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# RECONSTRUCTION PLANS AFTER THE 2009 L'AQUILA EARTHQUAKE. FROM BUILDING PERFORMANCE TO HISTORICAL CENTRE PERFORMANCE

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**Abstract.** *The interest for the seismic performance of existing unreinforced masonry structures has grown in the last decades. This is shown both by the scientific research and by the technical codes. However, when the 2009 L'Aquila earthquake occurred no guidelines were available for the repair and the strengthening of the historical centres as a system. In this paper the multidisciplinary framework which led to the Reconstruction Plans of 23 historical centres, belonging to the municipalities of Lucoli, Ovincoli, Rocca di Cambio, Rocca di Mezzo and affected by the 2009 seismic event, is summarised. This is done with specific reference to building and structural issues, while additional material on town-planning concerns can be found in a monographic book. The seismic performance of an historical centre is a problem of several scales. The routes network of the historical centres around L'Aquila, and of most Italian historical settlements for that matter, is characterised by reduced cross section, limited curvature radii and low redundancy. The global seismic performance of an entire historical centre, and of a larger section of the surrounding territory, can be governed by the performance at singular points. Here the out-of-plane failure of a façade can strangle an access route to an urban district or even a major territorial connection. Hence, the specifications in the Reconstruction Plans, although involving an overall improvement of the performance of all the buildings, need to be differentiated in a consequence-based approach, linking local collapse to global performance. The careful consideration of several issues, e.g., vernacular construction techniques, geometric analysis of survey drawings, the use of laser scanning, contribute to a better understanding of observed performances and to a more aware strengthening design.*

## 1 INTRODUCTION

The interest for the earthquake performance of existing unreinforced masonry buildings has known a marked increase in the last decades. This is proven, among other things, both by conferences [1]-[3] and by building codes. The commentary following the 1980 Irpinia (Southern Italy) earthquake [4], is the first Italian standard to prescribe a global non-linear seismic assessment, while the innovative code issued in 2003 [5] takes advantage of the previous experience accumulated with EuroCode 8, especially from section 3 on existing buildings; with the revision of the Italian Standard performed in 2005 [6], local collapse mechanisms are mentioned for the first time in a mandatory document. Assessment and interventions on historical and listed buildings are addressed in details within [7], later amended [8] to be coherent to the new Italian Structural Code [9]. In the same decade innovative documents for cultural heritage buildings have been proposed within an International setting [10]-[11].

In this scenario, extremely simplified for the sake of conciseness, emerges the lack of guidelines for the assessment and for the risk mitigation of historical centres. So far their strengthening is considered simply as a result of the strengthening of single buildings. However, the historical centre is a system and as such “the whole is more than the sum of the parts”.

This concept was clearer within the town-planners community. Fera [12], for the first time in Italy, moves the focus from single elements to the city as a system, considering technical, economic, political tools for the risk management. Cremonini [13] proposes an integrated analysis of the city, from the building to the fabric, to the spatial organisation of the functions, to the earthquake performance. Sanfilippo and La Greca [14] present a series of case studies with contributions from town-planners, architects, economists, geographers, historians, structural engineers, geologists. Fabietti [15] introduces the concept of Minimum Urban Structure as system of public and private spaces that has to remain functioning in case of an earthquake, supporting the economic and social functions of a city. Scalora [16] develops a method of analysis open to different disciplinary contributions and to several scales of observations: from building, to block, compartment, precinct, fabric, historical centre; in this way he is able to assess what the Available Urban Structure in case of an earthquake will be. It is worth to note that this last contribution is focused on the historical centre of Siracusa, Sicily, studied exactly a decade before by Giuffrè [17]. This research is a masterpiece in analysing the building details and the structural behaviour of minor architectures of an historical centre but, at the same time, highlighted the difficulty of bringing together the work of town-planners, architects, geotechnical and structural engineers. In 2003 Beolchini [18] proposes a quantitative assessment of earthquake performance of an historical centre, although making reference to conceptual elements (such as regular areas) not directly linked to urban fabrics. His approach is reinstated by Ferlito and Pizza [19] for the evaluation of the emergency mobility in case of an earthquake.

The 2009 l’Aquila earthquake forced a multidisciplinary approach, also because many municipalities asked the support of Italian universities for the preparation of Reconstruction Plans of their historical centres. Many interesting contributions have been prepared, mostly independently, during 2011 and 2012 by different research groups [20]-[23].

In this paper the work performed by "Sapienza" University of Rome, in a multidisciplinary group led by Lucina Caravaggi, for the municipalities of Lucoli, Ovindoli, Rocca di Cambio and Rocca di Mezzo, Homogeneous Area no. 9 (Figure 1), is presented. These are the first plans for an entire homogenous area, 23 historical centres, to be proposed. A complete account on the plans, whose preparation has been carried out between March and December 2011, can be found in [23] and at: www.ricostruzioneareaomogeneaneve.it. In April 2012 the first draft of the Italian guidelines for historical settlements appears [24], and it is interesting to note that several of the recommendations to be found therein have already been considered by these Reconstruction Plans. This is evidence that several topics have become mature within the scientific community and were ready to be shared with public officials and private practitioners.

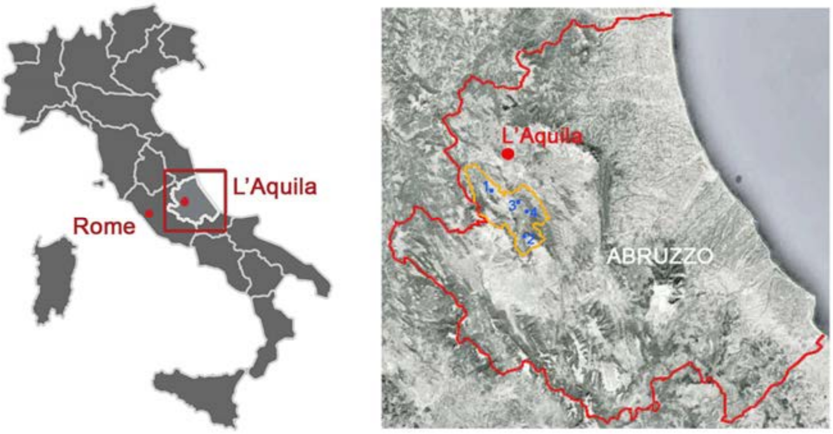



Figure 1: Homogenous area no. 9, within the Abruzzo region. Municipalities of: 1 = Lucoli, 2 = Ovindoli, 3 = Rocca di Cambio, 4 = Rocca di Mezzo. The historical centres have a height above mean sea level between 950 and 1450 m.

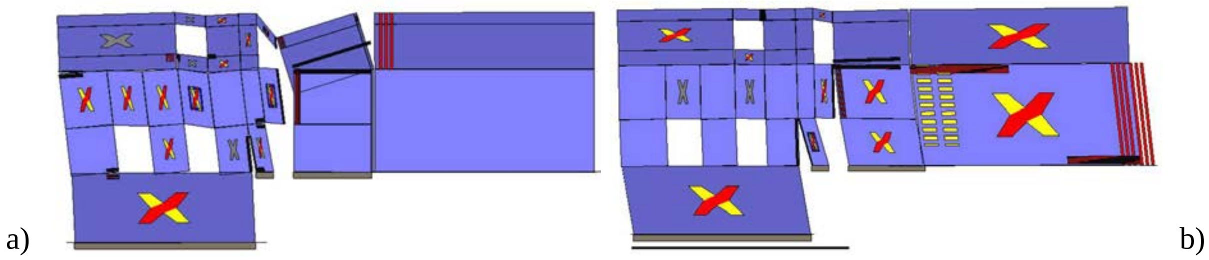



Figure 2: Damage state of a Building Aggregate of Prata, municipality of Lucoli: a) as-built; b) after injections on some of the walls (underlined) [25]. The aggregate has been modelled by means of 3D-Macro [26].

## 2 GOVERNING THE INTERVENTIONS

### 2.1 Building Aggregates

According to the procedure established after the 2009 earthquake, the private owners of properties belonging to historical centres cannot perform reparations or retrofitting independently, but they have to establish consortia referred to Intervention Building Aggregates. A first step considered in the Reconstruction Plans is that of defining such aggregates. In the Italian standards and codes there was no definition of Building Aggregate, which is here defined as: a set of inhomogeneous buildings without separations, or connected by means of structural links more or less effective, interacting during an earthquake. Such interaction needs to be assessed both in the as-built state and after the envisioned interventions. Partial interventions, due to uncoordinated design by different stakeholders, can induce an uncontrolled migration of the damage from a zone of the aggregate to another (Figure 2). Moreover, within the guidelines for the practitioners prepared s part of the Reconstruction Plans, the simplified procedure proposed in [8] for the assessment of the global response has been compared to non-linear static analyses.

### 2.2 Categories of intervention

The Reconstruction Plans suggest the category of intervention for each of the approximately 3000 buildings belonging to the 23 historical centres. The Categories of Intervention are derived from those in Italian Building Code [27], but are specialised because referred to historical buildings, belonging to a specific area, damaged by an earthquake. These categories are: Ordinary Maintenance, Extraordinary Maintenance, Requalification, Restoration, Renovation, Demolition, Reconstruction. The Implementing Technical Standards, for each category and for each element, specify: performance criteria (the objectives to be pursued), allowable interventions (a casuistry of possible interventions among whom it is necessary to choose), execution guidelines (specifying the scope when one intervention can be more effective than another). A matrix relates the Categories of intervention to the constraints on structures, position, shape, material, colour (Table 1). In order to show how the categories of intervention can be applied on actual buildings, a few graphical examples are produced: the Figurative Standards. These worked-out case studies allow presenting more effectively to the practitioners the Implementing Technical Standards, which have a written-only format, and to guide public officials in the review on the design proposals.

Table 1: Constraints associated to each category of intervention.

| Ordinary Maintenance | Extraordinary maintenance | Requalification | Restoration | Renovation | Demolition | Reconstruction |
|---|---|---|---|---|---|---|
| structure | structure | structure | structure | - | - | - |
| position | position | position | position | position | - | position |
| shape | shape | - | - | - | - | - |
| material | material | - | - | - | - | - |
| colour | - | - | - | - | - | - |

### 2.3 Building Units

Since the early stages of the drafting of the Reconstruction Plans the problem of the morphological reference for the categories of intervention has been stated. Such reference cannot be the cadastral parcel, because sometimes too wide, some others too fragmented, to adequately represent the physical condition of the buildings within the historical centres here considered. Such morphological reference is found in the Building Unit, defined as a portion of the urban fabric made of a three-dimensional aggregation of roof-to-foundation built cells, presenting some individual characteristics from the typological, morphological, architectural, structural and/or functional standpoints [28]. The Building Unit usually consists of several real estate units. To the Building Unit are linked quantitative information (number of stories, heights, and so on) and qualitative information (high-quality architectures). The Building Unit contributes to describe the spatial relationships and the topological interactions between the single elements of the urban fabrics, recognising their possible configurations and how they have been produced. The knowledge of the architectural features of the Building Units will also contribute to the seismic strengthening design. The Building Unit is identified based on: i) the geometric analysis of the cadastral map, of the aerial photos, and of the façade layout (opening arrangement and horizontal structures alignments), ii) the survey of the decorative elements (opening cornices, roof eaves, balconies, and so on), iii) the building typology (Figure 3). Moreover, the façade investigation can lend information of the different building phases. The recognition procedure of the Building Unit is meant as an evolutive and incremental process, open to new and additional information originating from a more extensive survey of the building.

According to the previous definition, the Building Units of historical centres are systematically identified and to them the categories of intervention are linked. The process of assigning a category of intervention is based on the seismic damage of the building, its quality, its current state of maintenance and alteration. The categories of Maintenance are assigned only if the building is habitable; moreover, to habitable buildings a higher category of intervention is assigned shall the owners wish improving the earthquake performance of their building. The choice between Requalification, Restoration or Renovation is based on the quality of the Building Unit and on the quality of the surrounding constructions, while Reconstruction has been confined to buildings with substantial collapses. In the whole Homogeneous Area, Requalification is assigned to about 80% of the Building Units, Restoration to about 17%, Renovation to 0.7%, Reconstruction to 1.7%, Demolition to 0.6%. With the exception of Ordinary Maintenance, which can be limited to a single real estate unit, interventions shall be performed at least on the whole Building Unit. However, the consequences of several structural interventions shall be evaluated on a Building Reference System, which can comprise even the whole Building Aggregate.

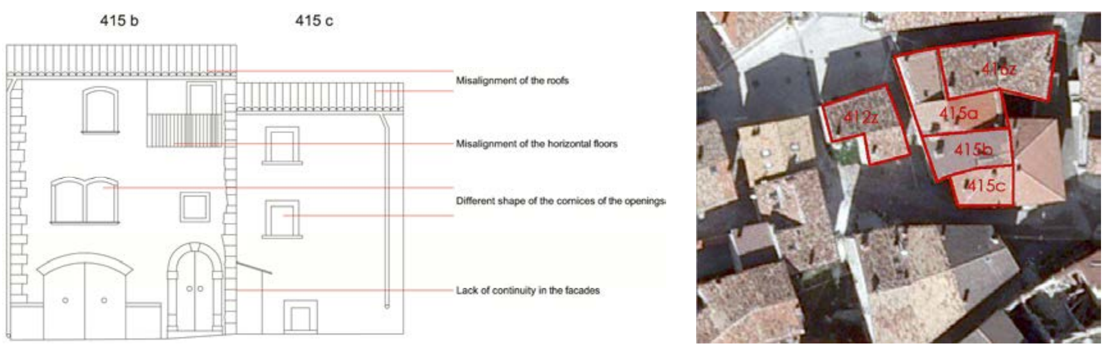
a)  b)


Figure 3: Identification of a Building Unit in Terranera, municipality of Rocca di Mezzo.
Analysis of the: a) Elevation; b) Aerial photograph.

## 3 INVESTIGATING THE FEATURES OF THE HISTORICAL CENTRES

The identification of the Building Units and of the appropriate Category of Intervention need a preliminary knowledge of their history, construction details, vulnerability. The Reconstruction Plans give the chance to perform specific investigations. Archive and literature sources before 19th century do not supply secure information about neither the palimpsest nor the so-called minor urban fabrics. Therefore, a direct survey of relative and absolute chronological indicators has been performed. Stratigraphic relationships are defined based on the observation of cornices and other decorative elements, of arrangement and modification of the openings, of alignments and irregularities of façades, of vaults and external stairs, of the interlocking of masonry intersections, of patent discontinuities, of the manufacture of stone and encasements, of functional additions and of wiring, plumbing and meter allocation. At least six growth phases, between Middle Age and 20th century, are summarised for most of the historical nuclei. Based on such data higher quality Building Units are identified, and these will receive additional financial support from the State.

Apart from scanty written evidence and direct observation of chronological indicators, information about construction phases can be derived from the Morphanalysis, which is based on the study of the layout of the masonry walls, of the cells, and whole architectures [29]. Morphanalysis can lead to the recognition of non-synchronous wall intersections, frequently responsible for the activation of local collapse mechanisms. Such mechanisms can be identified also through the examination of performances. Masonry crumbling has been observed several times, due to the use of non-dimensioned natural stones, inadequate connection between external leaves, poor mortar quality. Sometimes the crumbling has been triggered by large timber elements embedded in the masonry, as an historical earthquake-resistant intervention (Figure 4, refer also to [30]). In addition, this type of masonry does not allow very effective connections between the walls; hence, the façades are prone to out-of-plane mechanisms, especially if the roof develops some thrusts on the walls. In-plane damages have been more severe in the case of irregular arrangement of the openings and extensive reduction of the cross sections due to wiring, plumbing and meter allocation. Towering or added elements can induce severe damage, due to dramatic change of vertical stiffness.

a)  b)

Figure 4: Masonry crumbling induced by an internal timber tie. Colle, municipality of Lucoli.

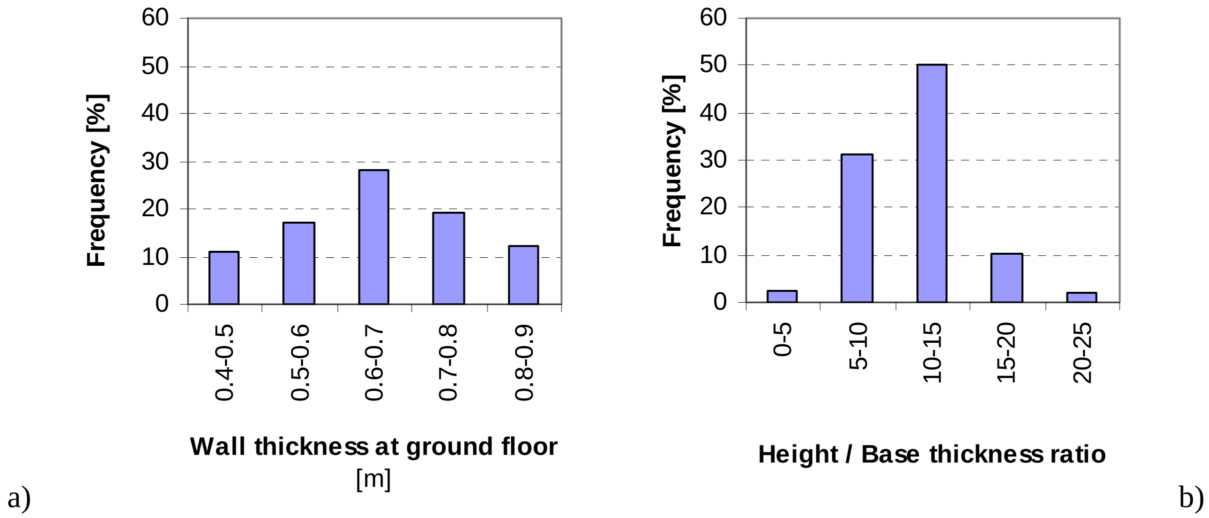



Figure 5: Geometrical parameters of the walls in the 23 historical centres (296 samples). Distribution of frequencies: a) Wall thickness at ground floor; b) Height / Base thickness ratio.

Table 2: Geometrical parameters of the walls in the 23 historical centres (296 samples).

| | Wall thickness (ground floor) [m] | Wall height [m] | Wall spacing [m] | Spacing / thickness ratio [-] | Height / thickness ratio [-] |
|---|---|---|---|---|---|
| mean - std dev | 0.53 | 5.56 | 3.21 | 4.33 | 7.83 |
| mean | 0.70 | 7.51 | 5.29 | 7.99 | 11.29 |
| mean + std dev | 0.87 | 9.46 | 7.36 | 11.64 | 14.75 |

Non-structural elements, such as roof-tiles and chimney pots, have failed frequently, being hazardous for the people leaving the buildings and for the search-and-rescue teams. Reinforced-concrete ring-beams and slabs have sometimes worsened the performance of the building. All strengthening interventions, both historical and modern, are systematically mapped in order to assist the practitioners in the design process. From this brief list it is clear that vulnerability is entangled with constructive details. In addition to the survey of the elements previously mentioned, approximately three hundred masonry walls are investigated, surveying thickness, spacing between transverse walls, total height, and related ratios. Average thickness at ground floor is approximately equal to 0.7 m, typical height-to-thickness and spacing-to-thickness ratios are equal to 11.3 and 8, respectively (Figure 5 and Table 2). Such geometric database is possible the first on historical buildings; it will help practitioners for preliminary assessment of their buildings and can guide the choice of suitable sizes for future physical and experimental tests. Moreover, specific structural details have been documented, such as an overhanging beam used for the roof eaves, or site-specific wall anchors resorting to timber, not always effective in preventing damages [30].

## 4 LOCAL DAMAGE AND GLOBAL PERFORMANCE. SOME CONCLUSIONS

The differences of vulnerabilities, the spatial variation of earthquake ground motion, the possible stratigraphic and topographic local amplifications, involve an uneven damage distribution between municipalities, within a historical centre and along a Building Aggregate. The damage occurred to the buildings of the historical centres is documented in terms of rate and distribution of uninhabitability. The percentage distribution of the habitability outcomes of each historical centre can be very different, and uninhabitability can be as high as 52% in Rocca di Cambio and can exceed 70% in Colle and Prata, within the municipality of Lucoli, despite the macroseismic intensity been estimated between VI and VI-VII European Macroseismic Scale, with the exception of Colle, Rocca di Cambio and Terranera (Rocca di Mezzo) where a VII intensity is estimated [31]. However, uninhabitable buildings are not equally damaged. Damage can vary as for extension and grade. In order to fine tune the damage assessment, all the survey forms of uninhabitable buildings are quantitatively analysed, in order to assess how much the damage to each structural component is extensive and severe (Table 3). Moreover, assigning a weight to each component (Table 4), it is possible to determine a synthetic damage index for each building. The index can be as low as 0 (no damage to all structural components) and as high as 1 (very heavy damage in more than 66 % of elements of each structural component). The weights in the tables are assigned based both on expert judgement, resulting from a few hundred inspections after the 2009 earthquake, and literature data. A damage index of the whole historical centre is derived from the damage index of its Building Units; this can be as low as 0.05 in Santa Jona (municipality of Ovindoli), and as high as 0.37 in Colle (municipality of Lucoli). The distribution of Building Unit Damage Indexes is compared to the results of the level 1 seismic microzonation, carried out within the Reconstruction Plans, highlighting possible topographic effects in Rocca di Cambio, Rovere (Rocca di Mezzo) and in sectors of Lucoli Alto and Casavecchia (Lucoli), and stratigraphic effects in Collimento and Prata (Lucoli).

The level 1 seismic microzonation is carried out not only for all the Reconstruction Plans perimeters but also for all the buildings, areas and routes assigned to emergency management. As a matter of fact the performance of an historical centre, or even a larger territory, cannot be seen as the simple sum of the performances of its elements. There are interactions between strategic buildings (e.g. city hall, school, police station, and so on), their surrounding open-air areas, the routes connecting them to the residential areas, to the emergency areas (for materiel stocking and for sheltering of the population), to regional facilities (hospitals, fire-fighters barracks, motorways, and so on), and the buildings located along such routes.

Table 3: Building Unit Damage Index. Influence of damage grade and extension. Note that grade and extension are independent one from the other, and more than one grade of damage is possible for each structural component.

| Grade | Very heavy | | | Medium severe | | | Slight | | |
|---|---|---|---|---|---|---|---|---|---|
| Extension | > 66 % | 33-66 % | < 33 % | > 66 % | 33-66 % | < 33 % | > 66 % | 33-66 % | < 33 % |
| Weight | 1.000 | 0.660 | 0.330 | 0.500 | 0.250 | 0.083 | 0.330 | 0.165 | 0.054 |

Table 4: Building Unit Damage Index. Influence of structural component.

| Component | Vertical structures | Floors | Stairs | Roof | Partitions | Pre-existing damage |
|---|---|---|---|---|---|---|
| Weight | 0.50 | 0.20 | 0.10 | 0.10 | 0.05 | 0.05 |

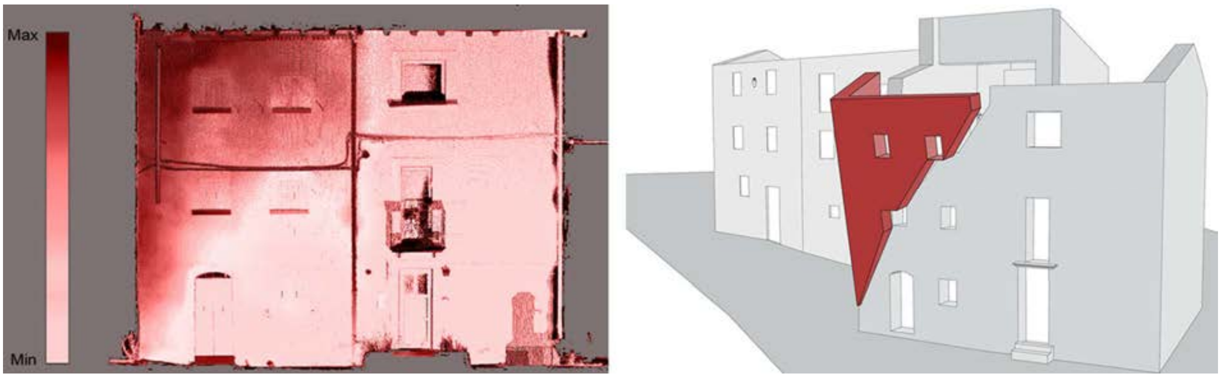



Figure 6: Identifying local collapse mechanisms through laser scanning [34]. Rovere, muncipality of Rocca di Mezzo.

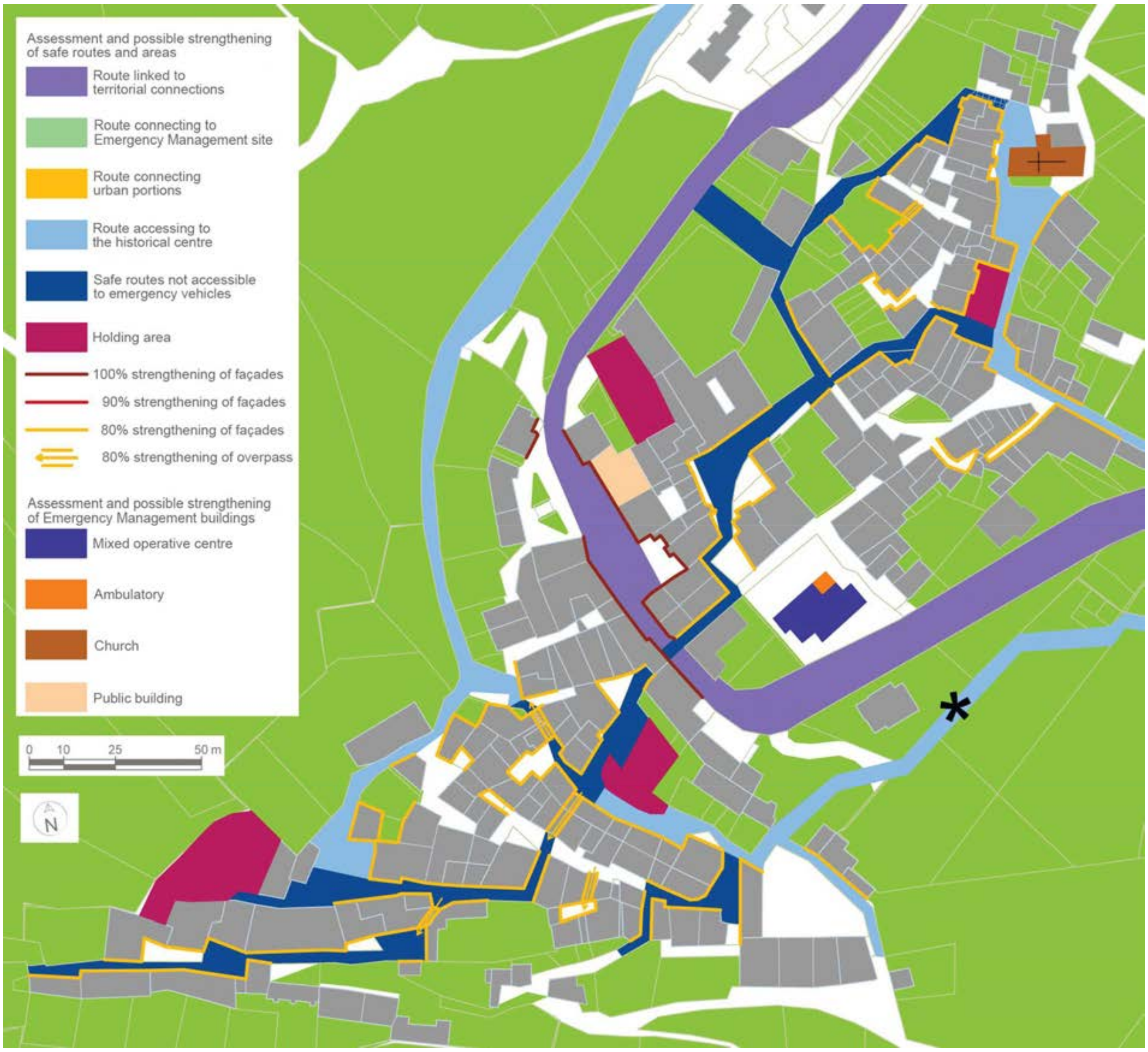



Figure 7: Interventions for the management of an earthquake emergency. Collimento, municipality of Lucoli.

Hence, general town-planning instruments cannot avoid addressing the seismic risk mitigation of historical centres. It is necessary to foster a rational upgrading of territorial ties, of urban connections, functions and societal spaces, of public networks. Usually Italian historical centres show a low redundancy of the system of roads and alleys. Therefore, local out-of-plane overturning of a few façades can strangle the whole system [32]-[33]. The vulnerability to such mechanisms is analised, as mentioned, with reference to building geometry and to local construction details. Moreover, specific procedures are proposed to assess the effectiveness of the connections between masonry walls, through the previously quoted Morphanalysis. Additionally the delicate task of identifying the local collapse mechanism is resolved resorting to three-dimensional laser scanning [34]. The representation of deformation can make the assessment more robust through an appropriate kinematism selection and a careful representation of the actual geometry (Figure 6). What is clear is that although the mechanisms usually affect a local portion of the building they can influence the global performance of the historical centre. Hence "local" and "global" are strictly entwined. The Reconstruction Plans can improve the disaster performance of the historical centres, by improving the overall performance of each building and by scaling intervention policies based on the consequence of a local performance on the global behaviour (Figure 7). Consequently, for each historical centre of the Homogeneous Area all the routes are classified as territorial connections, or connections to Emergency Management sites, or connections between urban portions, or routes accessing to the historical centre, or safe routes not accessible to emergency vehicle, or secondary routes. Safe routes are identified so that the maximum distance to a dwelling entrance is less than 50 m, in order to account for the presence of snow for several months of the year. For each of these routes specific requirements are stated for the overlooking façades, according to a damage tree approach. Hence, façade on primary routes will need to resist a higher seismic action compared to façade overlooking local routes (Figure 7). Thus, by linking local collapse to global performance the Reconstruction Plans will foster a systemic improvement of seismic performance and will guide the allocation of public expenditures within a limited-resources scenario.

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