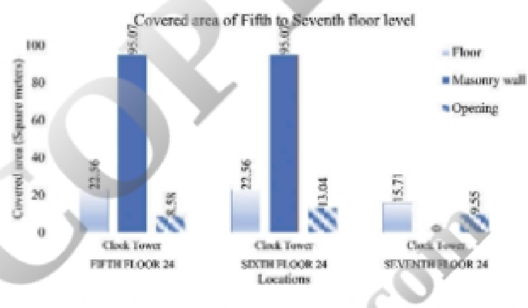

Figure 15. Covered area locations of fifth to the seventh floor level of the senate hall building

(Towers, Masonry walls, Arches, Domes), construction materials (Bricks, Stones, Timbers) and mechanical properties, cracks and damages, collapse and failure, strengthen and restoration, retrofitting and restoration are prime importance to our heritage/Old building. Due to numerous atmospheric conditions like seepage, moisture, temperature effects, rainwater, the construction and decorating material have continuously deteriorated overall building elements such as masonry walls, arches, towers, and roofs. The main portions in the walls and ceiling have shown algae and small plants generated in joints and cracks. For the importance of the building, retrofitting and renovation works have been performed from time to time for safety purposes. The entire survey of the building has prepared the geometrical plan with the actual covered area of each floor shown in Figure 10 to Figure 13. The entire building dimensions, geometrical plans, and actual covered area of each specific component of the structures (floors, openings, and masonry walls) have recorded for future perspective. The 3D model of the entire building has been built using the FEM tool, which can be used in the restoration work for future references shown in Figure 16.

The 3D model of the building has been considered decorating materials of the fundamental elements such as arches, columns, porches, facades, domes and stairs. The building's longitudinal and transverse cross-sectional views have been shown in Figure 15.

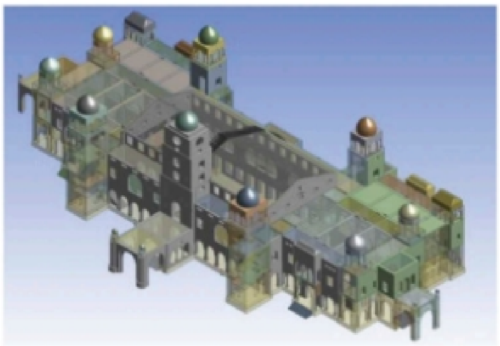

Figure 16. 3-D digital model of unreinforced masonry senate hall building

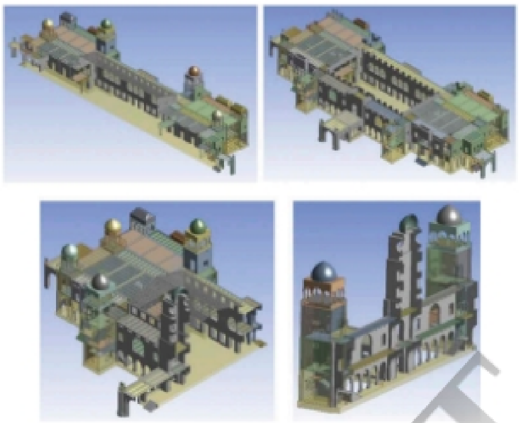

Figure 17. Internal view of the senate hall building

7 CONCLUSIONS

The study has been focused on the detailed measurement of the building for developed geometrical plans after visual inspection. The covered area (Masonry walls, floors, openings) has been recorded on each building level during visual inspection. It is beneficial for the renovation and rehabilitation of the building after future consequences occur.

The study is constructive for retrofitting and renovating the building due to major cracks and damages clearly visible during the survey after the 2015 Nepal earthquake. As exemplified in the senate hall building, the general damage and failure patterns may be summarized a) Huge relative displacement led to vertical cracking between the main central hall walls. The excess of shear or tension in the construction material may lead to such failures.

b) The second-floor wall is observed to witness overturning and cracking. Also, the upper part of the wall may face vertical cracks generated due to bending about its vertical axis. c) Dislocation of the corners. The shear and tearing stress may lead to cracks in the vertical corners. These cracks may lead to initial failure. Also, the wall panels get displaced due to a deficiency of link between the wall and corner of the tower. The top portion of the boundary wall may fail due to excessive displacement. d) The roof structure has witnessed deformation and displacement. The wall panels may face cracks in the horizontal direction. e) Roof tiles are falling and slipping. f) Failure at the corners and openings are observed. g) The masonry wall of the SH buildings may also fail due to the lack of earthquake-resistant attributes. In addition, the use of new material during construction is also a severe threat to the health of a structure. It is further recommended that the 3D model of the building along with its floor area could be related to its mechanical properties.

ACKNOWLEDGEMENTS

Both the authors gratefully acknowledge the cooperation of the engineer in charge of Mr. Naveen Kumar Allahabad university to provide the information about the senate hall structure.

REFERENCES

1. Kumar, A. & Pallav, K. 2017. Static and Dynamic Analysis of Masonry Tower of Allahabad University, India, *VIII ECCOMAS Thematic Conference on Smart Structures and Materials (SMART 2017)*, pp 821–830.
2. Kumar, A., Pallav, K. & Singh, D.K. 2017. Static and Dynamic analysis of Stone arch of Allahabad University, *Proceeding of International Conference on Recent Innovation in Engineering and Technology, Jaipur, India, 18th -19th Feb 2017, ISBN: 978-93-86291-63-9.*
3. INTECH. 2011. *Survey reports of full assessment of Allahabad University was conducted by INTECH India Private Limited.*

Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems – Zingoni (ed.)

On the characterization of materials and masonry walls of historical buildings: Use of optical system to obtain displacement maps in double-flat jack tests

M. Acito & E. Magrinelli
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

C. Tiraboschi & M. Cucchi
Material Testing Laboratory, Politecnico di Milano, Milan, Italy

ABSTRACT: Among the testing techniques aiming at the mechanical characterization of masonry, the double flat-jack testing method is widely adopted to identify the local value of significant parameters needed to perform structural analyses, such as elastic modulus, Poisson's ratio and compressive strength. The experience gained from many applications has allowed not only to collect experimental data concerning different types of masonry, but also to highlight the difficulty in the interpretation of the results and the limitations of both single and double flat-jack tests. Although the accuracy of the flat-jack technique in detecting strength and deformability behavior of masonry is still debated in the technical literature and practical activities, changes in the testing procedure aiming at ascertaining the validity of the test results have not been formally defined yet. After a brief description of the standard test procedure and its uncertainties, the present paper proposes an upgrade of the test procedure for improving the level of reliability of the test results. In particular, an experimental case study related to a historical brick masonry building located in Italy is presented to point out the additional information necessary to validate the results of the testing process.

1 INTRODUCTION

When dealing with the structural safety assessment of existing masonry buildings, an adequate knowledge of the mechanical properties of masonry is essential to carry out accurate numerical analyses. The strength of masonry under flexural, compressive, tensile and shear stress states can hardly be determined through laboratory tests because of two main reasons. On the one hand, the extraction of undisturbed specimens is not a simple operation. On the other hand, it is very difficult to sample and test masonry components (e.g. bricks and mortar) and correlate their mechanical properties to those of the whole masonry through analytical (Hilsdorf 1969) and numerical (Acito et al. 2008a) models. Furthermore, in the case of historical buildings, there are several restrictions on the application of highly destructive procedures, since the removal of specimens is not in line with the principles of monumental heritage conservation. Among the most performed in-situ tests, the flat-jack test allows to characterize the local stress level as well as the deformability properties of masonry. Being only slightly destructive, this testing technique is suitable also for buildings of historical value. Even though the flat-jack method is widely used (Jurina et al. 1980; Rossi 1982; Binda & Tiraboschi 1999) and considered a reliable tool for the estimation of the mechanical parameters of masonry, it involves some uncertainties which may affect the validity of the test results. Several experienced authors, such as Binda et al. (2004) among others, have discussed about the difficulties in the interpretation of the test results due to the anomalies commonly found in the outcomes as well as the lack of a strong theoretical framework to correlate experimental data with actual mechanical properties. Moreover, in the case of double flat-jack test, when the failure of masonry occurs outside the wall specimen (WS) between the two flat-jacks, the correlation between strength of masonry and pressure becomes a difficult task. As a consequence, the definition of objective criteria for ensuring the reliability of the test results is essential. Over the years, test results have been indirectly validated using back analysis and relatively sophisticated numerical models. The choice of the most suitable numerical modeling strategy is usually driven by the simulation purposes, the level of accuracy required and the computational time as well. These aspects have led to the definition of two distinct approaches for the numerical analysis of masonry, namely the micro- and macro-modeling. The micro-modeling is particularly apt to investigate

DOI: 10.1201/9781003348443-323

local mechanisms, such as cracking phenomena (Gianbanco et al. 2001; RILEM TC 177-MDT 2004; Lourenço & Pina-Henriques 2006; Chaimoon & Attard 2007), while the global behavior of masonry structures is usually analyzed by macro-modeling, where mean values of stress and strain are considered (Acito & Milani 2012; Acito et al. 2016; Jain et al. 2020; Acito et al. 2020; Acito et al. 2021; Magrinelli et al. 2021). The present work is intended to provide practical suggestions for upgrading the double flat-jack test procedure and improving the reliabilty of the outcomes for a better interpretation of the masonry behavior. To this purpose, a complementary optical-based displacement monitoring method is proposed in addition to the standard displacement measurement through LVDTs. The system allows for the real-time monitoring of the stress-strain evolution in an easy and detailed way thanks to the high-density distribution of the reference nodes, which have to be arranged on a wall surface larger than the WS. In the present work, the results from the experimental campaign carried out on the brick masonry walls of a historical building located in Lodi (northern Italy) are selected to discuss the proposed method and to clarify which additional data are necessary to improve the validation of the results of the testing process (Cucchi et al. 2012). The method presented in this work includes an optical system for the measurement of the relative displacements of the flat-jacks and some reference nodes on the surface of the tested area. The system based on optical measurements can be assumed as a reference, but the position of the reference nodes can be also monitored during the test by additional LVDTs properly arranged.

2 INSIGHT INTO THE FLAT-JACK TESTS

2.1 *Test description*

The flat-jack testing method was originally calibrated to test brick masonry, but then it has been largely applied also to irregular stone masonry (Bettio et al. 1993). Moreover, this testing technique was firstly used for the in-situ detection of the local stress level of masonry and then adapted to determine the deformability properties of masonry and its strength, whenever possible. The test procedure of the single- and double flat-jack test were codified in ASTM C 1196 (1991) and ASTM C 1197 (1991) respectively. During the test, removable extensometers or displacement transducers (LVDTs) applied on the WS surface are used to provide information on vertical and lateral displacements of some reference points. Loading and unloading cycles can be performed at increasing stress levels in order to determine the deformability modulus of masonry. In order to estimate the compressive strength value, the maximum value of stress applied during the last loading cycle can be increased until the masonry strength is reached and the failure of the specimen occurs. The results of several experimental campaigns including both single and double flat-jack tests have been used to discuss the test procedure, as described in the research work by Gregorczyk & Lourenço (2000). Double flat-jack tests are usually combined with non-destructive tests, such as sonic and impact tests. As a matter of fact, a combined approach consisting of non-destructive and semi-destructive tests allows to extend the knowledge of the mechanical characteristics of masonry; moreover, the correlation between results of different tests can be useful to corroborate the validity of the results themselves.

2.2 *Review of the significance of the flat-jack tests*

Interpreting double flat-jack test results is a challenging step of the test procedure not only when clear anomalies affect the outcomes but also when they are apparently highly reliable. The uncertainties concerning the validity of the test results may impair the definition of the correspondence between the mechanical properties determined by flat-jack tests and the actual ones. Several experimental campaigns (Acito et al. 2008a; Binda et al. 2004) demonstrated that the outcomes are highly dependent on the type of the tested masonry, which may be affected by hidden irregularities. As far as the double flat-jack test is concerned, some considerations well clarify when the test is considered to be not valid. Firstly, the stress-strain relationship detected by the double flat-jack test could be characterized by apparent high stiffness. According to Binda et al. (2004), this behavior is typical of tests carried out on low-rise buildings (one- or two-story high) and due to the lack of reaction in the upper masonry caused by the low stresses acting on it (Figure 1).

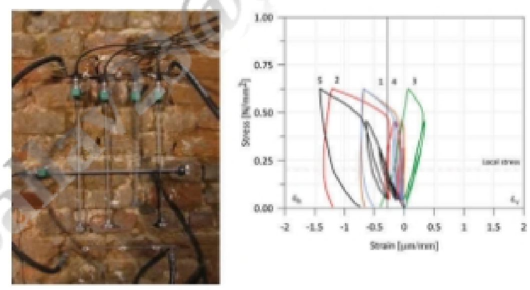

Figure 1. Execution of a double flat-jack test (J2) (left); example of stress-strain relationship detected by double flat-jack test when the upper stresses are low or in presence of irregularities (Sommariva Palace, Lodi) (right).

More precisely, according to Acito et al. (2008b), anomalies in the stress-strain relation are most likely due to the heterogeneity of the WS. As a consequence, special care must be taken in testing masonry walls characterized by irregular composition, such as brick or stone masonry with irregular mortar joints and/or high thickness. Secondly, the choice of the position of the cut for inserting the flat-jacks is another important