1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.252

Seismic isolation or supplemental energy dissipation for seismic retrofit of buildings

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Abstract

Seismic isolation and supplemental energy dissipation are well known techniques used since the 1970s, at the beginning mainly in new strategic structures, such us nuclear power plants, bridges and viaducts, public buildings. Few years later, the benefits of said techniques for the retrofit of existing structures were fully understood, and some application was carried out in different countries. In Italy, in the first three decades (1970s, 1980s and 1990s) said techniques were applied more often in bridges than in buildings. As far as existing buildings are concerned, in Italy the use of both seismic isolation and supplemental energy dissipation as retrofitting techniques is continuously increasing since 2003, following a series of destructive earthquakes (2002 San Giuliano di Puglia, 2009 L'Aquila, 2012 Emilia, 2016 Central Italy). Said earthquakes created the collapse of many old masonry buildings, and extensive damages to RC buildings as well, that were declared unfit for use. The guidelines for the repair of damaged buildings required not just to repair the earthquake-induced damages, but to improve the seismic behaviour of the buildings in comparison to their original undamaged state. The minimum target was a Capacity/Demand (C/D) ratio, in terms of PGA, of 0.6. Due to the very low capacity of most buildings, this target was not easy to reach with conventional retrofit techniques; that is why seismic isolation or supplemental energy dissipation have been often used. In particular, seismic isolation has the great advantage that most of the works are carried out at the basement level (or ground floor), avoiding strenghtening works at the elevation. This advantage is even more important in undamaged buildings, that can be retrofitted without interruption of use, with minimal impediment to occupants. The paper describes examples of retrofit of buildings both with seismic isolation and supplemental energy dissipation.

Key words: seismic retrofit, seismic rehabilitation, seismic isolation, supplemental energy dissipation, existing buildings

1 Introduction

The seismic vulnerability of European buildings has been unfortunately shown in all earthquakes occurred in the last decades, even the most recent ones. As far as Italy is concerned, the building stock is very old. Together with the centuries-old unreinforced masonry buildings of the historical centers of cities and villages, a big portion of modern buildings, mainly with RC framed structure, was built before the Eighties of the last century, without any capacity design approach, and very often without taking into account any earthquake input at all. In effects, a reliable seismic zonation of all the Italian territory is relatively recent, at the beginning of this century. Before that, despite there was the scientific knowledge of the seismic risk, many areas were not declared seismic by law, and consequently it was not mandatory to consider earthquake input in the design. The tragedy of the 2002 San Giuliano di Puglia earthquake, in which the only collapsed building was a school [1], causing the death of 27 children and a teacher, pushed politicians toward the approval of a new Italian seismic zonation. Together with the new seismic zonation, a new modern seismic code was issued in 2003, very similar to Eurocode 8. Amongst the novelties introduced by the new code, there was also a new chapter about design of buildings and bridges with seismic isolation, and the elimination of the previous requirement that each design of a seismically isolated structure or a structure with passive energy dissipation devices needed to be reviewed by the Public Work Council. Being said review process very slow, said requirement practically had stopped the use of seismic isolation and energy dissipation for about 10 years, despite Italy had started seismic isolation in the Seventies of past century, and at the end of the 1980s was world leader for number of bridges protected through seismic isolation and energy dissipation devices. In 2003, together with the new seismic zonation and the new code, a law was issued to start checking seismic vulnerability of all public buildings, as a first step towards the planning of their seismic retrofit. Special attention was devoted to schools, with the aim of preventing tragedies such as the one in San Giuliano di Puglia. Most of said checks shown the very high vulnerability of public buildings, and consequently priority list of interventions have been prepared and are continuously updated, as new checks are carried out. The process of reducing the seismic vulnerability of Italian building stock will be very long, but it did start. In some case the intervention consists in demolition of the unsafe building and reconstruction, but in most cases the choice is the seismic retrofit, for economic reasons.

After 2003, due to the new laws discussed above and the increased awareness of seismic risk, the use of seismic isolation restarted in Italy, but quite slowly in buildings. For example, the new school of San Giuliano di Puglia was seismically isolated, thanks to the donation of the isolators by all the Italian manufacturers of isolators at that time, and of the project consultancy by ENEA [2]. Some private residential buildings in San Giuliano di Puglia were rebuilt with seismic isolation as well. And other buildings in different regions of Italy were designed and built with seismic isolation. Some existing building was also retrofitted with seismic isolation [3].

It was only after the 2009 L'Aquila earthquake that seismic isolation became known outside the structural engineering community, thanks to its use in the so called "Progetto C.A.S.E." [4], i.e. the quick construction of new apartment buildings for the people who had lost their house due to the earthquake, that received large attention by the media. Said earthquake strongly affected an important city such as L'Aquila, with a long and important history and consequently an important historical center. The historical buildings and monuments were heavily damaged or collapsed, and also some modern RC building collapsed, killing 309 people. A large number of modern RC buildings were also damaged and declared unfit for use, leaving around 70000 homeless. Consequently, a large number of buildings was in need of some kind of intervention. The buildings with light damages were repaired in relatively short time, while those with heavy damages were subjected to important retrofit interventions, following the principle of "build back better". The guidelines for the rehabilitation of seriously damaged buildings required not just to repair the earthquake-induced damages, but to improve the seismic behaviour of the buildings in comparison to their original undamaged state. The minimum target was a Capacity/Demand (C/D) ratio, in terms of PGA, of 0.6. In case the retrofit cost was too high, demolition and reconstruction was allowed. Due to the very low capacity of most buildings, the target of C/D≥0.6 was not easy to reach with conventional retrofit techniques; that is why seismic isolation or supplemental energy dissipation have been often used. Examples of retrofit interventions with seismic isolation or energy dissipation are described below.

2 Seismic retrofit through seismic isolation

Seismic isolation has been used for seismic retrofit of existing buildings since the 80's of the past century [5]. In Japan, after the 1995 Great Hanshin earthquake, the use of seismic isolation increased a lot both in new and in existing buildings, thanks to the optimal behaviour of the few seismic isolated buildings in the epicentral area, some of them monitored. In 2012, about a hundred Japanese buildings were already retrofitted through seismic isolation, of which approximately one-third were public office buildings and 18% private office buildings [6]. In Italy, as in Japan, the use of seismic isolation both in new and existing buildings became frequent only after recent strong earthquakes, as discussed above. Most of the seismic isolation retrofit interventions carried out in the last 10 years in Italy concerns residential buildings, in particular those damaged and declared uninhabitable after the L'Aquila earthquake in 2009 or the Central Italy earthquake in 2016. Most of these retrofitted buildings have RC-framed structure, but there are examples of masonry buildings as well. [e.g.,7,8].

Seismic isolation has the great advantage that most of the works are carried out at the level where the isolators are installed, that usually is the basement level or the ground floor. Strenghtening works in the *superstructure*, i.e. the part of structure above the isolation level, are usually not needed at all, or strongly reduced in comparison with traditional techniques

(such as introduction of new shear walls, or increase of strength and ductility of RC members through metal or FRP jacketing). Consequently, the cost of intervention is reduced, in particular the cost portion not related directly to the structural intervention, but to demolition and refurbishment of non-structural parts. Furthermore, seismic isolation allows to reach the safety levels required by the seismic code for a newly constructed building, i.e. C/D ratio equal to 1, or very close to 1, while this is almost impossible with traditional techniques, at least at a reasonable cost. Mezzi and Petrella [9] report a cost comparison of alternative seismic retrofit strategies for two RC buildings damaged by the L'Aquila earthquake, showing that the strategy with seismic isolation allowed a saving higher than 30%. Furthermore, the C/D ratio obtained with seismic isolation was 1, while with conventional strategies it was around 0.7. Consequently, if the cost comparison is extended over the buildings lifetime, the savings obtained with seismic isolation are much higher.
In the seismic retrofit design of an existing building through seismic isolation, the intervention technology constitutes a fundamental part. Before inserting one isolator in each column, the vertical load shall be transferred in some way, and then the column can be cutted. Each case should be carefully analyzed; multiple factors, specific for each building, suggest to the Engineer the best solution in relation to:

- Positioning of the isolation level;
- Method of temporary transfer of the vertical load during the cutting operation of the columns and the installation of the isolators.

The load transfer usually takes place by means of two or more hydraulic jacks, installed between proper structural elements. Quite often the isolators are installed on the top of the columns of the basement or of the ground floor. The position of the isolators on the upper part of the column simplifies the inspection and maintenance operations, which are imposed by current regulations. A typical intervention procedure requires the following steps, with reference to Fig. 1:

- Enlargement of the columns at the basement and simultaneous preparation of ferrules to be used for the anchoring of the lower lifting steel brackets and recesses to be used for the lower anchorage of the isolator with dowels (Fig. 1a);
- Core drilling of the upper part of the column and provision of the ferrules for the anchorage of the upper metal brackets (Fig.1b);
- Installation of metal brackets and placing of hydraulic jacks to transfer the load to the brackets and unload the part of the column to be removed (Fig. 1c and 1d);
- Diamond wire cutting, removal of the segment of the column, and levelling of the lower surface (Fig. 1e and 1f);
- Insertion of the metal structure for the anchorage of the upper part of the isolator (Fig. 1g) ;
- Insertion and screwing of the isolator and subsequent grouting of the anchorage structures with antishrinkage cement mortar (Fig. 1h);
- Removal of jacks and consequent loading of the isolator (Fig. 1i).

It is worth noting that the anchorage of the isolator shall be mechanical, it is not allowed to rely just on glue or friction, because it would be unsafe. In the case described above and shown in Fig.1, the bottom anchorage is through dowels and bolts, inserted in the new portion of the enlarged column, while the upper anchorage is through a metal structure that embraces the column, and through bolts connecting the isolator to such metal structure. Of course the isolator shall be removable, as required in any international standard.

Fig. 2 shows a general view of the basement after all the isolators are put in place. It is worth noting that the enlargement of the existing columns shown in the previously described procedure is often needed for different reasons. First, it increases the stiffness of the columns, and thus guarantee that the enlarged columns together with the foundation provide sufficient stiffness (in the horizontal plane) below the isolators. The stiffness above the isolators is usually guaranteed by the existing floor, but in some cases the beams need some reinforcement, at least at the column/beam node. Furthermore, the column enlargement also increase their strength, and sometimes is needed to accomodate the isolator (otherwise a capital could be used).

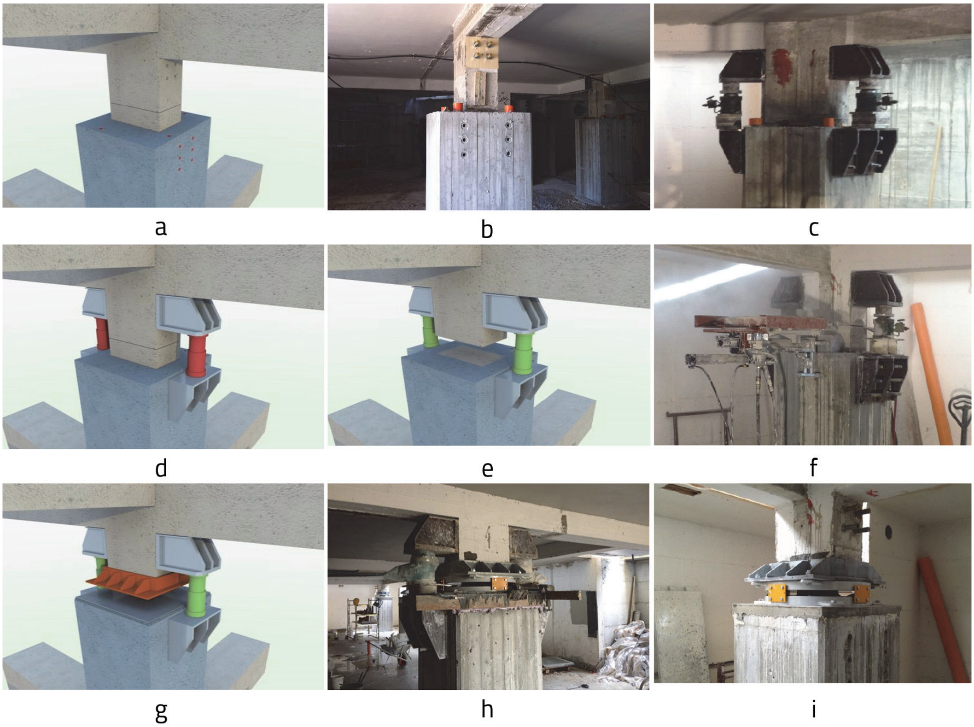

Figure 1. Steps of installation of an isolator in an RC column in the San Leonardo building in L'Aquila [10]

Figure 2. Isolators as installed in an existing building (San Leonardo building in L'Aquila) [11]

Other procedures for the installation of the isolators have been used, for example with the isolators installed directly over the foundations. Some examples are described in [12-14].

The types of seismic isolators mostly used in buildings in Italy are elastomeric isolators and double concave curved surface sliding isolators (European name for pendulum isolators) [15]. With the latter it is easier to reach high values of fundamental period (necessary to reduce as much as possible the accelerations transmitted to the superstructure) in relatively light-weight structures, such as low-rise buildings, since the fundamental period is not substantially dependent on the supported mass, but mainly on the radius of curvature of the devices themselves. In existing buildings, the accelerations should be reduced as much as possible, to avoid interventions in the superstructure. That is why pendulum isolators are the most used in retrofit of existing buildings. The example shown in Fig.1 and Fig.2 is with double concave curved surface sliding isolators.

3 Seismic retrofit through supplemental energy dissipation

Energy dissipation is always used in seismic design, to dissipate a portion of the energy transmitted by the earthquake to the structure. In the capacity design approach, the structure should have enough local and global ductility to dissipate a big amount of energy through controlled damage of the structural elements during earthquake. Collapse shall be avoided, in order to save lives, but it is accepted that the structure could not be repairable after a strong earthquake.

Conversely, since the Seventies of the past century the use of supplemental energy dissipation was proposed, i.e. the use of special structural devices designed, manufactured and tested with the scope of dissipating energy in a stable and controlled way, thus reducing the energy dissipation demand on the structural system, and consequently

avoiding or reducing damage in the structural elements. Of course, energy dissipation devices are effective when installed in positions where relative displacements are expected during earthquake. In framed buildings, the typical position of energy dissipation devices is in braces, that are elongated/shortened by the interstorey drift. The use of dissipative bracings to improve the seismic behaviour of framed buildings was initially proposed for new buildings by Skinner et al [16] and Pall and Marsh [17], but few years later their use in retrofit was studied as well [18, 19]. Since then, the application of dissipative braces started and continuously increased, mainly in new steel buildings, in particular in USA, Canada, Japan, Taiwan, etc. In effects, in new steel buildings the dissipative braces can be seen as the evolution of eccentric braces. In Europe, where the use of steel in seismic countries is not so frequent, the research focused on the use of dissipative braces to retrofit existing RC-framed buildings designed to non-seismic specifications or old seismic codes without the capacity design approach, and therefore lacking both ductility and stiffness. [20, 21, 22] The dissipative braces exploit the interstorey drift of such frames - otherwise too large - to dissipate energy, and thus strongly increase their ability to sustain earthquakes. More recently, many experimental tests on full scale RC frames were carried out, e.g. [23, 24]. The shaking table tests carried out on a RC frame with non linear fluid viscous dampers showed the capability of the dampers to dissipate up to 95% of teh input energy, thus strongly reducing the interstorey drift as well as floor accelerations *vis-à-vis* an identical bare frame [24].
In Italy, as discussed above for seismic isolation, after 2003 the applications of supplemental dampers in buildings increased as well, in particular in existing buildings. Before 2003, the applications were quite few, for example the retrofit of a school [25]. The mostly used dampers are steel hysteretic dampers, in particular buckling restrained braces, or non-linear fluid viscous dampers. In most cases, the supplemental dampers are used in braces, but other ways of applying them are increasing in the last few years.
Buckling Restrained Braces (BRBs) are braces in which a portion is designed to yield in tension/compression, and buckling in compression is avoided [26]. They have been extensively used first in Japan and then, starting at the end of the 1990s, in USA [27]. The first Italian and European application of BRBs was in 2004 [28], in a new prefabricated RC building. In Italy, the FIP MEC's implementation of BRBs foresees a separation of the dissipating function and the bracing function: i.e. a Buckling Restrained Axial Damper (BRAD®) (Fig.3a, in light grey) is installed in series with a steel tube (Fig.3a, in red). This separation of functions allows a cost reduction, and is possible because, when using BRB in RC frames (instead of in steel frames as usual in Japan and USA), the maximum displacement is much lower, and thus the dissipating portion of the brace is much shorter.
Most of the Italian applications of BRAD® in the retrofit of existing buildings concern school buildings. The first use of BRAD® in a school retrofit was in 2005 [29]. Now almost 50 schools have been retrofitted with BRAD®, together with some hospitals, residential buildings, office buildings, etc. Fig.4 shows some BRAD® as installed in two schools.

Figure 3. BRAD® as installed in the Altamura Hospital, Italy. Source: [10]

Figure 4. Buckling Restrained Axial Dampers (BRAD®) as installed in the Marsciano school in Perugia (a) and in the Consolino school in Vittoria, Italy. Source: [30]

The fluid viscous dampers (FVDs) typically used for seismic protection in Italy have a force vs. velocity constitutive law of the type $F=C\cdot v^{a}$, where F is the force, v is the velocity and a=0.15. This highly non-linear behaviour permits greater dissipating energy efficiency when compared to linear FVDs (a=1) or FVDs with a-exponent values between 0.15 and 1. In fact, a=0.15 guarantees significant energy dissipation even at low displacements and at low velocities, i.e. for all the duration of the earthquake, and for earthquakes more frequent and with smaller intensity than the MCE. Because of this type of behaviour, non-linear FVDs are particularly suitable to retrofit non-ductile RC frames that cannot reach high inter-storey drifts. An example of application of FVDs is the retrofit of a building of the University of L'Aquila, strongly damaged by the 2009 earthquake in the non-structural components [31, 32]. FVDs are often used for retrofit of industrial buildings (Fig.5).

It is worth noting that the use of supplemental energy dissipation devices is not higher than the retrofit with conventional strategies; conversely, often the cost is lower, because the energy dissipation allows to reduce the forces transmitted by the braces and thus the local strenghtening interventions are usually much lower. This can be easily understood considering that conventional retrofit interventions usually increase the strength and the stiffness of the existing structure, thus increase a lot the input energy. Conversely, the input energy is moderately changed with the retrofit with supplemental energy dissipation, and the benefits to the existing structural members are related to the energy dissipation.

4 Conclusions

The recent Italian experience of use of both seismic isolation and energy dissipation in retrofit of existing building show the reliability and cost effectiveness of such techniques. These retrofit techniques have been used in buildings damaged by the recent earthquakes, in particular in L'Aquila, but their use in non-damaged buildings is continuously increasing.

Figure 5. Fluid Viscous Dampers as installed in an industrial building in Italy

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