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Assessment of earthquake-induced damage in Quebec city, Canada

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ABSTRACT

A methodology is developed for first-order assessment of the seismic risk involving seismic hazard, local building inventory, and evaluation of respective vulnerability. Central to the vulnerability analysis is the concept of fragility functions used to determine the probability of exceedance of a specified damage state, where the nonlinear structural behaviour is defined by capacity curves. A new set of continuous hazard-compatible fragility functions is proposed for rapid risk assessment on urban and regional scales in interactive spreadsheet application. To demonstrate the method, it was applied in a dense urban environment of downtown Quebec City, Canada, for damage assessment of low-rise wood light frame and unreinforced brick masonry buildings. Earthquake scenario with M6.2 and distance 10 km from the centroid of the study area was developed from deaggregation of the seismic hazard defined by the current National Building Code of Canada-NBCC 2010. The ground shaking was represented with a simplified site-specific response spectrum, fully defined with spectral accelerations at 0.3 and 1.0 s. The results show that as much as 61% of the considered buildings would sustain certain degree of damage. The influence of epistemic uncertainties in the ground motion prediction and the site-class on damage estimation is evaluated.

1. Introduction

Physical damage and social and economic losses occurring regularly during strong earthquakes emphasise the need to reasonably predict the potential risks in seismic prone areas. The seismic risk assessment represents the process of measuring the negative impacts and their likelihood [6], and considers the combination of three input components: (i) hazard, generally defined by earthquake scenario with given magnitude and distance that may affect the study area over a given time period [3]; (ii) exposure or assets at risk, which in dense urban environment consist predominantly of residential, commercial and governmental buildings [15]; and (iii) vulnerability as the central component of the assessment, which introduces the susceptibility to earthquake impacts [8]. Key element in the vulnerability modelling is the structural capacity to sustain seismic loads and displacements. For urban risk assessment studies involving numerous buildings, the vulnerability analysis involves typically the concept of fragility functions representative for a group of buildings with similar structural properties, which combine the intensity of the seismic motion to the expected building damage states and loss levels. The standard outputs of vulnerability modelling are estimates of the potential physical damage and direct economic losses [16].

In the last years, various loss assessment tools were developed for regional seismic risk studies, e.g., HAZUS [7], SELENA [23], ELER [22]. A highly trained personnel, however, is required to prepare the input layers and run the programs. Hence the motivation for a relatively simple method for the evaluation of earthquake induced damage to buildings that could be eventually used by stakeholders. This paper documents the development of a method for rapid earthquake damage assessment which follows the standard procedure of performance-based earthquake engineering [13] and incorporates: (i) generic capacity curves which characterize the structural nonlinear behaviour (ii) simplified 5% damped site-specific response spectrum fully defined with spectral accelerations (Sa) at 0.3 and 1.0 s, referred to as seismic intensity measure (IM) and applied to estimate the structural demand for the scenario earthquake; and (iii) displacement based fragility functions to determine the probability of exceedance of specified damage state under various levels of structural response (vulnerability). The capacity spectrum method (CSM) was applied to obtain the displacement demand [4,7,11]. In addition, the method introduces a closed form formulation of fragility functions in terms of hazard-compatible IM. Predefined continuous fragility functions can be easily generated in interactive spreadsheet application opening the

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door to rapid risk assessment or earthquake induced damages on urban and regional scales and to sensitivity studies. In the second part, the method is applied in a dense urban environment of downtown Quebec City, Canada, over the inventoried 14,503 low-rise wood light frame and unreinforced brick masonry buildings. The considered earthquake scenario event was with M6.2, depth 10 km and epicentral distance 10 km from the centroid of the study area, developed from deaggregation of the seismic hazard defined by the current National Building Code of Canada (NBCC, 2010). The influence of the epistemic uncertainties in ground motion prediction and site-class is evaluated to provide upper and lower bounds of damage estimates.

2. Damage assessment method

The developed analytical method for seismic damage assessment follows the standard procedure involving three major modelling steps: (i) inventory of construction material, structural type, height and seismic design level of existing buildings; (ii) definition of earthquake scenario for the potential ground shaking intensity in terms of IM (e.g., spectral acceleration close to the natural vibration period of the buildings); and (iii) vulnerability modelling through seismic hazard-compatible fragility functions associated to IM (Fig. 1).

The vulnerability modelling represents a process of assessing potential physical damage and consecutive economic and social losses in terms of the intensity of the seismic motion. The vulnerability of a given building or a group of buildings with similar structural properties (generic building type) can be determined using: (i) observed damage accompanied with accurate records of the seismic motion during past earthquakes (empirical method), (ii) experts' opinion, (iii) analytical methods involving simplified mathematical models of structural response, (iv) comprehensive fully time-domain numerical modelling of structural response, and/or (v) combination of any of these methods [2,5,16,18]. The analytical method is the preferred option in case of insufficient damage data typical for regions with low to moderate seismicity. To accurately predict the potential damage, this method relies on the combination of representative capacity curves and fragility functions. Capacity curve describes the nonlinear structural behaviour under seismic loading obtained from pushover analysis, defined as a relationship between the lateral load and respective top displacement [1,8]. Capacity curves are combined with a response spectrum scaled to a given seismic intensity (IM) in order to estimate the earthquake induced displacement of a structure. The estimated structural displacement response is then compared to a set of standard displacement fragility functions that define the probability of exceedance of a given damage state, e.g., none, slight, moderate, extensive and complete [6,8]. To establish the fragility functions in terms of a full range of IMs, the procedure has to be repeated for various seismic intensity levels.

2.1. Seismic displacement demand prediction

The first part of the vulnerability modelling for a specific building type conducted in this study was inspired by the standard framework for performance-based engineering [13,17]. It starts with the definition of the intensity of the ground motion defined by two spectral accelerations at 0.3 and 1.0 s (Sa0.3 s and Sa1.0 s) as IMs to which buildings with short and long period of vibration are exposed, respectively. They are used to define a simplified 5%-damped elastic input response spectrum for given seismic scenario including local soil conditions (Fig. 2). The capacity spectrum method (CSM) is applied next for structural analysis [4,11]. The building is generally modelled as a simple equivalent single-degree-of freedom (ESDOF) system to approximate its structural dynamic response. The applied static force is gradually increased and the resulting force-deformation behaviour of the ESDOF is defined as capacity curve. The capacity curve can also be expressed in the same domain as the input spectrum as spectral acceleration (lateral seismic force) vs. spectral displacement (structural deformation) relationship, and typically consists of: linear portion up to the yield point representing the outset of eventual structural damage; intermediate elliptical degrading-stiffness portion bounded by the ultimate point at which the maximum lateral strength of the building is attained (Fig. 2). The ESDOF model allows for simple and rapid generation of building capacity curves which can be validated with more detailed modelling [7,8] or with experimental tests [9,19]. In addition, the use of a simplified ESDOF

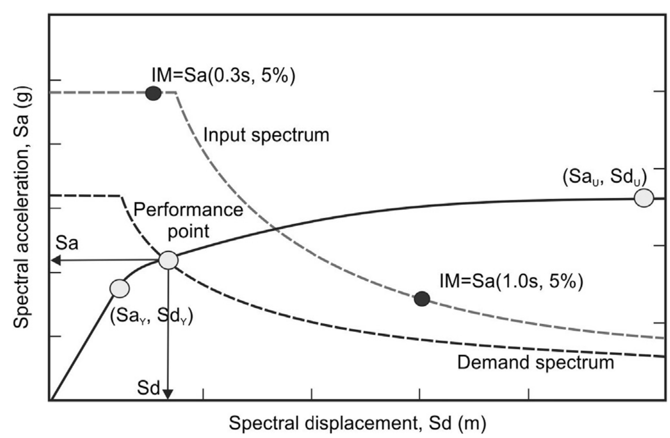

Fig. 2. Capacity spectrum method: determination of the performance point at the intersection of the demand spectrum and the capacity curve.

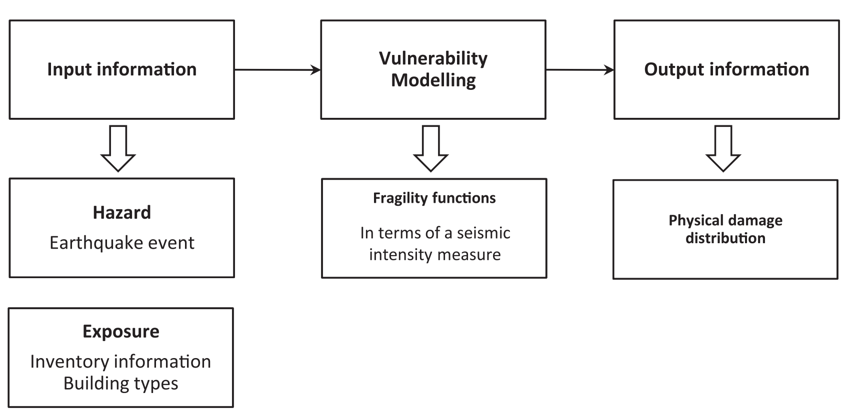

Fig. 1. Framework for seismic damage assessment.