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HISTORY OF AN EARTHQUAKE

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SUMMARY

The first images of the collapse of the school in San Giuliano di Puglia, due to the October 31st, 2002, earthquake went around the world. This occurrence raised the problem of the safety of the school building. But if the school collapsed immediately, causing the dead of 27 children, the other constructions of the town did not behave well under seismic actions. The seismic micro-zoning performed by the Italian Civil Protection Department, pointed out that the urban area of San Giuliano di Puglia is characterised by high amplification factors. This was not the only reason for such disaster. In fact, the analysis of the damaged buildings showed that almost all of them were made of perforated bricks and poor mortar and presented very large openings in the masonry walls, whose effectiveness was even reduced by the facilities. The objective of this presentation is to show, both to technicians and not technicians, the most relevant images of this catastrophes, selected from the images collected by RAI. The result is a film that represents the history of the seismic event, points out the most important lessons that can be learned, summarises the emergency activities, the post-emergency phases, with the demolition of the very damaged buildings and the beginning of the reconstruction. All the people hope that such a tragedy will not happen any more: this is the aim of our presentation.

INTRODUCTION

The earthquake that on October 31st, 2002, struck Molise region in Italy, became very famous because of the collapse of the elementary school building in San Giuliano di Puglia, which caused the death of 27 children and one teacher. The first images of the collapse went around the world (Figs. 1 and 2). All the people could see the hope of the parents, of finding their children alive under the debris of the building, dying hour after hour (Figs. 3 and 4). Perhaps if the school would not have collapsed and there were not such innocent victims, the Molise earthquake had been already forgotten by technicians and politicians. As a matter of fact it has not been a very strong event. The main shock had a magnitude of 5.3, and the same intensity had the higher aftershock, which happened the day after. Actually the seismic event interested a large area of Molise, but damages were not uniformly distributed on the territory. Severe damages were only in San Giuliano di Puglia, and even there these were concentrated in a part of the town, which included the unlucky school.
As well known, the seismic risk, i.e. the expected loss at a specified site due to an expected earthquake, is related to: i) the seismic hazard, which is a characteristic of the area; ii) the seismic vulnerability of the

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structures and iii) the exposure, which is related to the use of the territory, i.e., the distribution of the peoples, to the presence of infrastructures and to the use of the buildings. In order to reduce the seismic risk we should reduce one or more of the risk component. Obviously, we cannot act on the seismic hazard, although the knowledge of that is very important to define the actions on structures. We can change the exposition, choosing the best locations for our new cities and facilities and we can reduce the seismic vulnerability of new and old constructions.

Fig. 1. The collapse of a building during one of the first shocks

Fig. 2. The first night after the earthquake is approaching

Fig. 3. The search for children at the school

Fig. 4. Works at the school site

This aim of this paper, which will also be presented in a film version, is to analyse and explain in popular language what happened and why, in order to give a contribution in learning from that earthquake. The objective is to show, both to technicians and non technicians, the most relevant images of this catastrophes, selecting all the most interesting images collected by RAI (Italian National Network). The result is a film that represents the history of the seismic event, points out the most important lessons, which we can learn by this earthquake, summarises the emergency activities, the post-emergency phases, with the demolition of the very damaged buildings and the proposal for the anti-seismic reconstruction.

SEISMIC HAZARD ANALYSIS

San Giuliano di Puglia is a very small town of about 1200 inhabitants, located in a pleasant site (Fig. 5). Three zones can be individualised: i) the ancient centre, very interesting from a historical and architectural point of view, located on the top of the Southern hill; it was almost ruined and uninhabited in some internal zones; the most interesting constructions were San Giuliano Church and Palazzo Marchesale; ii) the central area, placed on the “saddle”, developed around the main street, the “Corso”, with buildings of the first decades of the twentieth century; iii) the Northern side, formed by buildings of 50s, often with concrete structure, which includes also the Western side. This different topographic situation reflects the seismic hazard and the occurred damages. Before the October 31st, 2002, earthquake, the area of San Giuliano di Puglia was not classified as seismic zone, even thought it was already mentioned among the “high seismic risk areas” [1]. In the new classification [2] it has been included in zone 2, characterised by a_g=0,25g.

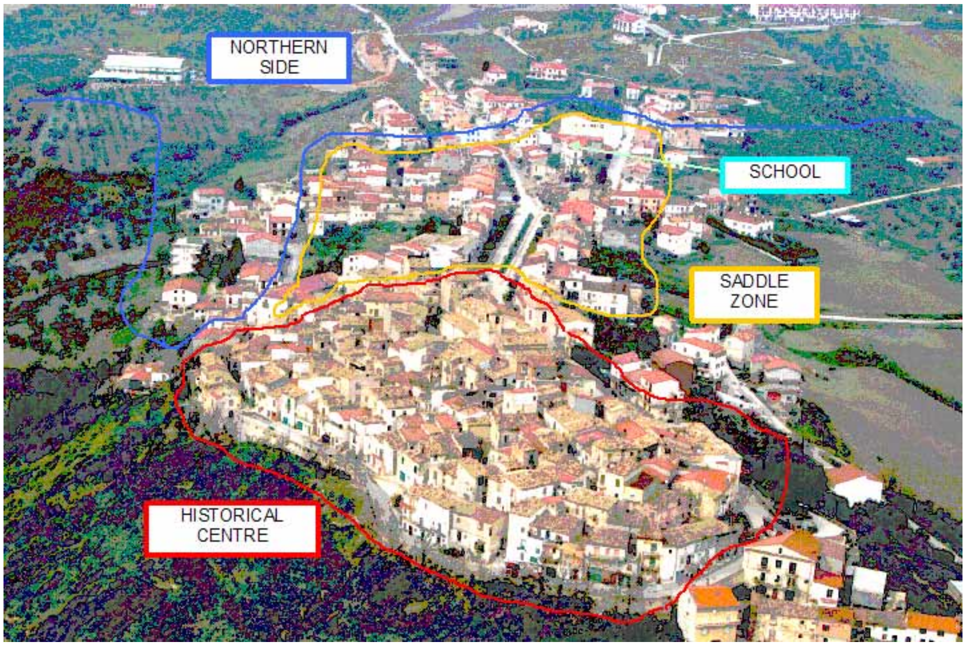

Fig. 5. The three zones of San Giuliano di Puglia

Hazard analysis

As well-known, the seismic hazard at a site is the measure of the earthquake intensity expected during a specified period of time. The parameters generally used to describe the seismic intensity level are the Macroseismic Intensity (MCS scale is commonly used in Italy), based on the damages observed in the defined area, and the Magnitude (for example Richter scale), which is a measure of the energy released at the source. None of these parameters is suitable to represent the seismic hazard. The new Italian seismic classification is based on the Housner Intensity, which can be better related to the damage to structures during an earthquake, and on the Maximum Macroseismic Intensity [3]. Besides, all the seismic codes refer to the Peak Ground Acceleration (PGA) to identify the seismic level for each zone. This is very useful for engineers and can be easily read from the corrected accelerograms (i.e., in which the effects of the noise have been eliminated). However, it should be noted that the scientific community does not consider it a suitable parameter to represent the ground motion and the related damages to structures, since it is associated to an high frequency impulse and is very sensitive to the correction technique.

Probabilistic seismic hazard assessment provides the value of a ground motion parameters (PGA or PGV) or a site spectrum with a given return period (under Poisson assumption it is also the parameter or spectrum with a given probability to be exceeded in a fixed time interval). The analysis is usually performed according to Cornell’s methodology [4] and requires the definition and characterisation of seismic sources and the choice of a proper attenuation law [5]. Since the intensity of historical earthquakes is mainly measured according to a macroseismic scale, a conversion to a magnitude scale is moreover necessary to obtain results in terms of ground motion parameters. The seismic sources which could affect the site can be selected by the analysis of historical data (seismic catalogues, which report source information, and macroseismic databases, which collect information about the observed local macroseismic intensities). At present, 80 seismogenetic areal sources are identified in Italy [6]. Each selected source must be characterised in terms of maximum magnitude and expected number of earthquakes as a function of magnitude. The attenuation laws for Italy were estimated from the records obtained by the Italian Accelerometric Network, set up by ENEA and ENEL in 70s and operated at present by the Italian Seismic Survey, which is part of the Civil Protection Department.

The analysis of the historical data pointed out that the seismic sources that can affect San Giuliano di Puglia are far from it and localised along the ridge of the Apennines. The maximum intensity at the site was estimate to be equal to VIII-IX MCS, observed both during the 1456 and 2002 events. Twenty-two events in the last eight centuries having intensities higher than V-VI MCS were observed. The return period has been estimated equal to about 250 years for VII-VIII MCS event and to 500 years for VIII-IX MCS event. With reference to a return period of 475 years (i.e., 0.1 probability to be exceeded in 50 years), this analysis gave for San Giuliano di Puglia a PGA of $0.165g$ [7]. It is worth noting that this value is lightly higher than $0.15g$, which is the maximum value for Zone 3 and is much lower than the minimum value for Zone 1, equal to $0.25g$.

Seismic microzoning

Due to administrative reasons, the seismic classification assumes the municipality area as unity. However, the expected motion can be different in a municipality area, depending on the soil condition, both in terms of amplitude and frequency content. The seismic microzoning study allow the subdivision of the territory in smaller areas, each characterised by the same amplification factor of the seismic motion, from the bedrock to the surface.

A methodology aiming at the seismic microzoning was recently developed and tested by ENEA in a small area located in the Central Apennines in Italy [8]. The study was developed in the following steps: i) detailed geological and geomorphological surveys of a wide area, which includes that of interest; ii) geomechanical characterisation of the rock-mass; geotechnical analysis of the soil, geoelectrical and seismic-refraction surveys to assess the geometry of the deposits; iii) measure of compressive (Vp) and shear (Vs) seismic wave velocities, by means of seismic-refraction prospecting; alternatively, cross-hole and/or down-hole tests should be carried out; iv) installation of temporary free-field triaxial velocimetric arrays aiming at the recording of both ambient noise and small magnitude earthquakes, in stations where the previous analyses pointed out local conditions which could induce amplification effects of the ground motion; analysis of the velocimetric records in time and frequency domain, to point out local effects; v) numerical modelling. The microzoning of the area is performed taking into account all the collected data. Strong motion recording or a suitable numerical modelling could allow to define the amplification factor for each zone. As well-known weak motion recordings could give amplification factors much higher than the effective ones.

The Italian seismic code accounts for the local effects by defining different soil classes, each characterised be a spectrum shape and an amplification factor S of the acceleration at the bedrock: S=1.00 for rigid soil (A), S=1.25 for medium consistency soils (B-C-E), S=1.35 for low consistency soil (D). The consistency of the soil is mainly measured by means of the shear wave velocity Vs.

Just after the earthquake, the Italian Civil Protection Department appointed a technical commission to perform the seismic microzoning in San Giuliano [7]. The results can be summarised as follows (Fig. 6):

a) the historical centre is classified as A1.2, i.e., soil A and amplification factor S=1.2; the saddle area is classified as B1.6 (soil B, S=1.6); the Northern side is B1.4 (soil B, S=1.4); small areas with lower hazard, at North and West of the historical centre, have been classified as A1.0 (soil A,

S=1.0);

b) the urban area was also divided into zones, characterised by three different degrees of slope instability hazard: LR – low risk, with instable soil thickness $t<1$ *m*; MR – medium risk, $1<t<3$ *m*; HR – high risk, $t>3$ *m*);
c) some stream phenomena have been pointed out, in the East side of the town, not related to the seismic event.

As you con see, the seismic microzoning reflects what already said about the presence of different areas (historical centre, saddle zone and North side) characterised by different topography and built in different ages. It is worth observing that the maximum spectral amplitude expected at San Guliano in zone B1.6 is lower than the amplitude suggested by the Italian Code for zone 2. This occurrence is mainly due to the fact that the amplitude at the bedrock is very close to the minimum value for zone 2.

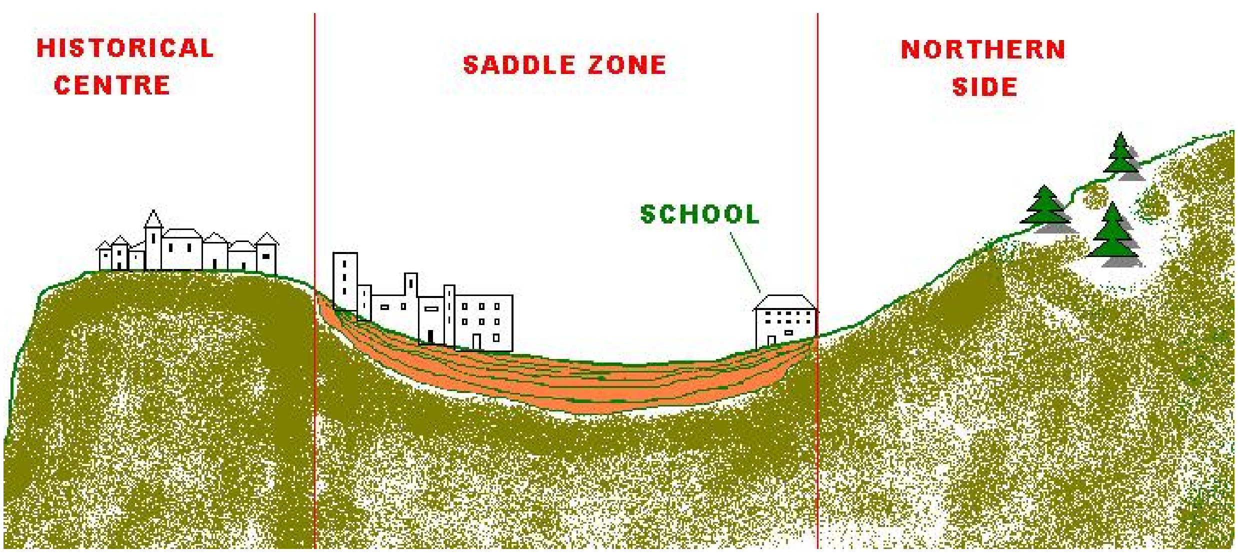

Fig. 6. Microzoning: plan view and N-S section

SEISMIC VULNERABILITY OF BUILDINGS

The damages that an earthquake causes in a building depend from the its seismic vulnerability. This can be evaluated by individualising all the collapse mechanisms, which could affect the structure, and calculating for each of them the seismic factor that turns the structure into this mechanism. The practical application of this definition implies the use of a numerical model, which is often full of uncertainties, especially in the case of old masonry constructions. In fact, materials properties and construction details, such as connection degrees between the walls and between walls and floors as well as the restrain at the foundation, are not known. In this cases the experimental analysis is the only chance. In other studies buildings were classified according to their structural and material characteristics and defining a fragility scale [9]. These data were collected during the emergency phase after previous seismic events. Also in this case, under the supervision of the Italian Civil Protection Department, teams of engineers visited all the damaged buildings, pointing out the damages and declaring them usable or not. This work was also useful for the next post-emergency phase.

In the post-emergency phase, a Technical-Scientific Group (GTS) composed also by ENEA researchers, on behalf of the municipality of San Giuliano di Puglia, carried out a detailed analysis of all the buildings in the town. These were classified in very seriously damaged buildings, and therefore to be demolished, damaged buildings that could be repaired and seismically improved and building that could be used immediately. On the basis of this analysis, the demolition of the first buildings, the safeguard of second ones were planned, in order to eliminate all the not repairable structures and to make accessible as much street as you can and to allow the people to return in their usable houses. This very hard work allowed also to deduce a terrific set of very useful information on the seismic vulnerability of structures for engineers and architects and to set up methodologies and techniques of analysis in the post-emergency phase, which is a valid heritage to let known.
About 50% of the constructions in San Giuliano di Puglia were masonry masonry, made of perforated bricks or stones. Half of the remaining 50% was of dressed stones masonry and had flexible floors, and half was made of very good masonry or concrete structures. Also with reference to damages the urban area can be divided into three zones: 1) the historical centre, characterised by damages of medium level; 2) the saddle zone, in which very high damages have been observed; 3) the Northern side, with light damages.

Fig. 7. The historical centre composed by complex systems of buildings

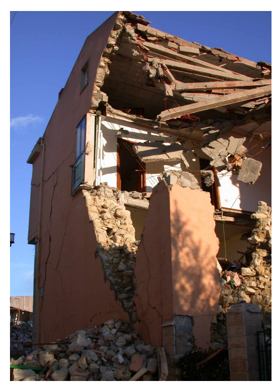

Fig. 8. The typical "a sacco" masonry with heavy fill

Historical centre
The medieval historical centre of San Giuliano (Fig. 7) is characterised by masonry constructions, made with stones irregularly placed with very poor mortar. Almost all the constructions in the historical centre were made of masonry, most of them (75%) with stones irregularly placed with very poor mortar. Only in a few cases good masonry have been observed. Almost always the typical "muratura a sacco" was used,

with very low effective thickness and very heavy fill (Fig. 8); the two sheets were often not linked between them. The most usual collapse mechanisms were the inflexion of them and the typical cross cracks (Figs. 9 and 10). Often recent restoration works, made without improving the strength of masonry, hided the actual conditions of the walls, which looked to be in very good conditions (Fig. 11). Most of the horizontal structures were steel or timber floors (75%), while only 10% are vaults and 10% concrete floors. Sometimes the pull out of the beams from the walls was observed. The vaults supported the seismic action very well where suitable supports were at the springings. In other cases the vaults collapsed, especially were not suitable interventions had modified geometry and loads (Fig. 12).

Fig. 9. Not effective connection

Fig. 10. Typical cross cracks

Fig. 11. A well dressed historical building

Fig. 12. A restored vault collapsed

Other characteristics typical of Italian historical centres also influenced very much the seismic behaviour. The structural organic unity was often composed by a chaotic system of buildings, structurally dependent one on the other or simply placed close together, without respecting the joints criteria nor the maximum suggested size of buildings. They have height and size in plan very different, resulting in very irregular stiffness. The behaviour of such structures is quite complex. This situation makes very difficult the interpretation of the structural behaviour and almost impossible any numerical modelling. Even thought the site is not of high seismicity, it is worth noting that the historical centre supported well a number of events in the last centuries. Foundations of buildings are, of course, in masonry, not at the same level, often directly on the rock.

Saddle zone

The develop of the saddle zone started in the first half of the twentieth century with masonry constructions and continued in the second half with concrete buildings. About 50% of the constructions were poor masonry buildings, 25% good masonry buildings and 25% concrete or mixed (masonry-concrete)

buildings. The horizontal structure were steel or timber and the other 50% were concrete floors.
The saddle area was characterised by two alignments of buildings at the sides of the "Corso", each of them called "stecca", composed by different constructions placed close together (Figs. 13 and 14).

Fig. 13. The East "stecca" in the saddle area

Fig. 14. The West "stecca" in the saddle area

Fig. 15. Poor masonry, bad connections, lots of openings: all the defects are in this building

Fig. 16. Too many openings in the walls made of perforated bricks

Fig. 17. The niches for the facilities were a characteristic in San Giuliano

Fig. 18. The concrete roof shifted with reference to the building

The most impressive feature was that lots of buildings were made of perforated bricks, certainly not suitable to absorb vertical nor seismic actions (Figs. 15 and 16). The most usual collapse mechanism of walls was due to shear actions. In fact, the typical cross cracks in the walls could be observed, due to the very low strength of the walls, which is to be related both to their very thin thickness and the presence of too many openings in the external and internal walls. Another characteristic was the presence of niches for the facilities, which played an important role in reducing the wall strength (Fig. 17). Recent restoration interventions often made worse the vulnerability, because they introduced heavy concrete elements not well connected to the masonry (Fig. 18). As pointed out by the seismic microzoning, soil in this area is sometimes unstable. In fact, damages due to soil yielding were detected. Also concrete buildings showed serious damages in this zone (Figs. 19 and 20).

Northern area

The Northern area represents the future of the town. Modern concrete buildings containing more than one apartment have been built. Damages were very low. It is worth noting that buildings almost undamaged have defects and require an anti-seismic improvement. The most important case is that of Figure 21, in which the different blocks are simply placed close together without seismic joints: the resulting structure is extremely long and the well-known phenomenon of hammering could happen. Also same masonry constructions present the same problem (Fig. 22). In the first case the buildings should be separated, in the second one the two buildings could be connected to make them an organic unity.

Fig. 19. A concrete building in the saddle zone

Fig. 20. Joint badly executed

Fig. 21. Concrete buildings without seismic joints

Fig. 22. Two masonry buildings just placed close together

POST-EMERGENCY PHASE AND SOCIAL ASPECTS

On the basis of the previously described work GTS performed the demolition plan and the main street were opened in order to allow people to reach their houses (Figs. 23 and 24). In fact, the town was inaccessible after the earthquake and protected by the police. ENEA performed also a sociological analysis on the population of San Giuliano di Puglia in order to extract useful information to be used in the reconstruction phase. The importance of the social aspect is now obvious: engineers, architects, geologist are conscious of the limit of the just technical approach and ask for the contribution of sociologist, both in the emergency phase and in the reconstruction phase. The aim is also preparing people to future disasters. A significant sample of the population was defined: people of different age and that have suffered different degree of damage to their house were interviewed. The main results can be summarised as follows: i) most of the people wants to continue to live in their town, even thought lots of young people must go out to look for job opportunities; ii) most people want to return to their house or at least to reconstruct it at the same place; iii) they believe that a safer reconstruction is possible, especially using the new anti-seismic technologies. For this latest aspect the role of ENEA is very fundamental.

Fig. 23. Demolition works

Fig. 24. The saddle area after the demolitions

THE RECONSTRUCTION OF SAN GIULIANO DI PUGLIA

Seismic codes are usually based on the assumption that structures should be resistant enough to stay up after low to medium intensity events, the stresses remaining in the linear-elastic range. In the case of strong earthquakes they could be damaged seriously but the collapse should be avoided. In any case the only important goal is to preserve human lives but not the integrity of buildings. This philosophy turned to be not economically sustainable because the reconstruction after strong but also medium events was too much expensive and because the contents might be lost. On the other hand, an anti-seismic building could be too much expensive, if it is designed resistant enough to support the earthquake effects in the linear-elastic range. This problem is amplified in the case of buildings, such as libraries, with very high loads that translate in very high horizontal forces, when seismic actions are present. Speaking of existing buildings, it is worth to remind that the most common traditional restoration technique, used in the past to enhance the seismic behaviour of monumental structures, which consisted in introducing localized reinforcements (traditional devices, usually steel bars or cables), increase the overall capacity of the structure to work as a whole, providing important links between discontinuous elements and thus conferring increased ductility, but in many cases they return to be inadequate to prevent collapse in the case of earthquake [10].

Since 80's researchers from all over the world have began to devote their effort to better investigate new technologies in the fields of earthquake engineering, used in the past only for nuclear power plants or particular constructions. These are passive systems, such as base and floor seismic isolation systems, energy dissipation systems consisting of various types of passive devices (elastic-plastic, viscous, viscous-elastic and electro-inductive dampers), hydraulic coupling systems using innovative shock transmitters, systems formed by shape memory alloy devices and also semi-active and active control systems of vibrations. The choice of the more useful anti-seismic system is related to the characteristics of the seismic action and to the characteristics of the buildings. As in previous analyses, the urban are is to be divided in three zones. The microzoning of San Giuliano di Puglia pointed out the possibility of landslides at the East side of the saddle area, while there is no problem about the soil characteristics and the amplification factors. So a wide choice for the structural solutions is possible.

New buildings in the Northern zone and Saddle area

Most of the collapsed or demolished buildings are in the saddle zone. Some of them will be rebuilt in the same site, others in the Northern zone, which is the expansion area of the town. In that case we propose to use seismic isolation, which has been greatly developed in the last 25 years and is now a fully matured technology, and is not only reliable but also cost-effective. It is based on the idea of reducing the energy transmitted from the earthquake to the structure by changing the structure's dynamic characteristics, i.e. increasing its natural period, in order to make it farther from the period of the main harmonic components of the seismic actions. This change is usually achieved through the use of special devices, the "isolators" (Fig. 25), with very low horizontal stiffness and appropriate damping, which separate the structure from the motion induced by the earthquake. The first application of base isolation in Italy was in the 8-stories isolated buildings of Telecom-Italia at Ancona, seismically tested by ISMES, ENEL and ENEA, laterally moving to 110 mm and successive suddenly releasing, by means of the use of explosive bolts (Fig. 26).

Fig. 25. Base isolated house in Rapolla (Potenza, Italy)

Fig. 26. Test of the Telecom building in Ancona in 1991

Repairing and seismic improving

Seismic isolation could also be used for existing buildings not damaged by the earthquake, but designed without anti-seismic criteria. A relevant example if the building in Fabriano, Italy, only lightly damaged by the 1997 earthquake, which needed an seismic improving intervention, achieved by means of a base isolation system (Fig. 27).

Alternatively, passive energy dissipation devices can be used. In fact, recent studies showed that passive energy dissipation devices have also a great potential for reducing the seismic risk of several types of structures [11]. In particular, great interest arose in the research activities for the development and optimisation of energy dissipation systems of various types: viscous, elastic-plastic, viscous-elastic and electromagnetic systems. The strategy consists in dissipating a part of the seismic energy in specified zones of the structure, expected to experience important relative displacements during an earthquake. Energy dissipation devices concentrate in themselves most of the energy to be dissipated, preserving other structural elements from major damage. Energy dissipation devices are sometimes used in parallel with base isolation devices, with the main aim of reducing base displacements. Relevant experiences have been carried out on devices at ENEA Casaccia Research Centre by means of shake table (Figs. 28 and 29), while an interesting example is the seismic reinforcement of the Gentile Fermi school in Fabriano (Fig. 30).

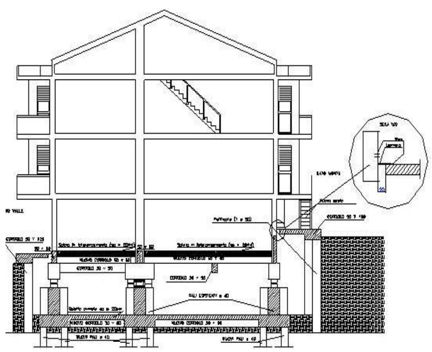

Fig. 27. The building in Fabriano seismically improved with base isolation

Fig. 28. Electro-inductive damper installed on the MISS mock-up

Fig. 29. Visco-elastic damper installed on the MISS mock-up

Fig. 30. Visco-elastic dampers installed in the Gentile Fermi school in Fabriano

Seismic improving of buildings in the historical centre

In the historical centre all the buildings suffered damages, but they will all be repaired. The repairing works should respect the usual requirements for historical construction: they should be reversible and not-invasively. Conventional interventions, such as restoring of walls and of connections between them and stiffening or substitution of floors, should be associated with innovative devices, in order to absorb tension, and to let masonry dissipating energy by means of its micro-cracking.

Fig. 31. Bell Tower of S. Giorgio in Trignano

Fig. 32. Four SMA devices were installed at Trignano

In order to achieve that Shape Memory Alloys (SMAs) have been adopted for the restoration of the Bell Tower of S. Giorgio Church in Trignano, Italy, damaged by the 1996 Reggio Emilia earthquake (Figs. 31 and 32) [12]. They are metallic materials endowed with unusual properties associated with the reversible transformation between two crystalline phases, known as *austenite* and *martensite*. Amongst the very unusual SMA thermo-mechanical properties, the super-elastic behaviour is the most useful feature for the seismic protection of monuments. A typical super elastic cycle of a SMA wire subjected to tension is shown in Figure 33.

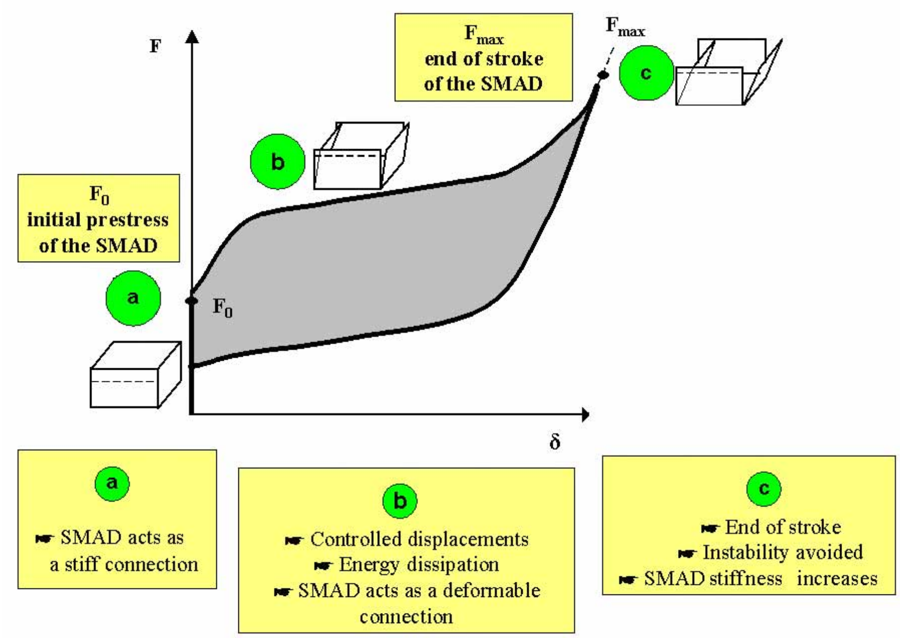

Fig. 33. Super elastic cycle of a SMA wire

After an initial, almost linear portion (corresponding to the elastic deformation of the material in its austenitic phase) the curve shows a super elastic loading plateau. It is not due to yielding but to the stress-induced phase transformation from *austenite* to *martensite*. The removal of the stress induces a reverse phase transformation from *martensite* to *austenite*, which allows almost complete strain recovery. In view of said reversible phase transformation, a very large number of similar cycles may be applied without any damage of the material. The absence of sensible residual deformations allows the realization of Shape Memory Alloy Devices (SMADs) in which no permanent displacements are present when they stop working. Conversely, using traditional devices, it is possible to exploit their yielding and the consequent force-limiting characteristic, but permanent residual displacement are present when forces are removed.

SMAD should behave as follows: a) under service loads, the SMAD does not apply any static force to the structural elements that connects (and consequently it is called “self-balanced”); under low intensity horizontal actions (wind, small intensity earthquakes), the SMAD is stiff, as a traditional device, and no displacements are allowed; b) under higher intensity horizontal actions (strong earthquakes) the SMAD stiffness reduces, allowing "controlled displacements"; they should permit the masonry to dissipate part of the energy transmitted by the earthquake, mainly thanks to micro-cracks formation in the brick walls, taking care to avoid dangerous macro-cracks; in the meantime, due to SMAD reduced stiffness, smaller forces are transmitted to the cultural heritage structure and it, consequently, should be able to sustain a high intensity earthquake without collapse; c) under extraordinary horizontal actions, the SMAD stiffness grows up, in order to prevent from excessive displacements and instability. SMA devices were also used to connect the tympanum and the roof of the transept of the S. Francis’ Basilica in Assisi, seriously damaged by the 1997 earthquake.

CONCLUSIONS

The area of San Giuliano di Puglia is characterised by very high amplification factors, due to the presence of a significant soft layer above the bedrock, especially in the saddle area. Anyway, taking into account the amplification values estimated by the seismic microzoning study, the maximum acceleration at the surface is not higher than that suggested by the Italian Seismic Code for zone 2. The collapses of the buildings are also to be related to the very poor quality of the structural material and structural type. 70% of the buildings are to be reconstructed. We suggest to reward these people for their bad luck by a new anti-seismic safe town.

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