# Accounting for the “block effect” in structural interventions in Lisbon’s old “Pombaline” downtown buildings

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ABSTRACT: The so-called “Baixa Pombalina” (18th century historical centre of Lisbon) represents an important architectural and cultural compound. Since their construction, but particularly after the onset of reinforced concrete, the buildings of “Baixa” have been subject to modifications. Although these modifications are often not visible externally, they can affect the seismic behaviour of the historical buildings. In this paper, the need to account for the “block effect” in structural interventions is addressed as it seems debatable to analyse the individual buildings separately from the block.

## 1 INTRODUCTION

Lisbon’s “Baixa Pombalina”, the historical downtown rebuilt after the disastrous 1755 earthquake, is composed of approximately sixty blocks, most of them rectangular and consisting in average of seven buildings, see Fig. 1.

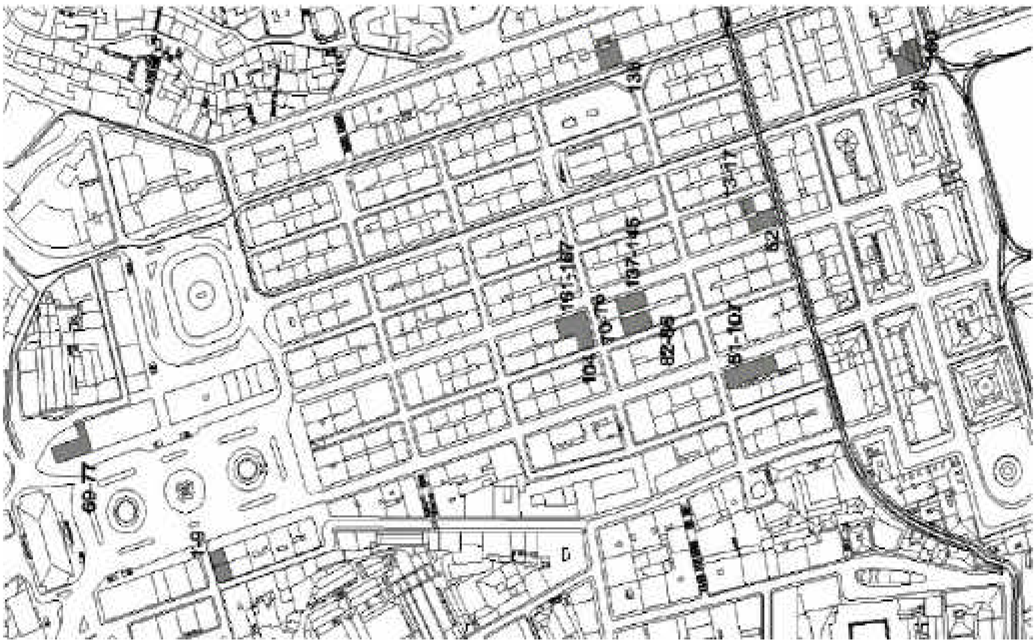


Figure 1: Lisbon’s historical downtown, showing the typical rectangular blocks. Areas shaded represent buildings already surveyed by Oz, with “Martinho da Arcada” shown in the top right.

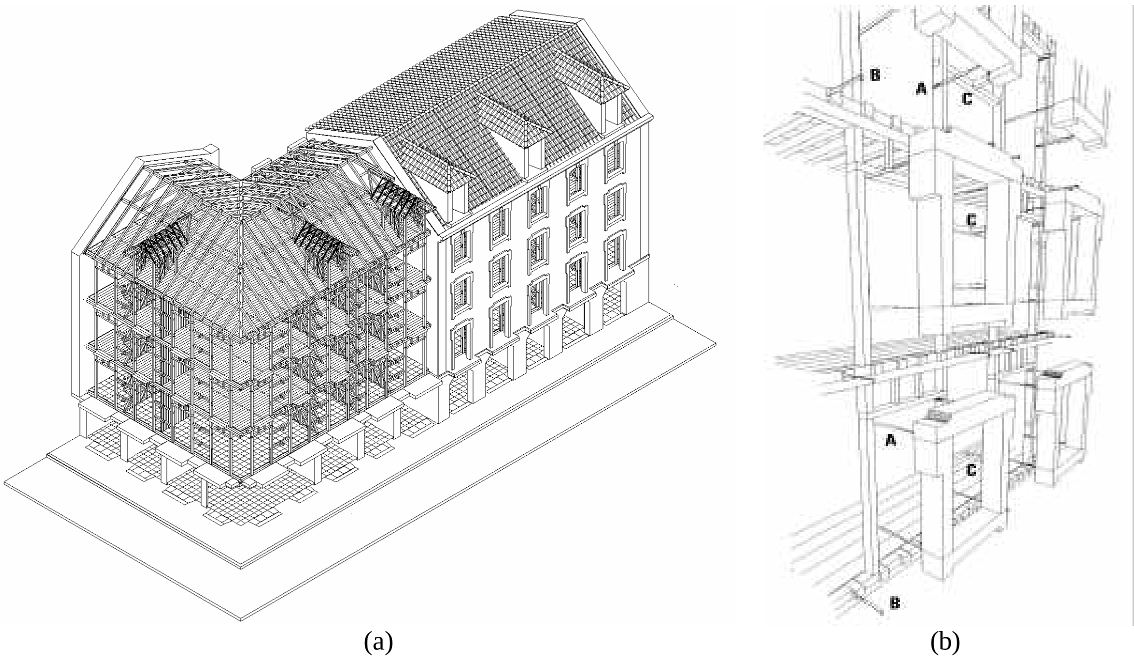
Within each block, the buildings are constructed side by side, sharing the same gable walls. Some of the blocks have suffered, particularly after the onset of reinforced concrete, deep structural modifications, carried out in a piecemeal process, building by building. It is desirable (except for safety reasons) that no modifications are now allowed in the blocks which survived until the present day with the original Pombaline structure mostly unchanged. But it seems reasonable to admit, in the already modified blocks, that new alterations can be introduced using modern materials and technologies, as a result of renovations sought by the owners, maintaining, at the same time, the existing architecture. Here "Pombaline" is the term coined after the Marquis of Pombal, the prime minister at the time of the 1755 earthquake, who took most of the decisions regarding the reconstruction of Lisbon.

The current practice to validate, through structural analysis, the construction of new buildings or intrusive rehabilitation interventions in the buildings inserted in blocks has been based on structural models which assume each individual building as being isolated. Although such a piecemeal approach can be acceptable for vertical loading (if correct calculations are carried out for the gable walls which gather load from two buildings), its application for horizontal loading, namely seismic forces, is debatable. In fact, the behaviour of the structure for horizontal loading is related to an extended structural system involving the whole block, not merely the building in consideration. As a matter of fact, not only the structural performance of the new or modified building is affected by the presence of the rest of the block, but also the structural behaviour of the block might be influenced by the alterations carried out in the individual buildings. In this case, the current practice may lead to erroneous analysis of the safety level of the structural interventions.

## 2 STRUCTURAL CHARACTERISATION OF THE "BAIXA POMBALINA"

### *2.1 The Pombaline buildings*

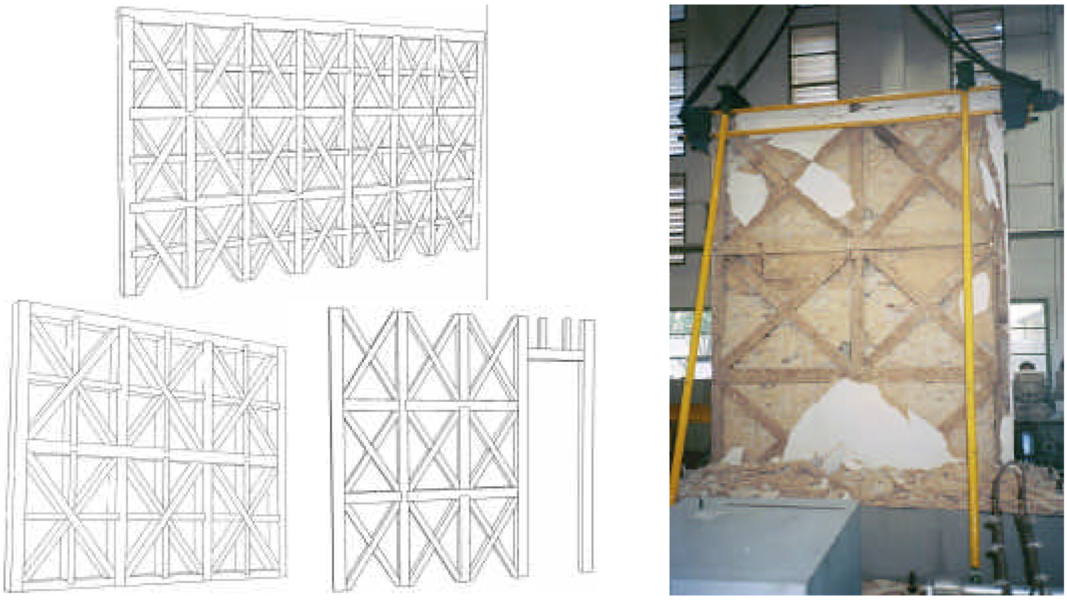
In line with the post earthquake measures designed by the chief engineer, Manuel da Maia, the new buildings during the first decades of reconstruction after the big shake incorporated a set of features intended to provide them with adequate seismic behaviour, enabling them to resist horizontal loads and to dissipate substantial amounts of energy. Among these measures, the so- called "gaiola" or "cage" system stands out, see Fig. 2a. The system consists of a set of timber members embedded along the inner face of the main stone masonry façade walls, see Fig. 2b. To these members and to the ashlars around the openings, an internal timber grid is connected by means of iron cross ties (A). Further bracing is provided by the timber floors whose diaphragm




(a) (b)

Figure 2: Aspects of the Pombaline construction: (a) building with the façade walls removed to show the timber bracing system; (b) detail of the timber frame and anchoring system to the main façade pilasters.

action is enhanced by iron ties (B), bolted to the floor beams and deeply embedded in masonry main walls, and by timber connectors, named “hands” (C), nailed to the above mentioned timber grid and also embedded in the masonry. The confined facade pilasters are then connected to a two-directional vertical bracing system of timber framed walls with light ceramic and rubble masonry infill, see Fig. 3. The “gaiola” designation was coined because the building seemed like a big cage, with the carpentry work high up in the air, generally some floors ahead of the masons.



(a) (b)

Figure 3: Examples of the composite timber-masonry walls: (a) three main types of internal timber arrangement; (b) a large specimen recovered from a demolition, used for laboratory test up to collapse.

The “gaiola” system is considered an innovation of the Pombaline city planning, adopted when it was found out that, due to complicated property expropriation and reassignment, the buildings needed to have four floors instead of two, as was Manuel da Maia’s initial idea and was the case at Vila Real de Santo António, in the Algarve. It is said that the building concept was implemented by one of the architects, Carlos Mardel, after a load test on a large scale model in the main downtown square, using units of soldiers to generate the dynamic actions. But, presently, it is assumed that most of the constructive details of the new structural system were produced by the master draughtsmen of Casa do Risco (Draughtsmen House), used to the design of timber structures for ships. These details were probably handed down to the building carpenters orally or by means of drawings and sketches and were soon lost (França, 1987). They gave rise, meanwhile, to a "know-how" that lasted, although suffering substantial degradation, until the first quarter of the 20$^{th}$ century, when the last "gaioleiros" (buildings using the system) disappeared.

Notwithstanding the many references to a possible code, regulating design, establishing member sizes, connection details and constructive procedures, no document has been found specifying the “gaiola” construction or establishing its mandatory character. The first modern Portuguese seismic code, dated from 1958, starts with a reference to “the code published after the earthquake of 1755” but, unfortunately, it seems that such a code never existed in writing. In fact, the earthquake of 1783, in Calabria, Italy, appears often in specialized literature as having given rise to the first rules for seismic construction, namely, the adoption of timber framed walls with mortared stone infill, instead of rubble. However, the concept seems to have been inspired on the Pombaline constructional system, as recognised in Barucci (1993).

Records on the original design of the Pombaline buildings seem not to be available. In the city council archives only documents pertaining to the successive modifications requested by the owners are available. But the buildings of the historical downtown are grouped in rectangular blocks, measuring in plan around $70 \times 25$ m$^2$, with a narrow central yard measuring $45 \times 2$ m$^2$. The buildings had originally five floors, including ground floor and attic, see Fig. 2, and the height of the façade was approximately equal to the width of the main streets, being constant for all the buildings. Each block has stone masonry walls in the external walls and in the internal walls facing the central yard. These walls are around 0.9 m thick at the ground level, with a slight reduction in the upper floors. The main walls are connected transversally at ground level by other masonry walls, 0.5 m thick. Some of these walls are continuously extended further up above the roof, separating the different ownership and acting as fire walls, see Fig. 2. The structure of the first floor is generally made up of stone masonry arches and vaults. From the first floor up, the pilasters of the exterior walls, both in the façade and in the back yard, are strengthened as detailed above.

More detailed information on sizing of the different timber members can be found in the reports of the various surveys carried out by Oz (1994-2000) and in several other documents, Farinha (1967), Segurado, Silva (1997).

The foundations rest generally on a timber grid laid on short timber piles, intended only to stiffen the alluvial soil and to create a good working platform at the ground water level. In many places where the new buildings are laid out on the remains of pre-earthquake buildings (street slabs, footings, masonry blocks), these older constructions were used as foundations.

### *2.2 Modifications on the constructions*

The main changes undergone by the buildings in "Baixa Pombalina" are: (a) construction of extra floors; (b) inadequate widening of existing façade openings and removal of walls and pillars, notably on the ground floor; (c) addition of steel and reinforced concrete elements, see Fig. 4. A survey carried out by the city council, DCEOD (1993), showed that around 80% of the buildings still had the original "gaiola" structure, if the modifications in the shops at the ground level were disregarded. By then, the structure of 12% of the buildings, randomly distributed in the sixty blocks, was totally replaced by reinforced concrete.

(a) (b) (c)

Figure 4: Main changes in Lisbon's historical downtown buildings: (a) extra floors; (b) opening enlargement and wall removal; (c) addition of reinforced concrete and steel members.

For the purpose of the works being carried out, the following criteria to classify the modifications are currently under consideration: (a) Buildings with significant modifications – structural changes in more than half of the building's original volume, with or without extra floors; (b) Buildings with moderate modifications – structural changes between 1/5 and 1/2 of the original volume, with no more than one extra floor; (c) Buildings with slight modifications – structural changes in less than 1/5 of the original volume, without extra floors.

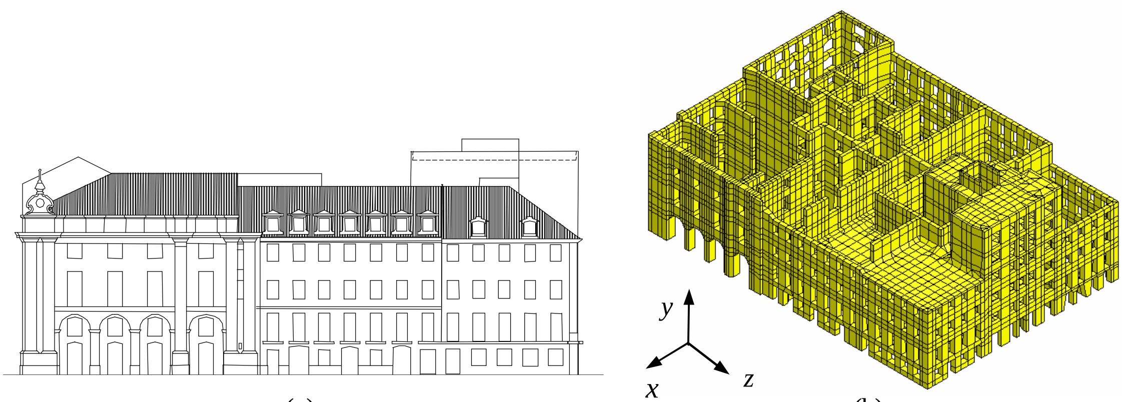
## 3 A CASE STUDY

It is expected that the "block effect" may be felt, essentially, in two forms: (a) Globally, the force distribution obtained from the individual analysis of each building will be different from the force distribution calculated when the entire block is taken into consideration (it is expected that the simplified analysis of each building can be both conservative or unsafe); (b) Locally, severe changes of stiffness in the buildings, resulting from the addition of reinforced concrete and steel members, will result in damage due to pounding effects. In order to assess the global block effect a case study is considered next.

For this purpose, the block of Martinho da Arcada has been considered, see Fig. 5a. This block, which faces the Praça do Comércio in Lisbon, is of a considerable size, with an area of $62.5 \times 43.5$ m$^2$ in plan. The height of the individual buildings ranges from 18 to 25 m. Although this particular block is not exactly typical, it was possible to collect rather detailed data, and a thorough modelling was carried out. Following an initial request by DGEMN, the Directorate General for National Buildings and Monuments, for a detailed survey of one of the buildings, the rest of the block was also surveyed, although in less detail, and then adopted for structural analysis, in a joint initiative of Oz and University of Minho, Ramos and Lourenço (2000).

The structural survey of the block indicated that around 50% of the original structural system was severely modified and only 20% of the structural system was in its original configuration. In particular, a reinforced concrete frame structure had been inserted in one of the buildings and several reinforced concrete and composite steel-concrete slabs had also been inserted. Experience has demonstrated that the large mass associated with these structural elements usually results in premature collapse of the external masonry walls.

The finite element model included shell elements, to represent the reinforced concrete slabs, the composite slabs and most masonry vaults on ground level, and volume elements, to represent masonry walls, masonry arches and stone vaults in the arcades as well as reinforced concrete columns, see Fig. 5b. The composite internal walls and the wooden floors were not considered in the analysis. However, the loads associated with these elements were included in the model. Nonlinear constitutive laws were adopted for the masonry and for the reinforced concrete, with the exception of the slabs that were assumed linear elastic throughout the analysis. In fact, the slabs were considered in the model to simplify the definition of loads and to introduce their rigid diaphragm effect for seismic analysis.

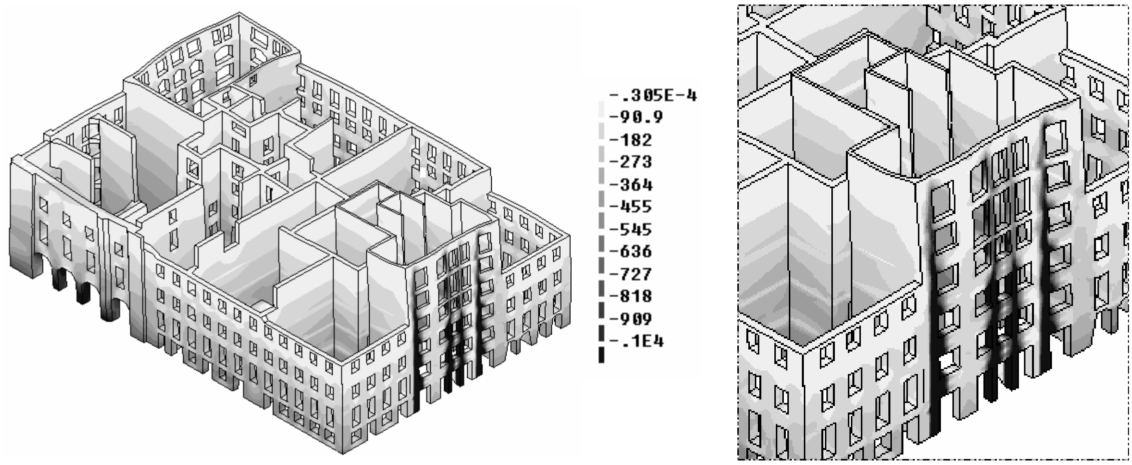



(a) (b)

Figure 5: Case study for "block effect" analysis: (a) main view; (b) adopted finite element mesh.

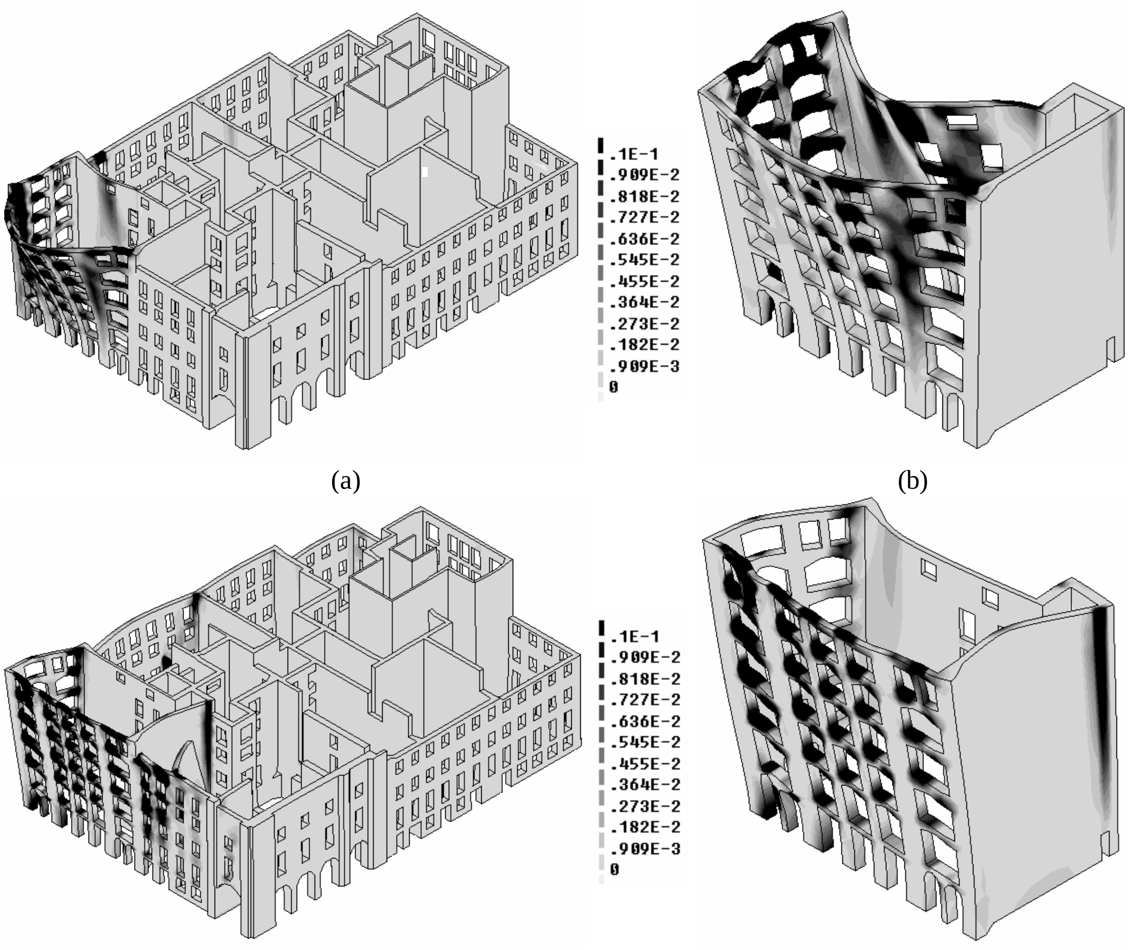
The compressive stresses obtained in the analysis for the case of vertical loading is illustrated in Fig. 6a. The average value of the compressive stresses at the base of the buildings is around 0.5 MPa but stress peaks of 1.5 MPa can be encountered, namely in masonry columns. Such peaks can be considered acceptable as it is expected that the columns are made of good quality masonry. In the areas where reinforced concrete columns exist, the stress peaks reach 5.5 MPa, which is a notably high value in comparison with average stresses, see Fig.6b. Nevertheless, in terms of vertical loading, it seems that both the structural changes (introduction of structural elements with stiffness and weight very different from the original construction, and removal of the composite internal walls), do not affect the safety of the block.

In relation to the seismic behaviour, it should be expected that the removal of the composite internal walls affects the safety of the construction. All the horizontal action must be resisted by the external walls and the lack of bracing will result in premature collapse of the structure. Fig. 7 illustrates such a statement, where the collapse, under seismic loading, of a corner building that suffered severe structural modifications is presented. The global safety factor of the construction is only 0.7 (less than 50% of the value required by the Portuguese code), if calculated with the full block. An isolated calculation of the corner building is incapable of reproducing the correct structural behaviour and gives, in this case, a conservative result of the failure load with a global safety factor of 0.5. In this case the block (assumed correct) ultimate load is 40% higher than the isolated (obviously erroneous) ultimate load.




(a) (b)

Figure 6: Compressive stresses for vertical loading (kPa): (a) complete block; (b) detail of reinforced concrete columns.




(c) (d)

Figure 7: Cracking in the model at ultimate load for a horizontal load combination (maximum principal strain): loading in the *x* direction for (a) block (safety factor is 0.7) and (b) single building (safety factor is 0.7) and loading in the *z* direction for (c) block (safety factor is 0.7) and (d) single building (safety factor is 0.5).

Finally, it is stressed that the areas where reinforced concrete elements have been introduced present smaller displacements than the original constructions. Such a deformational behaviour can result both in damage associated with pounding or actual collapse of the slabs, should the bond of the masonry walls be insufficient to resist the higher forces generated. Such a type of localized damage was not included in the present model and analysis.

## 4 PROPOSED METHODOLOGY

Based on the above results it seems justifiable to propose a simple methodology to deal, in a systematic way, with the issue of deep structural alterations in the blocks of Lisbon historical downtown, eliminating the risks inherent to the traditional approach, by adequately taking into account the “block effect”. Such methodology should consist of the following steps, to be carried out along a reasonable time span by the local / national authorities:

I. Complete survey and identification of all sixty blocks of “Baixa Pombalina”;
II. For each of the blocks, perform a survey of the existing structure, a characterisation of the structural materials and a classification in the categories proposed in Section 2.2;
III. For each of the blocks, construct a finite element model and perform the analysis, determining the forces in the structural elements. For the blocks with significant or moderate structural modifications, the analysis should be carried out using software easily available for practitioners;
IV. In case of a request by an owner or developer acting on a building located in a substantially modified block, the survey and model of the complete block should be provided;
V. The intervention in the building would only be approved if it is demonstrated that no negative contribution to the safety of the block occurs.

As for buildings belonging to lightly modified blocks, non intrusive / reversible retrofitting measures should be adopted, to ensure adequate seismic safety without harming their historical value.

### *4.1 Survey and characterisation*

This is one of the main tasks of the proposed methodology. The large developments in the last years resulted in a comprehensive set of tests, devices and techniques, mostly non-destructive or low invasive, enabling the gathering of the data required to construct and validate structural models (phases 1 to 4 in Table 1). These methods are of interest not only before the intervention but also during and after the intervention, as modelling of the structure is only one specific phase of the overall process. In all, seven phases can be identified, as shown in the same table.

Table 1: Phases of interventions where inspection and assessment techniques are used.

| Phase | Scope | Code |
|---|---|---|
| **I) Before the intervention** | **1. Preliminary investigation and survey** | **PIS** |
| **IA) Before modelling** | **2. Appraisal of the geometry of the construction** | **AGS** |
| | **3. Assessment of material mechanical properties** | **AMC** |
| **IB) During modelling** | **4. Model validation** | **MV** |
| II) During the intervention | 5. Quality assurance | QA |
| III) After the intervention | 6. Evaluation of the effects on the intervention | EEI |
| | 7. Monitoring of the structure | MS |

Table 2 indicates the fields of application of the main methods currently available to engineers and architects, pointing out the three phases related to modelling. Laboratory tests have not been considered. Samples of the materials can, certainly, be collected from the building, and later can be subject to a complementary set of laboratory tests, providing adequate information on the properties of the materials.

Table 2: Main tests, devices and techniques for structural assessment of ancient buildings.

| Tests, devices or techniques | **PIS** | **AGS** | **AMC** | **MV** | QA | EEI | MS |
|---|---|---|---|---|---|---|---|
| Automatic theodolite | | | | **X** | | | X |
| Boroscopy and videoscopy | **X** | **X** | | | X | X | |
| Electric strain gauge | | | | **X** | | | X |
| Flat jack | | | **X** | **X** | | X | |
| Forced vibration | | | | **X** | | X | X |
| Helix pull-out | **X** | | **X** | | | | |
| Load cell | | | | **X** | | | X |
| Mech. Displacement gauge | | | | **X** | | | X |
| Mechanical pulse | | **X** | | | X | X | |
| Optical crack meter | **X** | | | | | | |
| Pendulum and tele-coordinometer | | | | **X** | | | X |
| Pendulum Schmidt hammer | **X** | | **X** | | | | |
| Penetration | **X** | | **X** | | | | |
| Penetrometer and SPT | | | **X** | | | | |
| Radar | | **X** | | | X | | |
| Resistography | | | **X** | | | | |
| Semi-destructive shear | | | **X** | | | | |
| Sonic and ultrasonic | | **X** | | | X | X | |
| Thermocouple and thermometer | | | | **X** | | | X |
| Thermography | | **X** | | | | | |
| Tilt measurement | | | | **X** | | | X |
| Topography and photogrammetry | | **X** | | | | | |
| Vibrating wire crack meter | | | | **X** | | | X |
| Vibrating wire strain gauge | | | | **X** | | | X |
| Vibration measurement | | | | **X** | | X | X |
| Visual damage survey | **X** | **X** | **X** | | | X | |
| Visual specialist inspection | **X** | | | | | | |

### *4.2 Modelling*

The preparation, modelling and analysis of composite constructions like the Pombaline buildings can be extremely complex and time consuming. The diversity of the structural schemes together with the use of different materials, results in the need to adopt simplified numerical models of the constructions, in order to make the analysis feasible. The obvious difficulty is the trade off between the ability of the model to accurately represent the structural behaviour of the construction and the level of simplification (and inherent costs).

As an example of detailed finite element modelling, it is possible to represent the actual geometry of the timber framed inner walls, see Figs. 3b and 8. In this case, a wall panel with $2.54 \times 3.42 \times 0.20$ m$^3$ is shown, including the various constituents: wood, mortar rendering and infill material. Here all geometrical dimensions were surveyed to represent the actual thickness of all constituents (LNEC, 1997). From a modelling point of view, there is no difficulty in considering the different constituents with individual elastic and non-elastic properties. It is known that a key aspect involved in the ultimate strength of this type of construction is the behaviour of the connections between timber members. For this reason, interface elements have been adopted to simulate the spring non-elastic behaviour of the connections. Another relevant issue is the representation of the interface behaviour between the timber members and the masonry infill, where most of the non-linear phenomena occur. This detailed model, which incorporates non-elastic behaviour of the constituents and the interfaces, requires extensive input of material data, which is not available at the present time.

The model shown in Fig. 8 includes 3365 elements and 13527 nodes, resulting in a total of approximately 40000 degrees of freedom. This example focuses on the internal bracing walls with timber members of the Pombaline construction. It is not realistic to use such detailed models in large scale analysis, not only because the geometric and material properties of the constituents are difficult to characterize but also to the time / economic demands. One possibility, that was considered in the large scale model, is to represent such complex walls by simplified macro-elements that assume a continuum homogeneous material. Obviously the elastic and non-elastic properties of the material should try to represent the actual behaviour of the structure, for example, from the simulation of existing experimental tests (LNEC, 1997). In a complete building or block of buildings, the external masonry walls and the gable walls between buildings must also be considered in the analysis. For most large scale analysis, it seems less debatable to model both regular masonry and irregular masonry walls assuming a continuum homogeneous material.

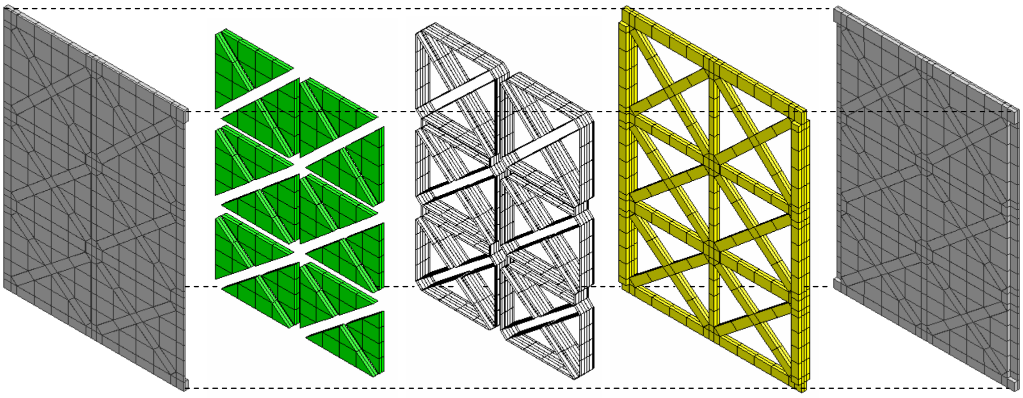



Figure 8 : Detailed model of a timber framed panel (3365 elements).

## 5 COST ESTIMATE

From the experience gained so far in field and office work pertaining to Lisbon's historical downtown the estimate of Table 3 can be made.

The above estimate seems quite reasonable compared to Lisbon's City Council's annual budget. Moreover, the estimated costs can be spread over a number of years. The amount per building, around 27 000 Euro, seems quite reasonable as well, taking into account the high real estate prices in the area, not to mention its importance as architectural heritage.

Along the above line of reasoning, only the modelling of significantly altered blocks would be necessary as only for these blocks should requests for new alterations be acceptable. However, modelling of the majority of the blocks is advised in order to assess the soundness of all the historical downtown buildings, in particular their seismic safety. Some work could possibly be spared by taking advantage of similarities among the original blocks.

Table 3: Costs involved in survey and characterization and modelling (kEuro).

| Task | Cost per building | Cost per block | Total |
|---|---|---|---|
| Architectural survey | 10 | 70 | 4 200 |
| Structural survey | 9 | 63 | 3 780 |
| Materials characterisation[1] | | | 250 |
| Foundation survey | 2 | 14 | 840 |
| Geotechnical survey[2] | | | 400 |
| Modelling | | 30 | 1 800 |
| Total | | | 11 270 |

[1] Resorting to overall survey and to sampling [2] Resorting to sampling and to existing data

## 6 CONCLUSIONS

The approach traditionally used in the project approval and intervention, permitting significant modifications in the buildings included in blocks of Lisbon's historical downtown may lead to erroneous structural assessment. Here, it was demonstrated that the structural behaviour of an isolated building is different from the same building inside a large block, as occurs in the "Baixa Pombalina" in Lisbon.

A methodology that aims to regulate the interventions in Lisbon's historical downtown area has been proposed and it may be applied in a systematic manner, at least in urban areas of substantial historical and architectural value, allowing for their preservation through a reduction of the seismic vulnerability of their buildings and blocks. For this purpose, the necessary in situ tasks and office studies have been addressed. In particular, it is advocated that municipal departments should make available, to the owners and developers involved in rehabilitation / interventions, validated structural analysis models, capable of attaining a double objective: (a) enable the consideration of the "block effect" in the structural design of interventions required in a particular building; (b) provide evidence that none of the remaining buildings in the same block is deleteriously affected by the actual intervention in the building. The costs involved in the proposed studies, although significant, do not appear to be out of proportion both with respect to the municipality's budget, to the real estate value of the buildings and to the heritage character of the area.

An important spin off of the proposed methodology is the possibility to retrofit the buildings of Lisbon's historical downtown, which presently seem to feature a high seismic vulnerability, certainly not in agreement with their value as architectural heritage.

## ACKNOWLEDGMENTS

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