On the Seismic Vulnerability of a Renaissance “Palace with Loggia”: a Limit Analysis Approach

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We present the first results of the analysis of seismic vulnerability carried out on a historical brickwork building of the fifteenth century in Ferrara, taken as being emblematic of a type of construction that was very common at that time, characterized by a large loggia on the ground floor. The study was conducted using the method of kinematic analysis in compliance with new Italian legislation regarding seismic events. A 3D Laser Scanner survey of the main façades has enabled a detailed representation to be made of the present geometry of the building. A more thorough investigation of the historic records and type of building has provided further useful information for an accurate estimate of seismic vulnerability.

INTRODUCTION

Seismic vulnerability analysis of existing buildings of historic value is a subject on which increasing attention has been focused for some time now. Careful examination of the most serious seismic events which have affected historic towns has shown that most cases of collapse have not so much depended on the limit of compressive strength being reached in the masonry of the load-bearing walls, as on loss of stability due to overturning of these walls out of their plane.

J. Heyman conducted pioneering studies [1, 2] of a method for analysing historic constructions based on limit of equilibrium condition, which indicates the possibility of applying limit analysis theorems to assessment of the load-bearing capacity of masonry. In Italy Heyman’s experience has been taken up and developed by A. Giuffrè through the study of historical construction techniques, an indispensable premise for culturally sustainable restoration, and processes of seismic vulnerability analysis of historic buildings [3, 4]. In the last decade, application of limit analysis to the study of masonry structures has undergone numerous developments: among these may be noted contributions in the analysis of church buildings [5-6], which often show common characteristics; classification of the most widespread and likely collapse mechanisms for historical buildings [7], thanks to which investigations of seismic vulnerability may be made even in the initial stage of survey [8]; more specific studies on the stability of masonry walls affected by seismic accelerations orthogonal to their plane [9-10]. The methodology approaches provided by these studies have become part of the technical literature compiled for Public Institutions [11]; they testify to the careful attention afforded nowadays to the problem of conservation of historical buildings in seismic areas.

The importance of evaluating the out of plane overturning in existing buildings has also been recognised by Italian legislation [12], which sees kinematic analysis as an indispensable tool for estimating seismic vulnerability.

The initial results are presented here of an analysis of the seismic vulnerability of a fifteenth century building in Ferrara; the choice of building was based on the important role the building now has as the Administration Centre of the University, as well as its being one of the best examples of this type of building with a loggia: investigations have revealed, in fact, the high level of construction expertise achieved by the builders of the past and the introduction of solutions to structure and distribution problems which became widespread during the Renaissance in Ferrara. The analysis presented is based on assessment of some collapse mechanism considered to be typical of this type of building with loggia in Ferrara, which allows for more awareness in the setting up of global analyses and in identifying the most significant aspects in order to draw up some initial proposals for structural improvement.

Description of the Building

The building stands beside the church of San Francesco and is thus called the ‘palace of San Francesco’, otherwise known as the ‘Palace of Renata di Francia’ because of the presence there, between 1536 and 1554, of the Duchess, wife of Ercole II d’Este and daughter of the French King Louis II [13]. The Palace of Renata di Francia is today a composite, stratified organism, conserving many traces of its past history; the building has two storeys, the ground floor and the first (called ‘*nobile’*) floor, organised around a central square courtyard **(fig. 1)**; on the ground floor there is an arcade creating, on three sides of the court, an access corridor to the service rooms, while on the fourth side, facing north, there is a great loggia connecting the courtyard to a large park at the rear.

There is a main south-north axis which enables a perspective view of the entire depth of the bulding area; the loggia, right from the imposing entrance, functions as a ‘link’, thanks to which the large rear garden is strongly integrated with the building.

The main residential rooms are in the blocks to north and south of the courtyard; in the first one, on the ground floor, there is the loggia passage, divided by a middle line of columns into two distinct spaces, the area to the south being the larger; a second, very characteristic feature, to the east of the larger loggia, is the imposing staircase leading to the rooms of higher prestige **(fig. 2)**. The blocks to east and west of the courtyard function as connecting wings between the main ones and have corridors aligned with the arcades on the ground floor, which open onto rooms of minor prestige.

ANALYSIS OF HISTORICAL RECORDS

The collection and study of historical records has enabled the reconstruction of events to which the palace was subjected and the gathering of information about modifications of structural layout and of the most important load-bearing components with regard to seismic vulnerability. The main construction periods which have affected the building in the course of its history may be summarised as follows:

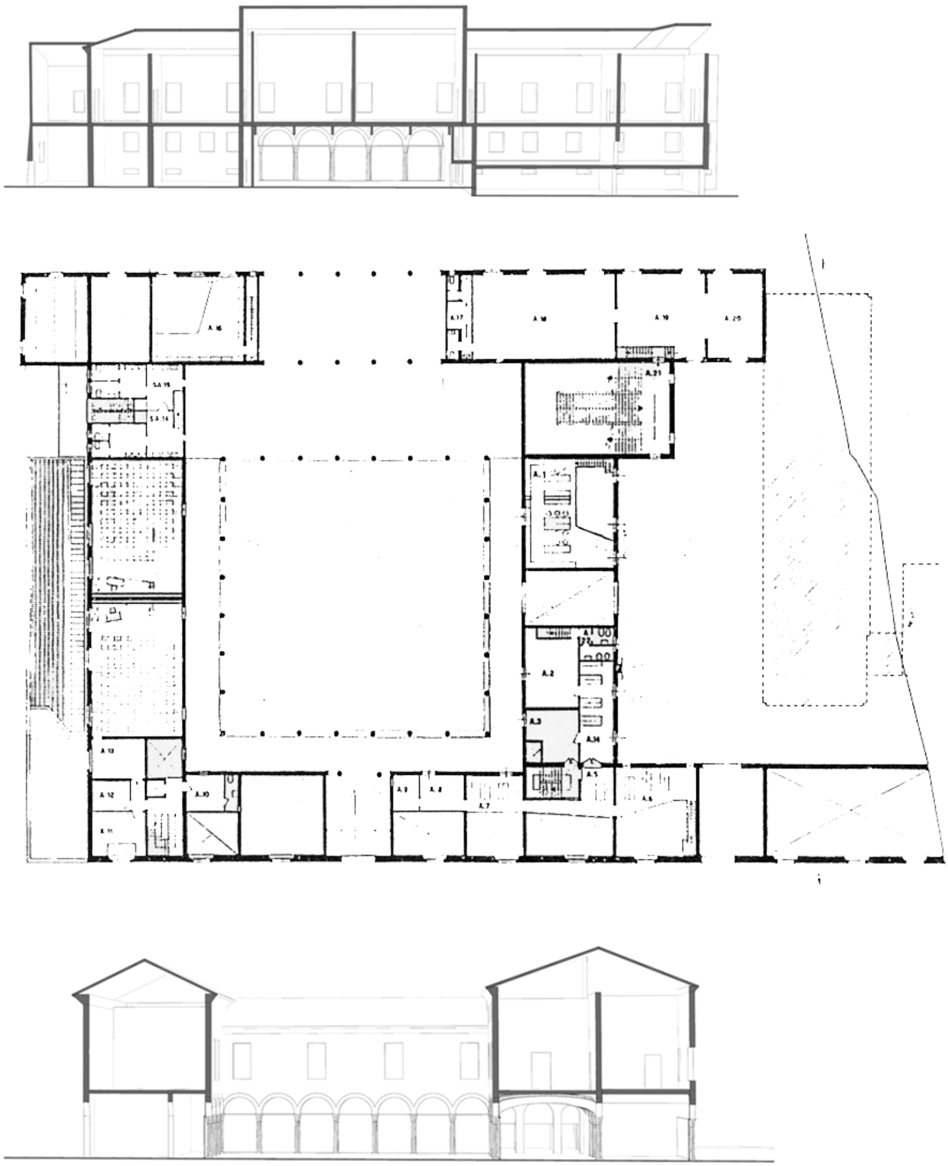

Figure 1. Plan of ground floor and sections of the Palace of Renata di Francia (W-E, S-N)

Figure 2. Great loggia and monumental staircase

1474

Purchase by the Duke Ercole I d'Este of the property located on the boundary of the medieval city at the convent of San Francesco, where another house used to stand, and commencement of transformation works by Pietro Benvenuti dagli Ordini. The building was planned as a luxurious mansion for various residential or official uses connected with the requirements of the Court; the palace was built in an urban area of recent development, that led to the creation of a modern straight road, which became the location of some of the city's most important buildings.

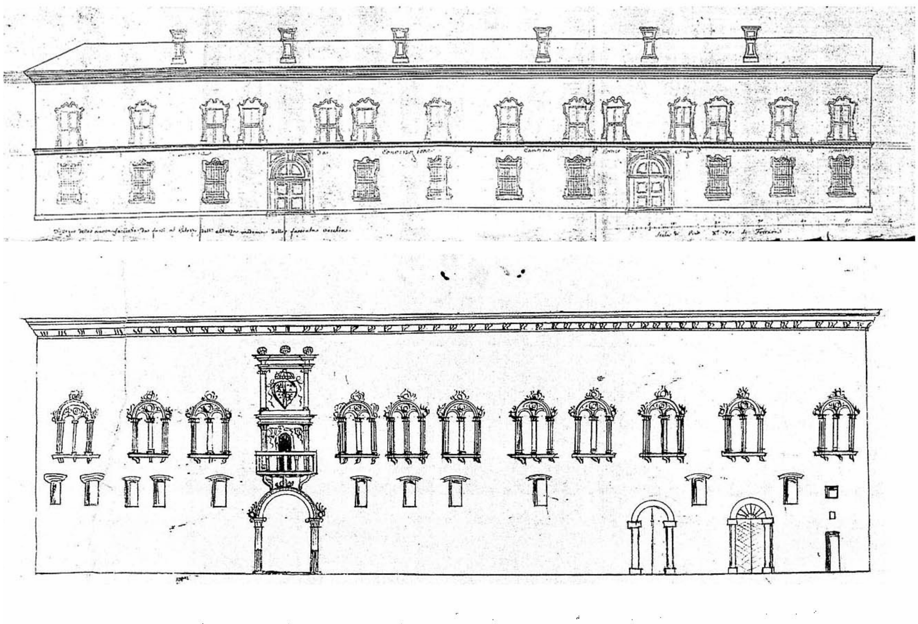

Figure 3. Design of the main prospect of the palace and of its fifteenth-century version

In the first stage the central courtyard was built, with its typical Benvenuti-style capitals, and the large loggia recorded in the building records: “for supply of two stone columns with bases and capitals for two loggias built in the house of San Francesco”.

The style of the fifteenth century palace was marked by a Late Gothic emphasis, as is shown by a sketch of the ancient façade made by the historian Girolamo Baruffaldi at the beginning of the eighteenth century **(fig. 3)**, in which strong similarities may be noted with other important works of Benvenuti, with particular regards to the style of the windows and the main entrance, attributed to Biagio Rossetti [14], apprenticed to Benvenuti in the building works. The initial layout of the Palace of Renata di Francia shows a distribution system with great accessibility and solid, rational composition, in which rooms are arranged in a free, spacious manner; colonnades, balconies and porticos, traces of which are still visible among the accumulations of time, succeed each other and overlap leading clearly towards external areas.

1485

Major works by Biagio Rossetti to turn the building into the residence of Giulio Tassoni. Succeeding Benvenuti as Court architect, Rossetti superintended the large building works, during which the building was to become one of the most splendid and reknowned buildings in the city; in the northern block, a great hall was built looking out onto the park, with a long series of windows embellished by “eight columns of red marble with bases and capitals for the upper loggia, facing the garden”. When the work was finished, in 1487, the new building was called ‘Belvedere’, to emphasise the wonderful panoramic effect of the new upper loggia, thanks to which the eye was drawn beyond the medieval walls adjacent to the palace, out towards the extensive countryside as far as the poplar woods of the Po. Records show the sizes of the new rooms: on the ground floor the second loggia has a “floor on the garden side 36 feet long [14.5 metres], 18 feet wide [7.2 metres]” and on the courtyard side a “floor 44 feet long [17.7 metres], 20 feet wide [8 metres]”; the width of the two loggias on the ground floor is the same as it is today; on the upper floor, above the two loggias, there are two large halls, the one facing the park being “83 ½ feet long [33.6 metres], 19 feet wide [7.6 metres]” and the one facing the courtyard “68 feet long [27.4 metres], 20 feet wide [8 metres]”. The arrangement of the northern block is therefore composed of a double loggia on the ground floor, surmounted by two large rooms, of which the northern one faces the garden with a large upper loggia; the construction appears to be reduced to a minimum and the structural features having a marked slenderness to them, forming a kind of brickwork framing in order to allow the light, the air and the views ample freedom to interact with the inside space.

1491

Partial collapse of the building and new works directed by Biagio Rossetti. The structural arrangement had probably facilitated a serious collapse, in consequence of a heavy snowfall on February 7th; as the historian Caleffini records [15]: “it ruined part of the palace of the nobleman Giulio Tassoni**;** on Monday the hall of the house of San Francesco collapsed entirely including the roof”. The great hall had fallen down together with its roof, requiring the removal of the Tassoni family to another of their properties. Rossetti, being charged with the repair work, said that the collapse occurred “because the anchors had come out of the wall”. The previous spatial arrangement was maintained, but some vaults of the ground floor loggia facing the garden were closed and the upper loggia was remade to a less audacious design.

1534-1535

Major works by Ippolito II directed by Battista Tristano. The building, which in 1534 was part of the inheritance of Ippolito II, Archbishop of Milan and future Cardinal, underwent considerable rebuilding of its interior appearance, as the closure of the middle row of columns of the loggia, as verified by the delivery of 1900 stones, which was still visible at the beginning of the eighteenth century **(fig. 4)**.

Much attention was given to the redesigning of the garden: the future purchaser of Villa d’Este in Tivoli incorporated into his property new lands made available by the demolishing of medieval walls following the completion of the great Erculean Addition; an idea of the layout of the sixteenth-century park, finally transformed in the second half of the nineteenth century, is given by a survey from the eighteenth century.

1536-1554

Period of residence of Renata di Francia, Duchess of Ferrara. There are few traces of her presence in the architecture of the building: nonetheless, the historical and personal events in the life of Renata di Francia left a close association with the palace which still bears her name today.

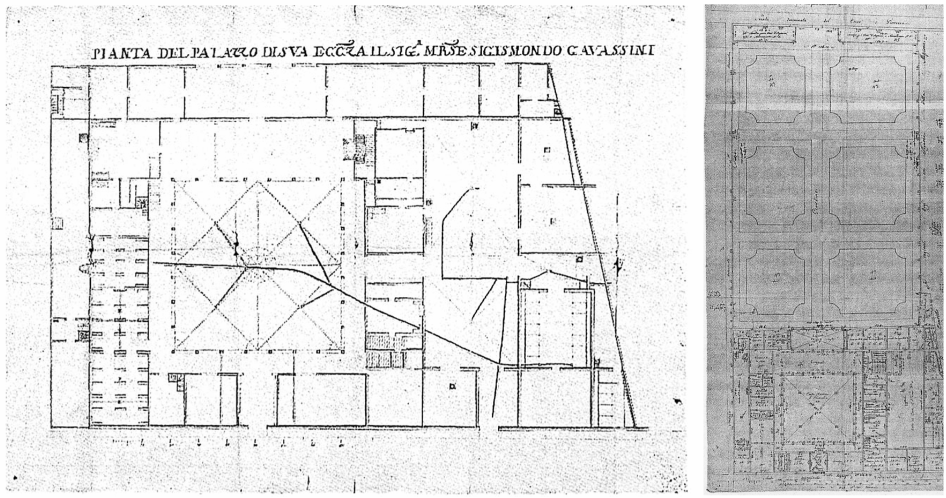

Figure 4. Plan by F.M. Frizzi and survey of the garden by G. Frizzi

1570

Great earthquake in Ferrara. The event remained a memorable one for those who witnessed it, both in the city and in the Italian Courts; chroniclers narrated in abundant detail the seismic event, providing us with a valuable picture of the devastation and damage to which the monuments of the city were subjected:

> At about three o'clock the ground was struck with such violent shaking that the walls were swaying mightily and seemed to touch one another, indeed the Castle, the Churches, the Convents of the city and other minor buildings suffered great damage. [16]

> …the great damage caused by this fourth tremendous earthquake, the effects of which were more disastrous than may be imagined; among the buildings affected were the Old Castle which appears to be seriously damaged and which saw the collapse of its roof, the New Castle which collapsed almost in its entirety [...], the tower of Castel Tedaldo which threatened to fall, the palace of His Excellence [the Duke] in Corte Nuova, the Bishop's palace which, in consequence of the great damage to it, was for the most part demolished and rebuilt, Palazzo Contrari which was propped up in many places and partly demolished, almost all Palazzo Paradiso, the Cardinal's palace at San Francesco, the main marble façade of the Duomo which became detached from the perimeter wall and threatened to fall… [17]

> … in the evening, after midnight, came another, far greater, which caused many houses collapse and killed many people; I also, being then in my study where I am writing these few lines, thought that the house was sure to fall upon my head, so violently did the walls shake together. In fact, I wondered that they remained standing. So great was the rumble of the earthquake and the uproar of the people in a panic that it seemed the world was coming to an end; this happened at the hour in which people are at home and many died due to the fall of chimneys and walls… [18]

The exent of the damage done to the Cardinal’s palace at San Francesco is not specified, and it has not been possible to analyse the records of the ‘Camera Ducale’ concerning the works that followed. At the time the palace was not inhabited by the Cardinal, who left Ferrara in 1536; upon his death in 1572, the building became the property of his nephew Cardinal Luigi, who did not live there and who sold it in 1582; from that date the building leaves forever the world of the Estense Court, which subsequently left Ferrara when the city passed to the Papal State in 1598.

1738

Beginning of the major renovation works of the Gavassini family carried out by Girolamo dal Pozzo. In the centuries following the Estense period there are no indications of particular operations and due to the owner’s economic difficulties there was no remedy for the inevitable deterioration of the ancient building; in 1736 the Marquis Gavassini, on becoming owner, had a survey drawn up of the static conditions of the building:

> First of all, according to the survey made a few days ago, it appears that the main façade is leaning towards the street in various places, in one of which the incline is of 12 and a half ounces [42 cm]; what is worse, in connection with this wall are two other parallel load-bearing walls, one in the middle, as high as the first floor, and the other, facing the courtyard, which rests on the marble colums of the arches, the foundations of which are giving way. Both of these walls are leaning towards the street and, pushing against the façade, increase the danger of collapse. Besides this, the colonnades lining the courtyard have many marble columns which are also leaning; because of the incline of these columns the walls they support, which serve as parapets for the balconies above, are leaning in their turn. Consequently, the marble columns above the parapets, which support the roof, are also leaning. These cannot be straightened unless the ones beneath are straightened first; but this cannot be done without first demolishing everything.

The works began in the same year and led to the rebuilding of the façade on the street in its present arrangement, as shown by an estimate of costs that envisages “ the squaring up of all the windows of the façade, removal of the existing marble cornices and renovation of the windows in the modern style”. The front was demolished, starting from the south-west corner, for “a length of 60 feet [24 metres], from the ground floor to the rooftops, and rebuilt”.

For the wings of the courtyard a solution was adopted, still visible today, whereby the arches of the upper balcony were closed, removing the fifteenth century columns; traces of these columns and the original raised passageway are still visible in the wall face.

Finally, in the northern block the loggia was reopened, involving the demolition of the part made by Ippolito II and also the staircase from the same period; in its place the great monumental staircase was built, the work of the Veneto architect Angelo Santini. The new staircase gave onto a series of prestigious rooms larger than the previous ones, especially in their height, with the construction of great artificial vaults, in the eighteenth-century manner, to accommodate which the entire building above the loggias was raised; this operation altered the static arrangement of the roofs and introduced the large wooden trusses in place of the pitch beams, which were supported by the middle wall.

Figure 5. Traces of modifications to the side balconies of the courtyard and traces of the upper arcade facing the garden

Artificial vaults were made for all ceilings of the building, including the double loggia, covering the fifteenth-century floors or else, if these had irrevocably deteriorated, replacing them. To this building stage may be attributed the closure of the upper loggia facing the garden, replaced by rectangular windows of the same kind as those inside the courtyard. Traces of the old loggia openings, in line with the arches beneath, may still be seen in the wall face **(fig. 5)**.

1959-60

Permanent concession to the University of Ferrara and the start of restoration work directed by the architect Piero Bottoni. The architect, in his project statement, described the general condition of the building as follows [19]:

> Since the structure of the building appears to be sound enough and in a good enough condition to be used to the maximum, the project does not envisage any demolition of architectonical features that have a precise arrangement of their own; with the aim of making available as much of the space as possible, a reduction of the height of some rooms is planned, while keeping their total height in a certain part, so as to maximise the utility of space for offices or other uses. In this manner these halved rooms will keep their sense of grandeur just the same, which ought to be conserved as a typical feature of this ancient building of artistic value.

There have always been mezzanine floors in the building; the surveys of the works provide information on choices of technique and consolidation:

> Laying of new floors to replace the present ones of deteriorated or unsafe wood. Laying of new floors with H-beam girders resting on the side walls and duly mortar-sealed inside the masonry. These girders will be laid at an interaxial of 0.90 m from one another and will be linked with floorbricks fitted with mortar and covered by a 2 cm concrete upper slab.

The extensive laying of new floors involved a second alteration to the structural arrangement, as it replaced the ancient wooden beams, well anchored to the masonry by tie rods and stoppers and lined up with the columns of the arcades, with laid girders of lesser pitch. The restoration also uncovered once again the fifteenth-century floor of the loggia facing the garden.

ANALYSIS OF TYPOLOGY

The construction of the Palace of Renata di Francia belongs to an architectonic tendency, particularly common in Ferrara in the early Renaissance, making widespread use of a typology of ‘palace with loggia’; the historic origins of this phenomenon lie in the great building works of the ‘*delizia’* of Belriguardo, begun in 1435 near Voghiera [20]; a work of great cultural as well as constructive value, destined as a summer home for the Estense Court; many values are combined in the work: a reinterpretation of the classics, from Vitruvius to Pliny to Tacitus to Cicero, the attempt to measure up to the experiences of antiquity, the prestige of the dominant family and lastly the desire to create an architecture for the new life style developing during the Renaissance, one of culture and refinement. The building becomes a modern transposition of the Roman *domus* and is arranged with precision into two aligned courtyards along a main axis chosen by astronomical principles; the two courtyards are surrounded by colonnades recalling ancient *peristilia* and the many rooms, distributed on two levels, are of high quality and arranged as to enable the Dukes and their guests to move about easily among buildings and parks, courtyards, pools and private gardens. There is a main central block separating the two courts, higher than the side blocks, in which on the ground floor, in symmetry with the entrance hall, there are two large living rooms and alongside them the marble staircases leading to the upper floor, which holds one enormous room. The structure consists of two longitudinal walls, joined by huge composite beams 15.8 m long; the load-bearing walls, rising to the roof, form the space of the great hall of the upper floor. The slenderness of such a structure was responsible, at the end of the Estense period, for the decision to demolish the entire first floor with the great hall, bringing the present level of the roofs to just above that of the ancient wooden beams **(fig. 6)**.

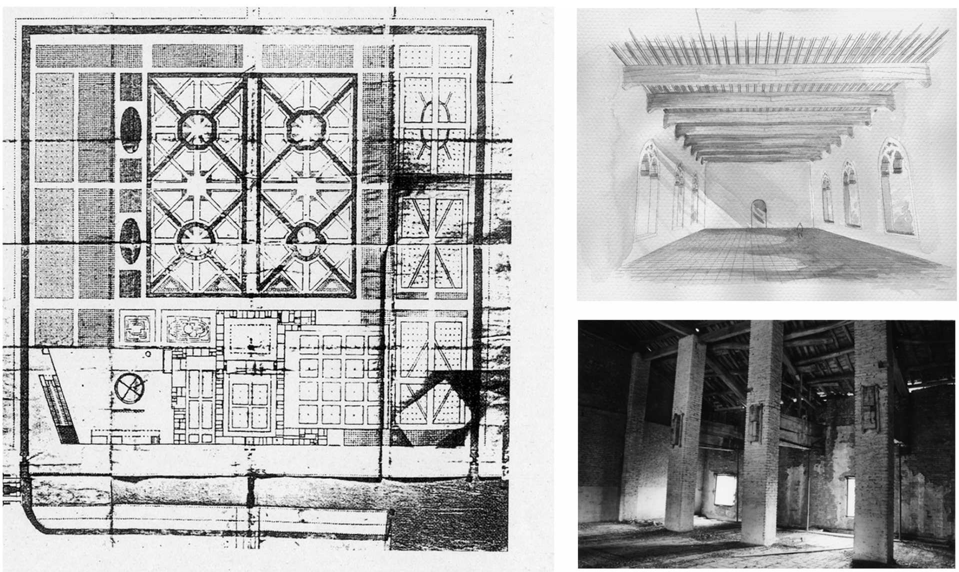

Figure 6. Plans of the Belriguardo palace in XVI cent.; reconstruction of the ground floor rooms and picture of the actual remainders

The type of palace built at Belriguardo was further developed with the construction of the Romei family house, standing opposite the Palace of Renata di Francia **(fig. 7)**; situated on a site of irregular size it has the same layout of two courtyards, alongside the street entrance, while there used to be a third courtyard, behind the main one, aligned with the entrance gate and the loggia; there are two rows of colonnades which give the layout a great sense of spaciousness; on the ground floor of the central block the large loggia is situated, at one time a linking feature between the two courtyards, and above this the great reception hall receiving light from both sides.

Figure 7. Main courtyard of Casa Romei and view of the loggia

The plan of a loggia opening onto one or more courtyards or gardens with the great hall above is the main stylistic feature which became widely used in Ferrara in the fifteenth century and that was to appear in many new or already existing buildings.

The architectural identity of the prestigious palace was well-developed by the third quarter of the fifteenth century and consolidated in the works of the Palace of Renata di Francia: Benvenuti planned the building according to rules of which Biagio Rossetti was later to demonstrate his thorough assimilation; two major works by this master builder of Ferrara show great affinity with the former. The first is Palazzo Costabili, known as Ludovico il Moro, in which may be seen the double loggia **(fig. 8)**. Located opposite the entrance; there is a wall separating the two areas of the loggia, which was probably a model for the similar wall made in the Palace of Renata di Francia by Ippolito II; on the first floor there are two large rooms, the plan of which follows that of the ground floor formed by parallel load-bearing walls.

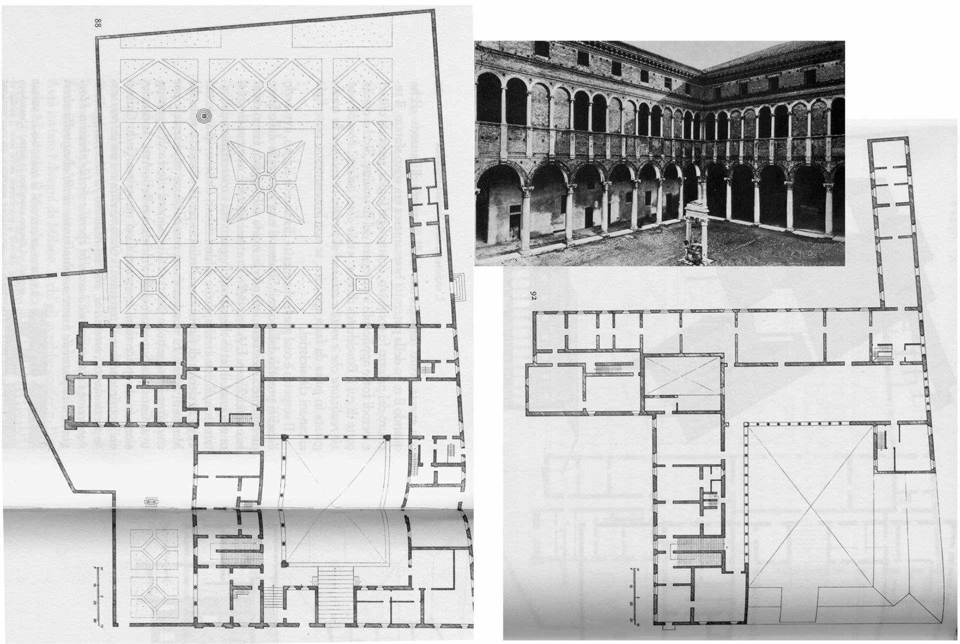

Figure 8. Plans of Palazzo Costabili and view of the courtyard

The second building is Palazzo Strozzi Bevilacqua, situated on the narrow side of Piazza Ariostea **(fig. 9)**; the ground floor is laid out around a colonnaded courtyard, with two loggias, set in the main blocks, of which that opposite the entrance is the largest; from this, through an entrance way now closed, it was possible to enter the rear garden; The side blocks have a second row of arches, still well conserved. The courtyard of this building shows clear similarities to the original layout of Renata di Francia and may be taken as a model for the reconstruction of its fifteenth-century appearance. A sequence of great loggias are aligned on the main axis, creating both private and public spaces that create a kind of filtering link with the large adjacent square, the heart of the great Erculean Addition.

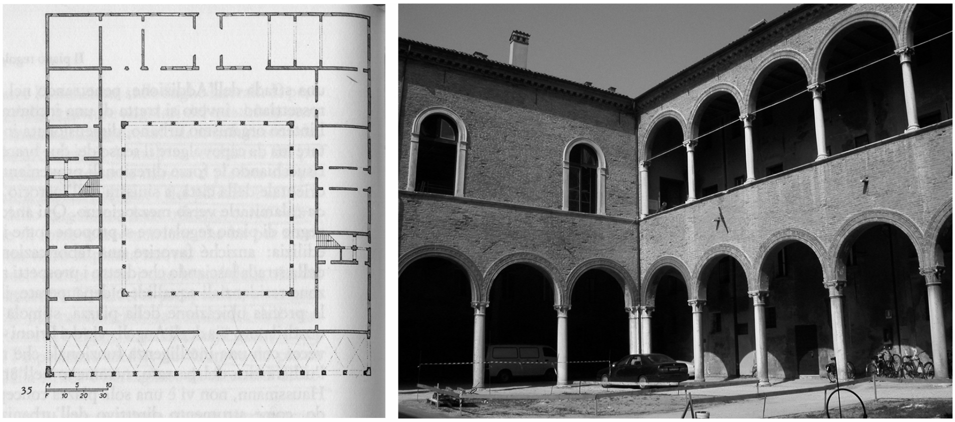

Figure 9. Plan of Palazzo Strozzi and view of the courtyard; longitudinal sections of both Palazzo Strozzi and the fifteenth-century version of the Palace of Renata di Francia

The stylistic and structural organization of these and other buildings shows marked affinities among them, to the point at which a definition may be made of a fifteenth-century style of ‘palace with loggia’.

3D Laser Scanner Survey

The complexity of the building made it advisable to conduct a precise examination of its present geometric layout; this was done with the aid of a 3D laser scanner survey which, together with a manual survey, provided extremely precise information.

The 3D survey was carried out particularly on the wall faces of the main façades of the building **(fig. 10)**, those chiefly subject to the phenomenon of overturning. A Leica HDS Cyrax 3000 was used with the aid of total station.

Figure 10. Dot clusters of the courtyard and of the main façade

The scanning of the façades was carried out with two-fold accuracy: an initial broad-pitch grid, used for operations requiring a lower level of precision, and a second in more detail; the chosen grids were, respectively, 5 x 5 cm and 1 x 1 cm for the internal courtyard and 5 x 5 cm and 2.5 x 2.5 cm for the other façades. Thanks to the aid of total station the dot cluster was referenced; it will therefore be possible in future to expand the survey very simply. The results were automatically data-processed to provide an easy-to-use means of support for the construction of 3D models employed at various levels of analysis.

ANALYSIS OF SEISMIC VULNERABILITY

The study of seismic vulnerability of the Palace in question was carried out by means of a global analysis of 'pushover' type, concerning the entire building complex or its individual parts, where these were easily identified and shown, and an analysis of the mechanisms of collapse with regard to specific areas of the building which, because of their geometry or construction features, may be subject to overturning.

These latter areas are difficult to capture in a global analysis, as they depend largely on the degree of connection between the structural components involved, such as the outer walls and the floors. The effectiveness of such connections, often made with ties, edge beams or reinforcement bands, may vary considerably according to the system adopted.

The new antiseismic legislation in Italy makes this kind of analysis obligatory in existing buildings, even of a global type, for which analyses of collapse mechanisms may be a fundamental addition for a better understanding of the behaviour of a building in a seismic area.

The kinematic analysis carried out on the Palace paid particular attention to the area of the loggia, which on both levels appears to be lacking an adequate number of orthogonal stiffening walls and proper connections between the load-bearing walls and the horizontal components. The choice of kinematisms was made on the basis of the geometric features and constraint of the walls; particular attention was given to the distribution of openings such as doors, windows, arches, where the most probable cracks are determined, and the butt hinges of the collapse mechanism; the main forms of overturning were drawn from available technical records. Concerning the parallel walls that form the elevation of the loggia, called A, B, C from south to north, consideration was given to overturning at their bases and at the floor of the first storey; the roof acts as a thrusting element in both cases, while the floor is only involved in the first case. The roof, built with trusses and frames without bracings, plausibly suggests a top thrust, as each truss is free to slide from the others; the first storey floor, consisting of flat tiles laid on girders without side reinforcements and with an upper slab, devoid of welded grid, may be affected by horizontal sliding in some of its parts.

The analysis of collapse mechanisms was made at various degrees, according to the complexity of the structural behaviour model employed. In conformity with legislation (attachment 11C), no tension resistance of the walls and infinite resistance in compression have been taken into consideration. For the assessment conforming to legislation walls A and C of the loggia were considered with the following data:

Ferrara: ground acceleration $a_g = 0.15$ g, with g= gravity acceleration.

Foundation layer: low cohesion sedimentary ground.

The procedures were carried out in Excel, as indicated by legislation (3.9, 3.10, 11C). The first kinematism considered for wall A concerns the overturning of a central wall panel, facilitated by the large distance of orthogonal walls, around a possible hinge on the ground floor and one on the first floor, shown in **figure 11A**. In assessing the load multiplier no consideration was taken of an eventual contribution to the tilting of the spandrels above the windows; the values of the multipliers are therefore corrected, in conformity with legislation(11.C.4), in spectral acceleration and compared with expected acceleration (11.C.8); the results are shown in **table 1A** (where G stands for 'ground floor', F for 'first floor').

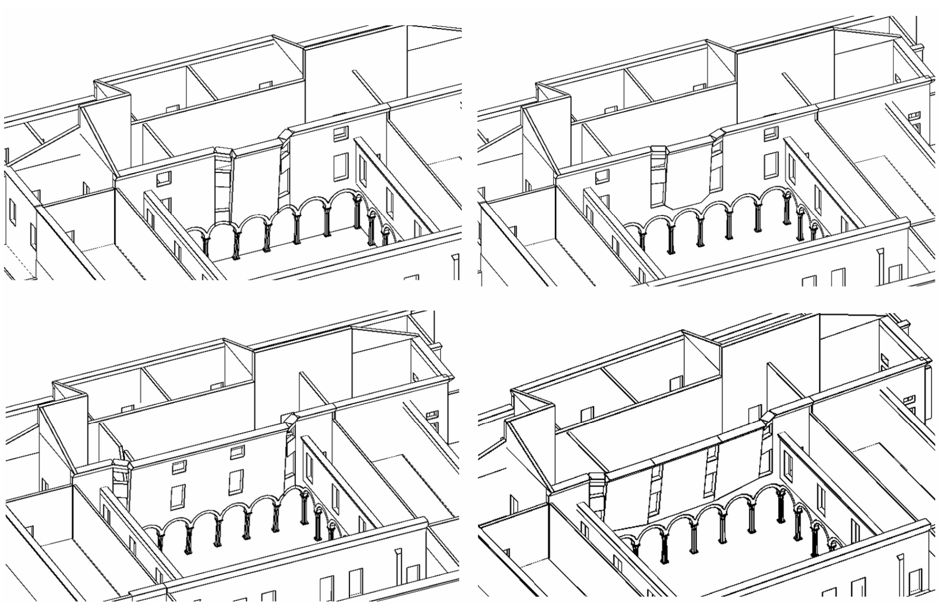

Figure 11. A: Kinematism type A-G-1 and A-F-1; B: Kinematism type A-G-2 and A-F-2

The values of spectral accelerations appear quite low compared with expected acceleration, such as to indicate the real structural weakness with reference to the presented hypotheses. A second degree of development of the same mechanism therefore took into consideration the two floors as not being thrusts; that is, assumed as 'rigid' in their planes following eventual consolidation operations that impede the relative sliding of sections of floor or roof; besides this, it is supposed that they are not effectively constrained to the latter. Thus the loads transmitted to the walls do not create a horizontal thrust, while maintaining a proper stabilizing function; the wall overturns and ‘slips out’ without horizontal attrition. The new spectral acceleration values are shown in **table 1B**.

It appears that the main influence on overturning comes from the wall masses rather than from loads transmitted from horizontals.

A second type of kinematism influences the entire front of the courtyard; the windows alongside the perimeter walls of the connecting wings facilitate the formation of vertical lines of discontinuity, as mentioned in the legislation (pt. 8.1.4). This gives the kinematisms of **figure 11B**; the corresponding values of spectral acceleration are shown in **table 1C**.

Table 1.

1A		
A-G-1	$a_1^* / g:$	0.034
	$a_g^* / g:$	0.202
A-F-1	$a_1^* / g:$	0.059
	$a_g^* / g:$	0.22
1B		
A-G-1	$a_2^* / g:$	0.054
A-F-1	$a_2^* / g:$	0.096
1C		
A-G-2	$a_1^* / g:$	0.035
	$a_g^* / g:$	0.207
A-F-2	$a_1^* / g:$	0.068
	$a_g^* / g:$	0.219
1D		
A-G-2	$a_2^* / g:$	0.050
A-F-2	$a_2^* / g:$	0.103

As was done previously, it is possible to assess how collapse mechanism may be influenced by suppositions of rigidity and absence of constraint in the horizontal elements. **(table 1D)**

On wall C similar kinematisms and spectral accelerations are obtained **(fig. 12A)**, as the load distribution and wall section geometry are analogous. In the wall may be noted the central orthogonal wall; evaluation of the multiplier took into consideration a joint between the two walls through the introduction of a detachment wedge of a 20° angle **(table 2A)**.

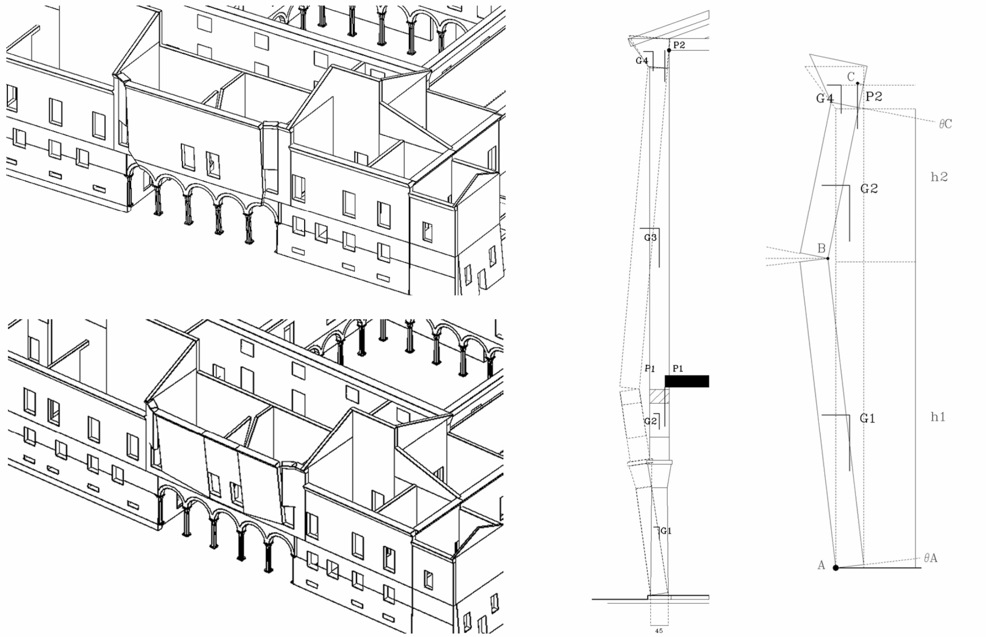

Figure 12. A: Kinematism type C-G-2 and C-F-2; B: Kinematism type A-V-1 and A-V-2

Lastly, effective constraints were assumed between the floors and the walls; in this case, if the floor is firm in its plane, the only mechanism of collapse is made possible by the formation of a vertical arc inside the wall; considering on wall A the rigid wall of kinematism 1, the possibilities are as follows:

- both floors rigid and constrained (arc between floor and roof, case 1);
- only the roof constrained (arc between ground and roof, case 2)

which give rise to the kinematisms of **figure 12B**. The spectral accelerations, corresponding to the minimum value of the collapse multiplier, were obtained with Mathematica 5.0 **(table 2B)**.

The values appear acceptable in assessment according to legislation. It is possible to obtain a further degree of development of this kinematisms by introducing a value of finite compression resistance in the walls and pillar stones, in accordance with legislation (OPCM 3431/05, 11D; DM 20-11-87);

introducing resistance values of $\sigma_{0,masonry} = 1.1 \ \ N/mm^2$ e $\sigma_{0,stone} = 16 \ \ N/mm^2$; also in this case values are obtained of spectral acceleration acceptable to legislation **(table 2C)**; on wall C values are slightly less favourable.

Table 2.

2A		
C-G-1	$a_1^*/g:$	0.037
	$a_2^*/g:$	0.053
	$a_g^*/g:$	0.202
C-F-1	$a_1^*/g:$	0.068
	$a_2^*/g:$	0.102
	$a_g^*/g:$	0.222
2B		
A-V-f,r	$a_1^*/g:$	0.378
	$a_g^*/g:$	n. .c.
A-V-g,r	$a_1^*/g:$	0.218
	$a_g^*/g:$	0.185
2C		
A-V-f,r	$a_2^*/g:$	0.266
	$a_g^*/g:$	n. .c.
A-V-g,r	$a_2^*/g:$	0.182
	$a_g^*/g:$	0.185

CONCLUSIONS

The kinematic analysis presented shows the great seismic vulnerability of the loggia structure; study of the construction features, the arrangements and their modifications over time has enabled hypotheses to be made of the behaviour of these under horizontal movement and has clarified the role of some structural constraints and connections. The importance of the latter, identified in kinematic analyses, suggests the general lines of intervention for improving the seismic resistance of the building. Moreover, the legislation itself considers effective connections between parts to be fundamental in developing global analyses, “which are based on the behaviour of the walls in their own plane, assuming their stability with regard to seismic activity out of their plane”. With reference to possible improvement plans, it should be noted that operations directed solely at firming the horizontals are ineffective if not accompanied by the creation of adequate links between these and the vertical structure. Consequently, it is advisable to constrain the roof, once firmed, to the walls: in this case, a satisfactory result may be obtained or, in any case, an improvement of resistance, above all if a similar operation is carried out on the floor of the upper storey.

ACKNOWLEDGEMENTS

The 3D survey was made with the laser scanner provided by the Department of Architecture of the University of Ferrara and with the technical support of D.I.A.P.Re.M. (Research Centre for Developement of Integrated Automatic Procedures for Restoration of Monuments - University of Ferrara).

REFERENCES

[1] Heyman, J., 1982, *The masonry arch*, Ellis Horwood Limited.

[2] Heyman, J., 1995, *The stone skeleton: structural engineering of masonry architecture*, Cambridge University Press.

[3] Giuffrè, A., Carocci C., 1999, *Codice di pratica per la sicurezza e la conservazione del centro storico di Palermo*, Laterza.

[4] Giuffrè, A., 1993, *Sicurezza e conservazione dei centri storici: il caso di Ortigia*, Laterza.

[5] Doglioni, F., Moretti, A., Petrini, V., 1994, *Le chiese e il terremoto*, ed. LINT.

[6] Cavalieri, L., Lagomarsino, S., Podestà, S., Zingone, G., 2000, *Vulnerability models and damage scenarios for the churches*; in *the Catania Project: earthquake and damage scenarios for high risk area in the Mediterranean*, CNR-GNDT.

[7] D’Ayala, D., Speranza, E., 2003, *Definition of collapse mechanism and seismic vulnerability of Historic masonry buildings*, Earthquake Spectra, v. 19 n. 3.

[9] Griffith, M. C., Magenes, G., Melis, G., Picchi, L., 2003, *Evaluation of out-of-plane stability of unreinforced masonry wall subjected to seismic excitation*, J. Earth. Eng., special issue: 1(7): 141-169.

[10] De Felice, G., Giannini, R., 2001, *Out of plane seismic resistance of masonry walls*, J. Earth. Eng., 5(2), 253-271.

[11] Blasi, C., Borri, A., Di Pasquale, S., Malesani, P., Nigro, G., Parducci, A., Tampone, G., 1999, *Manuale per la riabilitazione e la ricostruzione sismica degli edifici - Regione dell'Umbria*, Tipografia del Genio civile.

[12] OPCM 3274/03, 3431/05.

[13] Olivato, L., (cured by), 1997, *Il palazzo di Renata di Francia*, Ferrara, Corbo ed.

[14] Zevi, B., 1960, *Saper vedere l'urbanistica*, Einaudi.

[15] Caleffini, U., *Cronica della città di Ferrara dal 1471 al 1494.*

Biblioteca Ariostea of Ferrara (BAFe)

[16] Mss CL I, 443, Scalabrini, *Memorie antiche di Ferrara dal 164 al 1597.*

[17] Coll. Ant. Ms 294a, Anonimous, *Memoria de' gran Terremoti, e Ruine causate da essi nella cita di Ferrara l'anno 1570.*

[18] Mss CA 294b, de' Robertis, J., *Cronichetta dal 30 ottobre 1559 al 10 maggio 1592.*

[19] **Archivio Piero Bottoni**, Dpa, Politecnico di Milano, b.74. fasc. 1, doc. 1-4.

[20] Artioli, F., 1988, *Gli Estensi e la delizia di Belriguardo*, ed. Grafica Ferrares.