NEW TOOLS FOR SEISMIC VULNERABILITY ASSESSMENT OF UNREINFORCED MASONRY BUILDINGS IN OTTAWA, ONTARIO

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ABSTRACT
Recent earthquakes have demonstrated the seismic vulnerability associated with poorly designed masonry buildings in densely populated urban areas. Given the large stock of unreinforced masonry buildings in cities such as Vancouver, Montreal and Ottawa, there is an urgent need to assess the seismic vulnerability of older unreinforced masonry buildings in Canada. This paper presents results from an ongoing research program which forms part of a multi-disciplinary effort between the University of Ottawa’s Hazard Mitigation and Disaster Management Research Centre and the Geological Survey of Canada (NRCAN) to facilitate the data collection and seismic vulnerability assessment of buildings in dense urban areas. A general building inventory and its spatial distribution and variability are key variables needed for earthquake loss assessment and risk management. The Urban Rapid Assessment Tool (Urban RAT) is designed for the rapid collection of building data in urban centres. The Geographic Information System (GIS) based assessment tool allows for intense data collection and revolutionizes the traditional sidewalk survey approach to collecting building data. Currently, this research effort includes 8 major downtown neighbourhoods in the City of Ottawa comprised of approximately 14,000 buildings which includes a large stock of unreinforced masonry buildings. This paper presents data related to the condition of existing unreinforced masonry buildings in the City of Ottawa, including information on year of construction, occupancy class and structural irregularities relevant to seismic risk assessment.

KEYWORDS: building inventory, seismic vulnerability, earthquake risk assessment, unreinforced masonry (URM)

INTRODUCTION
Earthquakes pose significant risks to human life and infrastructure, particularly in areas that are unprepared. With 40% of Canadians living in areas of high or moderate risk of loss from an earthquake, such as Victoria, Vancouver, Montreal and Toronto, it is essential for individuals, businesses and governments to understand the potential hazards posed by seismic activity (Kovacs, 2010). In the Ottawa-Gatineau region, continuous urban growth places ever greater populations and infrastructure at risk to seismic events (Lamontagne, 2010). As such, it is paramount to plan and strategize in areas at risk of seismic related damage. Therefore, there is a need to invest in research efforts to increase our knowledge and preparedness in order to mitigate potential seismic related loss. Earthquake loss estimations provide knowledge to support effective actions by decision makers that can reduce potential damages to urban communities.

The contribution of this research is in seismic risk mitigation in Ottawa-Canada. We present a new set of Geographic Information System (GIS) and mobile tools that allow for rapid structural assessment in urban centres and results of these assessments that can be used for risk assessment and mitigation for unreinforced masonry buildings in the downtown core.

Geographic Information System (GIS) tools can facilitate rapid data entry, analysis and visualization of spatial data. GIS tools have been utilized in many emergency management applications (Herold and Sawada, 2012) and they provide an efficient toolset for loss estimation studies (Tari and Tari, 2002). As the consequences of an earthquake vary spatially, GIS-based mapping and analysis are a nexus that links the event of an earthquake with hazard specific information such as surficial geology (*cf.* Motazedian et. al., 2011) and structural variations. The success of mapping the spatial variability in seismic risk outcomes requires a well-developed database of building structures. Such a database can be effectively populated directly within a GIS system and as such a GIS has an essential role in earthquake risk assessment.

Unreinforced masonry (URM) buildings have consistently performed poorly in earthquakes. URM building construction is known to be the most seismically vulnerable construction type. Despite their inherent vulnerabilities, many URM buildings exist in populated urban areas of Canada (Bruneau and Lamontagne, 1994). Increase in awareness of the risk posed by existing URM buildings is vital. Consequently, a proper database of the URM building stock and their spatial distribution in urban areas, such as Ottawa, is critical in determining areas of seismic vulnerability, mitigation strategies, policies aimed at mitigation and for modelling post-disaster response scenarios.

This paper introduces a new GIS and Mobile GIS toolset developed for rapid site specific structural building assessment that can replace traditional sidewalk surveys. The Urban Rapid Assessment Tool (Urban RAT) is designed for the rapid collection of building data in urban centres. The Geographic Information System (GIS) based assessment tool allows for intense data collection and revolutionizes the traditional sidewalk survey approach to collecting building data. This paper briefly describes the methodology and procedure used in Urban RAT and provides a summary of its relevance and an application. In addition, the paper presents results related to the condition of existing unreinforced masonry buildings in the City of Ottawa that was collected using Urban RAT.

URBAN RAPID ASSESSMENT TOOL (URBAN RAT)

The Urban Rapid Assessment Tool (Urban RAT) suite modernizes the way building surveys are conducted. Rather than the traditional pen and paper sidewalk survey, the Urban RAT tool exploits the use of computers, web services and portable electronics in order to obtain and collect site specific building information.

Urban RAT is an ArcGIS-Google-Android system that contains two components: an in-lab application (add-in) built for ArcGIS 10.x within the .Net framework (in order to integrate ArcGIS and the Google API) and second, an on-site (Google Android) app that collects positional and visual information in addition to inputs that contain the same data. The on-site application data can be synchronized with the main ArcGIS database.

Within the lab, using a MS Windows PC with ArcGIS 10.x installed, the user is presented with a new toolbar called URAT (**Figure 1**)

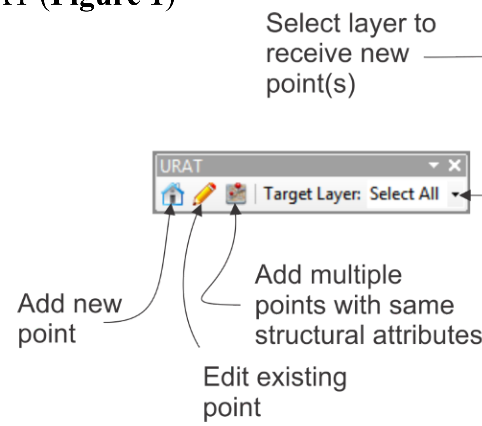


Figure 1: Urban RAT toolbar in ArcGIS 10.x (from Sawada et al., 2013)

Using this toolset, the user selects the simply clicks on a building represented on a satellite image within ArcGIS and this initiates two windows, one showing the form with building parameters to be entered (**Figure 2a**) and the second window opens Google Street View within ArcGIS at the location of the building that was selected (**Figure 2b**) allowing the assessor to examine the structure from many angles and enter parameters on the form. Once the form is complete the data is automatically saved into a new data layer with a point at the location of the assessment.

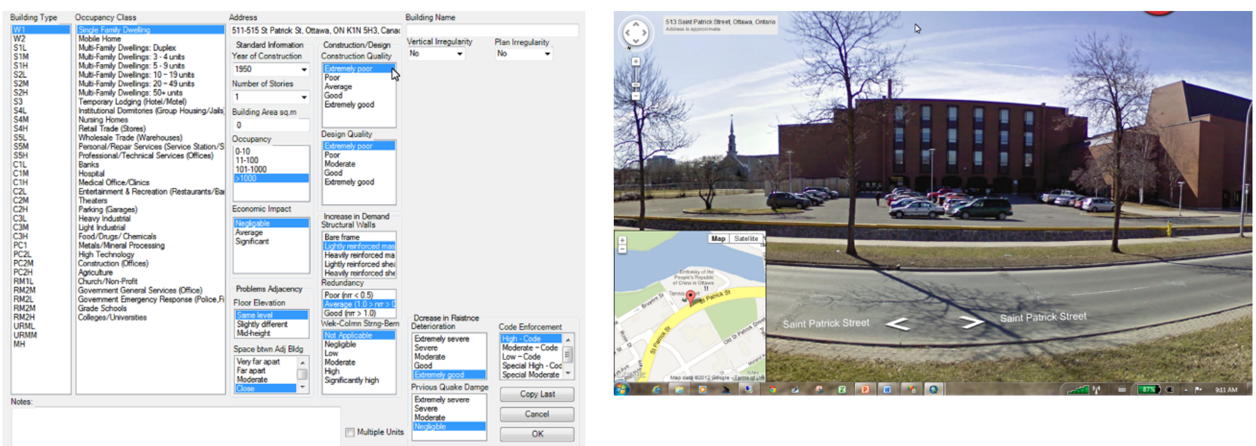


Figure 2: a) Building assessment form in Urban RAT; b) Google StreetView within Urban RAT and within ArcGIS open at location of building to be assessed (from Sawada et al., 2013)

Urban RAT suite's framework is designed to incorporate roughly 30 structural parameters. **Table 1** presents Urban RAT's parameters for assessment that are based on FEMA 154 (2002) and FEMA 310 (1998). The first theme ([1] General information) provides the basic information related to a buildings characteristics and structural system. The second and third themes ([2] Increase in Demand and [3] Decrease in Demand) represent endogenic engineering parameters which influence building vulnerability during earthquake events. The final theme ([4] Issues of

Adjacency) incorporates an imperative exogenic factor which can affect structural performance during earthquake ground shaking. Themes [1]-[4] are required for high resolution earthquake loss estimation studies. These variables and their respective values are presented to the user on the main URAT interface (**Figure 2**).

Table 1: Urban RAT theme parameters for assessment

[1] General	
Building Type	Year of Construction
Address	Number of Stories
Name of Building	Occupancy Class
Vertical Irregularity	Occupancy
Plan Irregularity	Economic Impact
Construction Quality	Design Quality
[2] Increase in Demand	
Structural Walls	Weak Column-Strong Beam
Redundancy	
Plan Irregularity	
Diaphragm Continuity	Torsional Irregularity
Re-Entrant Corners	
Vertical Irregularity	
Short Column Effect	Soft Story
(Captivated Column)	Weak Story
[3] Decrease in Resistance	
Deterioration (e.g. Corrosion)	Code Enforcement
Damaged from Previous Earthquake	
[4] Issues with Adjacency	
Floor Elevation	Space Between Adjacent Buildings

In some cases, the assessor will find that the Google StreetView is insufficient for assessment. As such, a mobile version of the virtual site assessment software can be used and will run on any certified Google Android tablet. There is no need to have an active wireless internet connection (Wi-Fi, 3G, 4G or otherwise) with Urban RAT mobile in order to make full use of the tablet's GPS and mapping functions. In Urban RAT mobile (**Figure 3**), all data is stored locally on the device as XML and CSV files which can be easily uploaded to the main ArcGIS program when the user returns to the desktop.

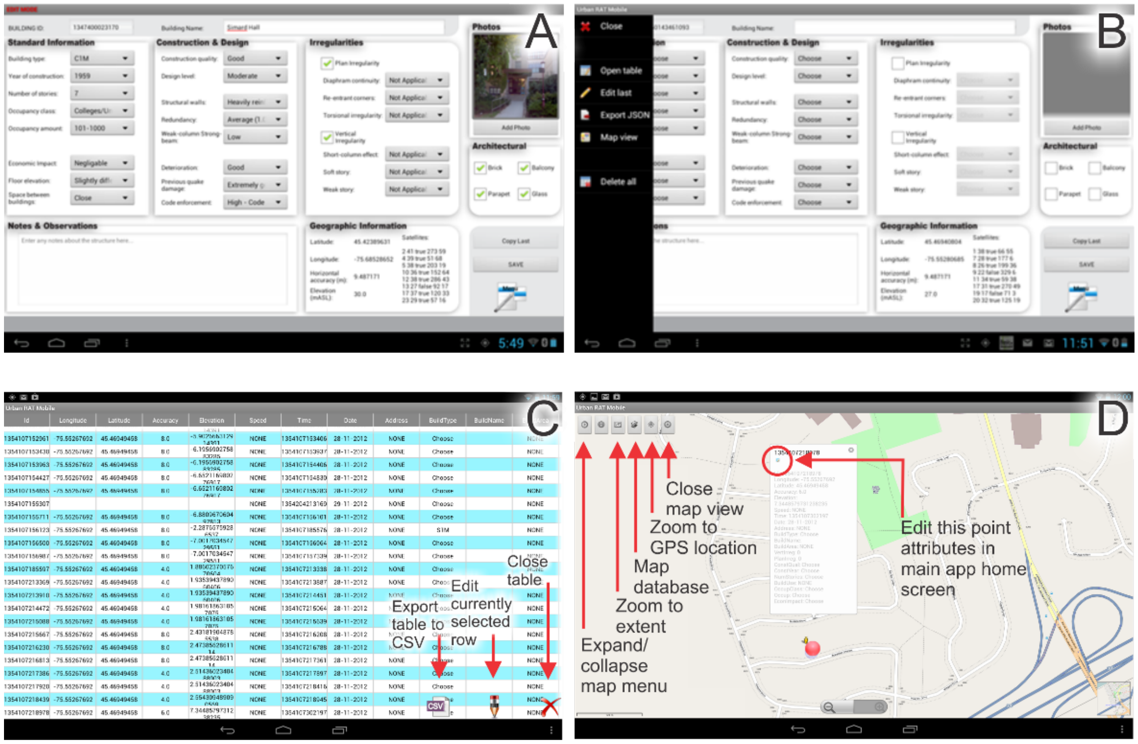


Figure 3: Urban RAT mobile: a) Main assessment screen, variables as in Table 1; b) Main menu used to switch between data entry screen, map and data table; c) Data table of stored assessment locations. User can edit or export to comma separated values file (CSV); d) Map of assessment area. User can plot all assessed points, select individual points for editing and see current location on map using GPS receiver in tablet.

For further information on details of the development and use of the Urban RAT suite refer to Sawada et al. (2013).

URBAN RAT IN PRACTICE

In the summer of 2011, the Urban RAT tool was used to construct a building database within the City of Ottawa. Data collection began in the downtown core by a structural engineering student. To date the number of buildings assessed is approximately 14,000 over 8 major neighbourhoods in the downtown core. In general, most downtown neighbourhoods in the City of Ottawa contain a combination of historical and modern buildings, including an important stock of unreinforced masonry buildings.

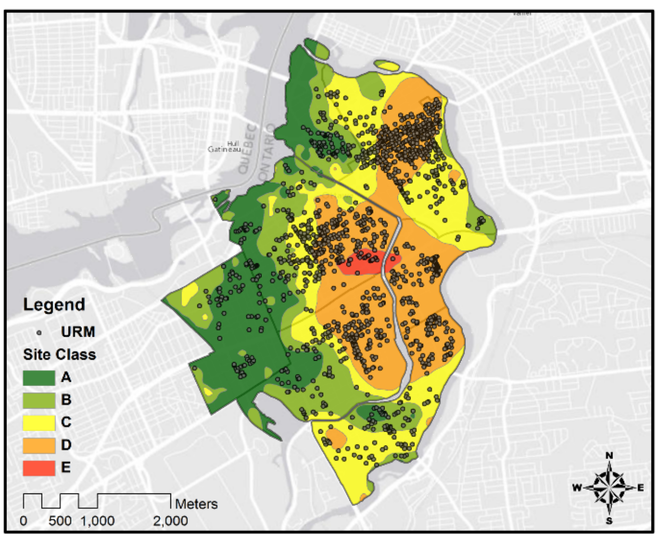
UNREINFORCED MASONRY (URM)

Many densely populated cities in Western and Eastern Canada (Vancouver, Montreal, and Ottawa) have large inventories of unreinforced or poorly designed masonry structures. Although measures have been taken to rehabilitate and increase the seismic resistance of important and historic structures, many existing unreinforced masonry structures have not been retrofitted and remain at risk in the event of a large magnitude earthquake (Bruneau, 1994). There is therefore a need to identify vulnerable structures and develop tools for assessing the seismic vulnerability of unreinforced masonry structures in Canada.

Masonry construction is considered the oldest of building materials. Most unreinforced masonry (URM) structures in North America were built before the implementation of stringent earthquake design requirements. Even today URM is still a common form of construction in parts of the world according to FEMA 154 (2002). It is important to note that unlike California, which banned the construction of unreinforced masonry structures in 1933, Canadian building codes permitted URM buildings to be constructed regardless of location or seismic zone until the mid-1970s (NRCC, 1975; FEMA P-774, 2009). The 1975 edition of the National Building Code of Canada, prohibited the construction of URM buildings in moderate to severe seismic regions (where more than 50% of the Canadian population lives), and required reinforced masonry to be a mandatory type of construction in masonry type structures (Bruneau 1995; Brzev, 2010).

URBAN RAT AND URM IN OTTAWA

Within the building inventory compiled in this research effort, a total of 1,493 (~11% of total inventory) buildings were classified as unreinforced masonry construction. It is important to note that the URM buildings assessed in this research effort are considered non-engineered structures usually built from prescriptive methods and lessons learned over the years of construction of URM. In addition to the structural make-up of any given building, another important variable in assessing the structural seismic vulnerability is the soil condition (surficial geology) in which it rests upon. **Figure 5a** illustrates the location and site soil classification (*cf.* Hunter et al., 2010; Motazedian et al., 2011) for each URM structure within the collected building inventory. In these Ottawa neighbourhoods, the URM building stock is located on several types of the site soil class conditions; however over 50% the URM buildings stock are located on site soil classification D & E which are considered stiff and soft soil profiles respectively (**Figure 5b**). These soil types include conditions of lower shear wave velocity that increase the strength of shaking of an earthquake (Williams et al., 1997).



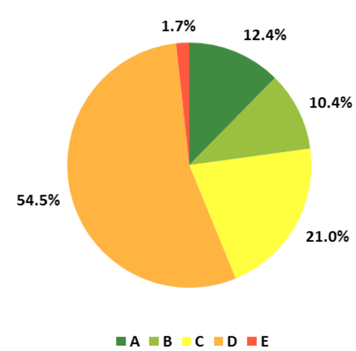


Figure 5: Site Soil Classification of URM buildings in Ottawa, Ontario: a) Spatial Location; b) Numerical Breakdown

The year of construction of a building delineates older construction from the new, more modern practices. All the downtown neighbourhoods in this research contain over 90% of buildings constructed before 1940. The year of construction of unreinforced masonry buildings is a indicator of the probable performance in the event of an earthquake. **Figure 6** illustrates that majority of URM buildings in the downtown core were built prior to the 1940s where no stringent seismic requirements where in place for the construction of URM. This indicates the importance of seismic retrofit and rehabilitation to assure that URM buildings are brought to a proper level of seismic safety according to modern code requirements.

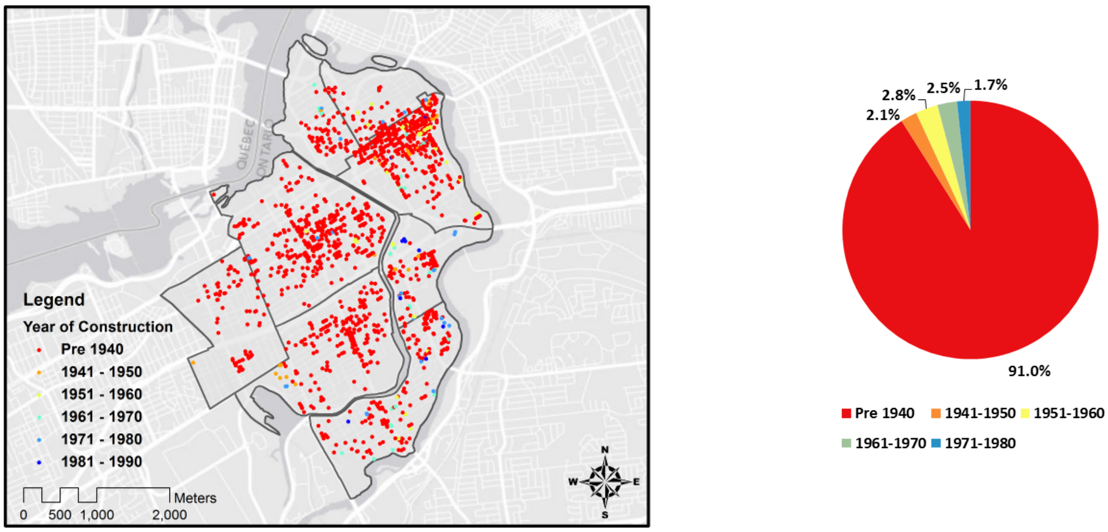


Figure 6: Year of Construction of URM buildings in Ottawa, Ontario: a) Spatial Location; b) Numerical Breakdown

Observations from previous earthquakes have emphasized that certain critical facilities such as hospitals should be designed to remain operational during and after an earthquake. As URM is the most vulnerable form of construction is it essential that URM buildings are brought to a reasonable level of safety and seismic performance. As displayed in **Figure 7**, a number of emergency response and medical facilities are located in the downtown core. In addition, educational facilities are tagged high importance in the National Building Code of Canada (NBCC) as they play a major role in post-disaster temporary housing and shelter (NRCC, 2010); our data indicates that there is an important stock of URM buildings in this category. Overall, the data demonstrates there is a rich mixture of occupancy class within the URM building stock with a majority of URM consisting of single or multifamily dwellings, temporary lodging and general service buildings (retail stores), however an important stock of buildings also fall in the post-disaster and high importance categories.

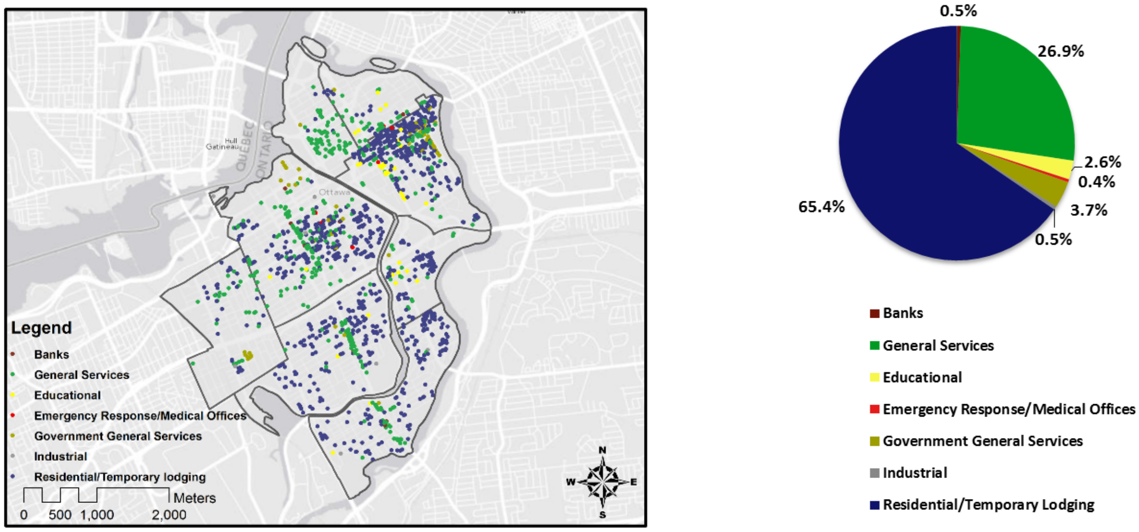


Figure 7: Occupancy class of URM buildings in Ottawa, Ontario: a) Spatial Location; b) Numerical Breakdown

Another important parameter that can affect building performance during earthquakes is the presence of structural irregularities. The data collected using the Urban RAT tool illustrates that the most common type of irregularity found in URM buildings are re-entrant corners caused by asymmetrical plan configurations and setbacks. In addition, some unreinforced masonry buildings contain first floor retail stores with one or two levels of family dwellings located above, particularly buildings along Bank Street – a street that is considered a major shopping and business district in the City of Ottawa. This building configuration typically results in a soft story effect due to display windows and large storefront openings. **Figure 8** provides a breakdown of URM buildings classified as regular and irregular structural configurations which include plan irregularity, vertical irregularity or a combination of the two aforementioned irregularity types.

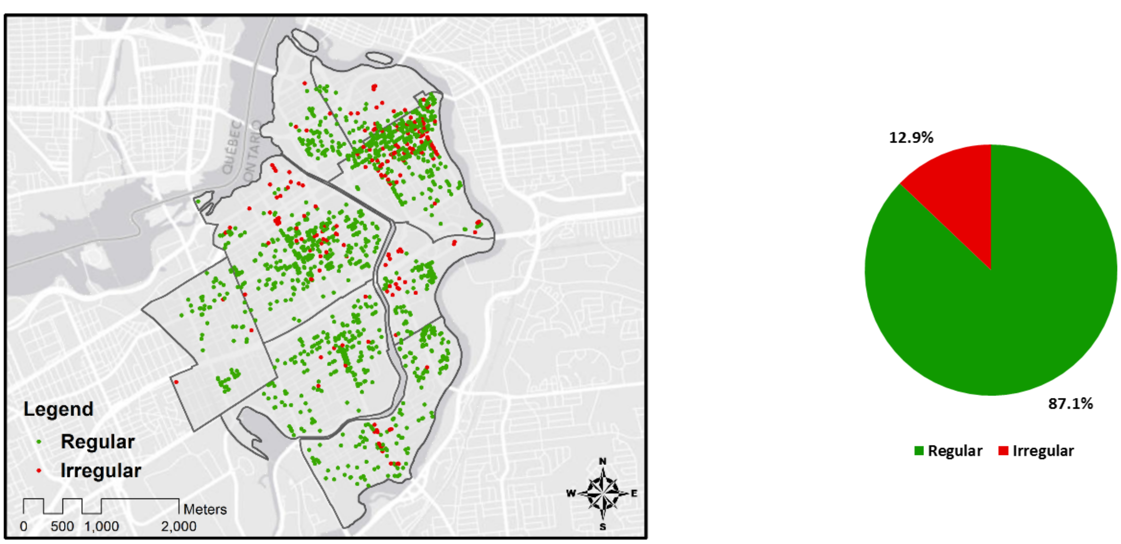


Figure 8: Regular vs. Irregularity URM buildings in Ottawa, Ontario: a) Spatial Location; b) Numerical Breakdown

LOSS ESTIMATION

Information obtained using the Urban RAT suite will be compatible for earthquake loss estimation programs such as HAZUS-MH and CanRisk. HAZUS-MH is a comprehensive software originally developed by the Federal Emergency Management Agency of the United States, and the National Institute of Buildings Sciences (see FEMA, 2006a). CanRisk is a Canadian engineering program developed by CSRN (Canadian Seismic Research Network) researchers that integrates site specific spatial information such as NEHRP-based soil conditions and ground motion with detailed user-input building-specific data. CanRisk is modular in that it can include modules to evaluate risk of various aspects of the built environment. Currently, the program includes a module to evaluate reinforced concrete buildings (Tesfamariam and Saatcioglu, 2010) and work is currently in progress to include unreinforced masonry and other construction material types. The program output establishes the damage level and risk index for a given building. Work is currently underway to integrate the data collected from the Urban RAT suite into the framework of CanRisk using a modified version of CanRisk for ArcGIS, called arcCanRisk.

CONCLUSIONS

Data collection of the building stock in a major urban centre facilitates various aspects of emergency preparedness and mitigation as the resultant data supports earthquake loss estimation. Many urban centres contain a large building stock, therefore software and hardware tools that can expedite data collection are fundamental to timely seismic risk mitigation decisions. The Urban RAT suite can better equip regions to mitigate and prepare for, respond to, and recover from natural disasters including earthquakes for emergency management purposes. The advancements in data processing and GIS has provided the foundation for the development of comprehensive loss estimation programs such as HAZUS-MH and arcCanRisk that can better serve decision makers in Canada. The City of Ottawa, an area of moderately high seismic risk, has a population of almost one million people and it is essential to evaluate distribution of seismic risk across the city, especially within heavily populated and historical regions such as the downtown core. This paper presented the preliminary results from the use of Urban RAT, a GIS-based tool that can be used to rapidly collect building data in dense urban areas. The tool was used to collect data from a large stock of URM buildings in the City of Ottawa.

The highlights of the Urban RAT suite and its application to unreinforced masonry buildings in the City of Ottawa as presented in this paper are summarized below:

- Urban RAT is a developed platform which allows for both in-lab/ virtual assessments and in-field /on-site assessments to be performed in tandem;
- The ability to perform in-lab/virtual site assessments optimizes time and efficiency of data collection;
- The inclusion of engineering parameters based on FEMA 154 (2002) and FEMA 310 (1998) provides data which can be used in loss estimation programs, and the potential to build a very well-developed building inventory across a large urban area;
- The majority of URM buildings assessed as part of this study are classified as non-engineered URM buildings;

- A large inventory of URM buildings assessed as part of this study were built prior to the development of modern seismic design guidelines and need to be evaluated to ensure a satisfactory degree of safety in the event of a large magnitude earthquake;
- Irregular building configurations is an important parameter that must be identified to assess the performance of URM buildings during earthquakes; An important part of the URM buildings assessed as part of this study fall in the post-disaster and high-importance categories (URM buildings that fall in these categories need to be assessed for structural integrity);
- Information and data collected from Urban RAT as presented in this study can be utilized in earthquake loss estimation models such as HAZUS and arcCanRisk to provide high resolution loss estimations which can ultimately be used in disaster management and mitigation programs.

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