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PROGRESS AND PERCEPTION OF SEISMIC STRENGTHENING IN A STONE MASONRY VILLAGE

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ABSTRACT

A mountain village in southern Italy was abandoned about twenty years ago because of earthquake risk and of the cost and uncertainties in its strengthening. Today, strengthening techniques are more reliable and commonly practiced and there is new interest in the rehabilitation of the village. At present, the complex, guarderd but not inhabited, may be accessed for study purposes, offering an exceptional opportunity as an open-air lab for experimenting in-situ studies and techniques, ranging from the analysis of masonry on full-size cases to the detailed study of vulnerability of a typical mountain village. Indeed, the situation of this center is not unique, but is representative of many mountain villages, some of which have similarly been deserted because of environmental hazard. The first part of a research program based on this village concerns the assessment of seismic vulnerability for the buildings. Results on a first set of buildings indicate a vulnerability level corresponding to the national average, with only a small variance. The vulnerability would be significantly reduced by a limited amount of strengthening interventions suggested by the survey, that would not involve extra costs besides those necessary for rehabilitation in order to inhabit the village.

Introduction

For many towns and villages that are many centuries old the problem of mitigating the seismic risk is strictly connected to quantifying and possibly reducing the vulnerability of their stone masonry buildings. The village of Laino Castello, located in the southernmost part of Italy, is posing an interesting problem of seismic risk management. Like many Italian historical towns, Laino nestles on a steep slope in an area of moderate-to-high seismicity, where the peak ground acceleration according to the recently issued national seismic zoning is 0.25g, with 475 years return period. Twenty years ago, after a period of a few years when highly damaging earthquakes had stricken the Country, the village, composed of about 70 stone masonry buildings, was abandoned because its seismic strengthening appeared necessary but not economically convenient: residents moved to a newly-built village nearby. In the elapsed period no significant seismic event occurred, therefore Laino suffered no damage, except from natural

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decay. Meanwhile, greater consideration for the cultural value of historical towns and villages has developed. The stronger sensitivity toward conservation is supported by more widespread knowledge and use of strengthening techniques that have become more reliable and affordable and are now regulated by very detailed codes in Italy and Europe. In this context, a new interest has risen for recovering and strengthening all, or a major part, of the village, that is of interest also for being located in the area of the Pollino Mountain Natural Park. It is worth mentioning that the situation that occurred at Laino is not unique, as other villages on the national territory present similar conditions, having been abandoned because of environmental hazard, mainly related to earthquakes and landslides. Many other mountain villages have similar characteristics, but are regularly inhabited, which adds interest to the results expected from the study of Laino. A view of Laino is shown in figure 1.

Figure 1. View of the village of Laino Castello

In order to analyze the seismic problem of Laino and to define possible interventions for improving its expected response to seismic events, the current level of seismic risk of the village must be evaluated, considering the recently updated local seismicity map and the vulnerability level of the buildings in the current conditions.

At the same time, the complex, being guarded but not inhabited, grants almost unlimited access to its buildings for study purposes, offering an exceptional opportunity as an open-air lab for experimenting in-situ studies and techniques. These range from the analysis of masonry on full-size cases, including a limited and selected number of partially destructive tests, with the objective of evaluating strength characteristics toward horizontal and vertical actions, to the detailed study of vulnerability of a typical mountain village, according to current techniques and to newly devised and possible refinements. For these reasons, the village has been chosen as subject of a research program with objectives that extend beyond the problem of Laino alone. The program is organized in the following points and is currently in progress:

- the refinement of the indications given by the national seismic map through the analysis of possible local effects, in order to improve the definition of seismic hazard;
- the analysis of vulnerability in the present state of the buildings; this task is performed

applying a method for vulnerability survey developed in Italy and adopted in several cases in different areas of the Country; the method, summarized in the following, yields a vulnerability index for each individual building, pointing out its possible deficiencies, and permits to develop statistics for the entire building stock;

- the estimation of vulnerability in different situations besides the present state of the building stock, which is partially degraded: the estimated original state when the village was inhabited, and the states that may be expected as a consequence of various possible reinforcement strategies suggested by the results of the survey. Basic interventions associated into strengthening strategies consist typically in improving the connections between vertical walls, and the quality and connection of slabs, in eliminating thrusts from roof structures, etc. On the basis of costs and vulnerability reduction, a cost-benefit analysis may be performed in order to support a decision-making process;
- the study of the mechanical properties of the stone masonry, that is typical of many mountain villages; for this point, detailed information is to be obtained from in-situ experimentation, that is being carried out by means of flat jacks.

First results and observations, particularly for what concerns the vulnerability analysis, are available and are presented here.

The local seismic history

The village of Laino was deserted in the early eighties of the 20th century. The catalog of historical earthquakes (Monachesi) lists five seismic events felt at Laino between the years 1630 and 1980, all of medium intensity. Indeed, the epicenter areas of earthquakes in the region have always been quite distant, with the exception of the earthquake of Pollino occurred in 1894.

The seismic zoning of the Italian territory introduced just after 1980 and based mainly on historical and statistical criteria assigned to the municipality of Laino the second category, that is, a medium seismicity, on a scale of three. A new classification, introduced very recently and based mainly on geological and geophysical criteria confirms Laino to be in the second category zone.

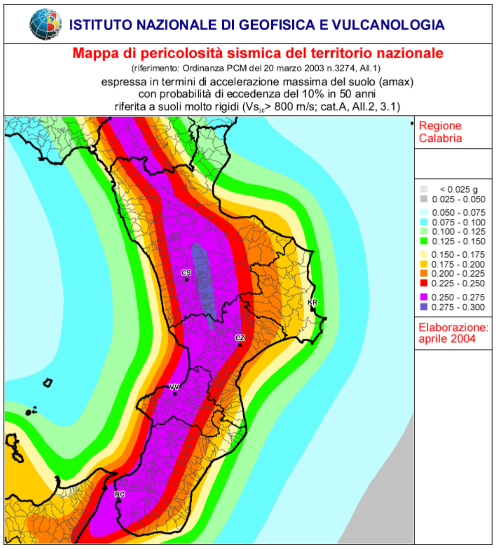

Figure 1. The hazard map for Region Calabria. Laino is located in the upper part of the Region, at the border between zones with expected peak ground acceleration of 0.225-0.250g and 0.250-0.275g.

The seismic hazard map produced by INGV, the Italian National Institute for Geophysics and Vulcanology (figure 2), that has a finer resolution, specifies a peak ground acceleration of 0.250-0.275 g for the reference return period (475 years), confirming the attribution of Laino to the upper border of the second category, that is a medium-high seismicity.

A first survey of the building stock has shown the absence of significant seismic damage in the 20 years after the village was deserted, in spite of a medium intensity earthquake that occurred in the Pollino mountain area in the early nineties. No cracks amenable to horizontal action appear, while slender elements like chimneys and some single walls standing alone after their counteracting elements were removed are well preserved in the original configurations.

The present state of the buildings

A first survey of the whole village, with recognition of each of its buildings has been carried out in order to appreciate the general situation by examining the common construction characteristics as well as the present state of damage and decay (Ambrogio, 2005).

The character of local construction may be well interpreted by the following points:

- masonry is basically made with local stone, usually gravel from the river and blocks of larger size, bonded with mortar; an external layer, up to 10 cm thick, consists of smaller stones and brick pieces that make the wall appear more regular; in some cases a further layer of plaster finishing is present;
- from the observation of several basements of the buildings, it appears that walls are directly founded on rock;
- floor slabs and beams are in timber, except for a small number of cases were vaults are present;
- roofs are simple, either of single-pitch or of gable type, mostly with eliminated thrust;
- in spite of the use of "poor" construction material, a good quality of workmanship may be observed in the construction of the masonry and in many details, like the absence of large openings at the lower levels of the walls, the absence of thrusts from the roof structures, the direction of slabs consistently normal to the slope, and the like;
- on the other side, some structural elements that are typically present in seismic areas, like ties and hoops, are rare here;
- buildings are often connected one to the other, in different aggregation layouts. Additionally, because of the slope, the buildings have irregular heights, varying from one side to the other.

As to the present state, the major problem seems to be in the absence of maintenance. In particular, roofs are now decaying and may worsen rapidly the situation of the rest of the buildings. Indeed, most of the crack patterns observed in the buildings are not indicating serious damage situations and are reasonably amenable to inconsistencies in the original conception, to local problems, or to natural decay. No damage from past earthquakes is evident.

The assessment of seismic vulnerability

The evaluation of the seismic vulnerability with a well-tested method that could offer also comparisons with other cases is the first step of this study. The following sections present a brief review of the method adopted and its first applications to the buildings of this case-study.

The method of the vulnerability index

After the severe earthquakes that struck Italy in 1976 (Friuli) and 1980 (Irpinia), methods for evaluating the seismic vulnerability of existing buildings were defined and developed. These methods were intended primarily to supply information on a large numbers of buildings, refering to towns and possibly whole regions, in order to gather information and build statistics for the assessment of seismic risk, with risk mitigation purposes. One method in particular, the method of the "vulnerability index", has been applied in several instances in different parts of the national territory and has permitted to obtain a good picture of the building stock characteristics of the surveyed areas, making also comparisons possible between areas (Benedetti, 1988; Petrini, 1993). It is briefly outlined here. The method is semi-empirical, as it involves observations and measuring of the building features and a limited amount of computations in order to derive a conventional value of lateral strength. It rests on the assumption that the level of vulnerability of a building may be expressed by a global parameter, the vulnerability index, obtained as a linear combination of partial indices grading the various structural and non-structural characteristics of the building. The method was originally devised for residential masonry buildings, the most common typology that had shown to be also the most at risk during earthquakes, and has been subsequently extended to other typologies. The grading process involves several steps. After surveying a building, each item to be considered is assigned to one of four classes according to its measured or observed characteristics; a numerical value corresponds to each class, yielding a partial index, that is modified by a factor indicating the confidence in the evaluation performed, and that is affected by a combination weight. The significance of the items considered (table 1) is very clear, these being simply the fundamental elements that contribute to the seismic response.

Table 1. Elements to be considered for vulnerability assessment

1.	Type and organization of the lateral force resisting system
2.	Quality of the resisting system
3.	Conventional strength
4.	Position of building and foundations
5.	Floor systems
6.	Horizontal layout regularity
7.	Regularity in elevation
8.	Maximum distance between parallel walls
9.	Roof system
10	Non-structural elements
11.	Present state of the building (damage, decay, etc.)

First results from the survey

A first set of 7 buildings, a 10 percent of the total, have been examined following the procedure for evaluating the vulnerability index and are the basis for the considerations developed in this work.

The buildings were chosen in order to represent different layouts that are recurring in the village: a compact, almost square plan and rectangular plans with different aspect ratios; one of the buildings considered had an almost square but very large plan layout. Figures 3 and 4 show typical plans and the front view of a building.

Considering the various points listed in table 1, the survey of vulnerability has permitted to highlight a few characteristics of this subset of the building stock that are expected to be reasonably applicable to the whole.

The first and the second point of the survey form concern the lateral force resisting structures. All the buildings examined may be attributed to class (*C*) in a set of four classes, down from class (*A*) that corresponds to the best situation, i.e. a structure that satisfies completely the normative requirements for new buildings.

The third point concerns the building capacity toward horizontal forces. A parameter, C, representing conventionally the resistance, is evaluated on the basis of the section of walls contrasting the force and of the characteristic shear stress, τ_k, of the masonry. The value adopted for τ_k highly conditions the parameter value. For the type of stone masonry considered, according to normative indications and to literature results a value between 4 and 5 N/cm^2 is expected. The upper value has been adopted here, upon inspection of the masonry. The experimental part of the research program, however, includes testing of the masonry in shear according to a test setup described in a following section. These experiments, in progress to date, will avoid the problem of interpreting the shear stress value from observation and tables. The final vulnerability assessment of the entire building stock will be based on this experimental datum eliminating a source of variability in the result. The conventional lateral resistance parameter, C, is defined as the ratio of the total shear that can be transmitted to the base through the wall sections and the weight of the building on the same sections. Various uncertainties affect the computed value of C. These uncertainties derive in a limited amount from considering only the self-weight. With the kind and thickness of masonry involved, including a fraction of one-third of the relevant live load, as requested for new design would not modify significantly the parameter value. The choice of the reference level at which sections have to be measured is a more significant source of uncertainty in these buildings of often irregular shape and, particularly, resting on a slope. At the same time, more sophisticated evaluations of the weights and of other factors are beyond the accuracy level of the method.

The fourth point is related to the foundation system. Almost all the buildings in the village, including those seven considered in the survey, are founded on rock. This positive aspect is counterbalanced by the slope of the ground that is consistently present in all the cases considered. The resulting value for this partial index is affected by both aspects.

Horizontal elements are considered at point 5. All the slabs were fabricated with the same technique: timber beams in chestnut, a tree abundant in the region, are all regularly spaced with the same interval, given by the application of a local traditional unit for linear measures that amounts to just over 1 meter. The slab is composed of chestnut boards and by a filling material, a mortar of poor quality, forming a base for the floor. This layer is thick and heavy: thickness is between 6 and 10 centimeters. In these conditions the floor structures are inconsistent with the two requirements for being classified in classes (*B*) or (*A*), i.e. satisfactory or good from the point of view of seismic adequacy: high in-plane stiffness and effective connection with the walls. Consequently, this point has generally been evaluated with class (*C)* or (*D*) depending from the specific case. This same point is, however, easy to improve: strengthening of the floor system would reduce vulnerability considerably and bring it into class (*A*). It is important to remark that this kind of intervention is quite standard in the rehabilitation of old buildings for new occupancy, even without reference to the seismic problem and would not impose additional costs for seismic protection. In the case of Laino, the elimination of the thick mortar layer and its substitution with lighter products would surely be performed. According to present technologies, the filling layer would be eliminated reducing the weight, and a thinner concrete slab including a steel net reinfocement would be laid on the timber boards and fixed to them and to the borders, realizing also a suitable connection with the walls. For this operation, attention should be exerted in avoiding excessive local stiffening.

The following points 6, 7 and 8 concern basically some geometric information. In particular, points 6 and 7 describe the regularity in the layout and in elevation. The latter is not respected when there are porches at the first story or when towers, lodges and the like are present and vary the height of different parts of the building. No porches that may induce a soft story behavior are present in Laino.

For point 9, roofs apply no thrust on the walls, yet no ring beams to connect and strengthen the upper border of the walls are present. As a consequence, roof systems are classified in class (*C*). Here again, simple rehabilitation interventions would upgrade this point to class (*A*). Indeed, roofs would surely be restored, in case of a new occupancy of the buildings.

Points 10 and 11, that concern non-structural elements and the present state of the buildings, are undoubtedly classified negatively, because no maintenance was performed for an extended period, causing degradation of many elements, like windows etc. Once again, these two points would rise to higher classes should the building be rehabilitated even without particular attention to the seismic question.

Table 2. Results of the vulnerability analysis on a subset of the buildings

Building #	**Number of stories**	**C, lateral strength coefficient**	**Vulnerability index**	**Vulnerability index after strengthening**
1	4	0.19	43.5	26.8
2	2	0.31	34.0	17.3
3	4	0.16	46.1	29.4
4	3	0.24	37.9	21.2
5	4	0.18	41.2	22.9
6	3	0.23	49.7	33.0
7	3	0.20	45.4	28.8

Table 2 shows the result of the evaluation on the sample. The second column indicates the number of stories of the building, the third column reports the lateral resistance coefficient, calculated for classifying point 3 of the survey procedure, the fourth column shows the vulnerability index evaluated for the building. The last column reports the vulnerability index that would be obtained in the assumption of carrying out the retrofitting interventions discussed for the floor structures, the roofs, and the general maintenance, i.e. those operations that would be required to inhabit the buildings again, but performed with special attention to the seismic requirements. The scale for the vulnerability index is 1 to 100, with 100 corresponding to the highest vulnerability.

A first remark concerns the conventional lateral resistance, with the assumptions made on the characteristic shear stress. In this first estimation τ_k was assumed equal for all the buildings considered and has no effect on the variability of C. One factor influencing this parameter is the weight of the building. Walls are similar for all the buildings, with thickness deriving mainly from local constructional tradition. As a result, the determining factor is the number of stories of the building, as may be seen comparing the second column and the third.

The vulnerability index values obtained have an average of 42.5 and a standard deviation of 2.2. These figures, compared with corresponding values obtained in other regions, indicate a medium vulnerability level. Indeed, the obtained average corresponds almost exactly to the national average computed from many different surveys in various parts of the Country, considering buildings characterized by a low maintenance state (Petrini,1995). The general standard deviation, however, is considerably higher than what obtained in Laino, because some of the surveys elsewhere had supplied consistently higher levels of vulnerability.

The improvement that may be obtained with interventions that are not particularly intensive, but are rather standard when a building is to be rehabilitated for new occupancy may be appreciated in the reduction of the vulnerability index shown in the last column, averaging 25.6, a rather low value also in the national perspective. These results must be interpreted considering that the approach is mainly intended to give a general picture of the quality of construction in a town or region and some first basic information on the individual buildings, that would subsequently require a more detailed analysis. Other intervention strategies, their consequences on vulnerability, and the corresponding costs will be developed on the complete set of buildings. Yet, this initial study indicates that a moderate value of the vulnerability index may be expected from the analysis of the complete data set and that simple retrofitting interventions would further improve this value.

Other activities

Besides the vulnerability assessment, other activities are in progress or planned for the near future. Among these is the mechanical characterization of the local stone masonry. This study includes the above mentioned experimentation with flat jacks for determining in situ the shear resistance. This test is classified as partially destructive, also if the damage to the masonry is limited and repairable. The scheme of the experimental setup is shown in figure 5. The two jacks are positioned vertically and are not aligned. In this layout, pressure from the two jacks generates shear in the masonry between them. These tests are in progress to date.

Recent developments in the criteria for assessing vulnerability concern consideration of the effects of continuity between adjacent buildings, constituting structural aggregates, as well as the effects of sloping ground (Chesi, 2002). Aggregation in its many forms is bound to influence the seismic response of the buildings, yet it is not effectively recognized in evaluation criteria in their present form. Some proposals that recognize the characteristics of aggregation do exist, but are still in development or in an experimental phase. Similarly, the slope of the ground is considered in the vulnerability index; however it gives rise to additional potentially problematic aspects that need investigation both on the vulnerability and on the hazard side. One of these aspects that may affect vulnerability is the misalignment of floors in adjacent buildings; another is the difference in height of different parts of a construction. Their study on the Laino database is planned upon completion of the current vulnerability analysis on the complete building set and the interpretation of its results.

Conclusions

A research program analyzing various aspects of the seismic response of mountain villages is based on the situation of Laino Castello, a village abandoned years ago because of seismic risk and now considered for seismic strengthening and new occupancy. An analysis of vulnerability of the buildings is in progress. First results on a reduced sample of buildings have shown vulnerability index values that are not very high and comparable to the national average for buildings that were subjected to low maintenance. The vulnerability would be already significantly reduced by a limited amount of strengthening interventions suggested by the survey. These interventions would not involve significant extra expenses with respect to costs for the normal rehabilitation that would be necessary in order to re-inhabit the village.

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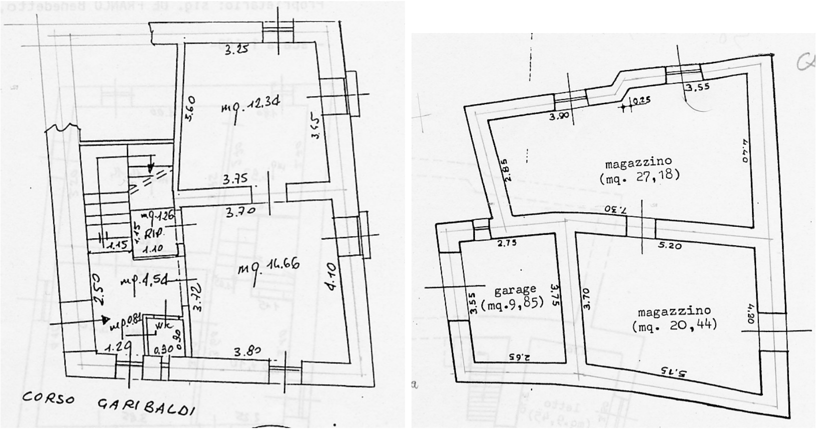

Figure 3. Two typical plan layout of the buildings of Laino, at ground level; shapes are often simple and compact.

Figure 4. View of a typical building

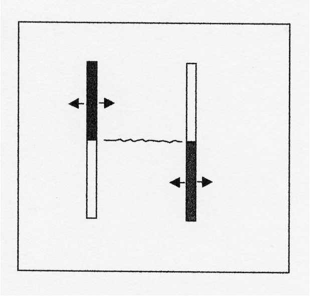

Figure 5. Scheme of the experimental setup for testing masonry in shear. Two parallel cavities contain the flat jacks, that are positioned as indicated by the solid black areas. Pressure exerted by the jacks generates shear stresses along the horizontal line, where a crack eventually develops.