BIM-based methodology for the seismic performance assessment of existing buildings

Metodologia para avaliação do desempenho sísmico de edifícios existentes com recurso a BIM

Gonçalo Lopes
Romeu Vicente
Tiago Ferreira
Miguel Azenha
Hugo Rodrigues

Abstract

The use of Building Information Modelling (BIM) has been changing the paradigm in the Architecture, Engineering and Construction (AEC) industry. Regarding the assessment of existing buildings, one of the applications of BIM with significant potential concerns the so-called "reverse engineering" (*i.e.*, the reverse process compared with the traditional design procedure), which consists in recreating the existing structure into a BIM model. Thanks to the high level of interoperability of BIM-based data, it is possible to transform this model into an accurate 3D computational numerical model, exploiting all the information collected and organised during the survey phase.

In this context, the present work presents a BIM-based methodology for the seismic performance assessment of existing mixed unreinforced masonry-reinforced concrete (URM-RC) buildings that consists of four phases: (1) Anamnesis, (2) Diagnosis, (3) Therapy, and (4) Control.

A case study building is presented to demonstrate the advantages and applicability of this methodological approach.

Keywords: BIM / Avaliação do desempenho sísmico / Laser scanning / Reabilitação

Resumo

O uso de *Building Information M*odelling (BIM) tem vindo a mudar o paradigma na indústria da Arquitetura, Engenharia e Construção (AEC). No que diz respeito à avaliação de edifícios existentes, uma das aplicações BIM com grande potencial diz respeito à chamada "engenharia inversa", que consiste em recriar a estrutura existente num modelo BIM. Graças ao elevado nível de interoperabilidade da informação usada no BIM, é possível transformar este modelo num modelo computacional 3D preciso, explorando todas as informações recolhidas e organizadas durante a fase de levantamento.

Nesse contexto, o presente trabalho apresenta uma metodologia baseada em BIM para a avaliação do desempenho sísmico de edifícios mistos existentes de alvenaria não reforçada-betão armado (URM-RC) que consiste em quatro fases: (1) Anamnese, (2) Diagnóstico, (3) Terapia e (4) Controlo.

É igualmente apresentado um caso de estudo de um edifício para demonstrar a aplicabilidade e as vantagens desta abordagem metodológica.

Palavras-chave: BIM / Seismic performance assessment / Laser scanning / Rehabilitation

Gonçalo Lopes
RISCO
Universidade de Aveiro, Portugal
gclopes@ua.pt

Romeu Vicente
RISCO
Universidade de Aveiro, Portugal
romvic@ua.pt

Tiago Ferreira
ISISE
Universidade do Minho, Portugal
tmferreira@civil.uminho.pt

Miguel Azenha
ISISE
Universidade do Minho, Portugal
miguel.azenha@civil.uminho.pt

Hugo Rodrigues
RISCO
Universidade de Aveiro, Portugal
hrodrigues@ua.pt

LOPES, G. [*et al.*] – BIM-based methodology for the seismic performance assessment of existing buildings. **Revista Portuguesa de Engenharia de Estruturas**. Ed. LNEC. Série III. n.º 13. ISSN 2183-8488. (julho 2020) 45-54.

1 Introduction

Unreinforced masonry (URM) structures represent the highest proportion of the building stock worldwide and in regions affected by destructive seismicity, and together with reinforced concrete (RC) buildings, they account for the largest proportion of casualties in earthquakes [1]. However, one typology that has revealed to be extremely vulnerable to seismic loads concerns the derived mixed URM–RC buildings. These have risen from the later introduction of RC structural elements (slabs, columns, ring-beams, etc.) into existing URM buildings, making them structurally more complex and unpredictable. The implementation of such practices, mainly in retrofitting interventions of existing unreinforced masonry (URM) building stock, has been spread all over the world, especially due to numerous vague recommendations given in certain building codes. Only in recent years, researchers have started to turn their attention to the seismic vulnerability of these structures, by studying and observing their particular damage patterns, mechanisms and interaction effects from coupling RC structural elements to URM loadbearing walls. Moreover, the beneficial nature of structural interventions with RC on URM buildings located in seismically prone regions is still a contentious issue for most of the research community [2]. A case study building from this typology will serve as an example for the application of the proposed methodology.

In this context, the present work presents a BIM-based methodology for the seismic performance assessment of existing buildings that consists of four phases, as illustrated in Figure 1 (using the Business Process Model and Notation (BPMN)): (1) **Anamnesis**, dedicated to the survey and collection of facts about the existing building, the structure and its environs. It aims at a better understanding of the complexity of different layers, historic phases, interventions and additions; (2) **Diagnosis**, dedicated to the analysis and interpretation of the collected facts in order to obtain the necessary understanding of the current state of conservation, the building's behaviour and performance, and to discern about the eventual need for intervention; (3) **Therapy**, corresponding to the actual retrofitting design and can be performed using a fully developed information model (as in the case of new design), along with advanced BIM-based analysis and simulation methods to predict the expected improved performance and the related life cycle costs from the application of the proposed retrofitting measures and to evaluate different retrofitting proposals; and (4) **Control**, entailing a series of cyclical and regular monitoring actions and the implementation of strategies for a preventive conservation plan.

2 Anamnesis – Building appraisal and testing

2.1 Building investigation data

The methodology for the seismic performance assessment of existing buildings presented in this work begins with their thorough inspection, which goes beyond what is strictly structural. In fact, in order to respect the history which often confers a distinctive character to a building, the inspection and appraisal should be accompanied by a historical survey which allows to date the structure, investigate and record the constructive techniques/

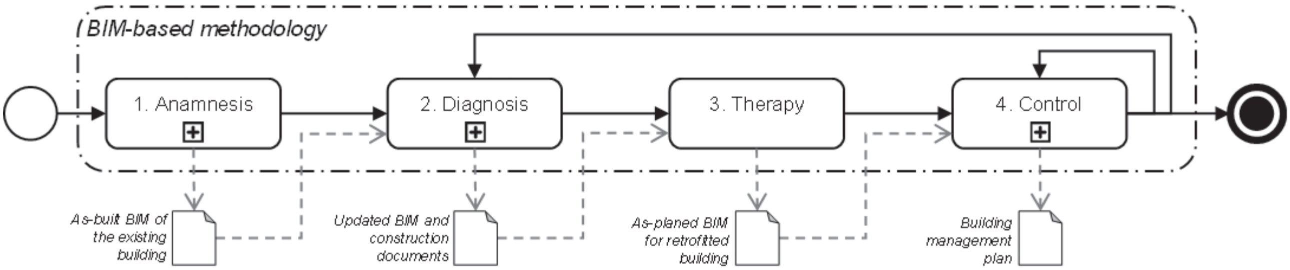


Figure 1 High-level BPMN model of the proposed four phases of the BIM-based methodology for the seismic performance assessment of existing buildings

a) Aerial view

b) Street view

Figure 2 Localisation and exterior aspect of the case study building

/typologies and their details, as well as analyse its evolution and which interventions and alterations have been made over the years, examine existing damages, etc.

The case study herein presented is an example of the building typology presented in the introduction section and consists in a residential palace from the 18th century located in the city of Aveiro, Portugal (see Figure 2). It is a two-storey URM-RC building with a gross implementation area of about 500 m^2 and with a 19 m wide façade facing southeast. The main loadbearing walls are made from uncut and fragmented limestone masonry with thicknesses between 550 and 720 mm, and the remaining partition walls are made with lathwork and plaster (the so-called "*tabique*" walls, in Portuguese) with thicknesses between 140 and 230 mm. The floors are made of timber joists and floorboards. In addition, the building underwent a rehabilitation intervention in 1979 which consisted in the addition of RC screed in some areas of the first floor and the replacement of a partition wall by a steel frame at the ground floor level.

2.2 Geometrical surveying

The rigorous geometrical representation of a building (and its surroundings) is a crucial step for the recording and inventorying of the current status of the existing building and the subsequent structural health assessment stage. In this context, geometric surveying techniques may be divided into: (i) contact techniques, such as manual techniques (tape measure, etc.); or (ii) non-contact techniques, such as image-based techniques (photogrammetry and videogrammetry), range-based techniques (laser measuring or laser scanning), or others techniques (tagging, photos, floor plans, etc.) [3].

Regarding the three-dimensional surveying of the presented case study building, the laser scanning has been used, since it is the one of the most used technique for the complete and detailed representation of existing buildings, which often present a complex architecture and unique geometrical features.

The working principle of a 3D laser scanner is essentially the swift capture of precise three-dimensional measurements reflected from an object or surface to a light sensor, creating a 3D construct called a "point cloud" made from multiple scans which are then unified through a process of "registration". After the scans are registered, a three-dimensional database is established that can be used throughout the building's lifecycle (see Figure 3).

The as-built architectural BIM model of the existing building was developed using the software Autodesk Revit 2019 with the point

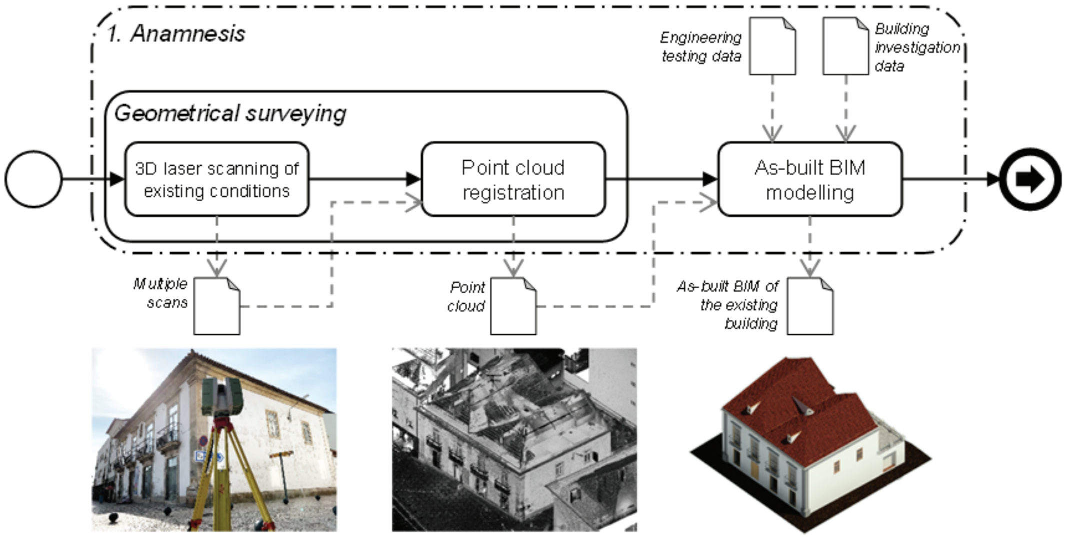


Figure 3 BPMN model of the anamnesis stage (point cloud to 3D geometry)

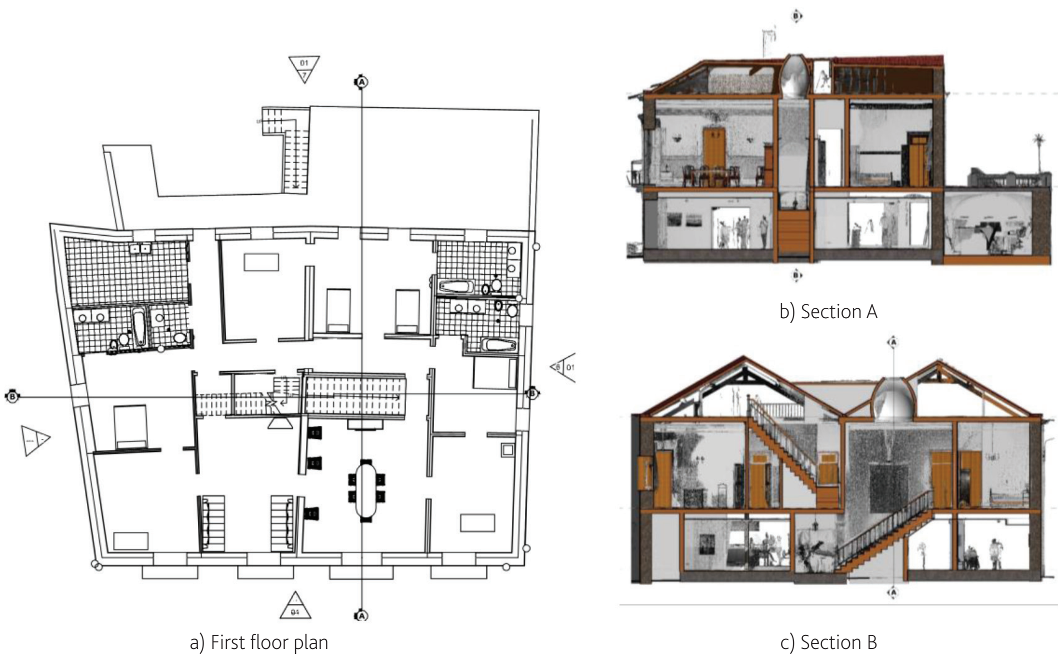


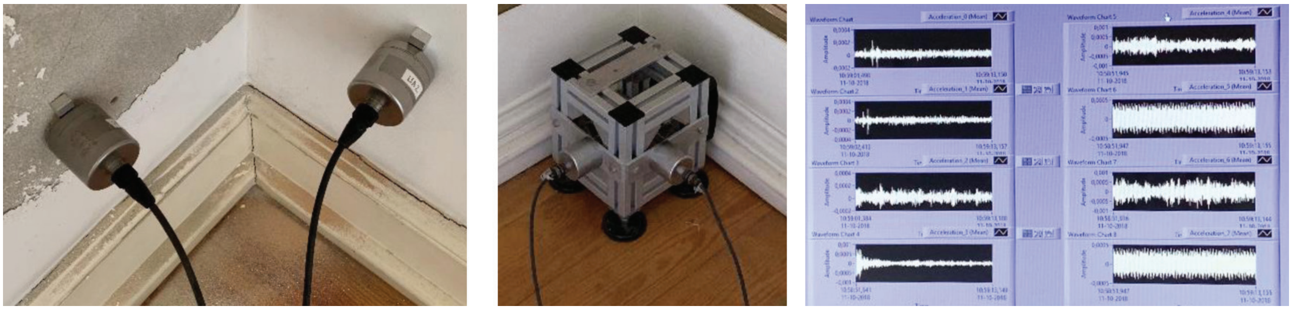
Figure 4 2D and 3D drawings extracted from the BIM model of the case study building

cloud data as the initial reference, saving many hours of digital modelling when compared with the traditional process (2D CAD-based). From the 3D model of the whole building, the BIM-based software is capable of efficiently generating both architectural drawings (see Figure 4) and analytical structural models.

With only this much, it is possible to gather and store significant qualitative (*e.g.*, architectonic style, decorative details, textures, interior layout, etc.) and quantitative (*e.g.*: material physical properties, dimensions, etc.) information about each modelled object, important for future use or simply for the record-keeping and inventory documentation of existing conditions.

2.3 Other engineering surveying and recording techniques

Different diagnosis, surveying and recording techniques are currently available for improving the knowledge level of existing buildings, as a supporting tool for their seismic response



a) Fixed setup b) Portable setup c) Data acquisition

Figure 5 *In situ* ambient vibration testing campaign

assessment. These techniques are used to locate, isolate, evaluate, or monitor physical phenomena affecting existing buildings, for example, the constructive details of the asset, estimation of mechanical properties of materials, to control the effectiveness of a determined intervention or even for structural health monitoring purposes (control stage). The type of technique can be classified according to its purpose, the contact to surface requirement, the level of intrusiveness (non-destructive, minor-destructive and destructive), the rating concerning the average cost and reliability of data acquired, or according to the appropriate time period to be used in intervention actions (before the intervention, during the intervention or after the intervention) [4,5].

In the scope of the case study and in order to support the calibration of the numerical simulations carried out in the next stage, an *in situ* ambient vibration testing campaign (see Figure 5) has been performed to measure the ambient vibrations, to capture the natural frequencies, mode shapes and damping ratios. The measurements were conducted using three setups consisting of pairs of measurement sensors (accelerometers) placed bidirectionally (x and y directions). Two of these setups were portable (roving sensors), permitting the data acquisition in different locations of the building, and the remaining one has been fixed in a reference position to support the scaling and assemblage of the results. The measurements have been performed in seven locations (or nodes): six at the first-floor level and one at the attic level.

3 Diagnosis – Seismic vulnerability assessment

Once the as-built BIM model is constructed, the next stage (diagnosis) can be conducted using advanced BIM-based analysis and simulation methods to assess the current state and/or to predict the expected improved seismic performance introduced by different retrofitting proposals (see Figure 6).

Firstly, the as-built architectural BIM model is adjusted into a structural/analytical BIM model inside the same BIM-based software. Then, thanks to the high level of BIM interoperability, it is possible to transform the as-built structural BIM model into an accurate 3D computational numerical model, exploiting all the information collected and organised during the survey phase. In the present case study, the recorded mode shapes and natural frequencies have allowed calibrating the material properties of the numerical model.

Disregarding heuristic/expert opinion approaches, the seismic vulnerability assessment of masonry structures can be carried out using two classes of methods: empirical (or statistical) methods and

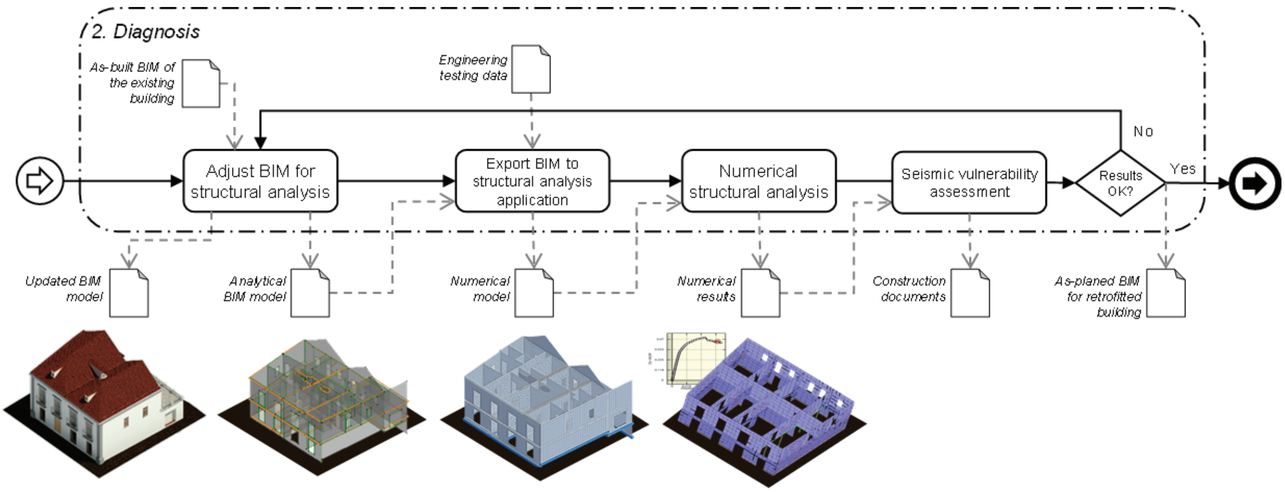


Figure 6 BPMN model of the diagnosis stage

analytical methods. The former can be divided into categorisation methods (which classify buildings into typologies characterised by the propensity of damage), or inspection and rating methods (wherein scores are attributed to each significant vulnerability component). The latter are based on the experimental validation of the various parameters used to define the vulnerability, based on refined numerical models, using either static or dynamic approaches (see for instance [6]). In addition, an attempt to exploit positive aspects of the two classes of methods above is made with the so-called hybrid methods. These combine numerical input/output from analytical models with statistical and probabilistic data to define exposure and vulnerability distribution, allowing the analytical burden to be reduced while grounding results in a geographical context [1]. A review of the procedures for the seismic vulnerability assessment of masonry structures has been made by [1] (including the methods, data requirements, data collection type, assessment type, approach, demand input and output).

Despite the wide variety of methods for assessing the seismic response of existing masonry structures (see for instance [7]), the present case study aimed at the comparison of the seismic response of a derived URM-RC building before and after its intervention by performing non-linear static (pushover) analyses, based on the macro-element approach, using the 3DMacro [8] software code. The pushovers have been performed for the building models before and after the intervention (without and with RC, respectively), in four directions (+X, –X, +Y, –Y) and for both static lateral force distributions (mass and modal/acceleration proportional). By the observation of the obtained results presented in Table 1, it can be stated that the intervention carried out in 1979 consisting in the addition of RC screed in some areas of the first floor and the substitution of a partition wall by a steel frame at the ground floor has not produced very significative alterations on the global seismic behaviour of the original building. Nonetheless, it can be stated that the capacity of the building has increased mainly in the +Y and -Y directions, whereas the stiffness has increased in all directions except in the +X direction (where it has decreased) and the ductility has reduced mainly in the +Y and -Y directions

Table 1 Comparisons of the results obtained from the models before and after the intervention

	Capacity	Stiffness	Ductility
Pushover + X Massa	0.043%	– 2.457%	0.151%
Pushover + X Acc	0.051%	– 3.185%	– 0.260%
Pushover – X Massa	0.531%	0.607%	– 0.069%
Pushover – X Acc	0.038%	0.982%	0.601%
Pushover + Y Massa	2.242%	6.041%	– 2.434%
Pushover + Y Acc	2.460%	2.742%.	– 2.263%
Pushover – Y Massa	2.059%	6.487%	– 2.125%
Pushover – Y Acc	3.046%	3.539%	– 2.909%

4 Therapy – Seismic retrofitting interventions

The goal of seismic retrofitting is the improvement of seismic behaviour of structures in order to improve life safety and the protection of the building's value. Thus, each specific individual case must be checked whether the costs of structural measures and the expected risk reduction are proportionate or reasonable. This can be achieved by different retrofitting strategies and techniques. Retrofitting strategies differ from retrofitting techniques, since the former is the basic approach to achieve an overall retrofitting performance objective (such as increasing strength, increasing deformability, reducing deformation demands), while the latter are the technical methods to achieve that strategy [9,10].

4.1 Seismic retrofitting strategies

The seismic retrofitting of a building can be achieved by the application of one or more of the structural or operational strategies listed below, which are graphically illustrated in Figure 7:

1) **Improving regularity**, on the basis of both global parameters (such as main plan and elevation dimensions) and global and local deviations from a regular ground plan and vertical shape. Moreover, regularity should imply uniform variation of the stiffness, resistance and mass of the seismic resisting elements in elevation and in plan, and comply with a predictable structural behaviour under seismic action, characterised by principal translational vibration mode shapes [11];
2) **Strengthening** of existing structural systems through additional structural elements or the doubling of existing structural elements [12]. With this strategy, the resistance and the stiffness are increased, while the deformation capacity is practically unchanged. Thanks to the higher stiffness, the deformation demand from the seismic action can be reduced to the available deformation capacity [9]. An example of this strategy is the addition of RC walls;
3) **Increasing ductility**, by means of increasing building's ability to withstand lateral loading in a post elastic range by dissipating earthquake energy and creating damage in a controlled widespread or locally concentrated manner, depending on the structural system and detailing [11]. With this strategy, the entire deformation capacity (elastic and plastic) is increased, while the ultimate resistance and the stiffness are only slightly increased. As an example, brittle structural URM walls could be made more ductile by means of additional bonded strips [9];
4) **Softening** of the structural system through a reduction in the stiffness, which decreases the forces by simultaneously increasing the displacement from seismic action. An example of this strategy is the seismic isolation through the insertion of a horizontally soft, high damping seismic bearings made of reinforced rubber layers. A further possibility is the removal of the stiff infills so that the structure can better deform horizontally [9];
5) **Reducing seismic action** through damping. In some specific cases, this can be realised in masonry buildings through the

insertion of dampers for seismic isolation which increases damping simultaneously with a reduction in stiffness [9,11];

6) **Mass reduction**, so that smaller inertial forces and smaller stresses are produced from earthquakes. This can be achieved, for example, by the replacement of heavier non-structural members with lighter ones;

7) **Changing the use**, such as a permitted declassification of the building to a lower importance class, so that the seismic action will be reduced as a result of lower importance factors.

In addition, FEMA 273 [13] recommends the local modification of structural components; and FEMA P-749 [14] recommends the stabilisation of foundations, increasing redundancy, and continuity of load paths.

Although most of these retrofitting strategies limit themselves to the modification of a single distinctive feature of the structure (ultimate resistance, ductility, stiffness, damping, and mass), in practice, they are often combined in order to optimally improve the main weaknesses relating to the seismic performance of each particular building under study. As such, the choice of the optimal retrofitting strategy relies on a good understanding of the dynamic behaviour of engineering structures and coordination with the future use of the building structure [9]. In this framework, it may be necessary to be more selective in the interventions on these buildings, by means of identifying the potential collapse mechanisms and acting only upon the weakest ones [15].

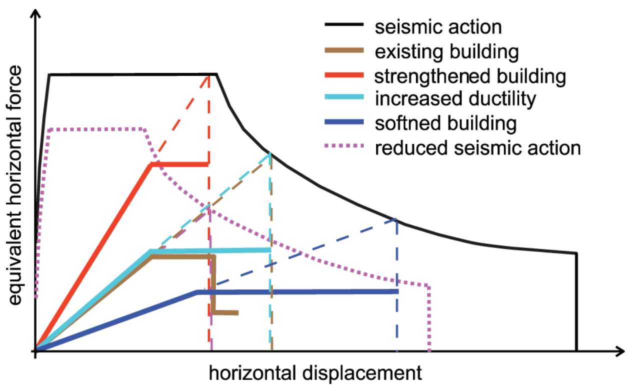


Figure 7 Influence of the implementation of several retrofitting strategies in the structural behaviour illustrated with the help of bilinear capacity curves. Adapted from [9]

4.2 Seismic retrofitting techniques

Seismic retrofitting techniques can be either global or local, based on how many structural members are affected:

1) **Local** (member-level) retrofitting methods. Some punctual interventions can be done by improving the individual members' capacity but keeping the building´s global behaviour, for example, transferring the out-of-plane loads to the orthogonal walls, for which the response becomes mainly in their own plane [16]. However, according to Marques *et al.* [17], the exclusive improvement of localised connections may induce excessive stresses due to the seismic actions and cause severe damages that can lead to the global collapse of the entire structure, especially when the building has not been conceived as a "box". For this reason, it is essential to assess the set of all critical individual discontinuities and singularities (*i.e.*, weak points). Local interventions include, among others: strengthening of individual structural elements (*e.g.*, RC jacketing), grout injections, re-pointing, transversal confinement of walls, etc.;

2) **Global** (structural level) retrofitting methods. These include measures to improve the building's response as a whole, *i.e.*, to allow the building to behave as a monolithic structure (box-behaviour). To reach this purpose, beyond the improvement of the structural connections between walls and walls-to-floors, it is also necessary to guarantee enough diaphragm action of the floors in order to ensure their role of transferring actions among the various structural elements, thus inhibiting out-of-plane mechanisms [17]. Global interventions include, among others:
   a) **Conventional methods**, based on increasing the seismic capacity of existing structure, such as addition new shear walls (either over-resistant or dissipative), insertion of ring beams at the floor/roof levels, strengthening of the existing walls formerly designed to withstand vertical loads only (perimeter walls, stairwell or elevator shaft walls), strengthening of floors (by overlaying a thin RC collaborating slab);
   b) **Non-conventional methods** of reduction of seismic demands, such as seismic base isolation (by decoupling the building super-structure from its substructure resting on the shaking ground) and supplemental passive damping devices (which allows concentrating the damage into a limited zone).

In this regard, Rai [18] presents a review of documents on the seismic strengthening of existing buildings. Additionally, the choice of the technique to be applied depends on the locally available materials and technologies (traditional or modern techniques, see [19]), cost considerations, duration of the works, architectural, functional and aesthetic considerations/restrictions [20], and on the required level of strengthening, which depends on the acceptable level of risk [21].

5 Control – Monitoring data

The last stage of the presented methodology concerns the control of the building performance level, through the whole lifecycle of the building in service. In this context, a common topic is the so-called Structural Health Monitoring (SHM), or Historical Heritage Management System (HHMS) [22]. Despite being a relatively new field, SHM technology has a great potential to offer significant economic and safety benefits for an informed and effective building management.

According to Chen [23], SHM is a process of in-service health assessment for a structure through an automated monitoring system, and it is a key element of cost-effective strategies for condition-based maintenance. In general, an SHM strategy consists of four major components (see Figure 8): (1) a sensor system (data acquisition);

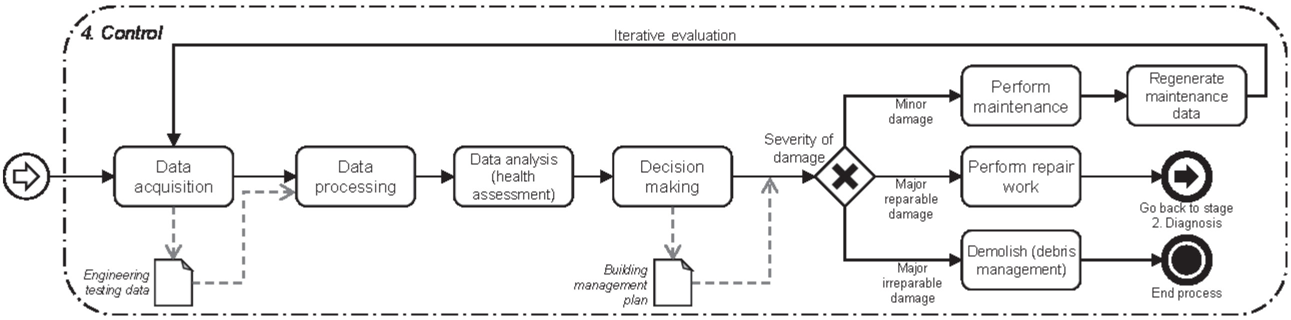


Figure 8 BPMN model of the control stage

(2) a data processing system (including data transmission and storage); (3) a data analysis or health assessment system (including diagnostic algorithms and information management), and; (4) decision making (comprising critical decisions regarding the current or future health status of the structure) [23, 24].

SHM techniques may be classified as **global** (*e.g.*, vibration modal data, such as natural frequencies and mode shapes) or **local** (*e.g.*, material testing, magnetic fields, radiography, X-rays, acoustics, etc.), based on if the method concentrates on the whole structure, or in part of it, respectively. In addition, measurement methods can be applied **intermittently** (implying a temporary deployment of the sensors and the acquisition system) or **continuously** (implying the embedment of the sensors in the structure for the real-time monitoring). In the latter case, a shift from a preventive time-based to a predictive condition-based maintenance strategy is achieved, reducing both the risk of severe structural failure and the overall maintenance costs by excluding unnecessary inspection activities [25]. Moreover, the continuous data feed can lead to significant improvements to the understanding of structural behaviour, particularly for masonry buildings, enabling to look at long-term effects/variations and transient phenomena [26].

Regarding the objectives of an SHM strategy, according to Farrar, Worden and Dulieu-Barton [27] these can be outlined as the following five levels, ordered by increasing and cumulative knowledge of the damage state: (1) Damage **detection**, giving a qualitative indication that damage might be present in the structure (or to alert to future damage in advance); (2) Damage **localisation**, giving information about the probable position of damage; (3) Damage **classification**, giving information about the type of damage; (4) Damage **assessment**, giving an estimate of the extent of damage; (5) Damage **prognosis**, giving information about the safety of the structure (*e.g.*, estimate of remaining useful/service life).

From the earthquake engineering perspective, the majority of the SHM are designed and installed in structures to monitor their dynamic motions continuously using accelerometers in order to track any changes in their structural integrity and detect damage. Some structures are also instrumented with tiltmeters and GPS sensors. The continuous recording of dynamic motions requires that the data are processed and analysed continuously and that the results are displayed in real-time [26].

Nevertheless, from a broader sense, the sensors utilised in SHM may be required to monitor not only the structural status (*e.g.*, strains, stresses, displacements, accelerations, vibrations, etc.) but also influential environmental parameters, such as wind speed, temperature, the quality of the foundations, as well as to detect deterioration and to assess damage for decision making [24].

In the present case study, the control stage concerns the measurement of the deflection of structural elements, by comparing the relative differences of the coordinates of pre-selected points from the point clouds obtained from different geometrical surveys. Thus, this SHM strategy, integrated with lifecycle management, will support the structural assessment, enabling an optimal operation and maintenance of the structure throughout (or eventually beyond) the building's design life.

6 Final comments

The proposed BIM-based methodology for the seismic performance assessment of existing buildings, focusing specifically on mixed URM-RC building typologies, is organised in four phases: Anamnesis, Diagnosis, Therapy and Control.

The adopted BIM framework has demonstrated considerable advantages comparatively with traditional processes, allowing to gather, analyse and share relevant information regarding many aspects related to different phases of a building's lifecycle.

Concerning the adopted case study building, once accurately known the geometrical information (based on a laser scanning survey), and estimated the structural loads, it was possible to predict the material properties based on the calibration of natural frequencies obtained numerically and experimentally from an *in situ* ambient vibration testing campaign. Then, non-linear static (pushover) analysis have been performed based on the macro-element approach, using the 3DMacro software, in order to assess the seismic performance of the analysed building before and after the intervention (without and with RC, respectively). According to the obtained results, it was possible to observe that the intervention carried out in 1979 has not significantly changed the global seismic behaviour of the building, whereby no retrofitting interventions have been identified as necessary.

Finally, the geometrical survey process used during the anamnesis stage will aid in the control stage (structural monitoring), should damage occur in the future, since it can help to detect significative deformations due to construction defects or cumulative ageing effects over time.

Acknowledgments

The first author would like to acknowledge the PhD grant (PD/BD/135201/2017) provided by Foundation for Science and Technology (FCT), within the scope of the Doctoral Programme InfraRisk (Analysis and Mitigation of Risks in Infrastructures). Thanks are also due to University of Aveiro, FCT/MEC for the financial support to the research Unit RISCO – Aveiro Research Centre of Risks and Sustainability in Construction (FCT/UID/ECI/04450/2013) and to the Research Unit ISISE – Institute for Sustainability and Innovation in Structural Engineering (UID/ECI/04029/2019).

References

[1] D'Ayala, D. – *Assessing the seismic vulnerability of masonry buildings*. Woodhead Publishing Limited; 2013. doi:10.1533/9780857098986.3.334.

[2] Correia Lopes, G.; Vicente, R.; Ferreira, T.M.; Azenha, M. – *Intervened URM buildings with RC elements: typological characterisation and associated challenges*. vol. 17. Springer Netherlands; 2019. doi:10.1007/s10518-019-00651-y.

[3] Volk, R.; Stengel, J.; Schultmann, F. – "Building Information Modeling (BIM) for existing buildings - Literature review and future needs". *Autom Constr* 2014;38:109–27. doi:10.1016/j.autcon.2013.10.023.

[4] Cóias, V.; Lourenço, P.B. – "Survey and Assessment of Portuguese Heritage Using Nondestructive Methods, in View of its Seismic Rehabilitation". *Work. Seism. Perform. Monum.*, 1998, p. 157-66.

[5] Maio, R.; Santos, C.; Ferreira, T.M.; Vicente, R. – "Investigation Techniques for the Seismic Response Assessment of Buildings Located in Historical Centers". *Int J Archit Herit* 2018;12:1245–58. doi:10.1080/15583058.2018.1503363.

[6] D'Ayala, D.; Meslem, A.; Vamvatsikos, D.; Porter, K.; Rossetto, T.; Silva, V. – "Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings". GEM Tech Rep 2015-08 v100 2015.

[7] Marques, R.; Lourenço, P.B. – "Possibilities and comparison of structural component models for the seismic assessment of modern unreinforced masonry buildings". *Comput Struct* 2011;89:2079-91. doi:10.1016/j.compstruc.2011.05.021.

[8] Gruppo Sismica. 3DMacro – Manuale Teorico. Catania, Italy [in Italian]: Gruppo Sismica s.r.l.; 2013.

[9] Wenk ,T. – "Seismic Retrofitting of Structures: Strategies and collection of examples in Switzerland", 2008.

[10] Lungu, D.; Arion, C. – "Intervention Strategies". A Rep. Work Packag. 4, PROHITECH Proj., 2006.

[11] Marini, A.; Passoni, C.; Riva, P.; Negro, P.; Romano, E.; Taucer, F. – *Technology options for earthquake resistant, eco-efficient buildings in Europe: Research needs*. Publications Office of the European Union; 2014. doi:10.2788/68902.

[12] Ravara, A.; Oliveira, C.S.; Carvalho, E.C.; Lopes, M.; Costa, P.T.; Delgado, R. *et al.* – *Reducing the Seismic Vulnerability of the Building Stock*. 2001.

[13] FEMA – FEMA 273 – *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*. Washington DC, USA: 1997.

[14] FEMA – FEMA P-749: *Earthquake-Resistant Design Concepts: An Introduction to the NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. Washington, DC: 2010.

[15] Lopes, M.; Meireles, H.; Cattari, S.; Bento, R. – "Lagomarsino S. Building Pathology and Rehabilitaion". In: Costa A, Guedes JM, Varum H, editors. *Struct. Rehabil. Old Build.*, vol. 2, Springer-Verlag; 2014, p. 187-234. doi:10.1007/978-3-642-39686-1.

[16] Sangirardi, M. – *Seismic Behaviour of Mixed Masonry-Reinforced Concrete Buildings. An insight into Modelling Approaches*. (PhD thesis). Universidade do Minho, Portugal and Politecnico di Bari, Italy, 2016.

[17] Marques, R.; Lamego, P.; Lourenço, P.B.; Sousa, M.L.; Marques, R. – "Efficiency and Cost-Benefit Analysis of Seismic Strengthening Techniques for Old Residential Buildings in Lisbon". *J. Earthq Eng* 2017;00:1-36. doi:10.1080/13632469.2017.1286616.

[18] Rai, D.C. – "Review of Documents on Seismic Strengthening of Existing Buildings". Doc No-IITK-GSDMA-Earthquake 2005;7:0-11.

[19] NIKER Project. D3.1 – "Inventory of earthquake-induced failure mechanisms related to construction types, structural elements, and materials". Deliv 31 2010:56.

[20] Arora, G.; Alam, M.P. – "A study on the seismic retrofiting of the structure". *Int J Adv Eng Res* 2015;9.

[21] Tomaževič, M. – "Seismic resistance of masonry buildings in historic urban and rural nuclei: Lessons learned in Slovenia". *Int J Archit Herit* 2011;5:436-65. doi:10.1080/15583051003792898.

[22] Zonta, D.; Pozzi, M.; Zanon, P. – "Monitoring Historic Buildings Using Distributed Technologies". In: P.B. Lourenço, P. Roca, C. Modena SA, editor. *Struct. Anal. Hist. Constr.*, New Delhi: 2006.

[23] Chen, H. – *Structural Health Monitoring of Large Civil Engineering Structures*. John Wiley & Sons Ltd All; 2018.

[24] Li, H.N.; Li, D.S.; Song, G.B. – "Recent applications of fiber optic sensors to health monitoring in civil engineering". *Eng Struct* 2004;26:1647-57. doi:10.1016/j.engstruct.2004.05.018.

[25] Peeters, B. – *System identification and damage detection in civil engineering* (PhD thesis). Katholieke Universiteit Leuven, 2000.

[26] Kasimzade, A.A.; Şafak, E.; Ventura, C.E.; Naeim, F.; Mukai, Y. – *Seismic Isolation, Structural Health Monitoring, and Performance Based Seismic Design in Earthquake Engineering: Recent Developments*. Springer; 2018.

[27] Farrar, C.R.; Worden, K.; Dulieu-Barton, J. – "Principles of Structural Degradation Monitoring". *Encycl. Struct. Heal. Monit.*, 2008. doi:10.1002/9780470061626.shm105.