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Development of exposure datasets for earthquake damage and risk modelling: the case study of northern Algeria

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Abstract

In recent years, significant economic and human loses have been caused by earthquake events across the globe, particularly in developing countries, where non-seismically designed buildings constitute a significant share of the existing stock. Algeria is one of those cases and has witnessed earthquakes in the northern part of the country, which indicated the urgency to establish a robust disaster risk reduction strategy. Building exposure is one of the main model components for natural hazard risk assessment and, typically, exposure models are defined from proxies, such as national census databases or local expert opinion, for the distribution of buildings and population. However, no specific indications on the best nature or size of a regional exposure model are available to provide guidance on large-scale seismic assessment studies. In this paper, a step forward is provided by engaging different Algerian stakeholders in the collection of in-situ building data through a user-friendly smartphone/tablet application, with the aim of aiding the development of building exposure and vulnerability models, as well as increasing the risk awareness among local population and practitioners. Subsequently, earthquake damage estimates are produced and evaluated over the buildings' lifetime in terms of exceeding slight, moderate, extensive and collapse damage states. The computed damage metrics are also used to provide input on the importance and usefulness of the in-situ collected data as a supporting data source in the development of exposure and vulnerability models. A discussion on the possible sources and size of the exposure model and preliminary guidance on conducting in-situ surveys are provided, with a view to a possible re-use in other contexts (provinces) with similar building stocks to the region addressed in this study.

Keywords Exposed assets · Building Taxonomy · Vulnerability · Earthquake damage scenario · Building inventory tool

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1 Introduction

Catastrophe risk modelling is essential for supporting risk management and decision-making processes, especially in less developed countries, where the required resources, datasets and tools might not be available. The key components for seismic risk assessment include hazard characterization, inventory of exposed assets and assessment of their vulnerability. Typically, exposure models for natural hazard risk assessment are based on proxies, such as national census databases and local expert opinion to define the distribution of population and buildings. While census-based data is wider and certainly necessary for the development of exposure models, the response of non-seismically designed buildings depends greatly on architectural and structural properties that can be merely observed in-situ or collected from blueprints. In the case of seismic risk, having information on the buildings' structural system is essential, as this feature has a large influence on how the buildings will behave and, consequently, on how damaged they might get, given a certain level of ground shaking. Furthermore, the technical quality of in-situ survey databases is typically higher, in terms of detail level, than the census, since the survey can be performed by a technical agent (architect, engineer or technician) and will be reviewed and approved during the post-processing stage. Therefore, in-situ data collection would reduce the unavoidable uncertainties in seismic risk assessments via a more realistic modelling of the building exposure.

Large-scale seismic risk assessment constitutes one of the key elements for mainstreaming disaster risk reduction. Such an element requires the development of three models: seismic hazard, exposure and vulnerability of the exposed assets. Over the last few years, several endeavours have been devoted to building exposure modelling adopting various sources of information such as census data and satellite images with the support of field surveys and inventories. Remote sensing, such as Interferometric Synthetic Aperture Radar (InSAR) and aerial photography as well as Light Detection and Ranging (LiDAR) has been adopted to capture the types, geometric characteristics, footprint and height of buildings (Korkmaz and Kutay 2010; André et al. 2001)). Sousa et al. (2017) used open-access data from OpenStreetMap (OSM Statistics 2015) and CORINE (Bossard et al. 2000) initiatives in the development of exposure models of industrial buildings for 36 countries in Europe. Although these data sources, on their own, are obviously not enough for the development of an exposure model, they can play a key role in its development. In Algeria, several advances have been made in seismic hazard assessment (e.g., Bouhadad and Laouami 2002; Peláez and Hamdache 2004; Delouis et al. 2004; Peláez et al. 2006; Laouami et al. 2006; Harbi et al. 2010; Hamdache et al. 2012; Gherboudj and Laouami 2014), in building vulnerability assessment (e.g., Djaalali et al. 2012; Meslem et al. 2012; Athmani et al. 2014; Boukri et al. 2018), and in the collection of information regarding elements exposed to the seismic hazard (Algerian census, RGPH 2008). Nevertheless, numerous limitations still exist hampering the use of comprehensive and well-grounded data of the exposed assets in the assessment of seismic risk at a municipality level. Moreover, although a variety of seismic risk assessment studies have been conducted (e.g., Benouar and Meslem 2007; Boukri et al. 2014; Tadjer and Bensaibi 2017), to the authors' knowledge, seismic risk studies employing high-fidelity exposure models that integrate population and capture the complex building stock attributes for a variety of realistic building typologies have not yet been reported for northern Algeria.

The motivation for the in-situ survey and desk study presented in this paper is to develop exposure datasets for northern Algeria using the province of Blida as a first case-study

region. The datasets feature the metrics of the prevailing residential building classes, such as the number of dwellings and buildings, as well as their spatial dispersion and replacement cost, which are fundamental inputs to reliably assess large-scale earthquake damage scenario. First, the characterization of the construction practice in the province of Blida is presented and the procedure implemented to determine representative metrics of the residential building stock is fully described. Subsequently, a critical comparison of the results on the building inventory using census and in-situ surveyed data that was collected using an Android smartphone/tablet application is carried out. The results on expected building damage distribution are also compared with the objective of providing relevant input for more effective future in-situ surveys of buildings, leading to consistent vulnerability and risk assessment outcomes.

2 Characterisation of the building stock in Blida

The building stock of the city of Blida dates back to the French colonial occupation era (1830–1962) during which low-rise masonry buildings with steel or wood floor joists were built. Some reinforced concrete (RC) buildings were also constructed during the 1950s to form low-income housing (known as HLM system) that are still operational to this day. Subsequently, after a cease in the first two decades following the independence (1962–1980), prosperity in the construction sector was witnessed during the 1980s and 1990s, which resulted in the urban extension of the province of Blida with many new RC moment-resisting frame (MRF) buildings. More recently, in 1999, an ambitious program was launched by the Algerian government with the aim of constructing one million dwellings in the country, leading to the delivery of 38 450 units in Blida alone, as of June 2017. The main structural system foreseen for this endeavour were buildings with dual RC structural system, *i.e.* MRF and shear wall.

2.1 Most common building classes (local construction practice)

In order to characterise the majority of the existing building stock in Blida, the following primary building classes have been identified:

- RC MRF buildings (prone or not prone to the development of a soft-storey);
- Dual RC system: MRF and shear wall buildings;
- RC shear-wall buildings;
- Unreinforced masonry buildings.

2.1.1 RC MRF buildings

In the province of Blida, RC MRF buildings are the most prevalent, representing about 60% of the residential building stock. A large part of the buildings of this typology was built in the 1980s by the owners themselves, without any consideration of seismic design provisions (see Fig. 1a). This typology is rarely found in the old city of Blida but is rather present in the surrounding areas, where urban extensions have taken place during that period. Typically, these buildings are low-rise (1–3 storeys) featuring RC frames with infill walls made of hollow bricks. Some buildings with a higher number of storeys can also be found (*e.g.*, 10-storey building shown in Fig. 1b) that were

Fig. 1 RC moment-resisting frame: **a** single- and **b** multi-storey building

constructed before the publication of the 1981 Algerian seismic code RPA81 (1982). The infill walls are present mainly in the residential part of the building (upper floors) while usually avoided at the ground floor facade. Therefore, this building typology is prone to the development of soft-storey behaviour during earthquake events. Moreover, even though most of these buildings have been built after 1981, the majority of them have unfortunately been constructed without consideration of seismic design provisions, which have not been enforced in private construction before 2003. In fact, these buildings have been severely affected during past earthquake events (e.g., Boumerdes in 2003, Mw 6.8).

2.1.2 Dual RC system: MRF and shear wall buildings

During the 2003 Boumerdes earthquake, significant damage to RC MRF buildings with brick masonry infill panels was observed. Consequently, a limitation for this structural typology was set in terms of building height (8 m maximum) in regions of high seismicity. As a result, the introduction of shear walls along with MRFs (Fig. 2) for buildings higher than two storeys (i.e., over eight meters) in locations of high seismicity (i.e., zone III according to RPA99 V2003 (2004) has become mandatory. Consequently, this dual RC system has become a common building typology in contemporary RC multistorey buildings in northern Algeria.

In this building typology, the structural system is composed of RC columns and beams, together with RC shear walls that rise from the foundation to the roof and can be exterior and/or interior (around the stairwells and elevator shafts). MRFs (columns and beams) carry lateral loads through bending where shear walls contribute significantly to the lateral stiffness of the entire structure which in turn contributes to the prevention of local damages (*i.e.*, brittle failures). The dual system may be very similar to a shear wall system in RC buildings hence a clear distinction is often not immediate. Further details on how the lateral-load resisting system is classified are provided in Section 3.4 of RPA99 V2003 (2004).

Fig. 2 Typical high-rise dual RC system MRF-SW buildings in Blida

2.1.3 RC shear wall buildings

In this building class, RC walls and slabs constitute the main structural elements and the walls play the role of resisting both vertical and horizontal loads. In order to allow for commercial activities and parking spaces, the shear walls are, respectively, oriented to be perpendicular to the façade (see Fig. 3b) and often avoided at the basement levels. Typically, the wall layout is symmetrical with respect to at least one axis in plan. This principle stems from the use of industrialized formwork tools (tunnel formwork), in which the walls and the slab (solid) are cast in a single operation (see Fig. 3a), thereby reducing the construction time significantly and making the system highly competitive. In northern Algeria, including the province of Blida—the case-study region—this type of construction has been
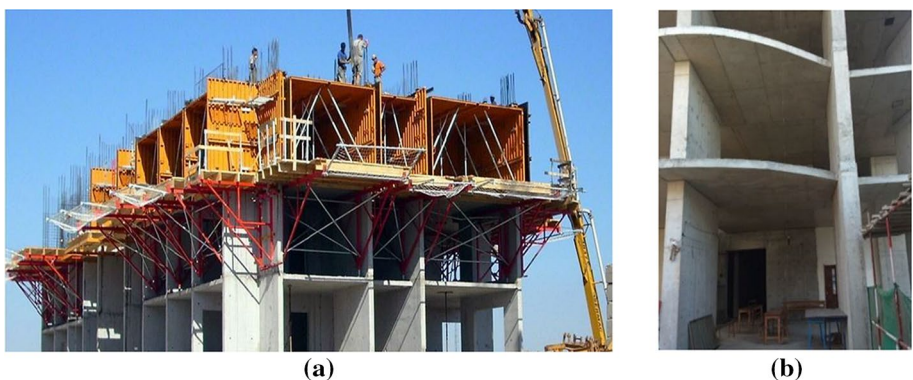
Fig. 3 Typical RC shear wall structure: **a** formwork and concrete casting, **b** details of structural components

recently adopted for medium- to high-rise residential buildings that are usually regular in plan and in elevation.

2.1.4 Unreinforced masonry buildings

Masonry buildings are the most common housing construction typology in the old city area of Blida. This building typology, mostly built before 1950, is no longer used in current practice. Buildings of this type are typically one to three storeys high (Fig. 4) and the slabs consist of wooden structures or shallow arches supported by steel I-beams. The bearing walls are usually about 400 mm to 600 mm thick, which justifies their adequate gravity load-bearing capacity. However, resistance to in-plane lateral forces of this building typology has been proven to be relatively weak compared to their gravity load resistance, which in turn results in a high seismic vulnerability (Remki et al. 2013).

3 Integrated methodology for building inventorying and exposure modelling

Developing a reliable exposure model that includes the location and value of the exposed assets at a province scale, to then be combined with corresponding vulnerability information, is not a straightforward task. The optimal source/tool for building class and structural attributes identification would be a national cadastre database featuring all the buildings and their relevant structural attributes. However, in Algeria, such a database does not currently exist. For this reason, a framework, whose general workflow is illustrated in Fig. 5, was adopted to collect building data for the development of the exposure model of the case-study province. The framework is based on two main components: (1) collecting data on elements exposed to seismic risk from available data sources, and (2) conducting in-situ surveys followed by a post-processing of the inventoried data.

(a) **(b)**

Fig. 4 **a** One- and **b** three-storey unreinforced masonry building
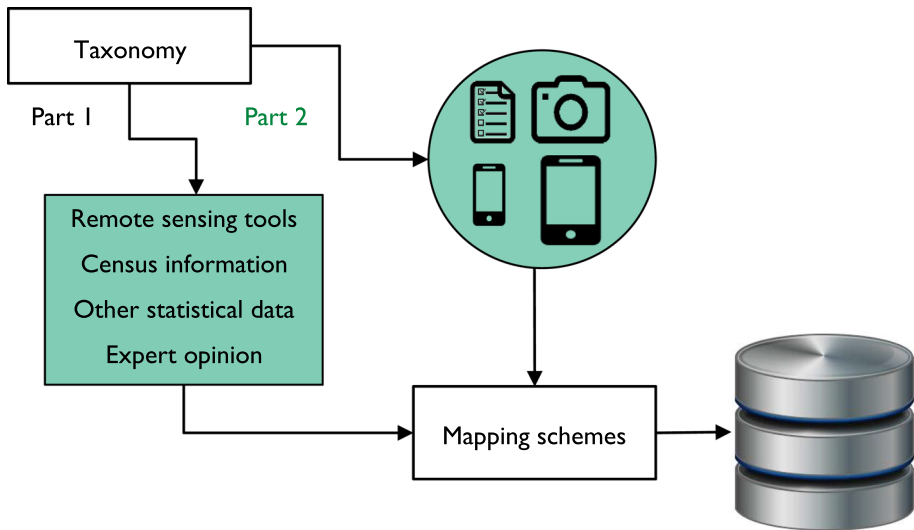
Fig. 5 General workflow of the framework for the exposure data collection

3.1 Available statistical data sources on dwelling and building inventory

Census data or other similar datasets, such as population ones, can be used as proxies to estimate the distribution of existing buildings and constitute a reliable source for the development of an exposure model. The census data source offers three main advantages: (1) it captures both formal and informal construction, enabling risk assessment in areas characterised by low social development; (2) it is performed at the smallest administrative level hence catering for a detailed risk assessment at a province scale; and (3) captures dwelling attributes from multiple variables thus favouring proper building class identification.

The first census in Algeria was carried out in 1966 and, since then, the Office for National Statistics (ONS) (2021) runs the census survey every 10 years. Still, the coverage of information about the building stock started only after 1987. This study uses the General Census of Population and Building released in 2008 (RGPH 2008) provided by the ONS, complemented with statistics on constructions built during the period of 1999–2017, provided by the Direction of Housing (2021), as well as the local experts' opinion, to develop an exposure model for the province of Blida. In other words, the 2008 census information was integrated with the data of all buildings constructed during the period of 2008–2017, using local experts' opinion, to form up-to-date census data. In order to represent the number of buildings for each typology within different municipalities of the province, they were divided into unit sites and their coordinates were presented as dots located in the centres of unit sites (*i.e.*, municipalities), as illustrated in Fig. 6. Then, the parameters available for each unit site were summed up.
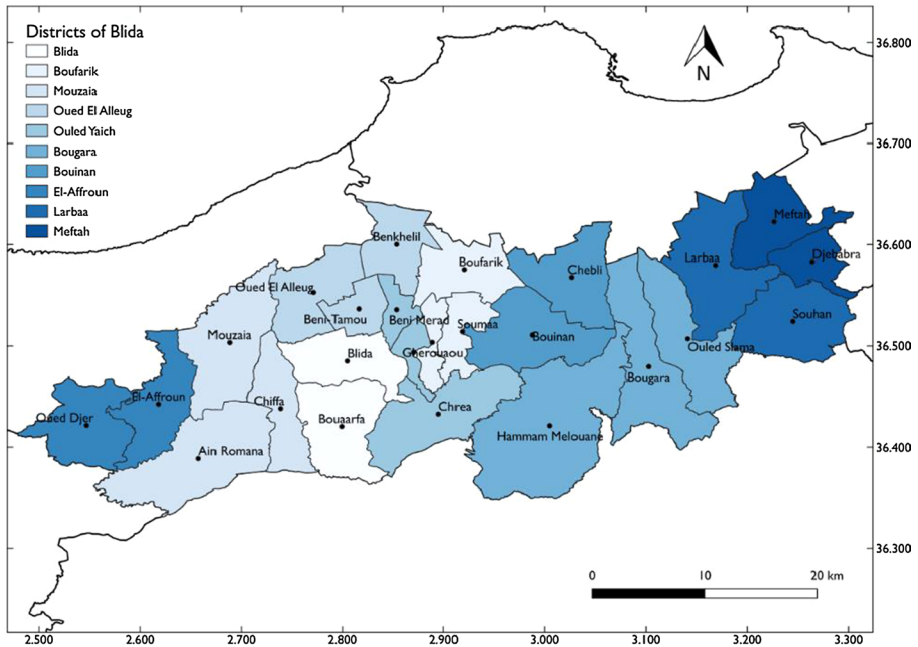
Fig. 6 Administrative division levels of Blida. The points on the map represent a site for risk assessment (i.e., the municipalities' centroids)

3.2 Definition of the building taxonomy

The type of construction, the number of units and dispersion of dwellings are some of the various attributes available from the building census surveys. For this study, different attributes have been used to define a taxonomy i.e., a set of building classes, namely the construction material, the type of lateral load resisting system, the date of construction (that is directly related to the design code level) and the number of storeys (height of the building). The first and second attributes were used to define four main building typologies, according to the description provided in Sect. 2: reinforced concrete moment-resisting frames (RC MRF); dual reinforced concrete systems: moment-resisting frames and shear walls (RC MRF-SW); reinforced concrete shear walls (RC SW); and unreinforced masonry (UM).

The year of construction also plays an important role regarding the classification of the building portfolio according to the type of seismic design. In Algeria, the first design code that contained provisions regarding the consideration of seismic action, the RPA81 (1982), was released after the earthquake of El Asnam in 1980 (Mw 7.1) and was revised in 1983, becoming RPA81 Rev.83 (1984). In 1988, this code was revised to become RPA88 (1989) in which the lessons learnt from the earthquakes that struck Constantine (Mw 5.9) and Tipasa-Chenoua (Mw 5.9) in, respectively, 1985 and 1989, were incorporated. The latest available version is RPA99 (2000), which was again amended after the 2003 Boumerdes earthquake (Mw 6.8), into RPA99 V2003 (2004). As such, for what concerns the year of construction, buildings constructed before 1981, from 1981 to 1999 and after 1999 are classified as, respectively, pre-code (PC), medium-code (MC) and post-code (C).

Table 1 Adopted taxonomy for the case-study province of Blida

Construction type	# of storey	Design level*	Building Class
RC MRFs	Low-rise (1–3)	Medium-code	RC MRF LR MC
		Post-code	RC MRF LR C
	Mid-rise (4–7)	Pre-code	RC MRF MR PC
RC shear wall	Mid-rise (4–7)	Post-code	RC SW MR C
	High-rise (> 7)	Post-code	RC SW HR C
Dual RC system: MRFs and shear walls	Low-rise (1–3)	Post-code	RC MRF-SW LR C
	Mid-rise (4–7)	Pre-code	RC MRF-SW MR PC
		Medium-code	RC MRF-SW MR MC
		Post-code	RC MRF-SW MR C
	High-rise (> 7)	Pre-code	RC MRF-SW HR PC
		Medium-code	RC MRF-SW HR MC
		Post-code	RC MRF-SW HR C
Unreinforced Masonry	Low-rise (1–3)	Pre-code	UM LR PC

*Design level defined according to the construction period: < 1981, 1981–1999 and > 1999

Furthermore, regarding the number of floors, i.e., the height of the buildings, three categories were considered: up to three storeys as low-rise (LR), between four and seven storeys as mid-rise (MR) and more than seven storeys as high-rise (HR). Combining the previously described categories, a set of classes was defined to classify each building typology according to its main characteristics, as described in Table 1.

According to the latest available census data (RGPH 2008), the building taxonomy in Blida consists of 82% reinforced concrete (RC MRF, RC MRF-SW and RC SW) buildings, 11% unreinforced masonry (UR) buildings and 7% of other typologies (OT) not foreseen by the adopted taxonomy (Table 1). For what concerns the date of construction, merely 15% of the building stock has been built before the implementation of the 1981 design code (RPA81 1982) and, specifically regarding the RC buildings, it is reasonable to consider that the majority of RC buildings were constructed when the RPA81 design guidelines were already established. However, for private residential construction, following the seismic design guidelines became mandatory only in 2003.

A municipality-based exposure model that accommodates the number of buildings for each vulnerability class has been developed by merging the building classification outlined in Table 1 with the Building Census survey of 2008. Given the fact that carrying out seismic risk assessment at a large scale is computationally expensive, assuming the buildings within each municipality to be located in the centroid of the corresponding municipality area is a common practice in natural hazard risk research (e.g., Bommer et al. 2002; Sousa 2006; Campos-Costa et al. 2009; Crowley et al. 2008). As shown in Fig. 6, a similar approach has been followed in this study. However, in case of non-uniform seismic hazard, this simplifying assumption could affect the accuracy of the seismic risk estimate as the ground motion might differ within the municipality territory.

In order to overcome this concern, a more accurate exposure model could be developed, in which a distribution of the building stock per municipality would be performed based on the population distribution dataset. Such a dataset would use an algorithm to allocate population count in accordance with the proximity to roads and train lanes, terrain slope, land cover and night-time lights (Dobson et al. 2000). However, the distribution of building

within each municipality would be biased toward regions where human activities are more noticeable (Silva 2013).

3.3 Mapping dwellings to buildings

A given building can accommodate several dwellings hence it is necessary to quantify the number of buildings from the number of dwellings to perform earthquake loss estimations. However, the number of buildings provided by the Algerian national census for the province of Blida is not disaggregated per building class. Hence, for the present exposure model, the disaggregation of the number of buildings for each type of dwelling was carried out by dividing the number of dwellings by the average number of dwellings per storey times the average number of storeys per building, as expressed by Eq. (1).

$$N_{buildings} = \frac{N_{dwellings}}{N_{dwellings/storey}} \times N_{storeys/building} \tag{1}$$

The dwelling fractions computed in the following sections include the range of number of storeys for each building type. Then, through expert judgment, the average number of storeys in each typology and the average number of dwellings per storey were defined, as summarised in Table 2.

3.4 Occupants per typology

For what concerns the population exposure, a similar method is applied, which requires the average number of persons per dwelling (which is commonly available in census data). The population of a given building class ($P_{building\ class}$) can be obtained by multiplying the number of dwellings for each building class ($N_{dwellings|building\ class}$) by the average number of people per dwelling ($P_{dwelling}$), as expressed by Eq. (2).

$$P_{buildingclass} = N_{dwellings|buildingclass} \times P_{dwellings} \tag{2}$$

For the above method, a check on the total population within each administrative boundary should then be carried out, to ensure consistency with the census data.

3.5 Floor area per typology

The average floor area for each building typology was estimated based on local expert opinion, as well as using Google information data on floor area for each building class in each municipality, given that census data does not provide information on floor areas of dwellings. The assumed values per each building typology are listed in Table 3.

The constructed area of a given building class ($A_{building\ class}$) can be obtained by multiplying the number of dwellings for each building class ($N_{dwellings|building\ class}$) by the average floor area per dwelling within that building class ($A_{dwelling|building\ class}$), as expressed by Eq. (3).

$$A_{buildingclass} = N_{dwellings|buildingclass} \times A_{dwellings|buildingclass} \tag{3}$$

Table 2 Average number of storeys as a function of building height and dwellings per storey

# of storeys	Avg. # of storeys	Comments on # of storeys	Dwellings per storey	Comments on number of dwellings per storeys
H: 1-3a	1.25	60% of 1 storey, 30% of 2 storeys and 10% of 3 storeys	1	Up to 3-storey buildings feature only 1 dwelling per storey
H: 1-3b	2	20% of 1 storey, 60% of 2 storeys and 20% of 3 storeys	1	
H: 1-3c	2.5	50% of 2 storeys and 50% of 3 storeys	1	
H: 4–7	5	Common practice in the country	2	Average
H: > 7	10	Common practice in the country	4	Average

Table 3 Average built area and replacement cost per building typology

Construction type	Number of storeys	Design level	Average built area (m^2)	Replacement cost (€/m^2)
RC moment-resisting frames	Low-rise (1–3)	Medium-code	90	180–630
		Post-code		
	Mid-rise (4–7)	Pre-code	170	
RC shear wall	Mid-rise (4–7)	Post-code		
	High-rise (> 7)	Post-code	340	
Dual RC system: moment-resisting frames and shear walls	Low-rise (1–3)	Post-code	90	
	Mid-rise (4–7)	Pre-code	170	
		Medium-code		
		Post-code		
	High-rise (> 7)	Pre-code	340	
		Medium-code		
		Post-code		
Unreinforced Masonry	Low-rise (1–3)	Pre-code	90	

The average area per dwelling for each building class together with the replacement cost per square metre needs to be defined separately for urban and rural areas within the replacement cost range shown in Table 3.

3.6 Replacement cost

Finally, the replacement cost per building type, which differs from the exposed value, was also estimated. In this context, the replacement cost refers to the value of replacing a building, in accordance with the latest building standards applicable in the country and includes the cost of the lateral load resisting system and the non-structural components (the land cost is not included). According to the Algerian Ministry of Housing Planning and the City (2021), the cost per unit of area, for different quality categories of residential buildings, ranges from 180 to 630 €/m^2 (Table 3). Due to the lack of more detailed information, a common unitary replacement cost of the buildings of all the municipalities in the entire province could be assumed. Accordingly, a range of replacement costs is stated, and no specific value is set for each typology, given that, within the province of Blida, the replacement cost varies considerably between urban and rural areas. Therefore, it was decided to maintain this range for all classes until additional research becomes available, to accurately define a replacement cost for each typology.

4 Census-based exposure model

As previously mentioned, the first and most common option to develop an exposure model is to use census data. This section presents an overview of the composition of the residential building stock in Blida using the available census data. In 2008, 127 205 residential buildings were reported, housing 149 775 dwellings (Fig. 7). These numbers have
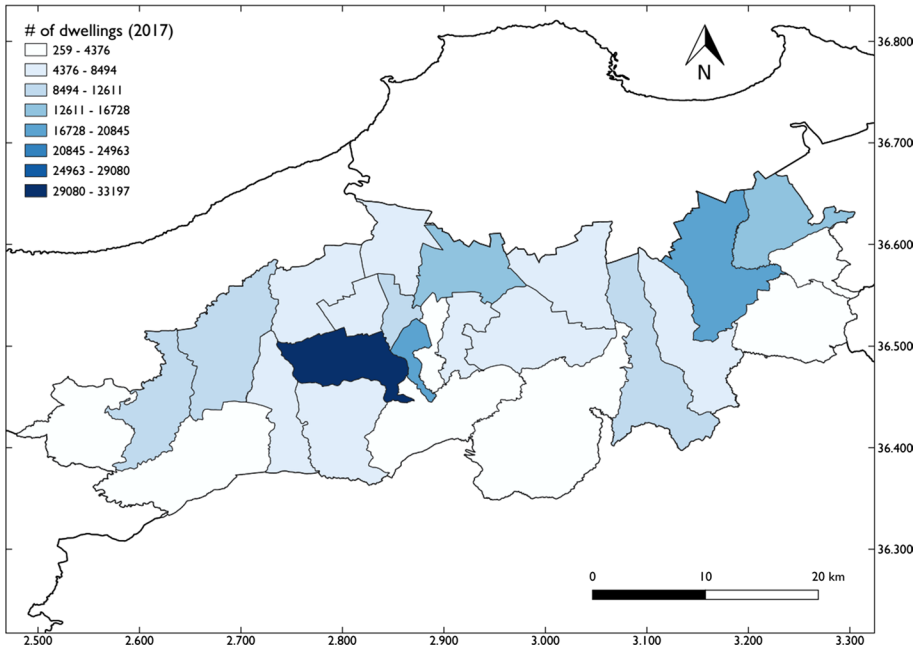
Fig. 7 Map showing the number of dwellings in Blida (2017) for the second administrative level (i.e., municipality)
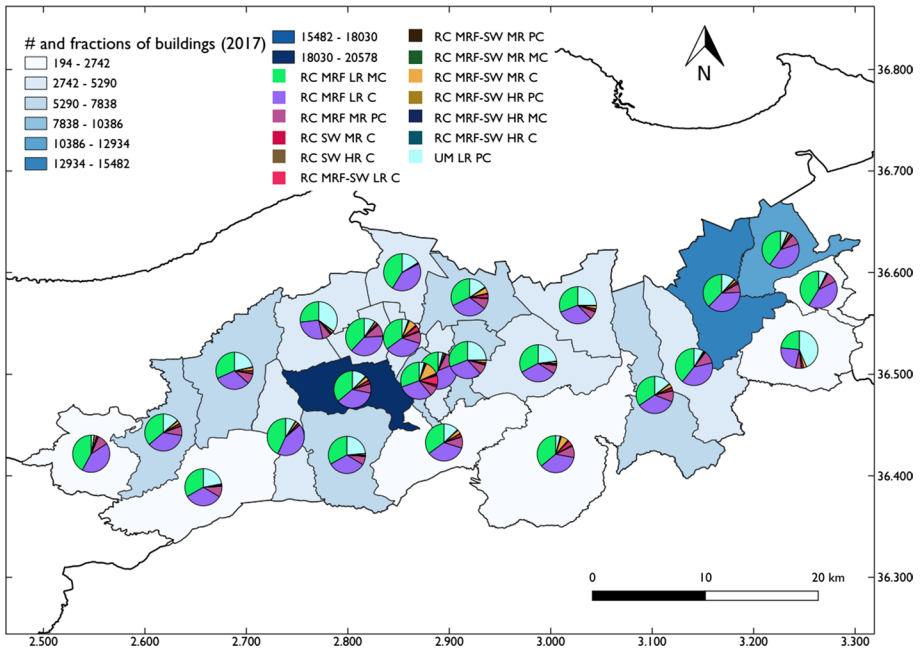

Fig. 8 Map for Blida at municipality level showing with pie charts the building fractions based on census data (2017)

increased significantly to 133 858 buildings and 205 477 dwellings in June 2017 (2021). The distribution among the municipalities is shown in Fig. 8.

The map in Fig. 8 therefore illustrates a proposal of the building fractions, in 2017 and in each municipality, for each building class defined in Sect. 3.2. This was derived based on official census data (the total number of dwellings recorded in 2017) together with the disaggregation proposed in Table 2, which is based on previous research (Djaalali et al. 2012; Athmani et al. 2014; Boukri et al. 2014, 2018; Baba Hamed et al. 2013) and local expert opinion. It is worth mentioning that, at the time of undertaking the present study, the above-described disaggregation was not available in the official data. Only the total number of dwellings is given in the 2017 official census and the previous versions of the census do not provide a breakdown in the same typology, which is used herein, defined in Table 1.

In order to disaggregate the total number of buildings per taxonomy class (Table 1), a significant amount of information was collected and reviewed. For the most common typologies, *i.e.*, RC buildings, a substantial amount of data was successfully gathered from different private and governmental institutions in order define attributes, such as the average number of dwellings, date of construction and building height. However, in terms of the number of buildings per each building typology, little information was available to reliably disaggregate the total number of buildings in each municipality per building class defined in Table 1. As such, in this study, the number of buildings per typology, used to calculate the percentages illustrated in Fig. 8, was derived considering official data (the total number of dwellings and their fractions as well as the total number of buildings recorded in 2008, in addition to the number of dwellings recorded in 2017) together with assumptions recommended in previous research (Baba Hamed et al. 2013) and by local experts.

5 In-situ survey-based exposure model

5.1 Data collection tool

Given that the data from census and additional sources presented in the previous section is limited, an alternative exposure model can be put together using in-situ survey of buildings in the study area. In this research a survey was carried out for 2902 buildings in the province of Blida, which have been inventoried considering characteristics such as: building use (i.e., housing, offices, public services etc.), age of building (i.e., code era), number of floors (i.e., height), construction material (i.e., masonry, RC, steel, timber or other), structural system (LLRS) as well as plan and vertical irregularity, state of preservation and the survey detail level of (total interior, partial interior or only exterior).

This additional data was collected via different actors, particularly university students and practitioners, in order to complement and crosscheck the census-based exposure model. This was achieved by adopting a proper building data collection form (Fig. 9a), proposed in a previous study (Grigoratos et al. 2018) for the city of Nablus in Palestine, that was reproduced electronically so as to rapidly and efficiently reach a large number of people living in large areas. Different fields corresponding to specific building information to collect were put together in a user-friendly Android smartphone/tablet application (Building Inventory Tool–BIT 2021), which was distributed among the aforementioned Algerian stakeholders. The in-situ survey was carried out by going into the field with a smartphone or tablet and collecting information directly next to the buildings (only exterior). The use of the BIT speeded up the process, with respect to paper forms, minimised
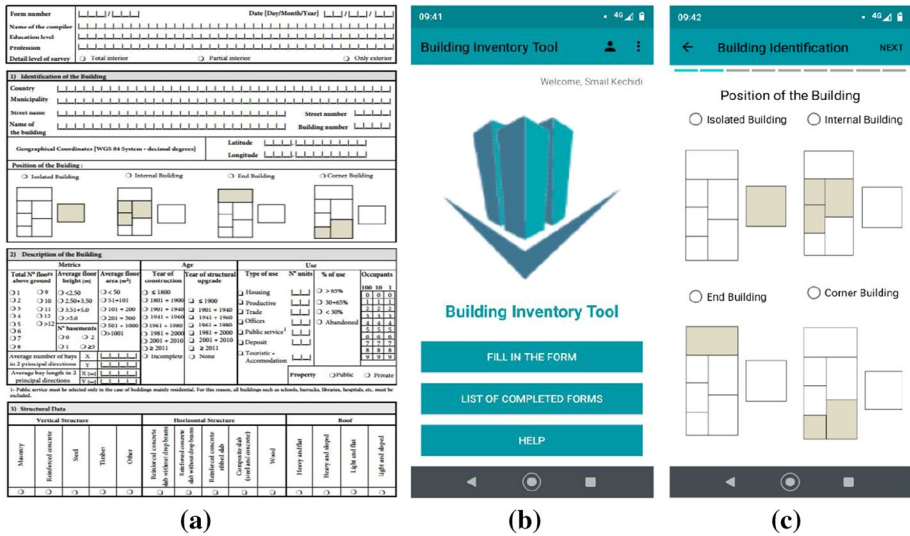
Fig. 9 **a** Building data collection form, **b** homepage of the Building Inventory Tool application and **c** Building Identification section

errors and stored exact information, such as geographic location and photos. The collected information is stored in the device (*i.e.*, smartphone or tablet) until an automatic upload to the web server is carried out. Furthermore, the application connects directly to a web-based platform (WBP) so that the information can be accessed in real time. In turn, the WBP allows performing real-time, scenario- and event-based seismic loss estimations.

5.2 Collected data overview and discussion

The criteria used for the building surveying were the following: Building Identification, Building Description, Structural Data, Structural Properties, Regularity, Geomorphological Data, Notes and Pictures. The Building Description section asks the user to indicate the total number of floors above ground, as well as the year of construction, as mandatory fields (Fig. 9a). The Structural Data section includes the constructional material of the vertical structural elements, in addition to the type of slab and roof. Whether or not the building has steel braces and/or RC shear walls can be indicated in the Structural Properties section in addition to the location, material and geometry of the infill walls. Subsequently, the criteria for regularity (in plan and elevation), adopted from Eurocode 8 (EC8) (EN 2005), can be documented. The Geomorphological Data section deals with the morphology of the site so that any potential landslides and local soil conditions can be flagged; the soil classification criteria are those provided by EC8. Lastly, Notes and Photos conclude the collection form, which were extremely useful to validate the surveyed data as well as to calibrate training initiatives. The use of the photos enabled the detection of human errors in filling out the forms, which in turn reduces the uncertainties in such large-scale assessment studies (Grigoratos et al. 2018).
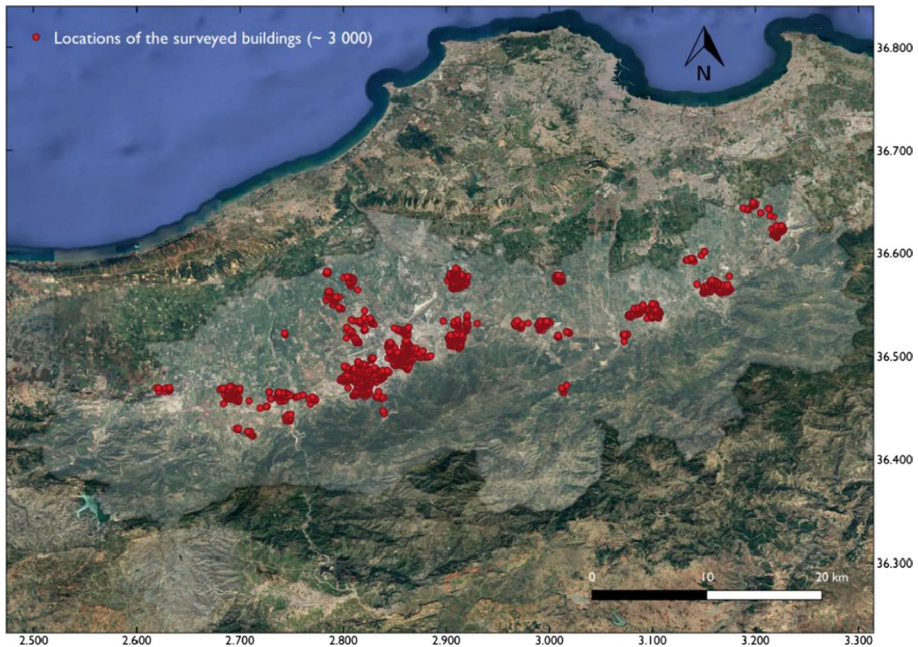
Fig. 10 Spatial distribution of the surveyed buildings within the province of Blida

Figure 10 illustrates the spatial distribution (locations) of the surveyed buildings within the province of Blida. All the collected data is available to all potential users (*e.g.*, students, citizens and authorities) of the WBP. The WBP is user friendly and puts together all the necessary information of the different risk components, as an integrated tool for decision making that produces risk information and real-time loss estimates. As it is shown in Fig. 10, the survey was conducted mostly in urban areas and some municipalities were not surveyed due to the fact that they are mainly rural areas with a comparatively small number of buildings. It is worth mentioning that the in-situ surveys took place during the summer of 2018. Therefore, the comparison between the most up-to-date census data (i.e. 2017) and the surveyed data in Sect. 6.1 was considered a more consistent approach. This approach also avoided the eventually difficult task of identifying the year of construction of recent buildings from an exterior assessment, to be able to exclude the ones built after 2008.

On the other hand, the map in Fig. 11 illustrates the survey-based number and percentage of buildings, grouped by typology, in each municipality, in a similar fashion to what was presented in Fig. 8. It is worth noting that the total number of buildings is evidently lower, when compared to the census-based data, therefore, the analysis and comparison of both data sources, in terms of generated building inventory and impact on risk assessment, were carried out (Sect. 6) adopting percentages rather than the absolute number of buildings.

Figure 12 presents a summary of the key characteristics of the collected building data using the BIT application. Around 15% of the surveyed buildings were built before 1981 and the percentage of medium- and post-code buildings is 35% and 48%, respectively, while the remaining 2% represents buildings under construction. Furthermore, the low- and mid-rise buildings prevail with 70% and 28%, respectively. A possible reason for this may
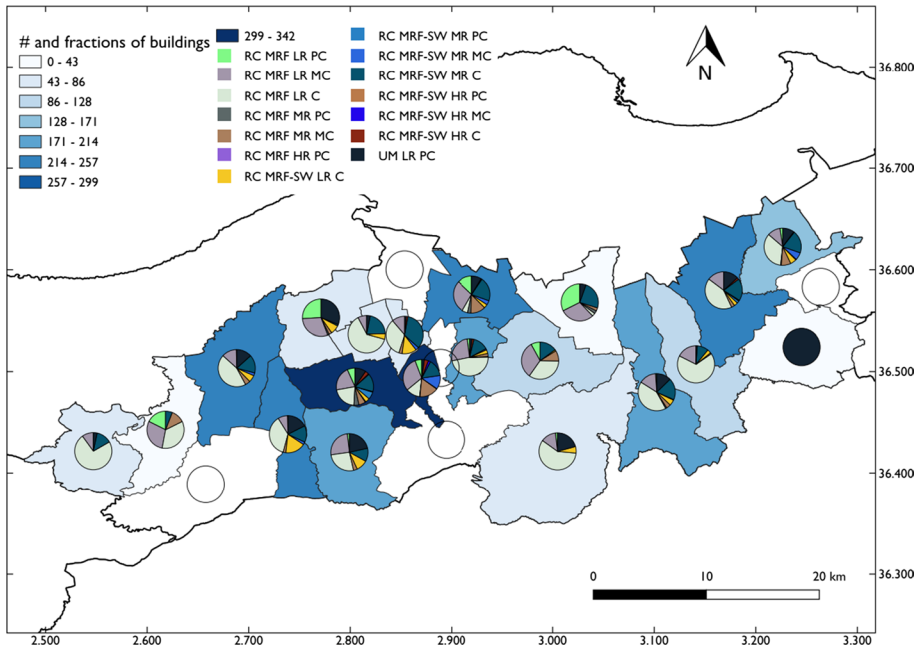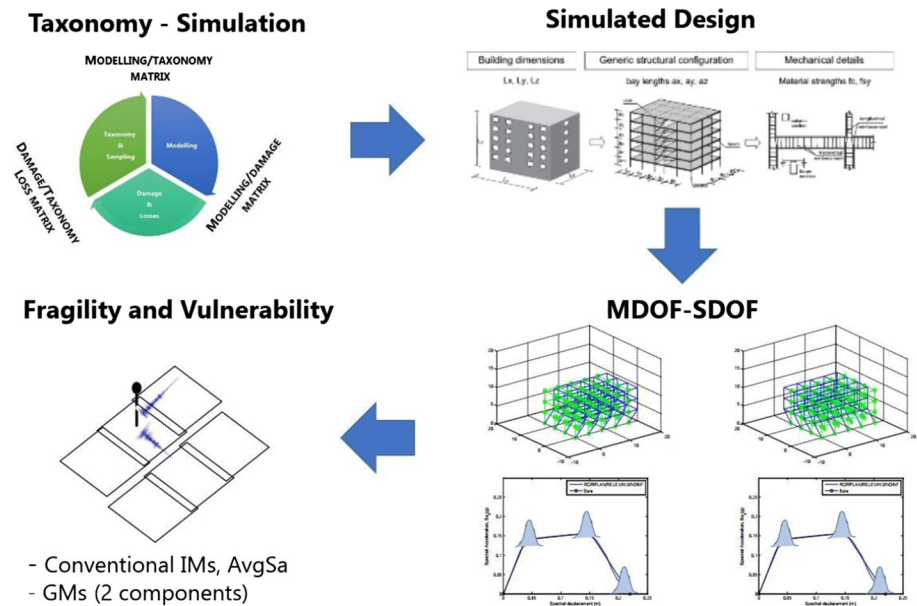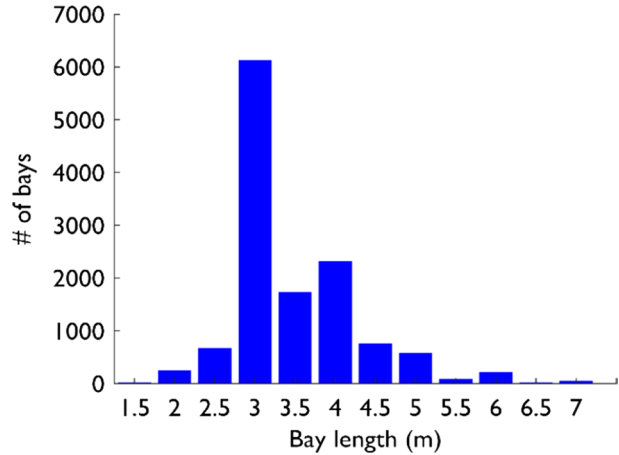
Fig. 11 Map for Blida at municipality level showing with pie charts the building fractions based on surveyed data
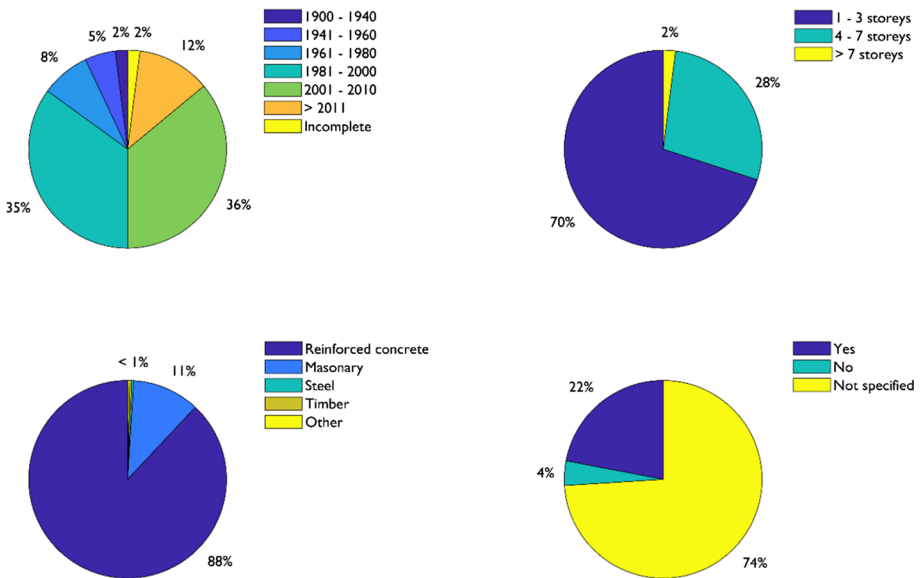
Fig. 12 Disaggregation of the surveyed data: year of construction (top left), number of floors (top right), construction material (bottom left) and presence of shear walls (bottom right)

Fig. 13 Distribution of bay length of all surveyed buildings

Fig. 14 Framework for seismic fragility assessment (Crowley et al. 2019)

be the fact that the density of the populated areas is high. The distribution of the construction material shows that the majority of the buildings are built in masonry and RC, which are the most common materials used in Algeria—88% of the collected buildings are built in RC, while 11% are made of masonry. The likelihood of having shear walls in the RC buildings is shown in Fig. 12 (bottom right). Regarding the more quantitative parameters, the bay length, which was evaluated in the field, was found to follow a lognormal distribution with a mean length of 3.47 m. Figure 13 illustrates the histogram of the bay lengths in both directions of the buildings.

Although all the surveyed data was not entirely employed in this study for the development of the vulnerability model, it can be used for the derivation of fragility functions. Figure 14 shows the basic workflow of a framework (Crowley et al. 2019) for generating fragility functions starting with the definition of Building Class Information Model (BCIM). The BCIM includes the information that is necessary to compute the total variability of the fragility function associated to a given building class. Inside the BCIM, the building class is characterized by its designation (collapsed taxonomy), the information about all the possible combinations of attributes that were collapsed (*i.e.*, the many-to-one mapping of the multiple variants of the taxonomy string into the adopted building class taxonomy) and statistical information about the architectural properties and design assumptions. Subsequently, a numerical model and a set of seismic capacity variables, derived from non-linear static analysis, which serve for the development of simplified numerical models for each building class. These steps were followed for the derivation of the fragility curves, as described in Sect. 6.2.

6 Comparison between census- and in-situ survey-based exposure and risk

Following the two described strategies for building data collection (census-based and in-situ surveyed), a comparison of the characteristics of the obtained different building inventories and of the corresponding impact on the damage assessment is carried out.

6.1 Exposure models

Two data sources were used: the 2008 census with an update in 2017 and an in-situ survey of 2902 (~3000) buildings within the territory of Blida. Firstly, the models from the two approaches are compared with respect to the distribution of buildings among the main typologies. Both models represent an important input for risk calculations, improving the
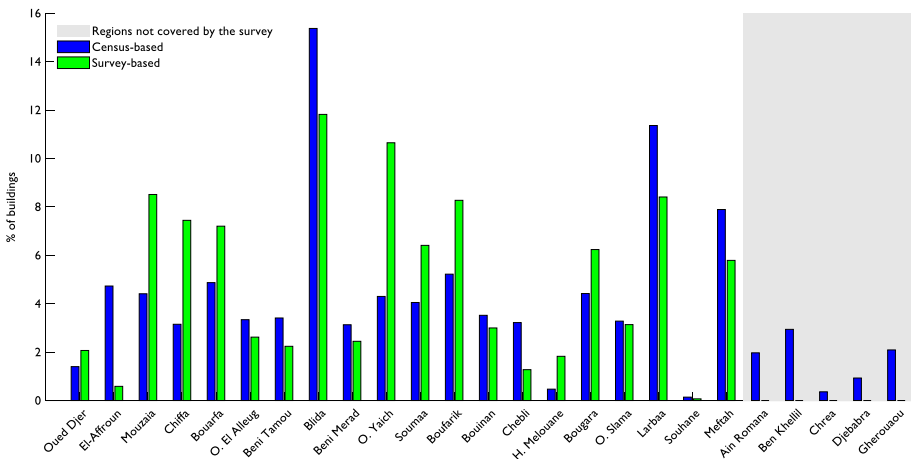

Fig. 15 Disaggregation of the percentage of buildings per each municipality

technical capabilities for seismic risk management in northern Algeria (Blida). Figure 15 shows the geographical distribution of the percentage of buildings from census and surveyed data within each municipality. Some discrepancies between the two data sources can be observed and are further discussed in Sect. 7. Moreover, as mentioned in Sect. 5.1, some municipalities were not surveyed (see shaded area in Fig. 15) due to the fact that they are mainly rural areas with a small number of buildings.

At the taxonomy level, the distribution of the residential buildings from both exposure data sources, for each building typology, is shown in Fig. 16. From the census-based data, 13 building classes were identified to describe the residential building stock in Blida whereas the surveyed-based data led to the identification of 14 building classes. The main difference between the census- and in-situ survey-based exposure models is that some uncommon building classes have been identified. Those classes have not been included in the comparative analysis and hence a total of only 11 classes are included in Fig. 16.

Both models identify low-rise MRF buildings with medium-code and code-based design (RC MRF LR MC and RC MRF LR C) as the predominant typologies. The absence of the RC SW typology in the survey database (buildings made up of shear walls as structural system) is not very important as it corresponds to 0.6% of the total number of buildings, according to the census-based exposure model. The largest differences between the census- and in-situ survey-based exposure models are observed for the RC MRF LR MC and for the RC MRF-SW MR PC building classes. The census-based model shows larger proportions, in general, for RC buildings with MRF as structural system (RC MRF LR MC, RC MRF LR C, RC MRF MR PC) and masonry buildings (UM LR PC) whereas the in-situ survey-based model shows larger proportions for RC buildings with dual MRF-SW structural systems (RC MRF-SW LR C, RC MRF-SW MR PC, RC MRF-SW MR MC and RC MRF-SW MR C). This difference can be, in part, explained by the fact that the building proportions in the census-based model for the province of Blida date back to 2008 whereas the survey was conducted during the summer of 2018. Although foreseen by the survey form, steel buildings were not considered in both exposure models due to the fact that neither the census-based nor the in-situ survey-based exposure model has steel as an option for residential buildings. Besides, the small share of steel buildings in Algeria is for commercial and industrial use, and not for a residential purpose.
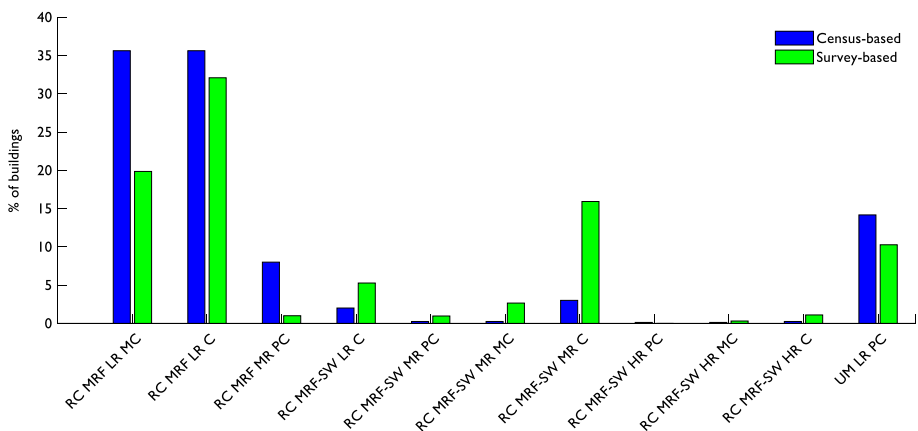

Fig. 16 Disaggregation of the percentage of buildings per each building class

6.2 Earthquake damage estimates

The influence of the differences in the distribution of the different building typologies that have been identified in the previous section, *i.e.*, the differences tested between the two exposure models, is now assessed in terms of earthquake damage estimates.

In addition to the exposure model, earthquake damage assessment requires the characterisation of seismic hazard and the definition of fragility and vulnerability functions. The North African hazard model (Poggi et al. 2020) developed by the Global Earthquake Model (GEM) Foundation (2021) was adopted. The model coverage extends from Morocco to Egypt along the Mediterranean coastline. It features a combination of distributed seismicity and faults sources; the former are calibrated on occurrence analysis of publicly available earthquake catalogue information, while the latter are derived from a thorough evaluation of information from both geological literature and direct analysis of GPS velocity fields. Hazard curves were computed using OpenQuake (OQ) (2021) for the following intensity measures: peak ground acceleration (PGA) and spectral acceleration (Sa) at 0.7 s, 1.0 s, 1.3 s and 1.5 s (coinciding with the fundamental periods of vibration of the different models representing each building class). The computation was performed on a grid of 1484 sites (spaced at approximately 1 km) with reference soil conditions corresponding to a shear wave velocity in the upper 30 m (Vs_{30}) ranging from 180 to 900 m/s. The resulting hazard curves are shown in Fig. 17 for the site representing the centroid of the province of Blida.

The vulnerability component, which characterizes the likelihood to suffer damage or loss given a hazard intensity, is defined by both vulnerability functions, *i.e.*, the relation between loss ratio and seismic intensity, and fragility functions, *i.e.*, the relation between probability of damage for each damage state and seismic intensity. Despite the notable advances in regional seismic vulnerability modelling in the last three decades, a uniform set of vulnerability or fragility functions covering all of the building classes in Algeria was not available. Moreover, most of the existing vulnerability functions have not been applied within a probabilistic framework for earthquake loss assessment (Benouar and Meslem 2007; Boukri et al. 2014; Tadjer and Bensaibi 2017). Therefore,

Fig. 17 Example of hazard curves calculated at different spectral periods for the province of Blida
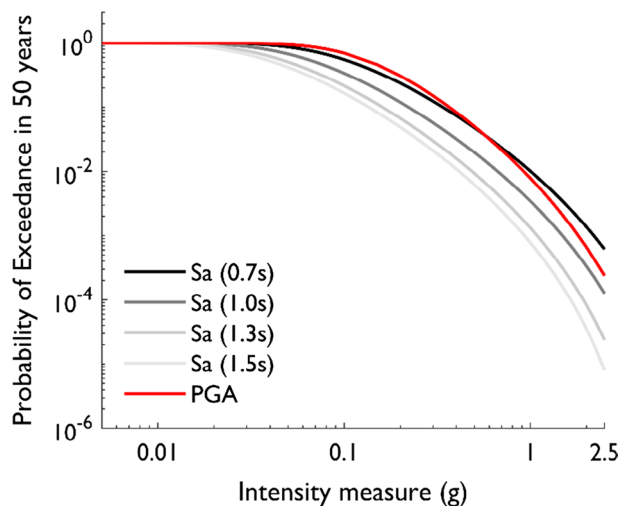
the following procedure for the derivation of fragility and vulnerability functions was adopted:

1. Development of simplified single degree of freedom (SDOF) numerical models for each building class, using data from the literature and results from experimental campaigns (*e.g.*, yield and ultimate global drift, elastic and yield period of the first mode of vibration, participation factor of the first mode of vibration, common failure mechanisms);
2. Selection of 40 ground motion records from the NGA-WEST2 database (Ancheta et al. 2013, 2014), and considering the local seismicity and tectonic environment, to properly account for the record-to-record variability. To this end, seismic hazard disaggregation at the location of the most urbanized centre of Blida supported the identification of the combinations of magnitude and distance, which contribute the most to the seismic hazard;
3. Performing nonlinear time history analysis to evaluate the structural response (maximum displacement and acceleration considered as EDPs) of the simplified numerical model for the selected ground motion records. This step uses the open-source package for structural analysis OpenSees (PEER 2006), and the Risk Modelers Toolkit developed and supported by the GEM foundation;
4. Evaluation of the structural responses of the numerical models, in terms of probability of exceeding each damage state for a set of intensity measure levels is defined (i.e., fragility functions) taking into account the uncertainty in the definition of the damage state limit.

As an example, the fragility curves for the RC MRF LR C building class are illustrated in Fig. 18.

A risk-based assessment is also known as the first step of the "PEER Integral" proposed by Cornell and Krawinkler (2000), "drift hazard" calculation in Krawinkler and Miranda (2004) and "time-based assessment" in Applied Technology Council ATC-58 (2011). Using the OQ engine, the hazard curves at the considered sites were integrated with the fragility functions of the given models, to obtain the mean annual frequency of attaining a particular damage state (*i.e.*, slight, moderate, extensive or collapse) over the buildings' lifetime, assumed as 50 years. Afterwards, this annual rate was multiplied by the total
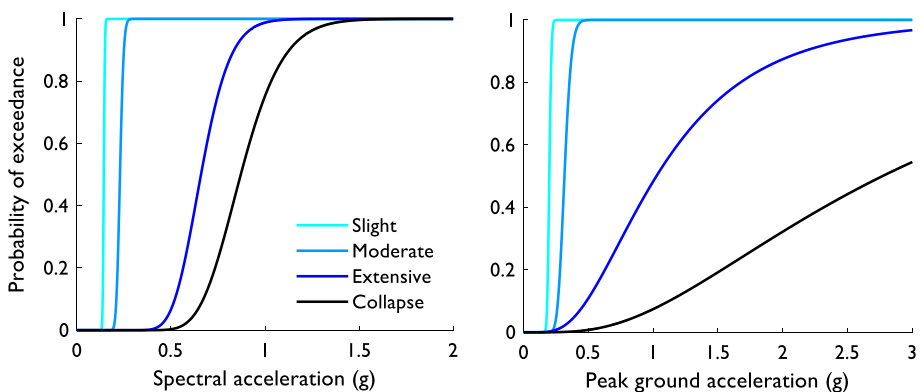

Fig. 18 Fragility curves for RC MRF LR C typology with different IM: (left) Sa at 1.0 s (best fit) and (right) PGA

number of buildings of the same class at that particular location to compute the number of buildings expected to experience that damage state (or less). The results are then presented in terms of the expected number of buildings achieving each damage state for each asset, as illustrated in Fig. 19. These results allow identifying the areas where the buildings are at highest risk, as well as the building classes contributing the most to the probability of exceeding different damage states within the overall province of Blida.

Figure 19 denotes a very similar trend of the damage assessment results, adopting both exposure models (census- and in-situ survey-based), with the in-situ surveyed data leading to less conservative results, with more buildings in lower damage states. The percentage of damaged buildings indicates that buildings under the same hazard conditions have different seismic risk levels despite of having, in principle, the same seismic design level and physical fragility (differences reside in the exposure models).

When further disaggregating the results, Fig. 20 shows the percentage of buildings, for each building class, for the different damage states, adopting census- and in-situ survey-based exposure models. For the extensive and collapse damage states, the percentages obtained with the in-situ surveyed data are much lower than those obtained with the census data, especially for the mid-rise buildings. This is mainly due to the fact that the newly constructed low-rise buildings are predominant within every municipality and have a lower fundamental period of vibration than that of mid- and high-rise buildings, which, being associated to stiffer buildings, might be an approximate indicator of higher acceleration demand hence higher damage. Furthermore, it can be noticed that the building classes RC MRF MR PC and RC MRF LR C from, respectively, the census- and in-situ survey-based exposure models, contribute the most to the collapse damage state while no contribution is observed from building classes that incorporate shear walls, namely RC MRF-SW LR C, RC MRF-SW HR PC and RC MRF-SW HR C.

The spatial distribution of the ratio of the percentage of buildings in the different damage states, resulting from the two exposure models (survey over census), is shown in Fig. 21, where the regions (municipalities) that were not covered by the survey are represented with
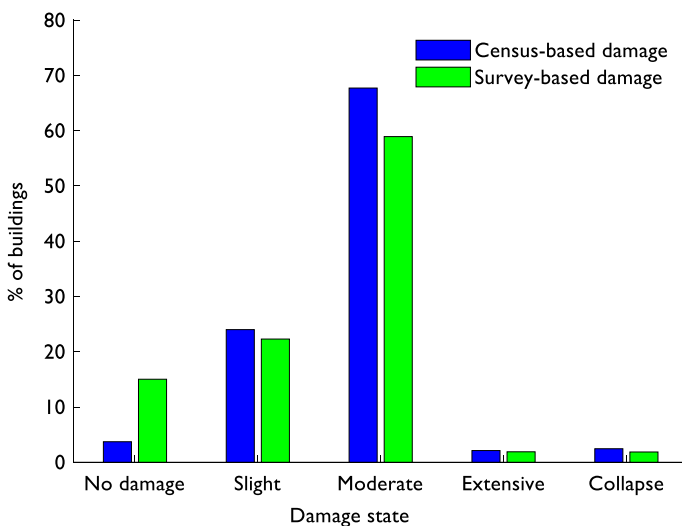
Fig. 19 Comparison of the percentage of buildings enduring different damage states adopting census- and survey-based exposure models
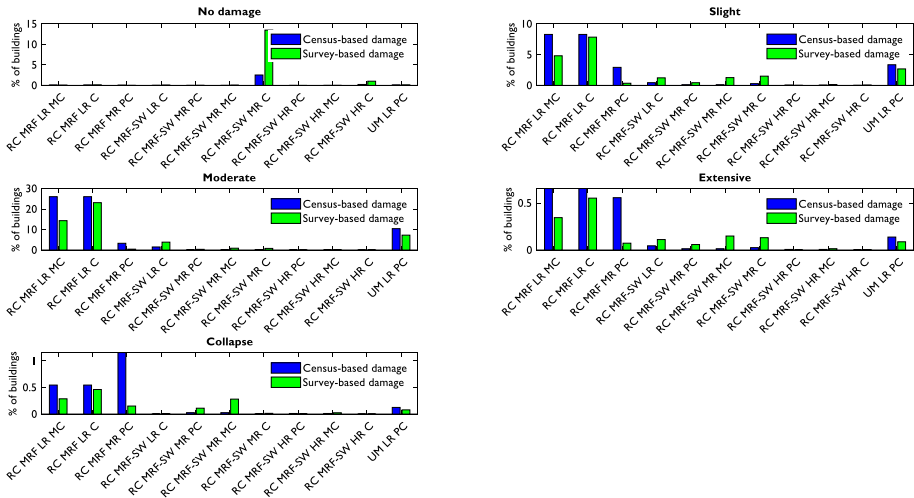
Fig. 20 Disaggregation of the distribution of damage levels per each building classes

dashed areas. It can be seen that ratios close to unity prevail in highly populated munici-palities (*i.e.*, urban areas) and very light and very dark colours, which indicate a high dis-crepancy in the risk estimates adopting the two exposure models, is typically witnessed in the municipalities that represent rural areas of the province of Blida where limited number of surveys were carried out (see Fig. 10). Therefore, the accuracy of the risk estimates is directly correlated with the number of surveys performed in a given region. More discus-sion on this aspect is provided in the following section.

7 Discussion on more efficient building surveys

The characteristics of the in-situ survey-based exposure models can be further investi-gated with a view to identify a threshold value for the size of the survey that guarantees an acceptable level of matching of the damage results, with respect to the full survey. Specifi-cally, using sensitivity analysis of the results, random selections from 1 to 2902 buildings, within the surveyed data, were carried out and comparisons were made. Given the random nature of the sensitive study, additional criteria for the selection from the survey database have been set so that the whole province (*i.e.*, all the municipalities) would be covered. Moreover, the distribution of the building typology percentages of the in-situ surveyed buildings within each municipality was forced to follow the same distribution trend of the census database. In other words, all the divisions should be surveyed within a given region and the number of buildings to be surveyed inside each division should be proportional to the number of buildings given by the census database in that specific division.

As a result, Fig. 22 shows the error between the percentage of the buildings experienc-ing a given damage state adopting full- and randomly selected-data, with increasing sam-pling size, from the survey-based exposure model, as a function of the percentage of total number of buildings given by the census-based exposure model.

In order to achieve a balance between, on the one hand, the exposure model accuracy and precision, and, on the other hand, the errors in the estimation of affected buildings, a
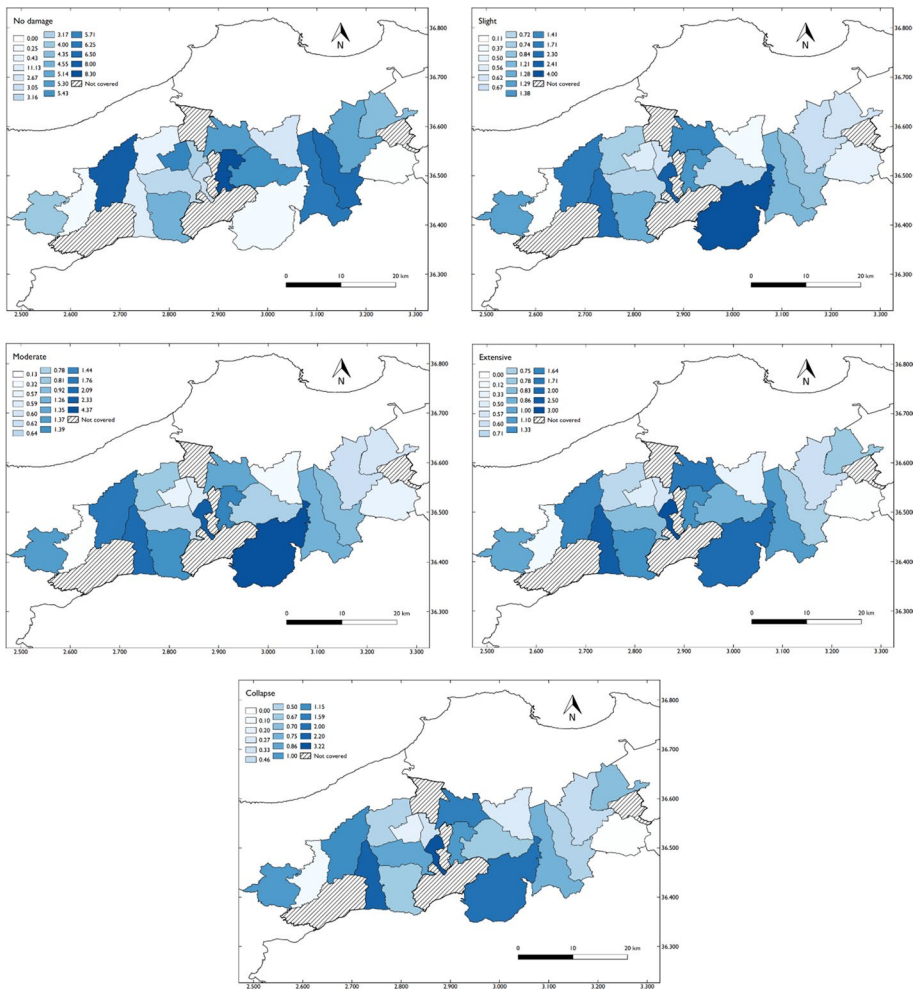
Fig. 21 Spatial distribution of the ratio of the building damages adopting in-situ survey- and census-based exposure models (survey-to-census)

value of 1500 buildings (~1% of the total number of buildings from census-based data) could be defined as a threshold above which less than 10% error is observed for all damage states if the no-damage state is disregarded. This assumption can be seen as acceptable, from the moment that decision makers are certainly more interested in the damage states causing high losses (extensive damage and collapse). Moreover, Fig. 23 shows the percentage of buildings, from census and the partially selected survey data (1500 buildings), within each municipality. Although significant scatter exists in the results related to the no damage state and the 1% threshold is less evident, the relevance of such a damage state for decision-making is minor hence not affecting the abovementioned approximate 1% trend.

Figure 24 illustrates the aggregated comparison of the different sources (census, full in-situ survey and partial in-situ survey) per damage state. It shows a similar trend of the results, in terms of the percentage of buildings experiencing different levels of damage (*i.e.*, slight, moderate, extensive and collapse) where the percentage of buildings related to
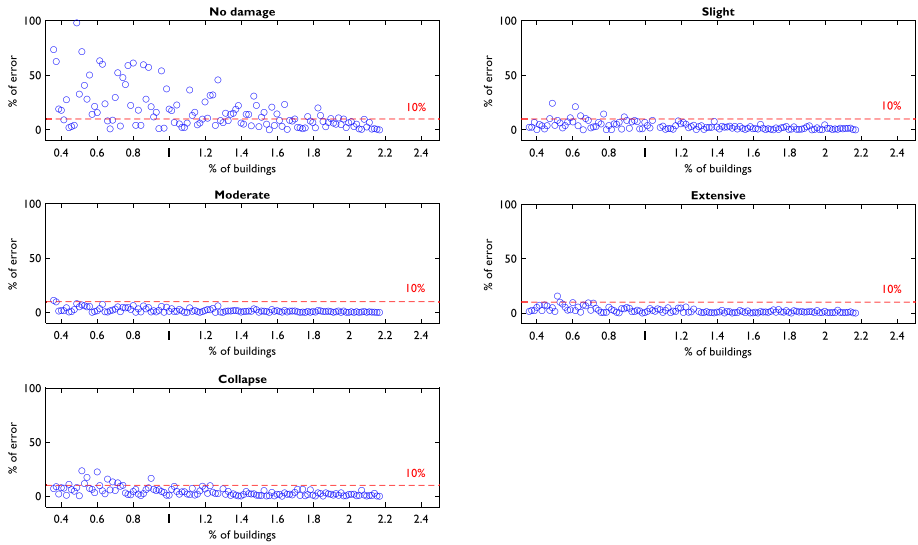
Fig. 22 Damage error between partial- and full-survey exposure models
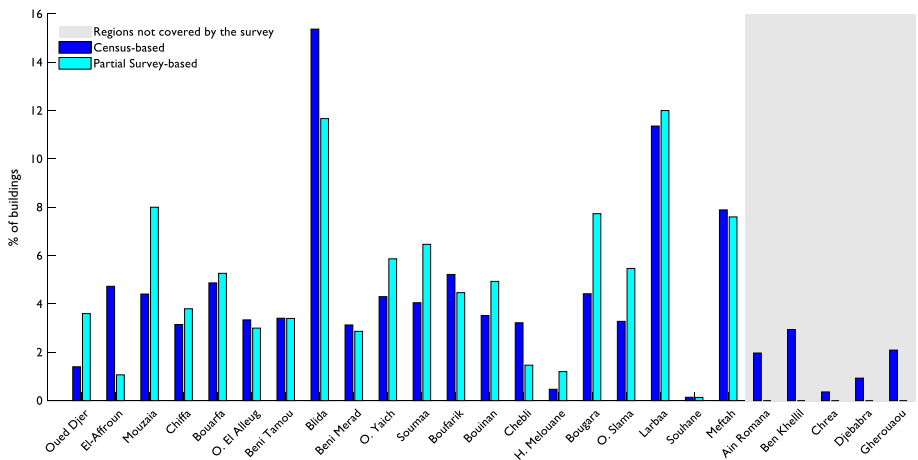
Fig. 23 Disaggregation of the percentage of buildings per each municipality

partial and full survey-based model are almost the same thus confirming what anticipated in Fig. 22. Finally, Fig. 25 shows the comparison of the damage estimation by the census, partial (1500) and full surveyed data disaggregated per each building class.

Overall, the development of the exposure model proposed within this study is to be regarded as an iterative process that aims at a continuous model updating rather than a static modelling at a single time step. The current state of the model should be used as input to optimise future data collection to most efficiently improve the overall model accuracy and take into account new evolutions in the exposed environment, such as urban growth patterns. Given that in seismic risk assessment the significant dynamics are not introduced
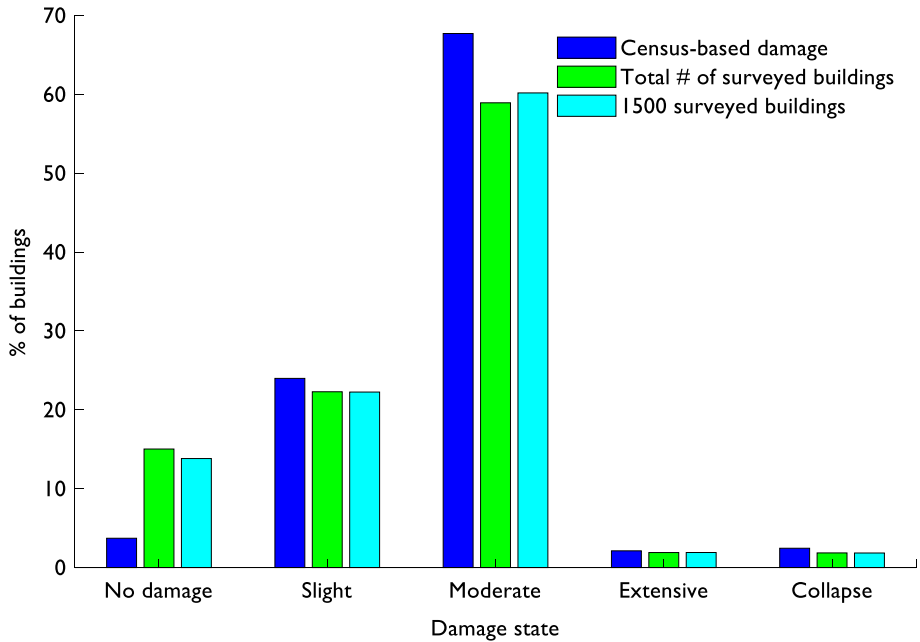
Fig. 24 Comparison of the damage levels for census- and surveyed-based exposure models
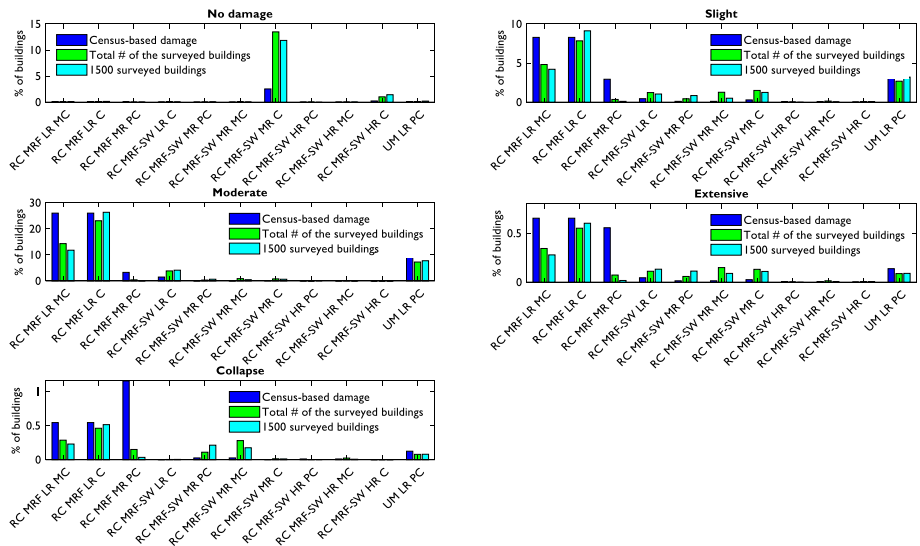

Fig. 25 Disaggregation of the distribution of damage levels per building class

by the hazard component but by changes of the exposed assets and their vulnerability, a continuous updating of the exposure model is essential to keep the overall risk model valid. This becomes particularly important in countries characterised by an increasingly high spatio-temporal variability and concentration of exposed assets in hazardous areas.

8 Summary and conclusions

Despite a relatively long history of research and development in earthquake engineering, risk assessment is a fairly new concept in Algeria. In this paper, a methodology to obtain an exposure model for residential buildings in northern Algeria was presented, adopting the province of Blida as a first case-study area. In particular, the relevance and required characteristics of the exposure model that would lead to accurate seismic damage and risk outputs were explored. The lack of reliable data at national and local levels to correctly classify the building stock was the major hurdle faced in this study. Census data was not the most reliable source of information, given that technical information is either not available or accurately collected. Additional information was obtained from some local institutions and constituted an important complement to census data, as they secured technical accuracy.

A fully census-based model was therefore developed and compared with an alternative exposure model based on data collected in-situ, through a specifically-developed app—Building Inventory Tool. The two models exhibited an overall agreement in terms of direct number of buildings for the typologies used to describe the building stock, whereas some differences were observed in RC buildings with shear walls. These discrepancies would likely be justified by the fact that the in-situ survey was carried out in 2018 whereas the census data refers to 2008, complemented with statistics on building construction during the period 1999–2017, which further highlights the importance of the in-situ surveys.

Subsequently, a comparison of the results on building inventory and impact assessment (in terms of building damage distribution) adopting census and in-situ surveyed data was carried out, considering both aleatory (record-to-record) and epistemic (damage state limits) uncertainties. The results on expected building damage distribution were compared with the objective of evaluating the effect of alternative inventory approaches. Preliminary guidelines on conducting in-situ surveys were then drafted, with a view to a possible re-use in other contexts (provinces) having similarities to the studied region. Further research is however necessary to make the most of the information collected in-situ, also considering more refined fragility functions. Moreover, an integrative approach allowing to combine the informative levels that are present in census and surveyed data was proposed, allowing a mixed type inventory to be used for seismic impact assessment. Open points with respect to a characterization of exposed assets include a possible extension of the taxonomy to support other (non-structural) elements (e.g., socioeconomic attributes).

Availability of data and material Available upon request.

Code availability Available upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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