ASSOCIAZIONE NAZIONALE ITALIANA DI INGEGNERIA SISMICA
ANIDIS
Italian National Association of Earthquake Engineering

XVIII CONVEGNO ANIDIS
L'ingegneria sismica in Italia
ASCOLI PICENO 2019
15-19 Settembre

Proposals for building resilient cities in the reconstruction in Central Italy

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Keywords: Earthquake damage, Reconstruction, Seismic isolation, Resilience

ABSTRACT

The necessity to reconstruct or retrofit most of the towns and villages in Central Italy, hit by the 2016-2017 seismic sequence, represents an occasion to reduce substantially the seismic vulnerability of the buildings and, therefore, to improve the global resilience. Due to the characteristics of the Italian historic centres, new systems are required. These should allow a simple and fast reconstruction, as well as the retrofit of cultural heritage structures by preserving their historical value. Two new solutions for the seismic isolation of buildings but also complex structures, such as building aggregates, are presented. They are both based on the realization of an isolation platform under the structure and are useful for existing and new buildings, respectively. In the first case, the proposed system allows the application of seismic isolation and therefore the complete retrofitting of the building without touching itself. In the second one the "as and where it was" reconstruction is possible.

1 INTRODUCTION

The seismic sequence that affected Central Italy since August 24th, 2016, caused several victims and also the collapse of several buildings. In the epicentre area, most of the structures collapsed completely. As a result, most of the historical centres must be reconstructed. Only few buildings, even though seriously damaged, can be retrofitted.

The reconstruction will require lots of money and also lot of time and obviously lot of work. Anyway, it should be considered a suitable occasion to improve the structural quality of the structures, both existing and new ones and, in other words, to build resilient cities.

The starting point is not very good. It is well known that the safety level of buildings in Italy is quite low. This translates in serious damage after earthquakes, even of low energy. The reasons are to be searched in the late seismic classification of the Italian territory and in the absence of a suitable maintenance. Furthermore, several structures are historic buildings, so they are to be considered part of the cultural heritage and therefore subject to constraints (Clemente, 2018).

A new philosophy in the structural anti-seismic design is needed. This should be based on the Zero-Earthquake-Damaged Buildings (ZED Buildings) criterion, which is the best starting point for resilience cities. The locution "Zero Earthquake-Damage Buildings" refers to structures designed to absorb the seismic actions corresponding to the design earthquake without damage. This means that, in case of an earthquake of the same intensity of the design one, the structure should substantially remain in the elastic range (Clemente et al., 2018).

This behaviour can be pursued in low seismicity areas using traditional technologies, obviously with a light increase of the construction cost. In high seismicity areas, ZED Buildings can be easily obtained using new anti-seismic technologies, such as seismic isolation and energy dissipation (Clemente 2017, Saitta et al. 2017). These technologies can guarantee the suitable balance among the requested safety level, the economic aspects and an acceptable time for the reconstruction (Clemente & Buffarini 2010, Clemente et al. 2016).

It is well-known that seismic isolation increases the fundamental period of vibration of a building, so that accelerations in the superstructure can be reduced significantly. This reduction is offset in terms of displacements, which increase substantially with the vibration period. However, in the presence of isolation devices, these displacements can be concentrated at the base of the building, while the superstructure behaves almost like a rigid body. Obviously the knowledge of the seismic input is a fundamental issue (Rinaldis & Clemente 2013, Clemente et al. 2015)

Nowadays, some tens of thousands of structures are protected by passive anti-seismic systems in over 30 countries. Applications have already been made to both new and existing civil buildings as well as industrial structures. In some countries, they include high risk plants. In a civil context, they concern not only strategic and public structures, but also residential buildings. In Italy, seismic isolation have become more and more popular especially after the 2009 L'Aquila earthquake (Clemente & Martelli 2019, Clemente et al. 2019). Recently, the behaviour under low energy earthquakes has been analysed for different kind of devices (Clemente et al. 2019, Clemente et al. 2016, Bongiovanni et al. 2018, Saitta et al. 2018).

Recent applications in Japan and in China have demonstrated the possibility of realizing building complexes on large-scale isolated platforms. In particular, the so-called "artificial ground" is an isolated platform from which numerous buildings of considerable size stand out (Figure 1). In Italy, similar concepts were applied for the new school of San Giuliano di Puglia (Figure 2) (Clemente et al., 2007) and the C.A.S.E. Project, realized in L'Aquila after the 2009 earthquake.

Such solutions are certainly to be preferred for building aggregates. These are typical of the Italian historic centres, like those affected by the 2016-2017 seismic sequence in Central Italy. A unique platform presents the advantage of reducing the seismic joints if compared to the isolation of individual buildings, and therefore possible constructive and maintenance complications.

In this paper two new solutions for the seismic isolation of buildings but also of complex structures, such as building aggregates, are presented. They are both based on the realization of an isolation platform under the structure and are useful for existing and new buildings, respectively. In the first case, the proposed system allows the application of seismic isolation and therefore the complete retrofitting of the building without touching itself.

2 EXISTING BUILDINGS AND NEW BUILDINGS

The typical historic old towns in Italy are composed by old masonry buildings. The buildings and the entire villages are part of the national cultural heritage. Often their historic and cultural value is priceless. Their conservation and preservation is a duty for us, in order to leave them to the future generations.

The retrofit of historical buildings is a quite hard task, due to the historical importance and to the daily presence of tourists. The traditional techniques, based on the increasing of strength and ductility, are not suitable for the following reasons:

- they are often not reversible,
- they make use of materials different and incompatible with the original ones,
- they change the original structural conception.

Figure 1. Lateral view of a complex of twenty one 6- to 14-storey buildings, all erected on an unique artificial ground at Sagamihara, Tokyo.

Figure 2. The isolated deck of the two-block school building at San Giuliano di Puglia, Italy, during the construction.

With reference to the last aspect, it is worth reminding that historic building were often designed without accounting for the seismic actions. As a result, they are vulnerable even to moderate events. Furthermore, historic buildings often present weak points, such as an irregular form both in plan and in elevation, the absence of vertical joints and transversal braces, an in-plane flexibility of floor slabs, and shallow foundations.

Under earthquakes of high intensity, traditional structures can just guarantee against the collapse, but cannot avoid heavy damage both to structural and non-structural elements. It is evident that, for cultural heritage buildings, a suitable equilibrium between the safety and the conservation is usually accepted, i.e., a partial seismic improvement is obtained preserving their original monumental characteristics, identity and historical value.

Base isolation is a suitable solution for the rehabilitation of historical structures. It aims at reducing the seismic actions on a structure, thus avoiding significant damage to it and its contents even under strong earthquakes, and presents very low interference with the structure itself.

For the structures that collapsed during the earthquake, the issue is if and how to reconstruct them. Is the so-called "as and where it was" reconstruction always possible? In some cases the geological and geotechnical conditions suggest not to reconstruct at the same site. These are the cases of areas with landslide hazard or where the local seismic amplification is very high. In these cases, continuing a war against the forces of nature could not be the right choice. Furthermore, the new buildings should be constructed according to the present safety requirements. Therefore also the "as it was" reconstruction should be better defined.

Base isolation is a suitable solution also for the reconstruction of historic structures and historic centres. It allows designing the new structure with the same architectural shape and distribution of the previous one. The regularization can be obtained just by deploying the isolation devices properly.

3 THE SEISMIC ISOLATION STRUCTURE FOR EXISTING BUILDINGS

The new solution proposed consists in the realization of an isolated platform under the foundations of the building, without touching the building itself (Figure 3). A discontinuity between the foundations and the soil is created by means of the insertion of horizontal pipes and the positioning of isolation devices at the horizontal diametric plane. Then the building is separated from the surrounding soil in order to allow the horizontal displacements required by the isolation system. So the structure is seismically isolated but not interested by interventions that could modify its architectural characteristics. This is very important for historical buildings (Figure 4).

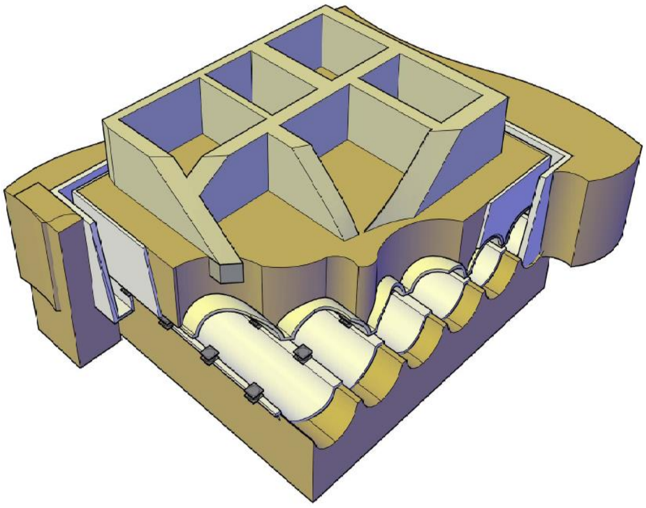

Figure 3. The Seismic Isolation Structure for Existing Buildings (SISEB): axonometric cross section

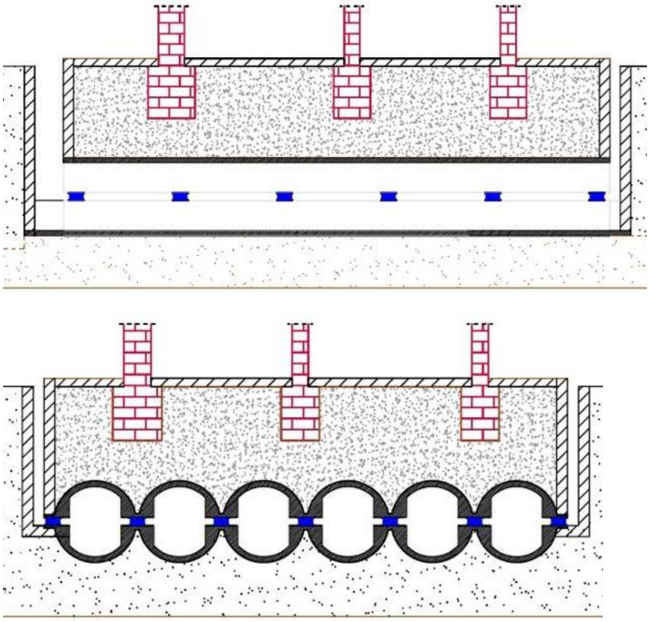

Figure 4. SISEB: longitudinal and transversal cross-sections.

Even underground level are not modified but can be part of the seismically protected building. In more details the construction phases are the following:

- A trench is first excavated at one side of the building and pipes are inserted by means of auger boring or micro-tunnelling technique; the diameter of pipes should be ≥ 2 m, in order to allow the inspection of the isolation system. The pieces of pipe should have a particular shape and are composed by two portions, the lower and the upper sectors, respectively, which are connected by means of removable elements (Figure 5). The connection elements placed in correspondence of the isolation devices are removed and each pipe is joined with the two adjacent ones, for example by means of a reinforced concrete elements.

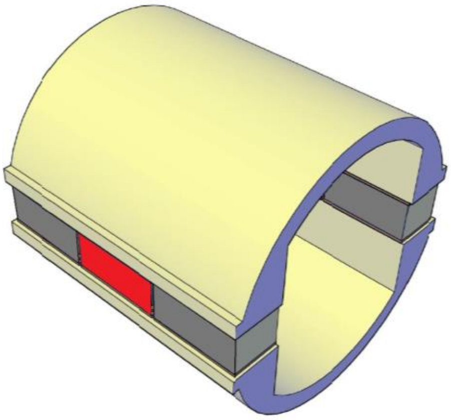

Figure 5. Pipe segment composed of two cylindrical sectors and removable elements between them.

- The isolation devices are positioned and the upper adjacent sectors are connected in correspondence of the isolators.
- Successively also the other connection elements are removed, so the lower and upper sectors are definitely separated.
- Finally, vertical walls are built along the four sides of the building and a rigid connection, a concrete slab or other, is realized between the building and the isolation system.

The size of the pipes must guarantee the accessibility and the possibility to substitute the devices. It is worth reminding that the solution presents the advantages that the building and its architectural aspect are not changed and so are the underground levels; this is a very important requirement for historical and monumental structures, but also for industrial buildings (Clemente et al., 2012).

The system was proposed in more than one case for the retrofit of historic buildings in L'Aquila, after the 2009 earthquake (Figures 6 and 7). This demonstrated the suitability of this solution also from an economic point of view if compared with traditional interventions.

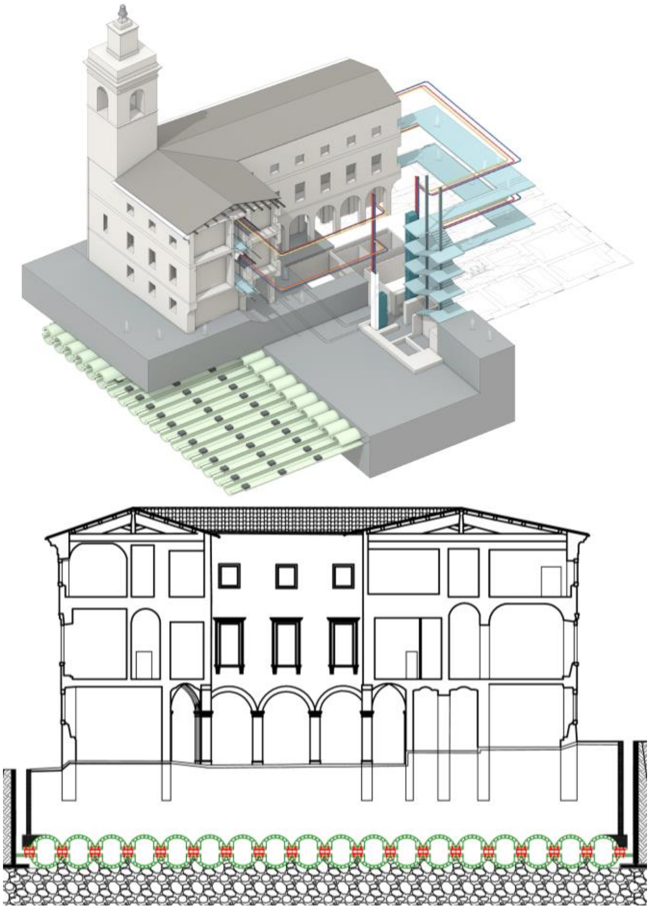

Figure 6. Axonometric and transversal cross-sections of the isolation system proposed for Palazzo Margherita, L'Aquila (Structural design L. Marchetti and C. Lufrano, Consultant for base isolation: P. Clemente and A. De Stefano, Company: IRPCO SpA Roma).

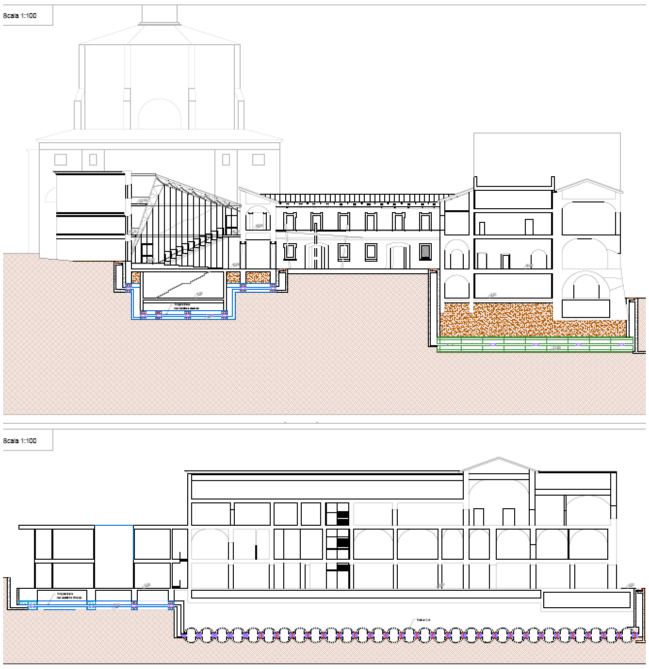

Figure 7. Cross-sections of the isolation system proposed for Palazzo del Governo, L'Aquila: (Structural design: M. Novembri, Consultant for structures: L. Marchetti and Themis Srl, Consultant for base isolation: P. Clemente, G. Buffarini, F. Saitta, Company: CO.GE. Costruzioni Generali SpA Parma, Imprendo Italia Srl).

For these proposals, the problems that can arise were studied in details. The results obtained in one case are reported in the following.

3.1 Problems to consider: vibrations and settlements

Two problems can arise during the micro-tunnelling operations: the soil settlement and the vibrations induced at the surface level.

With reference to the vibrations induced by micro-tunnelling, experiences supplied by large tunnelling works and from vertical boreholes suggest that minor threats should be expected from induced vibrations. Anyway, both theoretical and experimental deeper studies are needed. Instead, important problems can arise by settlements (Barla and Viggiani 2002, Miliziano et al. 2002).

To analyse the issues in details, a specific case study, carried out on Palazzo Margherita at L'Aquila, was considered (Buffarini et al. 2011, Clemente & De Stefano 2011). The results, obtained from a previous experimental dynamic characterization of the near site, allowed modelling the mechanical properties of the ground with accuracy. A FE 2-D model was set up and then exploited in *Diana 2* environment (Clemente et al., 2011). The 2-D model was useful to analyze a perturbation of limited width, due to the foundation and micro-tunnels. The vertical edges of the model were kept far enough from the perturbed zone, in order to minimize their influence. The nodes belonging to those edges were restrained by means of springs and dampers able to cut-off the wave reflection.

The soil was modelled as a layered continuum indefinitely extended, supported by the bedrock at 17 *m* depth. Layers of 1.0 *m* thickness were considered, whose elastic dynamic tangential modulus was consistent with the measured wave propagation velocities ($G_{dyn} = \rho \cdot \upsilon_s^2$). The Young's dynamic and static modulus were deduces according to the relationships: $E_{dyn} = G_{dyn} 2(1+\nu)$ and $E_{sta} = E_{dyn}/3$, ($\nu = 0.3$), respectively. The mass density was assumed equal to 2090 kg/m^3.

Eight node quadrangular elements were used, with aspect ratio near to one and regular shape. The plane deformation condition was imposed and the boundary nodes respected the following restraining conditions: vertical displacements were inhibited at the nodes belonging to the lower horizontal edge; horizontal displacements were inhibited at the nodes belonging to both the lateral vertical edges.

The presence of the building was simulated by imposing a load of 3000 *kN/m* uniformly distributed along its base width, which induces a local settlement. The pipe jacking induces an additional settlement to be estimated. The settlement due to insertion of pipes, originated by a stress release process, was computed as difference between the settlement due to the weight of the building plus that due to the insertion of the pipes and the settlement due to the weight of the building only.

The stress release during micro-tunnelling is a three-dimensional mechanism that shall be described by a plane-strain two-dimensional model, as previously stated. It is possible to reach that goal through a conventional hole-boundary force reduction approach known as "β-value method" or convergence-confinement method proposed by Panet and Guenot (1982) using the stress-release factor λ, varying in the range 0÷1 (Barla and Camusso, 2011).

Analyses are then based on the decrement of a fictitious internal pressure at the boundary of the holes in agreement with the β-value method. To apply that method inside the FE model, simply supporting elastic restrains are distributed along the hole boundaries, with operating direction orthogonal to them. By modifying the stiffness of the elastic supports it is possible to simulate the stress release. A null stiffness of the elastic support gives λ=1.

With λ=0.4 and *H/D* =3.5 (*H* is the depth of the pipe axis and *D* is the diameter of the pipes), the final computed value of the settlement was lower than 7 *mm*.

Increasing the stress release factor λ to 0.6 the settlement values increase of about 20%. Besides, passing from *H/D* = 3.0 to *H/D* = 2, keeping λ=0.4, there is an increment of the maximum displacement of about 27%. It is worth noting that in this case some uplift, of very low values, were pointed out around the hole.

Larger *H/D* ratios reduce the settlements but increase the cost of the trenches. Technologies to contrast the settlements exist and are consolidated even if they are too expensive.

A more detailed parametric study was carried out using 2-D nonlinear finite element analyses to understand the role of key factors such as strength and stiffness of soil and masonry, roughness of soil-structure interface, excavation sequence of tunnels, wall dimensions and openings configuration. The study identifies the design variables which influence the most the risk of structural damage and suggests the most effective damage symptoms to be monitored during construction (De Stefano et al., 2015).

4 SEISMICALLY ISOLATED BASEMENT FOR NEW BUILDINGS

A similar seismically isolated basement can be realized also for new buildings, of any type and material. It consists in a basement of reinforced concrete lightened with pipes of fiberglass or other material of suitable diameter (not less than 1.20 m, Figure 8). It is placed on the ground after the excavation and the preparation of the area.

The basement is composed of two portions, usually symmetric with reference to a horizontal plane (Figure 9). The lower portion is placed on the ground, the upper one supports the building. Between them, the seismic isolation devices are inserted, in order to obtain the decoupling of the motion of the upper portion, and therefore of the superstructure, with respect to that of the lower portion and therefore of the ground. Perimeter walls, connected to the lower parts of the tubes, complete the work. Between the upper part and the walls dissipation devices or other devices can be inserted, if necessary.

The system takes its cue from the previous one. Unlike this, it is intended for new buildings and involves the use of fiberglass pipes with improved grip. Pipes are not pushed in, but they are arranged as a collaborating formwork for concrete castings. They will be also a protection system in service.

The system can be arranged with modules, each of them composed of parallel pipes, with a diameter of at least 1.2 m, in order to allow inspection and replacement, of an appropriate length, placed at a distance of about 2.0 m, sufficient to position the seismic isolation devices between them. The overall system can have several modules (of appropriate width) connected to each other exclusively by means of the base and top plate, with appropriate spaces (for example of 2 m), in order to allow a comfortable passage for inspection and possible replacement of isolators (Figure 10).

The pipes, preferably in fiberglass, after production in the factory, are cut at the plant at a suitable height, generally at their half, and essentially are a formwork cooperating with the concrete, both lower and upper portion.

The construction of the platform can be carried out through the following phases:

- preparation of the reinforcement of the entire lower part and casting of the lower plate of suitable thickness;
- positioning of the lower parts of the fiberglass or other material and concrete casting pipes, with the provision of templates or, alternatively, of the housing for the brackets of the isolators, to be injected with volumetric stability mortar subsequently;

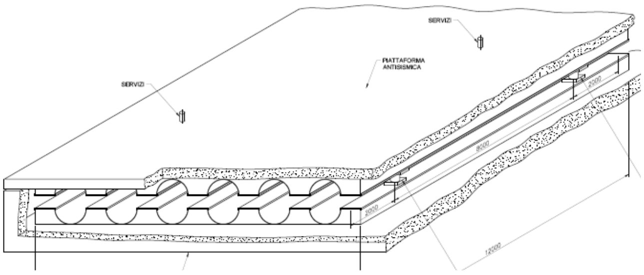

Figure 8. The Seismically Isolated Platform (SIP): axonometric cross-section

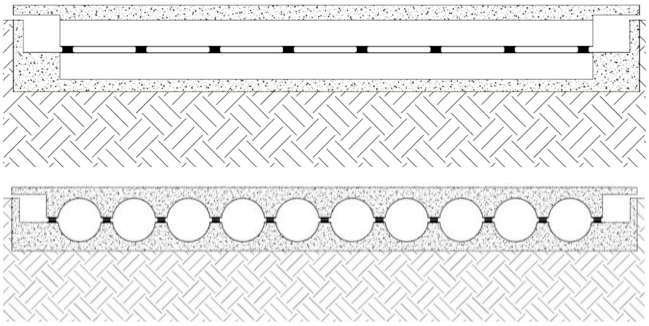

Figure 9. SIP: longitudinal and transversal cross-sections.

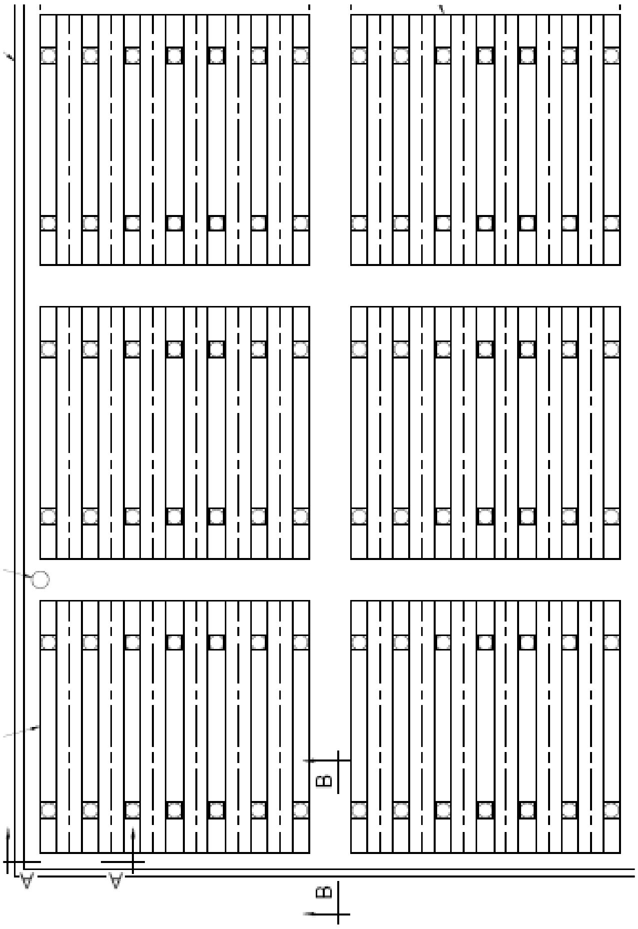

Figure 10. SIP: arrangement of the modules.

- positioning of the isolation devices;
- positioning of the upper cylindrical sectors of the pipes, with a suitable formwork;
- positioning of the reinforcement of the upper portion of the platform and casting of the concrete in the parts between the pipes;
- casting of the upper plate with a suitable thickness.

4.1 Possible applications of SIP

It is apparent that the Seismically Isolated Platform is a suitable solution for the reconstruction of historic centres destroyed by earthquakes, as those of the Central Italy (Figure 11). These were characterized by complex aggregates of masonry buildings, having irregular shape in plan and different heights.

Such a system makes the so-called “as and where it was” reconstruction always possible, with the limit already pointed out about the geological and geotechnical characteristics of the sites. It allows designing the new structure with the same architectural shape and distribution of the previous one. The regularization can be obtained just by deploying the isolation devices properly.

5 CONCLUSIONS

The reconstruction of the towns in Central Italy, which will require lots of money and also lot of time, should be considered a suitable occasion to improve the structural quality of the buildings. This is valid both for the buildings to be rebuilt and for those that will be retrofitted and seismically rehabilitated. The goal is to build more resilient cities.

To do that, a new philosophy in the structural anti-seismic design is needed, which should be based on the design of Zero-Earthquake-Damaged Buildings. In general, base isolation is the best solution, when applicable, both for the seismic protection of the new buildings and for the seismic rehabilitation of the existing ones.

The recent application of artificial grounds in Japan have demonstrated the possibility of realizing building complexes on large-scale isolated platforms.

With reference to this idea, two new systems for the application of seismic isolation have been proposed in this paper. They are both based on the realization of an isolation platform under the structure.

The first one, called Seismic Isolation Structure for Existing Buildings, can be applied to existing buildings or aggregates without touching the superstructures. This is an important requirement for historic buildings.

The second one consisted in an isolation platform, able to support any kind of building or aggregate, and therefore having as a goal the “as and where it was” reconstruction.

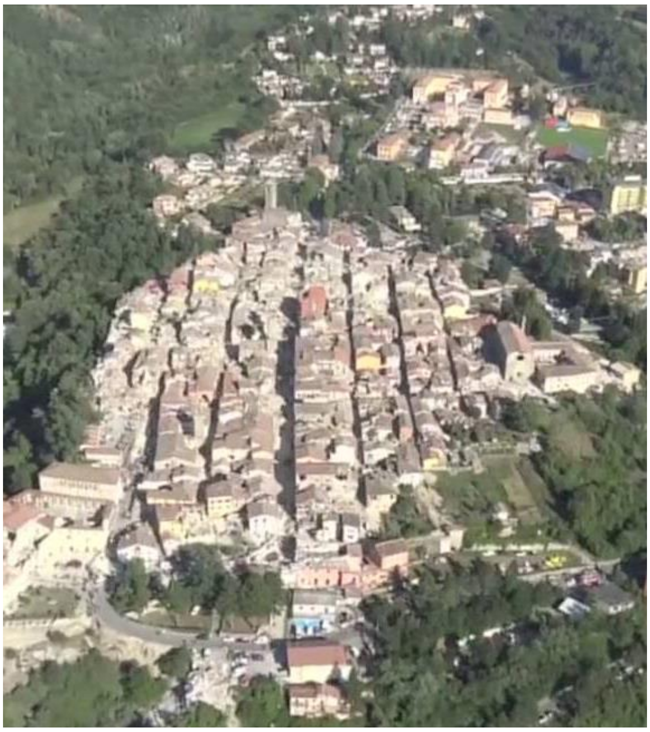

Figure 11. The town of Amatrice, Italy, almost completely destroyed by the 2016 earthquake. The use of seismically isolated platforms would allow to rebuilt the town “as it was” from an urbanistic and architectural point of view.

ACKNOWLEDGEMENTS

The Seismic Isolation Structure for Existing buildings (SISEB) is the subject of an international patent of ENEA and Politecnico di Torino (inventors P. Clemente, A. De Stefano and G. Barla). The Seismically Isolated Platform (SIP) is the subject of a patent of ENEA and Tekva (inventors P. Clemente, G. Paolini Famoos and A. Battilocchio). The authors thank all the colleagues who contributed in the studies carried out on these subjects.

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