

SEISMIC PERFORMANCE OF THE LOMBARD MASONRY BUTTRESS SYSTEMS

G. Angjeliu¹, T.E. Boothby², G. Cardani¹ & D. Coronelli¹

¹ Dept. of Civil and Environmental Engineering, Politecnico di Milano, Milano, Italy, giuliana.cardani@polimi.it

² Dept. of Architectural Engineering, Pennsylvania State University, Pennsylvania, United States

Abstract: *A brick masonry construction system developed in Lombardy region in the 12th and 13th centuries, with heavy ribbed quadripartite vaults, often supported on double-system piers. These features—brick masonry construction, quadripartite domical vaults, and heavy solid buttresses are the characteristics of Lombard Romanesque architecture. A previous study investigated the proportions of the solid trapezoidal Lombard buttresses characteristic of this system which feature a particular connection wall built over the aisle vaults and extended to the ground outside the aisle walls. This study deepens into the performance of the structural system for lateral actions through a limit analysis model. The spread of this construction typology in relation to seismic is examined as well, also in relation to the possibility that the system was exported to Tuscany and adapted to the needs of later gothic works. One case study is here analysed: Chiaravalle abbey church, one of the main Milanese heritage buildings.*

1 Introduction

French Gothic cathedrals were characterised by the systematic use of the pointed arch and the Gothic cross vault. In early versions of these churches, the lateral thrust of the nave vaults was countered initially by protruding and therefore thickened sections of wall (wall buttresses), then at later stages by rampant arches. Their adoption and evolution were determined by the search for an ever-greater height and natural lighting for the interior. With these new heights, the projecting buttresses, which counteracted the lateral thrusts, were of fundamental importance, since the side aisles alone did not provide sufficient buttressing. The Gothic cross vault covered both square and rectangular bays and was characterised by diagonal pointed ribs that, in addition to their reinforcing function, over time added a decorative role, extending the slender lines of the small columns that made up the pillar to the top, further emphasising the vertical lift.

In contrast to the French high gothic construction system, a native system of brick construction flourished in Lombardy during the twelfth and thirteenth centuries (Porter 1917). This construction system paved the way for the adaptation of the gothic style in Italy: the Lombard system gave rise to the system used in the later, primarily gothic work at the Duomo of Milano. The system of vaulting using preferably cross and ribbed domical vaults with rounded arches became widespread and only later using pointed arches and was probably exported to Tuscany and adapted to the needs of Santa Maria Novella and later gothic works (Smith 2022).

Salient solid buttresses are very common among Lombard Romanesque Churches. This element consists of an externally visible thick wall that helps support the thrust of the aisle and/or nave arch. The construction of the buttresses in these churches is quite variable. Many of these churches are built according to a double system, where there are two aisle bays for each nave bay, and the piers alternate between larger piers and

smaller piers, particularly in SS. Maria e Sigismondo in Rivolta d'Adda (MI) and in the Abbazia di Chiaravalle. In some cases of double system churches, as at the Duomo di Crema, the buttresses remain the same size and construction, while in other instances, the buttresses coinciding with a division between aisle bays only, the buttresses are smaller in size. The buttresses may penetrate the plane of the aisle roof, as at SS. Maria e Sigismondo, or they may be concealed beneath the aisle roof, as at Sant'Ambrogio in Milan. The construction of the buttresses also shows variation. Most, in keeping with the Lombard style, are built entirely of brickwork, except for San Michele Maggiore in Pavia, which was built with sandstone masonry.

Lombard masonry buttresses were built during the period from the 11th through the 14th centuries. The buttresses are a key building element and an important feature and recognizable in the Lombard style of building. Although it is not possible to determine a precisely followed proportioning rule, in a previous study (Rodriguez et al. 2018) it was possible to show, through our survey of these features, that these buttresses were built according to some clearly understood rule of proportioning and adapted to the work at hand. A similar system was used in the construction of the largest building in Lombardy at that time, the Cathedral of Milan.

The rules for the construction of buttresses appear to have been retained through three centuries, and to result in a construction at the Duomo di Milano that is, in many respects, similar to some of the much earlier buildings. Although the Duomo is not fully a 'Lombard style Church,' its construction bears some of the features of the Lombard style, in the relatively low proportion of its façade, and especially in the proportion of its buttresses. Ackerman (1949), in his analysis of the construction of the Duomo, has noted that the local masons had a particular attachment to the Lombard style, and were continually trying to make this very large program conform to the characteristics of the Lombard style.

2 Chiaravalle abbey



Figure 1. Chiaravalle abbey in Milan: a) view of the external northern side and b) view of the interior of the church with the difference in height of the three naves.

Chiaravalle abbey is located in the southern suburbs of Milan (Fig. 1), once a marsh, later reclaimed by Cistercian monks into fertile agricultural fields in 12th century. This is the first Cistercian abbey built in Italy. The church, named Santa Maria di Roveniano, was built starting from 1135, consecrated in 1221 and it took several years for the whole monastery to be extended and completed.

The plan of the church and the entire built complex strictly follows the rule of St. Bernard of Clairvaux. It has a Latin cross shape, with 3 naves, divided by massive cylindrical pillars (1.8 m in diameter), The nave is raised above the side aisles to bring more light into the church and is separated from the side aisles by large pillars. A gabled façade covers these distinctions, although the one visible today is the result of a stylistic restoration conducted in the early 20th century. The wide transept, on the other hand, has a single nave with small side chapels facing east, always in the tradition of St Bernard. The apse has a rectangular shape. The church has a total length of 52.55 m, a width of 16.67 m and the nave height is 13.91 m.

The naves, transepts and apse are all covered with ribbed cross domical vaults in brick masonry, despite the simplicity of the Cistercian abbeys demanded by the rule of St. Bernard. They have a square base, and each large central bay thus corresponds to two smaller bays on each side. The South side of the church has the beautiful cloister adjacent to the other working parts of the monastery, while the North side shows massive brick masonry buttresses. Although elements of the style are imported from the original French Cistercian mother churches, the Lombard character is prevalent, both in the use of forms and materials. In 14th century the original cross vault in the crossing was replaced with a ribbed octagonal dome around 7 meters high, carried by an octagonal drum with 8 mullioned windows and 4 squinches with concentric arches, connecting the dome to the four pillars below. The octagonal dome still has some very important wall paintings, partially saved and restored, of the Giottoesque school. From the Renaissance period onwards, many painters and artists worked at the abbey, making it one of Milan's most important monuments.

According to the tradition of the Lombard Romanesque style, the polygonal dome is hidden externally by a polygonal Tiburium. Above this dome, a lantern tower, around 28 meters high was built, also octagonal in shape with different sections and a conical roof (Figs. 1-2). The tower was used as a bell tower, as was the custom of the monks who prayed in the choir, (total height equal to 56 meters). The tower looks like an imposing structure and appears to be a challenging work on the part of its author, perhaps Francesco Pecorari, the architect of San Gottardo bell tower close to Milan Cathedral. The tower certainly added an important vertical load above the polygonal dome, which was designed already reinforced with buttresses. However, the tower is not massive, but has an elegant lightness, thanks to the numerous mullioned windows along its height, which tend to deflect loads on the corners of the octagon and thus on the ribs of the dome below.

During the centuries several important restorations were made on the church, bringing the church first to the Baroque style and then back to the Romanesque style (Bagnoli 1958), without affecting the masonry structures behaviour.

2.1 Lombard buttresses in Chiaravalle abbey

As already mentioned in a previous paragraph, the church has along its north side a characteristic element of Lombard Romanesque churches with a vaulted roof inside. According to the different dimension of the bays between the nave and the aisle, there is a double system of buttresses: the highest corresponding to each transversal arch of the main nave and the smallest in between, corresponding to the lower transversal arches of the aisle. In Figure 2a they are represented respectively in red and in pink. From the roof of the aisle, only the main buttresses are protruding (Fig. 2b). These elements present the following dimensions (Fig. 3): $H = 11,6-11,9$ m, $h = 8,14-8,24$ m and $W = 6,70-6,74$ m. These elements serve to counteract the lateral thrusts given by the cross vaults inside the naves, but are more massive and robust than the classic buttresses typical of the Gothic style, becoming a distinguishing mark of the Lombard style.

The South side of the church is not as open as the north side but has, again according to the rule of St Bernard, a cloister around which the various activities of the monks take place. This means that there are no buttresses reaching down to the ground, but only remain above the South side aisle (Fig.2c and d). Finally, it should be mentioned that the cloister, as we see it today, is the result of a punctual and careful reconstruction that took place in the half of the 20th century, after the demolition of more than 2/3 of it after the suppression of the Cistercian order at the end of the 18th century.



a)

b)



Figure 2. The northern and southern buttresses of Chiaravalle church: a) the external northern buttresses differently coloured according to their role: main one for the nave in red and the minor for the north aisle in pink; b) view of the northern buttresses from the lantern tower; c) the external southern buttresses, visible only above the aisle roof; d) the southern courtyard, where no buttresses are visible along the church wall on the left.

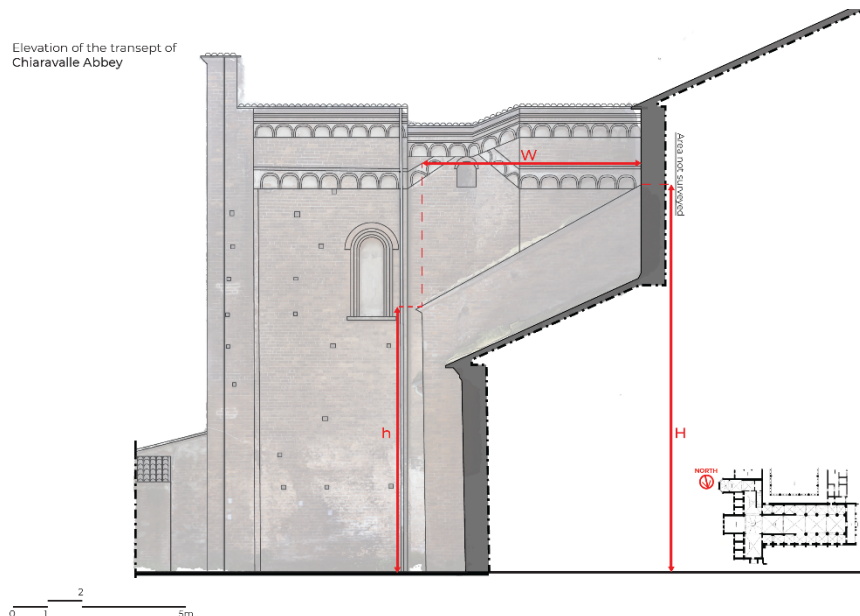


Figure 3. Upper and lower Height vs Width of the main buttresses in Chiaravalle church.

The quantities measured on the buttresses, can be used to define a relation between their lower h and upper height H and the width W . Those ratios can be compared with the buttresses proportions of other Lombard Romanesque churches as presented in (Rodriguez 2018), where a trend line, constrained to pass through the origin, gives the slope of H/W ratio as approximately 1.77 for the upper height H and 1.22 for the lower height h . Here in Chiaravalle church the measure ratios are 1,73-1,77 for H/W and 1,20-1,1,23 for h/W (Fig. 3), showing once again the respect of the rules of art in Lombard Romanesque constructions, including the Milano cathedral.

3 Structural model for Lombard buttress systems

A parametric study in relation to seismic response is carried out based on limit analysis to understand the structural behaviour of the buttresses, considering that the same construction typology was then built all over the country in all 'daughters' of this first Cistercian abbey.

Limit analysis is one of the methods considered by the Italian code (NTC 2018) for the seismic analysis of masonry buildings. Static approaches considering rigid blocks, separated by interfaces for the 2D analysis of

masonry bridges and structures have been proposed by several authors, (eg. Livesley 1992 and Baggio and Trovalusci 1998). Boothby (1994) proposed a static method for bridge arch and piers based on minimization of the total potential energy, considering block rotation and sliding at the interfaces. Boothby (1994) proposed a static method for bridge arch and piers based on minimization of the total potential energy, considering block rotation and sliding at the interfaces. A static limit analysis model has been developed here considering piers, arches and walls.

The analysis model considers a typical transversal section of Lombard Gothic churches. A symmetric geometry is considered as a simplification. The presence of the cloister on the South side is not considered. The geometry is based on surveys of Lombard churches (Rodriguez et al., 2018) showing the application of proportional design (Boothby 2023). The geometry is created in a parametric model, considering a range of dimension for the buttresses, within the previously examined proportion values.

In addition to the geometric parameters, also a variation of material properties at the interfaces is considered, changing the friction angle and cohesion.

The model considers a convenient division of the structure into blocks (Fig.4) for piers, arches and walls. Infinite compression strength and no tension strength for normal force and moment are assumed at the interfaces. Coulomb friction and cohesion are used to model the shear-normal force relation. A friction angle of 30 degrees and null cohesion were used.

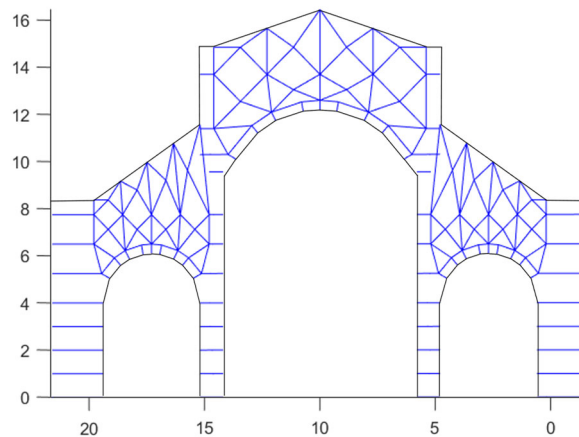


Figure 4. Geometry and block interfaces (units m)

The loads consider the weight of all the masonry members, with a unit weight of 18 KN/m^3 , and the roof bearing on the top of the interior piers. In addition, the weight of the longitudinal walls, bearing on the nave arcade, is considered in the interior piers in correspondence of the *tas de charge* of the nave arches. The weight of the lateral walls is added to the lateral piers, in correspondence of their position (towards the interior within the buttress cross section).

The analysis for gravity loading and lateral forces has been carried out, considering constant acceleration. The equilibrium conditions with the resistance conditions at the interfaces are solved to find a maximum static multiplier for the lateral load, using a linear programming solution. The plugin by Mosek (2021) implemented in Matlab was used.

4 Results

The results shown for the dimensions of Chiaravalle are the collapse mechanism (Fig. 5) with the static load multiplier of 0.124. Hinging takes place in the lateral buttress on the right. The interior piers have hinging at the base. Shear sliding and diagonal tensile cracking occur in the diaphragm wall. The arches show both hinging and sliding mechanisms. Sliding occurs at all arch-wall interfaces. Sliding and separation occur at the interface of the diaphragm wall and the aisle arch.

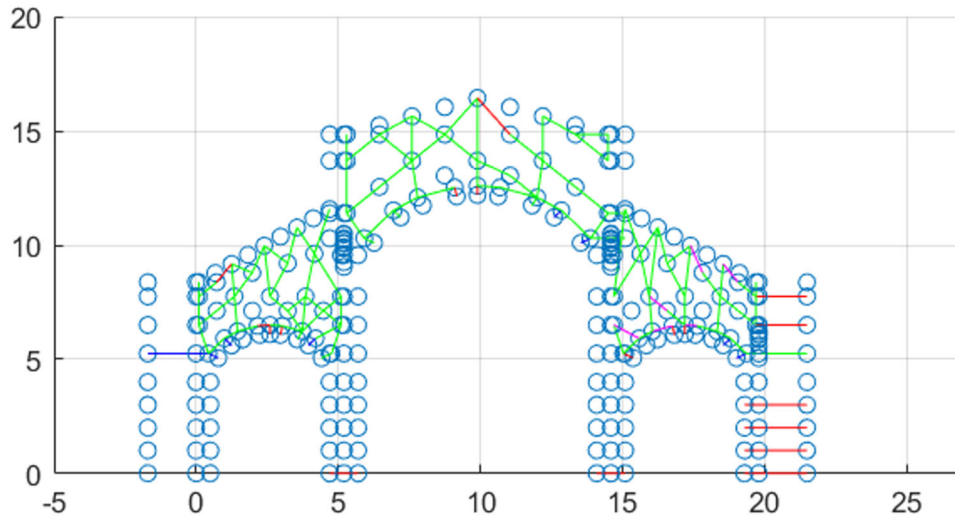


Figure 5. Collapse mechanism: hinge (red=sagging in arches, compression on right side in piers; blue=hogging in arches, compression on left side in piers) and sliding (green); walls, magenta=tension cracking, red= rotation.

The distributions of shear and compression forces with moments at the interfaces is the static solution for internal forces. The compression forces at all interfaces are shown in Fig.6, in the sequence starting with the lateral buttress, then the interior pier, arch and wall for the aisle and nave, and lateral buttress, arch and wall for the aisle again.

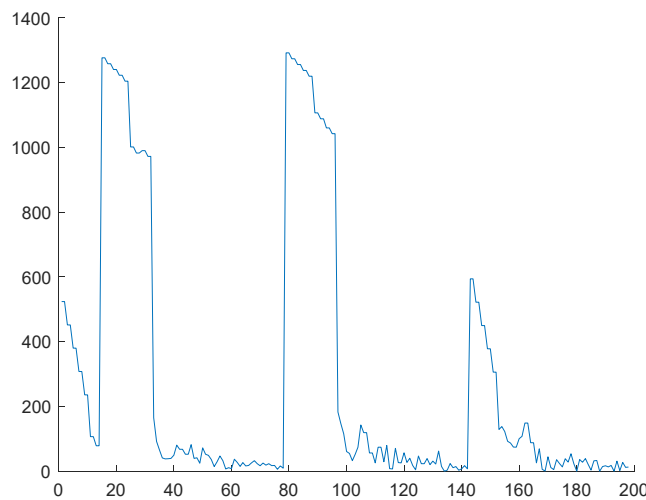


Figure 6. Compression forces at failure (peaks corresponding to buttresses and pillars)

The parametric analysis has been focused on the Lombard buttress proportions. Fig.7 shows the change in the seismic multiplier for constant acceleration, in relation to a change in the buttress width W , calculated as the sum of the aisle span, and the lateral buttress depth (see Figs.3 and 4). The variable part in the buttress width in Fig.7 is the depth of the wall projecting outside the lateral wall. Two sets of material properties are considered for the shear sliding resistance. A linear increase of the lateral load capacity is evident as a function of the buttress width W . The improved material properties directly influence the results. The interpretation of the result is based on the following analysis of the base shear forces and the collapse mechanisms.

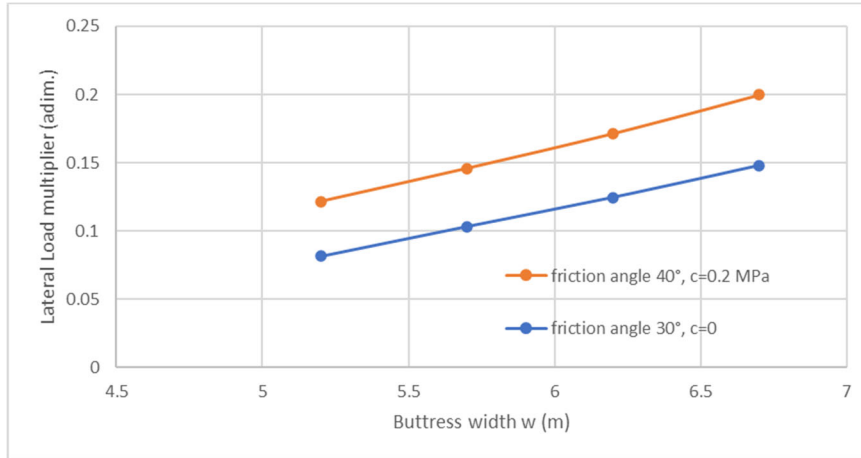


Figure 7. Lateral load multiplier as a function of buttress width.

The results for base shear in the piers and buttresses are presented in Fig.8, for the cohesionless case. The ratio $h/W = 1.37$ corresponds to the smaller depth of the buttress wall (member nr.4 in the figure); the shear transfer in the interior piers (members 2 and 3 in the figure) is close to that of the buttress wall 4. As the ratio of h/W reduces an increase in the role of the lateral buttress wall is shown. The typical proportions $h/W = 1.22$ correspond to an effective buttressing action, with the lateral Lombard buttress taking a double force (200 kN) relative to the interior piers in the shear transfer. Hence the increase of the collapse load is related to the increase of dimensions and resistance of the right lateral buttress.

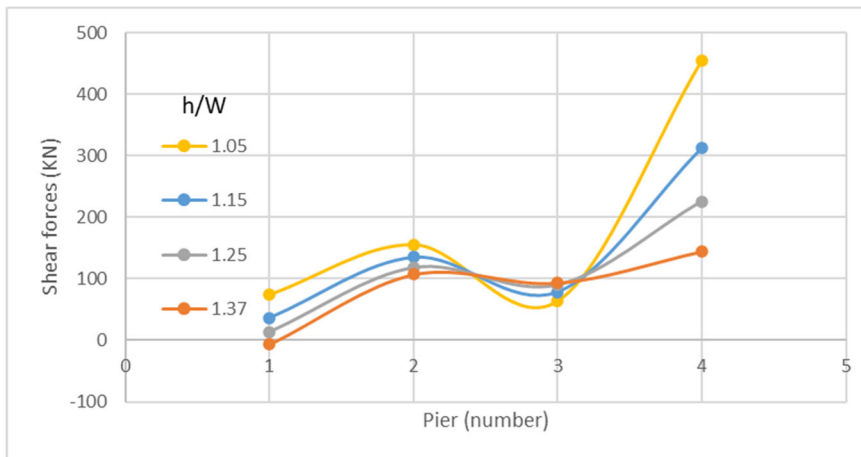


Figure 8. Shear forces at pier and columns basis, as a function of h/W proportional ratio.

Correspondingly Fig.9 shows the change in the failure mechanism. Starting from the cohesionless case, the smaller h/W ratio (i.e. the buttress is more stocky) shows both hinging and sliding occurring in the buttress on the right side; the diaphragm wall above the arch shows shear sliding only. On the contrary, a slender buttress with $h/W=1.37$ shows only a flexural hinge at the base, with much the same role as the interior piers (see the lowest curve in Fig.8 as well). The results for higher friction angle and cohesion are very similar, with the only difference of lesser sliding in the lateral buttress on the right.

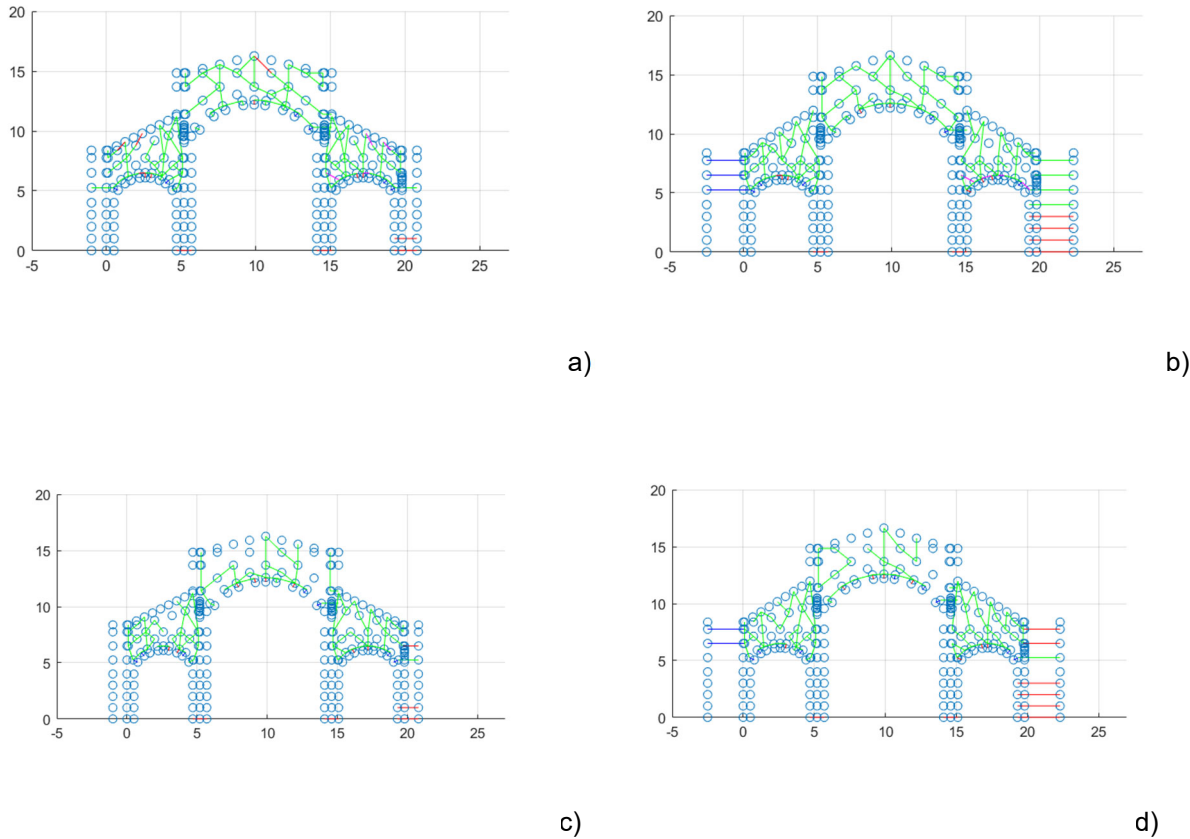


Figure 9. Failure Mechanisms for width of $h/w = 1.37$ (left) and 1.06 (right): friction angle 30° and cohesion $=0$ (top); friction angle $=40^\circ$ and cohesion $= 0.2MPa$ (bottom)

5 Conclusions

The Lombard buttress system is a widespread system throughout Italian and European heritage. A previous study of the proportions has been complemented here with an investigation of the seismic response.

The tool used for the numerical analysis is a static limit analysis model developed for this purpose. The use of rigid blocks with interfaces and of static equivalent actions, though a simplified representation of the complex response of masonry members for seismic loading, is adequate for the study of the effect of proportions.

The results show that the typical proportions correspond to an effective buttressing action, with the lateral Lombard buttress taking a leading role in the shear transfer. Both hinging and sliding mechanisms are relevant within the response of these members.

The analysis model considers a typical transversal section of a Lombard church, here represented by the case study of the Milanese Chiaravalle abbey. A symmetric geometry is considered as a simplification. Considering the presence of the cloister on the South side, that is a typical feature as well, will be part of the research developments.

6 References

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