EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Editorial: Earthquake-vulnerable buildings

This is the theme of this newsletter. The sole article describes the earthquake assessment and strengthening of school buildings in Portugal. This type of proactive approach to reducing earthquake risk to vulnerable buildings is most commendable. Most societies expect their heavily occupied public buildings to be safe in earthquake and other natural hazards. Those of us who live in recognized active seismic zones know that although we can't predict the timing of earthquakes we can expect them to affect buildings in often quite disastrous ways.

Just over these last three weeks I've been surprised how many damaging quakes have been reported around the world (and as usual, mainly along the edges of the earth's tectonic plates). So far in April, the USGS website lists 13 quakes with Magnitudes over 6.0. The largest was the M8.2 Iquique Chile event, followed by a M7.6 in the Solomon Islands, and another Pacific Island quake in Papua New Guinea registered M7.5. Fortunately, none of these earthquakes have had their epicentres close to large and dense populations so the death tolls have been small, but nevertheless, especially in Chile, a huge amount of damage to buildings, infrastructure and means of livelihood has occurred.

Since the devastating earthquakes in Christchurch over two years now, we in New Zealand are debating approaches we as a country should take to protect people, and therefore buildings, from severe earthquake damage. The Building (Earthquake-prone buildings) Amendment Bill has been introduced to Parliament and public submissions have just closed. The Bill aims to ensure earthquake-prone buildings are dealt with in a timely manner by way of a nationally consistent system and will require information about earthquake-prone buildings to be made available to the public.

A Government website summarises that the legislation:

- "Sets a national timeframe of 20 years for buildings to be strengthened or demolished, by requiring territorial authorities to assess buildings within five years and for work to be completed, or buildings to be demolished, within 15 years of assessment.
- Requires a publicly available national register on the seismic capacity of buildings to be established.
- Prioritises work on certain buildings, including buildings of particular significance in terms of public safety, and buildings that could, if they collapsed in an earthquake, impede a transport route of strategic importance in an emergency.
- Enables local councils to issue building consents for required work on earthquake-prone buildings without requiring other upgrades in certain circumstances.
- Owners of Category 1 historic places may apply for an extension of up to 10 years.
- Owners of other buildings will also be able to apply for exemptions from the national timeframe for strengthening. This provision is intended to apply where the effects of failure are likely to be minimal, and could for example include low use rural churches and farm buildings with little passing traffic."

I hope to be able to report later this year that we in New Zealand have achieved a widely-accepted balance between safety and cost.

Virtual Site Visit No. 36: Foundations for a ten storey apartment building

This building under construction is located just outside Wellington's CBD. It is an area experiencing redevelopment. The new building is adjacent to a similar size apartment built three years ago.

During the foundation construction process the presence of surface soft soils meant using cast-in place RC piles down to firm bearing. This was found at a depth of approximately 15 m. Figure 1 shows a typical pile reinforcing cage about to be lowered into the drilled shaft.

As usual, the pile layout was determined by the structural configuration of the superstructure. In this case the structure consists of a centrally-placed RC core with perimeter steel frames. The front and rear frames parallel to the street frontage are designed for gravity loads, but on the ends of the building the frames are so much larger. They will resist gravity forces from suspended floors spanning between the core and frames, and as well, assist the core withstand wind and seismic forces. The other important function of these two perimeter frames is to increase the torsional stability of the building. The large distance between them, approximately the length of the building, means they will work together to provide torsional restraint. The core, due to its short plan dimensions and door openings that reduce its strength and stiffness, needs help against torsional moments acting in plan.

The structural layout can be seen in Figure 2, while Figure 3 shows the deep beams in the vicinity of the RC core being concreted. These beams are designed to distribute the axial, bending and shear forces from the core into the piles which have been placed outside the core so as to reduce the forces the piles need to resist.

The placement of the core walls can be seen from the positions of the vertical starter bars that protrude above the slab surface. These bars will lap with other vertical reinforcement to resist the bending moments from wind and seismic loads. Shear forces in the wall will be resisted by layers of horizontal bars that are yet to be placed.

Fig. 1 A pile reinforcing cage with its welded spiral hoops to confine the concrete.

Fig. 2 The deep foundation beams under and outside the core, and perimeter pile reinforcing in the background.

Fig. 3 Concreting of the foundation beams/raft under the structural core walls.

Summary of the paper "Overview of Seismic Strengthening Interventions in School Buildings in Portugal" by Jorge Miguel Proença, António Sousa Gago and Teresa Heitor. From the Procedings of the 15th World Conference on Earthquake Engineering, Lisbon 2012.

Summary

This paper contains an overview of the seismic strengthening interventions in school buildings, within the scope of the School Building Modernization Programme. The selection of the schools to be retrofitted was based on the analysis of the time-frame for structural design codes in Portugal and the corresponding evolution of the construction practices and materials. This analysis led also to the identification of five building groups – "historical", masonry wall with RC slabs, "no code" RC; "low code" RC, and other less typifical building solutions (e.g.: precast RC).

The major problems for each of the former five school building groups are generally presented. Some of these problems stem from the absence or use of outdated structural design codes, aggravated by construction or detailing flaws. The implemented seismic strengthening procedures are outlined through a brief presentation of a collection of cases that exemplify the interventions in all the former main school building groups.

1. INTRODUCTION

The School Building Modernization Programme (SMP) was launched by the Portuguese government in 2007 to modernize over 330 public secondary school facilities in mainland Portugal. The fact that some of these schools are located in moderate-to-high seismic hazard areas and that a part were built without any (or with limited and outdated) earthquake resistant design concerns, led to the assessment and strengthening of a significant number of school buildings. The schools selected to be retrofitted generally correspond to those designed prior to the 1983 set of Portuguese codes (actions and reinforced concrete design) and located in areas considered to present the highest seismic hazard.

Secondary school construction in Portugal generally occurred in a centralized manner since the end of the 19th Century, following education models that evolved discontinuously along time, combined with the also discontinuous extension of the mandatory education levels and geographical dissemination of these schools. These characteristics led to a rather typified school building stock, that, when confronted with the evolution of construction practices and design codes for earthquake resistance, allows for the distinction of five building groups (identified in §2). Each of these building groups presents specific deficiencies, also outlined in §2, that were tackled with different approaches, exemplified in §3. In the end, some considerations are presented in terms of the need to include seismic assessment studies and measures in large scale building modernization programmes.

2. SELECTION OF SCHOOLS TO BE RETROFITTED AND BUILDING TYPOLOGIES

2.1. Selection of Schools

The selection of the schools to be retrofitted was then based on the analysis of the time-frame for structural design codes in Portugal and the corresponding evolution of the construction practices and materials: the first, "low code", design code was enforced in 1958 (at the onset of the generalized use of wholly reinforced concrete structures), slightly updated in 1961 (following the 1960, Agadir, Morocco, earthquake), and completely superseded by a relatively modern set of codes in 1983.

The "pre-code" constructive practices in existing school buildings correspond to reminiscent Pombaline (cage) timber frame construction in the late 1800s, followed by load bearing masonry wall structures with timber floors, from the 1900 to 1920s, with a progressive increase in the incorporation of reinforced concrete structural elements - floor slabs, beams and lintels - from the 1930s, an increasing number of columns, and the appearance of generalized one-way frames in the 1950s.

2.2. Building typologies

2.2.1. Historical buildings

This building typology roughly corresponds to major central schools initially built in Lisbon and Porto since the onset of the 20th Century following the French model of Lycée (Fig. 4). The spatial configuration is varied, although dominated by those extending partially or fully occupying the perimeter of the city block, defining one or more open courts. These schools are now considered buildings of acknowledged heritage and symbolic value.

On the whole, the structures of these buildings consist of outer and interior walls made of stone masonry and solid brick, which support the floors. Stone masonry exterior walls are usually very robust and may be 1.10 thick at their foundations and varying between 0.80-0.90m and 0.60-0.70m higher up. Interior walls, mostly made of brick masonry, are less robust and are rarely any thicker than 0.30-0.40m. The construction of this group of buildings coincides with the first applications of reinforced concrete and structural steel in schools, comparatively new materials in the building industry.

Fig. 4: Maria Amália V. De Carvalho

Except in gyms, where very light structures supported on steel trusses can be found, the roofs were of tile supported on wood rafters and frames which themselves are supported either on steel trusses or on the masonry walls. As a rule the steel trusses cross the span between the façades and there are no supports on the interior walls.

The main seismic vulnerabilities of these buildings are related to eventual inadequate strength and poor deformation capacity of the load bearing walls to in-plane and out-of-plane horizontal loads, deficient functioning of the floors as rigid diaphragms in their planes and deficient functioning of the connections between the orthogonal load bearing walls and between load bearing walls and the floors.

Fig. 5: Sá da Bandeira Lyceum, Santarém

2.2.2. Load bearing masonry wall buildings with reinforced concrete floors

During the 1930s and 1940s a new surge of secondary schools was built, initially adopting modernist architecture models and, later on, in the 1940s, progressing towards a more traditional architectural language (pitched roofs, decorative masonry in the main façades, etc) (Fig. 5).

These schools are generally composed of a single main building with a linear layout with "side corridor" configuration (from which a single line of classrooms led off), sometimes encompassing inner courts.

The structure of these buildings can be considered robust and mostly consists of load bearing walls of stone masonry (the exterior ones being at least 0.60m thick), ceramic brick or concrete block masonry (the interior ones are only 0.25 to 0.30 m thick), which support reinforced concrete slabs (as a rule voided, ribbed and reinforced in one direction) and reinforced concrete beams. The stairs are also of reinforced concrete, but solid. In areas where an open space is required, generally the entrance lobby and covered play areas, there are usually reinforced concrete substructures consisting of grids of reinforced concrete beams (main and secondary), which, supported on columns, support the overlying floor. Load bearing masonry walls that support the slabs of the upper floors and the roof slab are often built over these reinforced concrete main beams. The roofs of these buildings are tiled, using wooden structures as support. Where there is a roof slab (nearly always with reinforced concrete inverted beams) these structures are directly supported on the slab (or on the beams). In the absence of a roof slab, the roof usually consists of steel or wood trusses supported on the exterior walls of the building.

Studies undertaken in some of these schools have shown the following main seismic vulnerabilities in this building group:

- inadequate local resistance or inadequate deformation capacity of the load bearing masonry walls both to in-plane and out-of-place loads/displacements;
- malfunctioning of the floors as rigid diaphragms. This deficiency could be indicative of possible separation between the floor slabs and the masonry walls that support them;
- absence of the diaphragm effect at roof slab level, sometimes because of lack of reinforced concrete roof slabs and at others due to the roof slab failing to cover all the area;
- inadequate resistance and deformation capacity of the reinforced concrete columns;
- fall of ornamental elements from the façade and roof (gables, spires, etc.).

2.2.3. "No code" reinforced concrete structures

This group comprises the buildings whose structure was entirely made of reinforced concrete (slabs, beams/lintels and columns), but whose design did not consider seismic action. The number of school buildings concerned is quite small since the widespread use of structures wholly made of reinforced concrete only took off in the 1950s and the first EQ-resistant design code was published in the same decade, in 1958.

In terms of architectural layout, the concept of a single building is retained (apart from the possible addition of a second building for the canteen, kitchen, changing rooms and gym or other single / groups of buildings), with a linear layout and a "side corridor" or "central corridor". In the first case the layout is similar to that of the preceding constructive type, with masonry structure, and in the second the corridor runs down the middle with a line of classrooms on either side.

The structural system of the buildings that form the main block containing classrooms and administrative services generally consists of a reinforced concrete frame structure, with longitudinal façade and corridor frames made of columns and beams which support the loads associated with the slabs. As a rule the building has no beams running in the transverse direction and the floor slabs in the classrooms are voided (ribbed transversally) and those in corridors are solid. The buildings are divided longitudinally into blocks 15 to 25 metres long, separated by expansion joints of reduced thickness (usually 1 to 2cm). The roofs are sloping, tiled and supported on frames built up from the lower frames extension or on precast reinforced concrete trusses. Columns supported indirectly on beams occur fairly often, particularly when the space layout differs from floor to floor.

The dimensioning of the columns took into consideration simple compression, without bending moments, and smooth rebars, with an anachronistic detail that indicates limited ductility.

The detailing of the walls in elevation, in the façades and longitudinal corridors alike, constrains the columns laterally for most of their height, with the exception of regular openings (for stretched windows), which may give rise to the well-known short column (or captive column) effect. Sometimes the layout of the walls induces irregularities in plan (because they are asymmetrically distributed) or elevation (because they have totally or partially hollow floors).

The studies undertaken show that all the detrimental distinctive features referred to previously can give rise to increased seismic risk

2.2.4. "Low code" reinforced concrete structures

The design of school buildings after 1958 and before 1983 included a simplified seismic analysis using the so-called "seismic coefficient method". Comparative studies have shown that the prescribed seismic coefficient (ratio between the seismic base shear force and the total weight of the building above the foundation), of 0.10 for the highest seismic zones, is clearly insufficient, and that the rule for the (uniform) distribution of the base shear force along storeys is non-conservative.

Fig. 6: Rainha D. Leonor Lyceum

The 1st Standard Design was developed based on a linear configuration of the main building with several aggregated bodies (separated by expansion joints) and a "central corridor" layout (Fig. 6). The blocks that constitute the main building have a longitudinal development from three to seven bays, and are separated by 2cm wide expansion joints. In most cases the main building is elevated two floors, with roof slabs and sloping roofs. The main building presents a reinforced concrete frame structure, with longitudinal façade and corridor frames made of columns and beams which bear the loads associated with the slabs. The floor slabs are voided in the classrooms and solid in the corridors. Longitudinally the structural system considered for seismic action consists of the aforementioned frames, façade and corridor, which were designed for the horizontal forces in this direction (seismic coefficient of 0.10). Transversely the designers planned a more unusual structural system in which the solid corridor slab acts as a horizontal beam, making it possible to gather the transverse inertia forces and route them to the transverse substructures at the end (joint), thus serving as (transverse) supports of this beam. The structure is locked transversely by reinforced concrete diagonals in both lines of classrooms, hence enabling the resultants of the inertia forces to be routed from the floors to the foundation. Leaving aside the thickening of slabs in the classrooms under the respective end walls, the only existing transverse beams are in the joint alignments, in the same plane as the aforementioned diagonals. Considering the current seismic design actions, there is a widespread deficiency of strength in structural elements, as well as the risk of pounding between bodies separated by joints.

The pavilion-type solution, which started with the 2nd Standard Design, was used from the end of the 1960s and became steadily more important (Fig. 7). The more numerous academic pavilions, with variable height up to three storeys high, are developed based on a square plan around a central courtyard covered by skylights. Structurally speaking, all the pavilions have a framed structure using a reinforced concrete beam-column-slab system; the slabs are voided in the classroom areas and solid on the stairs and accesses (which are narrow cantilevered balconies).

Fig. 7: "Technical base" academic pavilion

The reinforced concrete frame structure of the classrooms consists of frames in the two directions, with expansion joints separating each of the blocks in four independent buildings. In all buildings inspected, with one or two elevated floors, weaknesses were identified near these joints, resulting from differences in deformability of neighbouring structural elements (slabs and beams). These deficiencies have consequences particularly with respect to the use of the building and its durability. The expansion joints were only 2-3cm wide, which is not enough given the foreseeable amplitude for the vibration of the buildings and may lead to the pounding effect. As expected, the seismic vulnerability assessment studies also pointed out to a general lack of strength (particularly in the

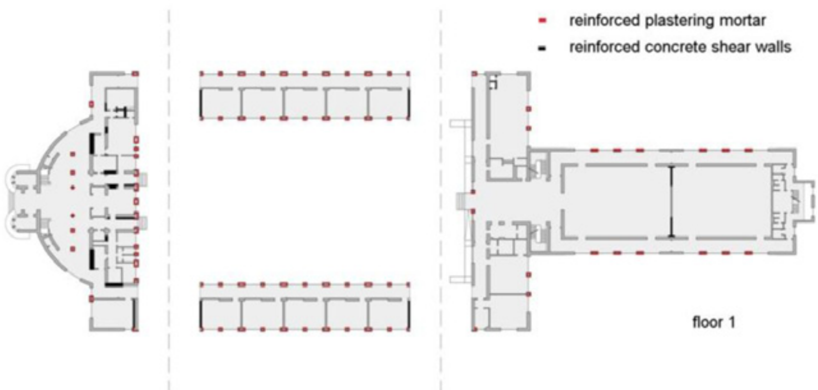


Fig. 8: Location of seismic joints and reinforced plastering mortar interventions

more generous corner columns, with little reinforcement) and outdated detailing rules in the critical cross- sections of these columns.

3. EXAMPLES OF SEISMIC STRENTHENING INTERVENTIONS

3.1. Historical buildings

This limited but important group of school buildings presented deficiencies common to all load bearing masonry wall buildings (also considered in the second group), in this case aggravated by in- plane deformability of the (timber) floor structures. The improvement of the behaviour of the load bearing masonry walls was generally accomplished through a number of variants of what could be called "reinforced plastering mortar" solution. A particular attention was devoted to improving the connections between orthogonal walls and stiffening the floor structures in their plane and improving floor to wall connections.

3.2. Load bearing masonry wall buildings with reinforced concrete floors

The deficiencies anticipated in terms of the lack of strength (and deformation capacity) of the load bearing masonry walls led to disseminated strengthening of these through the previously referred reinforced plastering mortar solution. Some variants could be found, both in terms of the tensile reinforcement– expanded steel wire or fiberglass meshes were the most common – or of the structural mortar – cement or lime based – depending on the works and the fact that the wall faces were exterior or interior. The reinforcement meshes were anchored to the slabs at floor level, also improving the floor to wall connections.

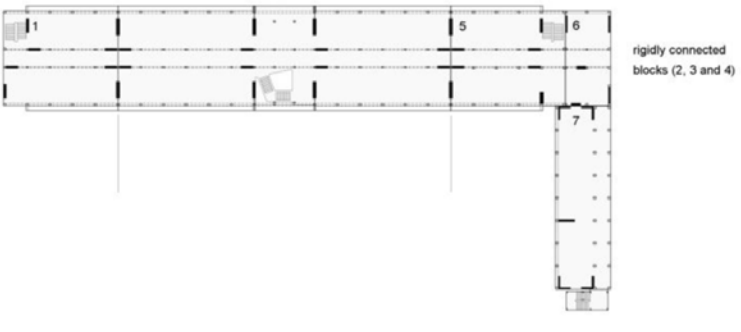
In some cases, the extricated and long dimensions of the main building (single building with no expansion joints) led to the division into separate, more regular, building blocks with the inclusion of new seismic joints (Fig. 8).

In those cases where the roof slab failed to cover the entire plan, some horizontal steel trusses were added (and tied) to avoid the independent behaviour of opposite walls. In other cases, a stitching procedure was devised to tie the roof slab to the wall cornice.

The possible fall of ornamental elements in the façade – such as gables above the main entrance – led to the erection of secondary stabilizing structures tying these ornamental elements to the structure.

3.3. "No code" reinforced concrete structures

In spite of the fact that there are few examples on this building group, the strengthening interventions generally considered a common approach. This approach consisted in the inclusion of stiffening elements – reinforced concrete shear walls or strengthening of existing masonry walls by means of variants of the reinforced plastering mortar solution – extended throughout the whole height of the building, with independent foundations, properly tied to the existing floor structures and evenly distributed, both in plan and in the two orthogonal horizontal directions. The pre-existent vertical elements (reinforced concrete



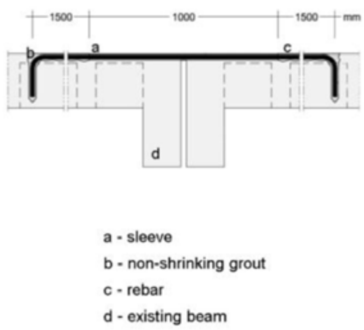


Fig. 9: Examples of location and orientation of RC shear walls and elastic connection between blocks

columns) were there on considered as secondary seismic elements, supporting the vertical loads and accompanying the (greatly reduced) horizontal displacements. The risk of pounding between adjacent blocks was tackled either rigidly joining these blocks and/or demonstrating that the amplitude of horizontal displacements was consistent with the joint widths.

3.4. "Low code" reinforced concrete structures

It should be stated that the different approaches for seismic strengthening of reinforced concrete buildings led to a variety of solutions that cannot be comprehensively described in the present paper.
This school building group covers a wide range of buildings, built accordingly to the aforementioned standard designs. The first of these Standard Designs EQ-resistant systems was proved to be sound in concept but, as a consequence of the low values for the seismic coefficient (and inappropriate distribution of inertia forces along height) and the insufficient thickness of the seismic joints, presented a series of deficiencies. These deficiencies were solved by different approaches in which the most common consisted in the construction of reinforced concrete shear walls (with individual foundations, generally with micro-piles) distributed in plan and in both directions (Fig. 9, left). Another common feature of these interventions consisted in rigidly joining groups of adjacent blocks and elastically joining groups of (rigidly joined) blocks, so that pounding between these could be dismissed (Fig. 9, right) shows a typical connection detail).

Another of the most common standard designs in this period corresponds to the "technical base" pavilion model. As stated before, the corresponding academic pavilions consisted of four blocks, separated by expansion joints (with increased risk of pounding) in which the structural elements (particularly the most generous columns) presented insufficient strength and inadequate detailing.

One of the most common strengthening solutions comprised the following operations: (1) elimination of expansion joints, stitching these and building a peripheral beam at roof level tying all four blocks; (2) construction of external slender reinforced concrete shear walls in some of the facades, tied to the existing structure and with independent foundations (through micro-piles).

4. CONCLUSIONS

The seismic vulnerability assessment and strengthening of secondary school buildings actions focused on the school buildings designed prior to 1983, the year in which the present structural design codes of practice came into force, located in the more earthquake hazardous regions of mainland Portugal. Invariably these studies have pointed out to insufficient earthquake resistance, either resulting from the increased vulnerability of certain building typologies (i.e., buildings with load bearing masonry walls, with timber and even with reinforced concrete slab floor structures) or of the requirements, presently insufficient, set by early generations of structural design codes. The strengthening solutions devised were dependent on the existing structural and building typologies, and, moreover, these also present a significant diversity within each of the former building typologies due to individualistic designer approaches. The seismic strengthening interventions here presented, chosen as the most representative, rely heavily on the increase of the buildings' global strength, implicitly assuming force-based analyses, paying also some attention to control, limitation and regularization of lateral displacements, as well as to aspects related to the forestalling of local collapse mechanisms.

The experience provided by Parque Escolar's School Building Modernization Programme clearly shows the need and the advantages of incorporation of seismic vulnerability assessment stages, and subsequent strengthening, in large scale building stock modernization, particularly, if these buildings present an increased importance (e.g. school and hospital buildings).

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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