Towards a safe school.
Case studies on seismic improvement in existing school buildings

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Highlights

From a construction point of view, school buildings present a wide array of case studies regarding their building techniques and the materials used, being closely linked to their construction era. The case studies presented concern buildings from the 1970s, constructed with reinforced concrete frames and which, over time, have undergone different upgradings to render them fire safe and make them disabled-friendly, that have changed the compositional and structural layout. As well, a comprehensive, seismic, energy and functional upgrading was planned.

Abstract

The problem regarding seismic risk for school buildings has become increasingly important over the last years and national projects have been set underway to improve and adapt existing buildings to seismic risk. Many schools were built during historical periods when, even though foreseeing anti-seismic measures, were based on prerequisites different to those of today. It has become an urgent need to examine projects for a vast number of existing school buildings in relation to the important social role that they have always played.

Keywords

Seismic adaptation, Construction techniques, School buildings

1. INTRODUCTION

The 2003 Presidency of the Council of Ministers Ordinance extended the seismic zoning to all Italian regions, thus, involving the elimination of previously non-classified zones and individuating four different levels of danger. This amendment immediately highlighted the need to intervene on buildings previously constructed to make them safe, in accordance with the law, in the event of an earthquake. The historical buildings constructed according to the different regulations in force at their time of construction include a large number of buildings designed and built without taking into account the pressures exerted by horizontal forces, or in areas previously considered safe from a seismic risk perspective.
If the problem exists and appears to affect the whole of the existing building patrimony in Italy that, having been constructed over many different centuries, displays specific and different morphological, material and construction features depending on their construction period, it has now become urgent, if considered in the light of the existing school buildings nationwide. There are many schools, of every type and level, that have been located in edifices dating from historical eras when design was based on prerequisites quite different to those of today, or situated in areas previously considered non-seismic zones.

To tackle this situation, the Italian government has taken steps to provide a new impetus for projects aimed at upgrading and rendering this patrimony safe. In 2014, within the Presidency of the Council of Ministers, a specific Unità di Missione was set up to guarantee the coordination among the different relevant ministries in managing the works to be carried out on the schools, as well as individuating and recognizing the different financing involved and support from local entities which directly manage the school buildings. The setting up of a register of school buildings, as foreseen in Law 23/1996, promoted in the taskforce’s founding document, resulted in highlighting, among others, that 55% of buildings had been built before 1975, in the period prior to the school regulation coming into effect, which, in that year, had introduced substantial changes in didactics and in construction. The need to adopt new criteria and new didactic methods often required quite important changes aimed at adapting existing buildings to the previous directive, with the introduction of spaces and variations in layout in order to become more functional and fitting to the changes required in teaching. However, very often, these works were carried out without taking into account the inevitable alterations which would have affected the entire building in the event of an earthquake. Moreover, also from a construction point of view, the school buildings present very diverse examples regarding techniques and materials used in their construction, related to their period of construction reflecting the different attitudes to building.

2. CASE STUDIES

In the disastrous earthquake that hit Aquila in 2009, the Catholic School, Istituto Santa Maria degli Angeli, was seriously damaged, to the extent of being declared unsafe. This historical complex, occupying an entire block built next to the city walls, was mainly built during the Renaissance and the fifteenth century, with the church façade located in the southern corner. In 1968, an extension was added to accommodate a school and a university student hostel, positioned next to the convent to complete the complex on the
eastern side. The new building, in the vacant space adjacent to the wall, was made up of two parts, one of six above-ground storeys and the other of two, and both with a hipped roofing. This situation led to adopting, to adapt to the plan for seismic improvement and restoration work, different approaches for the work to be done on the monumental part, where the actual consolidation and restoration was to be carried out, and also for the work to be done on the building from the 1970s.

The latter was carried out using a six-level R.C. framework, with the first being partially at basement level and positioned, without using structural joints, between the groundfloor, the central heating plant, the entry area and the old historical complex. A study was conducted with the engineers, S. Perno and S. Rossicone, to improve the building’s safety in the event of an earthquake. The findings highlighted that the two parts of the new construction were separated by a 3 cm joint on the first floor and a 5 cm joint on the second, and where the groundfloor, structurally continuous with the building and the entry area, on via Micarelli, had a masonry structure built before 1968, in line with the historical complex, and joined to the new rear structure in R.C. All sections were found to be lacking in bracing walls, except for the upper section where the lift shaft is a part of the floor’s bracing, and the floors are constructed in cement and brick with dividing reinforced cement slabs.

The study on the post-earthquake situation revealed important damages on the ground, first and second floors and signs of hammering in the joints between the adjacent parts as well as partial collapses in the walls and openings and the flooring. Moreover, in all the building, both on the groundfloor and first floor, diagonal lesions typical of shearing were found, which resulted in the brick cladding being extruded. Successively, checking the layout regularity and establishing the position of the centres of mass and flexural rigidity, there emerged that the lift shaft created a marked eccentricity and the danger of the beginning of a phenomenon of hammering in the construction joint between the two sections of the structure. Instead, for the height, it could be noted that there were no false supports, that the columns were continuous for the whole structure and that the masses showed marked variations, while the flexural rigidity, being tapered columns, varied along the upper height of the building. Moreover, the latter, on the vertical plane, was not regular due to the presence of longitudinal sections of marked variations in height, from six to two floors, between one part and the other of the construction. At first, in the design proposal for the seismic improvements, three possible solutions were studied: inserting R.C. shear walls, introducing seismic isolators at the base of the structure and positioning the concentric bracing with dissipative realization, legati all’epoca della costruzione, che connotano il diverso comportamento dei manufatti.

2. CASI DI STUDIO

Nel disastroso terremoto che ha colpito L’Aquila nel 2009 la Scuola parificata Istituto Santa Maria degli Angeli è stata notevolmente danneggiata, tanto da essere dichiarata inagibile. Il complesso storico, che occupa un intero isolato a ridosso delle mura di città, consta di più parti realizzate in epoca rinascimentale e cinquecentesca e si conclude nell’angolo meridionale con la facciata della chiesa. Nel 1968, è stato realizzato un ampliamento per ospitare un complesso scolastico e spazi destinati a un pensionato per studentesse universitarie, posizionato a ridosso del chiuso a concludere l’isolato sul fronte est. Il nuovo edificio, nello spazio del lotto a ridosso delle mura, si compone di due parti, una di sei piani e l’altra di due piani fuori terra, entrambe coperte con tetto a padiglione. Tale situazione ha determinato, nell’ambito del progetto di miglioramento sismico e di ristrutturazione, approcci differenti per gli interventi relativi alla parte monumentale, in cui è stato previsto il consolidamento e il restauro, e per quelli sull’edificio degli anni ’70. Quest’ultimo è realizzato con una struttura intelaiata in c.a. a sei livelli di cui il primo parzialmente interrato e posto, senza l’inserimento di giunti strutturali, tra un terrapieno, la centrale termica, la zona d’ingresso e il vecchio complesso monumentale. Su di esso è stato condotto uno studio, con gli Ingg. S. Perno e S. Rossicone, teso a ottenere un miglioramento nella risposta all’evento sismico. I rilievi costruttivi hanno evidenziato che le due parti del nuovo volume sono separate da un giunto di 3cm al primo livello e di 5cm al secondo, che il terrapieno, in continuità strutturale con l’edificio e la parte di ingresso, su via Micarelli, ha una struttura in muratura costruita precedentemente al 1968, realizzata in conformità a quella del complesso monumentale, e collegata alla nuova struttura retrostante in c.a. Tutti i corpi risalgono privi di netti di controvormento, a eccezione del corpo più alto in cui il nucleo ascensore costituisce in parte elemento di controvormento di piano, e gli orizzontamenti sono realizzati con solai latero-cementizi con solleta armate di ripartizione. Lo studio della situazione post-terremoto, ha evidenziato danni rilevanti localizzati al piano terra, al primo e al secondo piano e segnali di martellamento nei giunti tra parti contigue oltre che credi parziali di tamponamenti e di solai. Inoltre nell’edificato nel suo complesso, sia al piano terra e che al primo piano, sono state rilevate lesioni diagonali tipiche di una rottura a taglio, che hanno condotto all’espulsione puntuale dei rivestimenti in laterizio. Successivamente, verificando la regolarità in pianta del complesso e stabilendo la posizione dei centri delle mura e delle rigidezze, si è emerso che il corpo ascensore creava una forte eccentricità e si è evidenziato il pericolo dell’insorgenza di un fenomeno di martellamento nel giunto di costruzione tra le due parti della struttura. In alzato si è, inoltre, potuto notare che non superavano
The three solutions were then compared regarding their advantages and disadvantages in order to identify the best. The first hypothesis involved inserting, within the existing structure, a system of seismic-resistant walls, designed in accordance with the OPCM 3274 regulations and SLV checked according to the NTC 2008. The walls were to be positioned so as to balance the torsional effects that would occur during an earthquake. This would result in modifying the building’s flexural rigidity and would have an effect during seismic shaking and floor drift. The repetition of the modal analysis, once the earthquake-resistant walls were installed, would result in being able to check that the drift is different for the two volumes of different heights, and in the third eigenmode, a drift contrast, typical of raised irregular structures, could be detected.

The second proposal foresaw inserting seismic isolators below each R.C. column. This system of isolation is designed so as to contain the buildings’ structural response, becoming more elastic and dissipating the energy transmitted by the earthquake through cycles of high-level strain to a horizontal drift. The elastomeric isolators result in having a higher horizontal deformability level, due to the low shear modulus of the elastomer, an increased vertical rigidity, thanks to the confinement effect of the metal plates on the elastomer and a very high dissipative factor, due to the high level of compound damping used. Confined elastomer multi-directional sliding supports are used to increase the system period and adequately align the centres of mass and flexual rigidity. A SLC study was carried out on the design of the elements, taking into consideration severe seismic stresses (TR=1462 years), justified by the importance of the role of the isolators and by the high reliability that would be guaranteed.

Figure 1. Catholic School Istituto Santa Maria degli Angeli in L’Aquila: the survey and analysis phase.
The modal analysis, conducted taking into account the isolators, highlight how overall modal mass involved is, in this case, linked to the first three eigenmodes, that are borne only by the isolation system. Furthermore, it was found that the accelerations affecting the superstructure would be significantly reduced thanks to the shift in the main system periods towards spectral zones characterized by a lower power density, and that the shifts needed by the structure would increase due to the increase in the actual period, but would be absorbed by the system parts.

Installing the steel bracing linked to the R.C. frame by the metal elastoplastic dissipators is the third proposal. In this case, it is mainly required to establish the most ideal positioning in terms of layout and bracing elevation in order to guarantee an increased regularity and an adequate torsion rigidity, the bracing form, their rigidity and the dissipator features. Consequently, work on the R.C. structure was hypothesized to allow for stressed plastic strain before reaching breaking point, by fixing strips of preimpregnated carbon fibre onto the columns with epoxy resins. As well, it was thought to be opportune to tear down the stairwells and rebuild the structural juncture, between the two floor block and that of six floors, to ensure a better regularity in layout and elevation and to be able to have an overall picture of the structure and how it is made up of different volumes, separate but regular. Finally, the dissipators and K-bracing were designed to be inserted into the load-bearing skeletal frame; the redimensioning of the system to determine, at the beginning, the main eigenmodes in two directions for the two volumes with non-braced structures; and the rigidity and resistance values obtained from the analysis to be the basis to establish the size of the diagonal bracing profiles and the dissipators. A K-type bracing was chosen that, designed to remain elastic, uses coupled diagonal UPN profiles.
The diagonals are linked by steel connecting-plate bolting, the central one being connected to the dissipator, while the lower ones are anchored to the existing structure. A Type-E dissipator was proposed, made up of a profile, of only one steel sheet, which has a uniform plastic resistance, shaped so that its active part can be warped antisymmetrically and the three arms remain elastic during dissipation. By using the bracing-dissipator system, the existing frames result in being less exposed to damage and the whole structure increases its performance where expected accelerations are involved.

To individuate the most effective solutions during the designing stage, the three different solutions were compared to be able to evaluate their pros and cons. The first hypothesis undoubtedly has advantages, such as the possibility to control the overall lateral drift, inserting cross-sections, which realign the centres of mass and flexural rigidity, and the lack of any preliminary reinforcing work on the existing structures. However, a work of this type has problems regarding the layout of space, causing an increased stiffening in the structure and an increase in the vertical loads and shear stress on the foundations that would require an invasive and destructive intervention. As far as inserting the seismic isolators is concerned, the advantages highlighted involve the high energy dissipation level, the elevated durability and the low costs to maintain them, as well as the lowering of the spectral accelerations, with the consequent marked reduction in the design forces. In this case, the work could be limited to only the ground and first floors and making the cladding safe from the risk of being forced out and folding. However, on the relevant floors it would be necessary to intervene on the existing structure to make it suitable for a fixed base. Moreover, high structures, that are very old, do not gain any advantages from reducing the spectral acceleration and benefits from a measure of this type, as inserting isolators causes a marked shift with the consequent instability in the upper floors. In the hypothesis of inserting dissipative bracing, it appears to be advantageous to dissipate the energy by means of damaging the links where the excess seismic energy is directed. Moreover, in this case, there is a considerable increase in the resistance of the structure with a less intrusive and destructive intervention compared to introducing R.C. walls and with more flexibility in using the spaces available. On the contrary, however, problems could arise in the connection points of the existing bracing structure due to an increase in the axial forces on the structural frame. Therefore, possible works of a local type should be evaluated, so as to provide the structure with a higher flexibility and allow the foundations to counter the increase in vertical loads. The rigidity resulting from the bracing leads to a reduction in drift and, therefore, an
increase in the anticipated accelerations, shifting the basic time span of the structure into the highest pseudo-acceleration spectrum. However, inserting the links results in an increase in the structure’s dissipation levels when there is an unaltered demand and it is actually this that makes this solution very interesting and innovative.

During the same years, we also have the construction of the I.T.C.G. Brunelleschi School in Frosinone, built in the early 1970s and inspected and approved in ’76, the building is a structure that is laid out around an entry atrium leading to two three-storey blocks, used for classrooms, two gyms and a main hall on only one level.

In its present state, the school has many different problems from a functional and energy and seismic point of view and, therefore, in the design study for its improvement, an overall upgrading was foreseen. The works carried out over the years have involved building external fire-safety stairs and external lifts, not consistent with the distribution of space and the internal layout and allowing disabled access only to the classrooms.

In the design proposal, drawn up with the engineers S. Perno and M. Genovesi, it was planned to install short ramps providing access, from the atrium, to the new internal lifts in the classroom-volume and also to the gym and main hall areas, so that the atrium would become the real heart of the institute, also for the disabled, no longer being forced to enter from secondary entrances. On the upper floors, short staircases, adapted for the disabled, allow for accessing the secretary’s office on the first floor and other classrooms on the second, while the fire safety stairs were designed placing them in the most appropriate positions.

As far as the energy aspect is concerned, the school has external enclosure walls that are highly environment efficient and, therefore, a thermal insulation, with external plastering, was planned which would result in reaching the transmittance parameters as foreseen in the current regulation and, at the same time, contribute to transforming the existing prospectus, where external courtyard consoles, left in view, were points of possible water infiltration. However, the most important work was that forecasted for the structure’s seismic upgrading in R.C. For this, project designs were drawn up regarding the reinforcement positioning and, then, the findings were consulted from the trials carried out in 2006 by the provincial government on concrete and steel, that were compared with the materials used in the 1961/70 period. Finally, based on onsite trials carried out in 2007, the features of the foundation terrain were identified. The study on the conformation and configuration of the complex were conducted, then, on the subdivision of the building in different
sections and, then, a linear dynamic analysis of one of the volumes housing the classrooms, which had irregular characteristics on both the upper and lower levels. Beginning from a SAP modelling for the framework in reinforced concrete and oak foundation beams, a modal analysis was carried out with an elastic response spectrum, concerning the overall structural response under seismic conditions.

From this, it was found that, due to the eccentricity, the structure has 18 eigenmodes, that influence at least 85% of the mass. Following, the floor drifts were checked that resulted in being stronger in direction Y than in direction X, as also shown in the modal analysis, and it could be noted that the biggest interstorey drifts occurred on the first floor. The structure’s fundamental SLU was then checked under the action of vertical loads and it was observed that the building, designed with the admissible tension method, has an oversizing in some of the structural elements.

As well, there also emerged some anomalies in the response linked to the asymmetry of the structural system, that has a positioned corbel system, on every floor, on only one side of the multiple frame, so as to introduce an anomaly in the column shear and flexing responses on the first floor. The SLV was then checked by creating a Response Spectrum where the site coordinates were inserted, as well as the use of the class and nominal life of the building, the soil type, the topography co-efficient and the structural factor, obtaining a response spectrum function for the horizontal design. Finally, beams and columns were checked with the heaviest loading combinations, obtaining demand/capacity diagrams that highlighted the lack of response in the columns and the basement level and also in some beams.

Figure 3. I.T.C.G. Brunelleschi School in Frosinone: the survey and analysis phase.
The solution chosen in the project was to install shear R.C. walls so as to reduce the eccentricity of the centre of mass and centre of rigidity, increasing the resistance of the structural elements, particularly in direction X, diminishing the interstorey drift and seismic stress on the elements, that were not originally calculated, in order to counter the horizontal forces. It was decided to install shear walls where possible on the perimeters, so as to be able to work on the foundations without damaging the structure. It was also thought to place them along the frames damaging the existing elements as little as possible during the installing of the walls themselves foreseeing, moreover, that the connections between the different floors corresponded so as to be able to more easily drill into the R.C. sections.

Once the positioning of the walls was decided, they were placed in the model to check again the beams that had previously shown to be problematic. It could be noted that by installing the shear walls, the beams on the second floor, both shear and flexion, were all verified. Further modifications were planned to allow for checking specific situations and the executive project was drawn up for the shear walls – 3 and 4 walls – that were perpendicularly connected (increasing the reinforcement in the bordering zones both to strengthen the connection points and to allow the bordering zones to counter the traction generated on the dividing walls when the earthquake shifted in direction Y).

The third and last case study concerns a Lower secondary School B. Sisti in Rieti that, designed in the mid-1960s and completed only in 1976 following a modification in the executive project, is a multi-storey complex. Two blocks can be identified, one for the classrooms that are on four levels and one, separated from the classroom block by means of a technical joint, which houses the gym and, on the third floor, the main hall, adjacent to which is the Figure 4. I.T.C.G. Brunelleschi School in Frosinone: the intervention with insertion of shear R.C. walls.
caretaker’s lodgings. The building has a floor conformation that is not very resistant to seismic activity and also displays serious problems from a layout-functional point of view, where the relevant legislation is concerned. From the study, a fragmentation in the spaces and a difficult relationship between the classroom volume and that of the gym can be noted, as the different floors are positioned on offset levels of 112cm. Moreover, the external safety stairs are not integrated into the building, appearing as superfluous. Many facilities required for carrying out school activities, such as the library and art and music rooms, are missing, while the administrative offices are located in small areas and the external area has few trees and facilities for outdoor activities. One of the project objectives to adapt it functionally is, therefore, to create a flexibility in the school environments and introduce spaces for special activities.

It is important in a study for building restoration to have a detailed knowledge of the structure, of its design and how it was constructed to the extent that also the regulation has adopted the level of knowledge (LK) and the consequent factor of confidence (FC), using them as partial safety coefficients in individuating the modelling most relevant to the context. The data required for the two parameters are thoroughly described and listed in the appendix in article C8 of Circular n.617/2009 Istruzioni per l’applicazione delle Nuove Norme Tecniche per le costruzioni. In this case study, carried out with the engineers S. Perno and G. Lupascu, project designs of the school and the relevant geological report were found, with the terrain’s seismic features, and a geometric-dimensional and constructive relief was carried out. Based on the data obtained a check on the structural regularity was done, a factor that strongly influences how the structure responds to earthquake activity and the

Figure 5. Lower secondary School B. Sisti in Rieti: the survey and analysis phase.
choice of the type of analyses to carry out.

The horizontal and vertical regularity is governed by NCT2008 in point 7.2.2. For the former, both the density and approximate symmetry for the two orthogonal directions must be verified and the distribution of the mass and rigidity must be evaluated. Moreover, the ratio between the sides of a rectangle in which the construction can be placed must be less than 4, the size of possible recesses or projections no more than 25% of the total construction size in the corresponding direction and the floors and roof must result so they can be considered infinitely rigid compared to the vertical elements, and sufficiently resistant. For the school under study, the evaluation of the mass and rigidity distribution was positive for the layout at heights of 4.51, 8.00 and 11.49 and negative at a height of 15.5, while all the other requirements established by the regulation appear to be satisfied. For the evaluation of the vertical regularity it is necessary to verify that all the vertical resistant systems extend along all the height of the building, that the mass and rigidity remain constant or vary gradually, without any abrupt changes from the base to the top of the building and that any possible reductions in the construction section occur gradually from one floor to the other. In the case of the school in Rieti, the continuity on the vertical plane of the resistant systems is missing and the rigidity does not remain constant in passing from the first to the last level. Furthermore, the building shows a reduction in the section in the passage from the first to the second floor. The irregularities revealed infer the non-coincidence between the centre of mass and the centre of rigidity, that results in an instance between the agent force and resistant force and, therefore, an increase in the shear forces on some resistant elements. As well, interstorey drift was found that could be excessive.

Figure 6. Lower secondary School B. Sisti in Rieti: the intervention with insertion of K-type braces.
Once the model was completed, a linear dynamic analysis was carried out and the effects of seismic activity and their combination were calculated, shown by the project’s response spectrum, for each of the eigenmodes individuated. Then, the drifts were analyzed and it was possible to highlight that those regarding the interstory are not verified. It is important to note that the main drifts towards the frames correspond to the floor on the first level at about half the height of the building, as also confirmed in the relative data in the modal analysis.

The verification of the vertical load structural elements revealed to be satisfactory concerning the concrete tension, while in many columns, especially those subject to a wider area of influence and with reduced resistant sections, the steel column was better. The columns and beams were then checked concerning seismic activity to evaluate the level of the building’s safety, using a combination of actions and also taking into account the accidental eccentricity.

For the serviceability limit state, a SLD check was carried out, while for the last limit state a SLV check, using the factor q=1,5, as established in paragraph C8.7.1.2 of Circular n°617/2009 for existing constructions. Thus, some problems were highlighted in the columns and the existing roofing structure, where the ridge, roof ridge and roof valley beams do not directly rest on the columns and the network of cement brick layers is always in the same direction.

The roof is an element of irregularity as it is not positioned in a direct continuation to the underlying structural system. Some floor spans are also not of a thickness suitable to support the vertical loads and it was verified that the whole system is inadequate where seismic activity is concerned. The proposal for a seismic upgrading of the building foresees above all the removal of the pitched roof and the reinforcing of the floors by inserting steel crossbar beams or a R.C. slab, installing traditional and dissipative bracing and localized work on the structural elements. By only eliminating, in the structural model, the pitched roof, there was an improvement in the structure’s response to earthquake forces with a reduction in drift. By including, in the same model, without a roof, bracing, firstly of X-type and then of K-type, the response changed considerably, further reducing drift.

Therefore, the proposed project inclined towards using elasto-plastic K dissipative bracing and, on the horizontal level, X bracing. The bracing system was designed, inserted into new metal structures placed on the building’s perimeter and including the fire safety stairs and some added spaces necessary for the correct functioning of the school. In doing so, it was possible to obtain,
other than an undoubted functional improvement, also a transformation in
the building’s image. The positioning of the new metal structures allowed
for redesigning the two opposite rectangles, eliminating the projections and
recesses linked to the presence of the caretaker’s lodgings and the fire safety
stairs and resulting in a regular composition of the pure volumes.

3. CONCLUSIONS

As can be seen from the above it appears evident how today it is possible to
carry out a complete and delicate upgrading to seismically improve existing
constructions using different methods, materials and construction techniques.
However, the planning must begin from a thorough knowledge and analysis
of the structure to be able to work using the most suitable techniques and
considering the project from a global viewpoint. The work should not be too
invasive regarding the distribution and functional layout of the building and
the architectural image and, instead, should be able to provide a response in
the event of an earthquake guaranteeing the required safety in all existing
school buildings, built in different eras, and in relation to the important
social role that this typology has always played. Moreover, working on
schools constructed before the 1975 reform could provide an opportunity to
individuate new functional layouts and new energy solutions adapting to what
is currently required of them.

4. REFERENCES