**Rapid City-scale Seismic Assessment and Mitigation for Structures at Risk, through visual AI**

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**ABSTRACT**

In urban areas where building standards are not properly enforced, seismic events lead to devastating structural damages, together with massive human losses. Historically, there is a clear correlation between lack of structural norms and seismic damage. In the context of seismic assessments, a structurally unsafe building can be identified based on its response when subjected to dynamic in-plane and out-of-plane loading. In this study, we aim to leverage structural information from a set of virtual images, by first assembling the corresponding structural systems before assessing their structural robustness. Using publicly accessible street-level and satellite imagery, we formulate a framework for a rapid city-scale seismic assessment, focusing solely on low- and mid-rise structures - expected to be mainly unreinforced masonry (URM) structures. The in-plane and out-of-plane failure mechanisms are modelled based on the diaphragm action between rigid floor slabs (from plan imagery), with the material and geometric features of concrete and masonry shear frames, extracted through image segmentation (from street-view). Their response under cyclic loading is captured using a macroelement approach, which allows for the simplified dynamic analysis of each individually retrieved façade, at low computational and temporal costs. For incremental seismic intensities, endemic structural characteristics at risk are identified for different failure mechanisms, together with potential associated retrofitting measures. Using post-disaster imagery, we show that our model is capable to predict seismic risk with XXX% accuracy.

**Keywords:** deep convolutional neural networks; image segmentation; macroelements; nonlinear springs; retrofitting; satellite imagery; seismic analysis; street-level imagery; unreinforced masonry

# **1. INTRODUCTION**

Over the past century, significant progress in the field of structural engineering led to more complex and safer structural systems. Yet, in urban areas where building standards are not properly enforced, seismic events still lead to devastating structural damages, together with massive human life losses. Historically, there is a clear correlation between the lack of structural norms and seismic damages. In 2023, powerful earthquakes in Syria, Turkey and Morocco resulted in tens of thousands of deaths. These events demonstrated that most of the world’s urban areas, particularly in developing countries characterised by unplanned and vulnerable settlements, still face the ongoing threat posed by earthquakes. As cities continue to form, expand, attract, and experience a growing urban population, so do the risks posed by potential earthquakes (Tucker, 2013). Therefore, the need for proactive measures to detect vulnerable structural systems and enhance their seismic resilience is becoming increasingly urgent.

Current advancements in seismology allow for a relatively accurate prediction of the timing, location, and magnitude of earthquakes. However, only countries with robust economies can afford the costs of deploying and maintaining sophisticated seismic monitoring networks and associated advanced technologies. The reality is that seismic disasters are discriminatory, with lower-income countries often lacking the financial resources to invest in similar measures, leaving them more vulnerable to the devastating effects of earthquakes. In this study, we propose an open approach to address the disparities in detection and mitigation of seismic risk and ensure global equity in disaster risk reduction for safer communities worldwide.

We adopt a systematic parametrical approach to investigate the potential for an automated seismic risk assessment for portions of a given urban area, using publicly available street-level and satellite imagery. At the street level, our dataset consists of Google Street View (GSV) images of eligible facades of low- and mid- rise buildings. High-rise buildings are excluded from the dataset as a simplifying assumption, due to their seismic response having a higher probability of being governed by deformations of modes other than the fundamental mode (Kim & D’Amore, 1999), which implies additional complexity and higher computational efforts.

Low- and mid-rise structures to be encountered are most likely either unreinforced masonry (URM), concrete, or a combination of both, with older structures often being URM. In fact, URM structures are the predominant form of construction across urban areas globally, and have been recognised as one of the major threats to lifesafety during earthquakes (Abrams, 2001). Although masonry is the oldest form of construction, it is the most complex and least understood material in terms of strength and deformation (Roca et al., 2010). Due to the large-scope ambitions of our model, there is a necessity to analyse our bulk of retrieved images of facades at the lowest computational cost possible. Using a macroelement approach, based on the use of phenomenological constitutive laws for the masonry material, we simplify the retrieved frame into panel-sized structural elements, typically represented as a homogeneous material at structural scale. In general, the frame consists of three key blocks: piers, spandrels and node panels. Piers, spandrels, node panels, and openings (windows, doors) are identified and retrieved from the panorama images through visual AI. For a given façade, geometric dimensions of the block elements together with strength and stiffness parameters are retrieved through image segmentation. In the field of image processing, image segmentation involves partitioning an image into multiple regions based on certain characteristics such as colour, intensity, texture, or spatial proximity. The segmentation divides the image into regions that are homogeneous with respect to these characteristics, while also being distinct from neighboring regions. Each resulting region typically represents a specific object, to which we assign corresponding macroelement material strength and stiffness parameters.

Each façade image ID corresponds to an independent structural system. To obtain a full description of the building response, both in-plane and out-of-plane failure modes need to be considered. Therefore, the building is tested for both in-plane and out-of-plane loading scenarios using the macroelement approach. Macroelements represent the nonlinear behaviour at the scale of an entire masonry component (pier, spandrel or node panel). Failure modes are controlled by macroelement material parameters, previously obtained with visual AI. The proposed system formulation is based on the study conducted by Minga et al., (2020), which defines a building façade as an assemblage of 3D continuum rectangular blocks. Each block represents a macroscopic homogeneous depiction of a rectangular part of a URM component (pier, spandrel or node panels). All blocks interact with each other, through cohesive interfaces along all four of their faces, which takes into consideration the interaction between the different structural components.

To gauge the precision of the macromodel in predicting the response of masonry structures, numerical predictions are juxtaposed with post-disaster imagery. We show that our model can predict seismic risk with XXX% accuracy. Finally, retrofitting options are outlined and relevant options are assigned according to the predicted failure mechanisms for all affected structural systems.

# **2. LITERATURE REVIEW**

The present study takes advantage of publicly available environmental street and satellite imagery, which is initially gathered using remote sensing technologies. Remote sensing involves acquiring information about the environment from a distance, typically through sensors mounted on satellites, cars, drones, etc.. A major advantage is its ability to gather data over large geographic areas quickly and efficiently, providing comprehensive coverage that is otherwise challenging to achieve with traditional ground-based methods.

In recent years, remote sensing technologies have demonstrated great capabilities in facilitating pre-event vulnerability assessments of structures across vast geographical regions. For instance, Matarazzo et al., (2022) explored the potential of smartphone-collected datasets in infrastructure health monitoring. The researchers accurately determined critical physical properties, specifically modal frequencies, of two real bridges using smartphone data collected from everyday vehicle trips. They developed an analytical method to extract this information from both controlled field experiments and uncontrolled Uber rides on the Golden Gate Bridge, USA, as well as partially-controlled crowdsourced data from a highway bridge in Italy. Their analysis suggested that incorporating crowdsourced data from smartphones into bridge maintenance plans could extend the service life of new bridges by up to fourteen years (a 30% increase), without additional costs. Similarly, the aim of this paper is to leverage remote sensing outputs, in particular large image datasets, to formulate seismic assessments for residential and commercial buildings primarily.

Table 1 aggregates past studies which used a combination of survey data, satellite imagery, street-level panorama images, and other remote sensing techniques to produce seismic vulnerability assessments at a large scale. These studies incorporate visual AI methods, allowing for the extraction of a wide range of relevant features, including building footprints, structural materials, and vegetation cover. Subsequently, systems at high risk are formulated based on a range of empirical methods, which will be critically discussed under part 2.1.

Overall, the results show that, using remote sensing and visual AI, researchers can systematically analyse the characteristics and distribution of structures within a given area, and formulate a seismic vulnerability assessment at a neighbourhood or city scale.

## **2.1. Large-scale seismic models using Rapid Visual Screening (RVS)**

Most of the studies described in Table 1 use Rapid Visual Screening (RVS) methods to assess the resilience of structure in a seismic event. The advantage of RVS methods is that they do not require structural expertise for the formulation of the seismic risk. Moreover, RVS methods integrate large building stocks in a relatively short amount of time, and produce a rapid assessment at very low computational cost compared to rigorous analytical assessments.

**TABLE 1. Seismic Assessment Methods using Multiple Data Sources for Different Study Areas**

|  |  |  |  |
| --- | --- | --- | --- |
| **Study Area** | **Data Acquisition** | **Method** | **Reference** |
| Avellino, Italy | Satellite imagery (LANDSAT) + Airborne active LIDAR (Optech ALTM 3100) and passive (AISA-Eagle) data | Rapid visual screening - (Vulnerability index) | Borfecchia et al., 2010 |
| Siracusa, Sicily, Italy (Industrial area, 144 km2) | Satellite imagery (Google Earth) | Vulnerability curves | Borzi et al., 2011 |
| Bishkek, Kyrgyzstan (665 km2) | Satellite + Street-level façade imagery | Rapid visual screening (EMS-98) | Pittore & Wieland, 2012  Wieland et al., 2012 |
| Centre of Grenoble, France | Satellite + In-situ vulnerability data | Support Vector Regression | Panagiota et al., 2012 |
| Padang, Sumatra, Indonesia (87,573 building footprints) | Satellite imagery (IKONOS, LANDSAT) | Rapid visual screening (Seismic building structural type) | Geiß et al., 2015 |
| Antioquia, Colombia | Census + Satellite + Street-level façade imagery | Fragility curves | Acevedo et al., 2017 |
| Groningen, Netherlands (250,000 buildings) | Public data: National building database + Digital elevation map of the Netherlands | Rapid visual screening (Geometric classification) | Christodoulou et al., 2017 |
| Cities of Iquique, Rancagua, and Osorno, Chile | Census + Satellite + Street-level façade imagery  (Google Street View) | Rapid Visual Screening -(Seismic building structural type) | Rivera et al., 2017  Santa Maria et al., 2017 |
| Santiago, Chile (>200,000 buildings) | Street-level façade imagery  (Google Street View) | Rapid Visual Screening -(Seismic building structural type) | Aravena Pelizari et al., 2021 |

Although, in practice, RVS methods are fast and simple to implement, Harirchian et al., (2020), demonstrated that such procedures are tailored to the relevant region of interest, where RVS would be implemented. As such, the Turkish RVS (EMPI) and the Indian RVS (IITK-GSDMA), were shown are tailored to these specific countries. This indicates that RVS methods can not accurately assess seismic risk in regions for which they were not specifically designed. On the other hand, the American RVS (FEMA P-154) incorporates safety factors that can result in overestimation during damage evaluations (Harirchian et al., 2020). Similarly, in a recent study, Purushothama et al., (2023) also noted the conservative trend of the American RVS (FEMA P-154 and/or FEMA P-155). For strength-, displacement- and ductility-based nonlinear (static and dynamic) analyses, they derived performance parameters for the RVS method and analytically. For different building types, the performance scores for RVS were always higher, meaning that the estimated RVS capacity of the structure was always lower than or equal to the RVS demand at the near collapse limit state.

A recent study by Aravena Pelizari et al., (2021) uses street-level imagery to produce a large-scale seismic risk assessment in Santiago, Chile. The study uses deep convolutional neural networks (DCNNs) to explore the automated inference of Seismic Building Structural Types (SBST), which builds upon the research by (Coburn & Spence, 2002). The DCNN developed in their paper only considers two parameters to categorise systems at high risk: material and height. Thus, the methodology behind the structural assessment can also be classified as a RSV. In this sense, this is a purely computational paper. A rigorous methodology should take into account the dynamic response of each individual façade, because of the inherent nonlinearity of material stiffness and geometric stiffness under cyclic loads. Moreover, Aravena Pelizari et al., (2021) only look at lateral load resisting systems (LLRSs) without considering the effects of other important load cases, such as out-of-plane loading. The concept of hysteresis, which postulates that the current state or resistance of the system depends on the previous state of the system, is also omitted in this study. Finally, there are no conclusions on whether certain endemic structural characteristics are exposed to a higher seismic risk (such as heritage structures, vaults, high floor-to-ceiling heights…)

## **2.2. Review of rigourous structural modelling methods**

Significant efforts were made by the scientific community to computationally analyse masonry structures. The primary objective is to develop mechanical models capable of accurately simulating the structural response of masonry buildings. By doing so, researchers aim to predict how these structures will behave under extraordinary loads, thus identifying weaknesses and assessing safety. While computational analysis has been applied to design and assess new masonry buildings, its primary focus has been on evaluating the near-collapse behavior of existing structures, given their widespread prevalence and susceptibility to seismic events. In Table 2, we classify past modelling methods for masonry (D’Altri et al., 2019).

**TABLE 2. Review of past methods for the modelling of masonry structures**

|  |  |  |
| --- | --- | --- |
| **Model** | **Approach** | **References** |
| Block-based | Interface element-based | Gambarotta & Lagomarsino, 1997  Lourenço & Rots, 1997  Baraldi & Cecchi, 2017  Chisari et al., 2018 |
|  | Contact-based | Rafiee & Vinches, 2013  Çaktı et al., 2016  Beatini et al., 2017  Forgács et al., 2017  D’Altri et al., 2018  Foti et al., 2018 |
|  | Textured continuum-based | Ali & Page, 1988  Petracca et al., 2017  Serpieri et al., 2017 |
|  | Block-based limit analysis | Ferris & Tin-Loi, 2001  Orduña & Lourenço, 2005  Cavicchi & Gambarotta, 2006  Milani, 2008  Portioli et al., 2014 |
|  | Extended finite element | Abdulla et al., 2017  Zhai et al., 2017 |
| Continuum | Direct | Lourenço et al., 1998  Lopez et al., 1999  Cuomo & Ventura, 2000  Berto et al., 2002  Pelà et al., 2013  Bruggi & Taliercio, 2015  Panto et al., 2016  Degli Abbati et al., 2019 |
|  | Homogenisation pocedures & multiscale | Brasile et al., 2007a  Brasile et al., 2007b  Massart et al., 2007  Milani et al., 2007  Zucchini & Lourenço, 2009  Marfia & Sacco, 2012  Bertolesi et al., 2017 |
| Geometry-based | Static theorem-based | O’Dwyer, 1999  Block et al., 2006  Block & Ochsendorf, 2007  Fraternali, 2010  Block & Lachauer, 2014  Angelillo, 2015  Marmo & Rosati, 2017 |
|  | Kinematic theorem-based | Chiozzi, Milani, & Tralli, 2017  Chiozzi, Milani, Grillanda, et al., 2017  Chiozzi et al., 2018 |

Block-based models represent masonry structures by discretizing them into individual blocks, allowing for the consideration of the actual masonry texture and the main heterogeneities of the material. These models capture the behavior of masonry at the scale of its constituent blocks and mortar joints, which significantly influence its mechanical and failure response. They offer several advantages, including the ability to represent intricate structural details, derive mechanical properties from small-scale tests, and identify failure modes with clarity. Additionally, they inherently account for anisotropy and can simulate both in-plane and out-of-plane responses of masonry walls. However, block-based models are computationally intensive and typically limited to panel-scale structures due to their complexity. Furthermore, accurately defining the masonry bond in existing structures and assembling the model can be challenging and time-consuming. Despite these limitations, block-based models remain valuable tools for academic studies and specialized consultancy groups. Within this classification, block-based models are further categorized based on the formulation of interactions between blocks, offering various approaches tailored to specific modeling needs.

*2.2.1 Interface element-based*

In one of the earliest attempts to simulate the collapse behavior of masonry structures, mortar joints were modeled using zero-thickness interface elements, while masonry units, assumed to expand to account for the geometry of the joints, were represented with smeared crack elements within a finite element (FE) framework. This approach introduced a dilatant interface plasticity-based constitutive model capable of simulating the initiation and propagation of interface fracture under combined normal and shear stresses. Subsequent studies, expanded on this method by enlarging the blocks to accommodate zero-thickness interface elements for mortar joints, along with introducing potential cracks within the blocks. Lourenço & Rots, (1997) developed a multi-surface interface-based model concentrating all nonlinearities, including shear sliding, tensile cracking, and compressive crushing, within the interfaces. This model, widely adopted in subsequent years, was utilized in various applications, including historic non-regular stone masonry shear walls [60]. Further extensions of this interface model to simulate cyclic behavior were presented and validated in [61], emphasizing plasticity theory. Additionally, Gambarotta and Lagomarsino [62] devised a cyclic mortar joint interface model based on damage mechanics, featuring a constitutive equation postulated in terms of frictional sliding and mortar joint damage. Various strategies, like those presented in [62, 63, 65], employed cohesive interfaces with damage and friction to simulate masonry shear walls. Conversely, rigid block-based approaches with nonlinear springs, as exemplified by Malomo et al. [66], modeled the response of masonry joints and crushing for in-plane cyclic behavior analysis of masonry walls. Moving beyond 2D problems, recent efforts focused on 3D modeling, such as the extension of the multi-surface interface model by Macorini and Izzudin [71], incorporating geometric and material nonlinearity within a co-rotational framework. This approach has found widespread use in real applications [72, 73] and was adapted for simulating cyclic masonry responses [52]. Additionally, another interface constitutive model developed in [76] was coupled with elasto-plastic block elements for explicit cyclic analysis of 3D masonry walls, widely applied to study various mechanics aspects [51, 76, 77, 79].

## **2.3. Macroelement models**

Various approaches are used to simulate the nonlinear behaviour of masonry structures, which are commonly categorized into microscale, mesoscale, and macroscale representations. In both microscale and mesoscale modelling, the individual components of masonry, such as bricks or stones, and the mortar joints between them are explicitly represented. Each brick or stone, as well as each mortar joint, is modelled separately. The nonlinear behaviour is captured at this level by employing constitutive models for the materials. Nonlinear interface elements are used to simulate the behaviour of mortar joints, accounting for the development and propagation of cracks within them. However, due to their high level of discretisation, microscale and mesoscale representations are computationally expensive, which makes them unsuitable to be employed in our study. Such models are rather suitable for smaller systems. For instance, the studies conducted by Lourenço & Rots, (1997), Gambarotta & Lagomarsino, (1997) and Macorini & Izzuddin, (2011) use mesoscale representations for masonry shear walls. Chisari et al., (2021) employed mesoscale model for a single unreinforced masonry building.

Other studies represented masonry as a homogeneous material at the macroelement scale (Berto et al., 2002 ; Panto et al., 2016). Macroelement models divide the structure of interest into panel-scale components, typically piers, spandrels and intersecion/node panels. While in micro and mesoscale models, the units and the mortar joints are characterized by different constitutive laws, in macroscale models, the constitutive law reproduces the mechanical response of the panel macroelements.

The decision to adopt a macro element approach for analysing a large dataset of building frames for seismic assessment is driven by several considerations. First, macroelements models are typically employed for the analysis of the global seismic response of masonry buildings. while mesoscale models provide accurate predictions by explicitly considering the material's mesostructure, they are computationally demanding and time-consuming, especially for the analysis of multiple large-scale structural systems. In contrast, macroelement approaches provide a more efficient solution by employing simplified descriptions of masonry behaviour at the structural scale (Minga et al., 2020, Pantò et al., 2022).

* + 1. *Equivalent beam-based approach*

The present study, where only a few mechanical parameters are retrieved, demands a low computational time and cost for the structural analysis. A simplification technique known as the Equivalent Frame Method (EFM) can be employed before running a nonlinear analysis, assuming that spandrel elements are effectively bonded to the adjoining walls and connected to the floor tie beams. The study conducted by Rinaldin et al., (2016) outlined the potential of the EFM for modelling the strength and stiffness degradation of the microelements under cyclic loading, by using a multi-spring nonlinear elements connected by rigid links. However, this study is subject to multiple limitations. First, the use of nonlinear springs assumes simple geometries, which is unlikely to be the case for some of the retrieved buiding façades. Also, the out-of-plane failure modes are not considered, and very crude representation of the interaction between structural members.

Other previous studies, based on numerical and experimental tests, also confirmed that EFM can be successfully applied to unreinforced masonry buildings (Calderini et al., 2009; Magenes et al., 2012; Penna et al., 2015; Raka et al., 2015). In this method, the load-bearing elements of a masonry structure, which is inherently composed of discrete units such as bricks or stones held together by mortar, are represented as an equivalent plane frame (Roca et al., 2005; Caliò et al., 2012). In Figure 1, the equivalent frame is composed of macro-elements. Piers (Figure 1a), which represent the main resisting elements of the equivalent frame, are connected with spandrels (Figure 1b) though node panels (Figure 1c).

|  |  |
| --- | --- |
| A black and white square with diagonal lines  Description automatically generated | A black and white background with squares  Description automatically generated |
| (a) | (b) |
| A black and white grid  Description automatically generated | A screenshot of a computer screen  Description automatically generated |
| (c) | (d) |
| **Figure 1: Masonry shear wall discretisation into macroelements: (a) piers, (b) spandrels, (c) node panels and (d) equivalent frame model** | |

In Figure 1d), effectively, spandrels and piers are represented by nonlinear or elastic beam elements (in blue) and their intersection by rigid offsets (in red). The specific effective height values for masonry piers may be used to account for the actual deformability of the masonry walls. The use of these values instead of the actual height of the piers generally leads to an improved prediction of internal forces (Dolce, 1991):

However, irregularities in the number of openings (doors, windows) in facades could occur, following which the associated equivalent frame with deformable beam elements and connections are asymmetric. In this case, the portion of the wall without the window is modelled as a unique pier, and the macro-pier inserted into the model is usually connected to the remaining part of the frame by means of large rigid zones. The comparative study conducted by Siano et al., (2017) involved testing multiple sample walls characterized by increasingly complex geometrical regular and irregular configurations.

* + 1. *Spring-based approach*

Despite their simplified nature, macroelement models come with limitations. Typically, these models assume that any activation of out-of-plane failure modes is prevented. In reality, both out-of-plane and in-plane damages can occur simultaneously.

# **3. METHODS**

As outlined in the literature review, most previous studies rely on empirical methods to describe the seismic vulnerability of buildings. Our model is ambitious in the sense that it employs analytical methods at a large scale, based on a dynamic nonlinear numerical analysis. Other than an accurate modelling of the collapse mechanism under cyclic loading, our approach has a significant advantage over empirical methods, in the sense that the knowledge of a structure’s precise seismic response allows for targeted retrofitting solutions, such as internal or external bracing, at a second stage.

**3.1 An integrated method**

Essentially, when evaluating the seismic performance of a structure, it's crucial to take into account two distinct modes of failure: in-plane and out-of-plane. These failure modes represent different ways in which a building can experience structural damage or collapse when subjected to seismic forces. The in-plane mode refers to movement or deformation that occurs within the plane of the building's components, such as walls or floors, while the out-of-plane mode involves movement or displacement perpendicular to this plane.

In the assessment of a building's seismic behaviour, it is imperative to consider two distinct failure modes: in-plane and out-of-plane failures. In-plane failure occurs when a wall reaches its full capacity, which can manifest as flexural failure, shear failure with diagonal cracking, or sliding along bed-joints (Magenes & Calvi, 1997). The seismic response hinges significantly on material properties, particularly in cases dominated by shear failure, and on the in-plane displacement capacity, represented by the maximum deformation before losing load-bearing capability and succumbing to vertical loads. Typically, this displacement capacity is quantified in terms of drift ratio, defined as the ratio between lateral displacement and panel height. In contrast, out-of-plane failure modes can occur independently of the building's maximum in-plane capacity, involving rotation in the out-of-plane direction of inadequately connected building portions.

Although the out-of-plane response is often simplified using rigid body mechanism models or discrete element models, these analyses consider the interaction between in-plane and out-of-plane responses. Furthermore, the accuracy of out-of-plane assessments is contingent upon the boundary conditions imposed by in-plane behavior, underscoring the need for integrated methodologies that account for both responses in a single numerical model. Such an approach would offer practical applicability while ensuring comprehensive analysis of seismic behavior in professional practice.

**3.2**

(Bird & Bommer, 2004)

(Gattesco & Macorini, 2014)

(Najam, 2018)

(Zizi et al., 2022)

(Augenti, 2004)

**REFERENCES**

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