Review of methods to assess the seismic vulnerability of buildings, with particular reference to hospitals and medical facilities

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June 2015

This report has been produced for Evidence on Demand with the assistance of the UK Department for International Development (DFID) contracted through the Climate, Environment, Infrastructure and Livelihoods Professional Evidence and Applied Knowledge Services (CEIL PEAKS) programme, jointly managed by DAI (which incorporates HTSPE Limited) and IMC Worldwide Limited.

DOI: http://dx.doi.org/10.12774/eod_hd.june2015.dayaladetal

First published July 2015

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Acronyms

3D	Three-dimensional
CSM	Capacity Spectrum Method
DGM	Royal Government of Bhutan Department of Geology and Mines
EMS-98	European Macroseismic Scale
FaMIVE	Failure Mechanisms Identification and Vulnerability Evaluation
FEM	Finite element model
FEMA	Federal Emergency Management Agency
FRACAS	FRAgility through CApacity Spectrum assessment
GEM	Global Earthquake Model
GHI	GeoHazards International
IMRF	Intermediate-moment-resistant-frames
Iv	Vulnerability index
JDWNRH	Jigme Dorji Wangchuk National Referral Hospital
MRF	Moment-resisting frame
NDA	Nonlinear dynamic analysis
NRRC	Nepal Risk Reduction Consortium
NSET	National Society for Earthquake Technology
OMRF	Ordinary-moment-resistant-frames
PFA	Peak floor acceleration
RC	Reinforced concrete
SdoF	Single-degree-of-freedom
SEARO	Regional office for Southeast Asia
SMRF	Special-moment-resistant-frames
UNDP	United Nations Development Programme document
USGS	United States Geological Survey
VI	Vulnerability Index
VIM	Vulnerability Index Method

SECTION 1

Introduction

The scope of this document is to provide the Department for International Development (DFID) Nepal with an overview of relevant methods and accepted standards for assessing the seismic vulnerability of buildings, and particularly hospitals and medical facilities that constitute the Nepalese portfolio. This includes reinforced concrete and masonry buildings of various structural and geometrical characteristics. This report aims to describe in a simple yet scientific way the existing seismic vulnerability methods, in order to be understood by non-seismic-specialist civil engineers.

The report reviews the state-of-the-art procedures that are currently implemented within the vulnerability assessment framework. The advantages and limitations of each method are discussed, taking into account their suitability for the Nepalese hospitals and medical facilities stock.

Based on the outcomes of the abovementioned section and considering the Nepalese building stock, separate recommendations are made for each structural category, namely low-rise/mid- to high-rise reinforced concrete (RC) and non-reinforced/reinforced masonry buildings.

A brief review of relevant international standards/building codes is presented, summarising their accepted methodologies. The reviewed guidelines and codes include the recently released Global Earthquake Model (GEM) and the US Federal Emergency Management Agency (FEMA) guidelines, as well as Eurocode 8 and Indian standards.
The final part of this document includes examples of implementation of these methodologies to real case hospitals worldwide.

It is worth noting that the assessment of the structural vulnerability is of utmost importance in order to get an idea about the building's exposure to suffering structural damage as a direct effect of earthquake shaking. However, for high-priority structures such as hospitals and schools in particular, the vulnerability of non-structural and functional features can lead to severe functional and indirect losses (e.g. costs related to disruption of services) in the direct aftermath of an event and in the weeks and months to follow, which may far exceed the losses caused by structural characteristics (i.e. costs to repair structural and non-structural components). This is explicitly addressed by the authors in the associated document "Review of the Non-Structural Considerations for Seismic Retrofitting Hospitals" (D'Ayala et al 2015).

SECTION 2

State-of-the-art Methods for Seismic Vulnerability Assessment of Buildings

2.1 Introduction

The seismic vulnerability assessment of buildings can be carried out using essentially three possible assessment methods: empirical, heuristic, and analytical.

The **empirical method** relies on knowing past performance of buildings in given seismic events and being able to extract statistical functions that relate the probability of damage suffered by a building type, at a given site, to the expected shaking intensity. To produce such functions reliably, large sets of data are needed to cover the whole range of performances of a given building typology to the whole range of possible seismic intensity considered, and multiple observations of building performance for the same level of intensity. Once the functions are available and an earthquake scenario is defined (in terms of shaking intensity), it is then sufficient to score the individual building or typology against a predefined accepted probability of damage based on specific constructional and functional details in order to assess its vulnerability.

Although in theory this is an observational method and hence of good reliability, in practice several uncertainties about the way in which the data are acquired and treated limit its applicability at the scale of individual buildings. Nonetheless, some of the seismic vulnerability studies for single hospitals currently available in literature are based on this approach (as discussed in section 5 of this document), as it allows for a relatively quick identification of vulnerabilities on the basis of checklists.

The **heuristic approach** relies on expert judgment and on the possibility that a given number of experts will express similar judgment when asked about the performance of a given building typology subjected to a given shaking scenario. This relies on personal observation and experience and it is very useful when no other form of assessment can be carried out, however the reliability of the outcome can be very low. For individual hospital facilities this can be carried out in terms of a “walk-through”, aided by a standardised checklist, such as the one included in FEMA 577 (see section 4), which helps to identify specific known vulnerabilities and points towards possible mitigation measures. This approach can be repeated over a number of buildings of similar and diverse typologies and hence create a database which can form the basis for the development of a Vulnerability Index (I_v).

The **analytical approach** relies on the possibility of determining the response of a particular building, representative of a typology, by using structural analysis techniques and numerical tools. This approach is particularly suitable when studying a single building or a single typology. The reliability of the results is affected by the availability of specific data that fully characterise material and structural behaviour of the assessed typology or specific building. It is also dependent on the numerical tools available and by the ability of the assessor to interpret the results.

Procedures pertaining to these analytical methods are particularly recommended when assessing single buildings or a few buildings of similar typologies. They are also useful when assessing the improved performance due to strengthening and retrofit. However the following should be noted in applying these methods to hospitals and health facilities:

- Analytical methods are suitable to identify structural damage states, through structural analysis. They are less useful in quantifying the likely damage to content and non-structural elements.
- Many of the different analytical approaches that exist are specific to particular types of structure, and have diverse data requirements and computational burdens.
- When comparing results from different analytical methods it should be borne in mind that output in terms of vulnerability are dependent on different assumptions on the representative intensity measures chosen and representative response measures chosen.

The following sub-sections investigate the most significant methods to estimate the seismic vulnerability of RC and masonry buildings, with the aim to identify their seismic performance and propose strengthening interventions to improve their structural behaviours. As discussed in section 4, a more comprehensive and detailed review of existing methods for assessing seismic vulnerability of buildings is presented in the GEM guidelines (D'Ayala et al, 2014).

Both empirical methods and analytical methods for the derivation of the vulnerability functions of RC and masonry buildings are discussed by referring to specific applications.

The choice of the most suitable procedure is highly dependent on the resources available for the data collection, the computational expertise available, and ultimately the scale and aim of the study. Empirical procedures can be used for fairly large scale studies to define damage scenarios, however if the purpose of the study is to identify within a district or urban centre specific buildings in need of strengthening, so as to increase their seismic resilience, then a suitable analytical procedure should be preferred.

2.2 Empirical Methods

The use of empirical methods allows for an estimation of the vulnerability by using simplified models which process qualitative data collected on direct observation and/or expert judgement. These types of approaches are mainly adopted to investigate the structural performance of building typologies distributed at urban scale.

Among the approaches classified as empirical methods, the Vulnerability Index Method (or VIM; Benedetti et al, 1988), is widely used to assess masonry buildings and applications of this method are numerous (Oliveira et al, 2005; Barbat et al, 2008; Vicente et al, 2014). This approach is based on estimating the vulnerability of masonry buildings by calculating a vulnerability index (I_v) as the summation of weighted parameters associated with the structural features of the building typology, which have been observed to affect their seismic response. Data on the constructional properties of the building is required for the definition of I_v, while damage data from past earthquakes is used for the calibration of the vulnerability functions. By relating I_v to the observed global damage levels for a building typology with reference to macroseimic intensity levels, the I_v can be applied to regions characterised by the same building typologies and same level of macroseismic intensity or peak ground acceleration (Lagomarsino and Giovinazzi, 2006).

An approach similar to the VIM has also been recommended in the *Guidelines for Seismic Vulnerability Assessment of Hospitals in Nepal* (Guragain et al, 2004) for both RC and masonry buildings. This approach consists of proposing the use of vulnerability factors to estimate the performance of buildings by classifying them into building typologies associated to fragility curves, which are then used to determine the probability of a building type exceeding a given damage state for an earthquake with a specific intensity. Fragility curves can be developed by direct calibration with observed damage data, by expert judgement or analytical assessment. Since the available seismic data collected on Nepalese constructions is not sufficient to derive specific fragility curves with any of these methods, the Guidelines propose to use predefined fragility curves, derived from the scale described in the United Nations Development Programme document (UNDP, 1994) and European Macroseismic Scale (EMS-98; Grünthal, 1998).

2.3 Analytical Methods for Reinforced Concrete Buildings

2.3.1 The Capacity Spectrum Method and the Use of Nonlinear Static Analysis Method

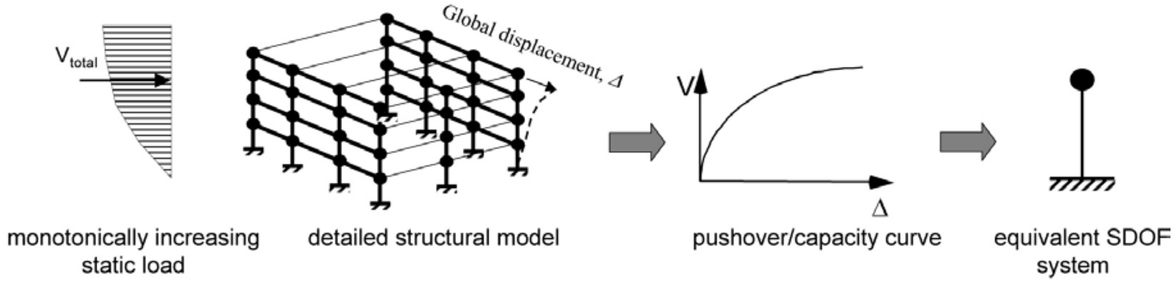
Earthquakes can cause buildings to vibrate and each building has a number of ways, or modes, in which it can vibrate naturally. In each mode, the building vibrates back and forth with a particular distorted shape called its mode shape, while the number of times it vibrates to and fro every second is the frequency of vibration for that mode. In particular, pushing a building sideways at its top and letting it rebound will result in a natural swaying motion; the number of times it sways back and forth every second is the fundamental frequency of vibration of the building, while the shape (i.e. the profile of the swaying motion) it takes up is called the fundamental mode shape. The fundamental frequency of vibration of a building depends on its mass and its stiffness (or how flexible it is).

The first step in estimating a building’s response to different levels of ground shaking consists of building an accurate computational 2D or 3D model of the structure. Such a model is subjected to a lateral (e.g. sideways) load distribution that represents the force generated by the earthquake ground motion (Figure 1). This lateral load pattern is chosen to have the same shape as the fundamental mode of the structure’s vibration. The total load is then increased in successive steps to create a relationship between the intensity of the applied load (measured in terms of the total force applied at base of the building, known as base shear) and the deformation of the building (measured in terms of roof drift, i.e. the roof displacement normalised to the building height). The analysis terminates when the building (virtually) collapses. This procedure is often called pushover analysis and the force/deformation curve obtained is called a pushover curve.

To predict the seismic performance of a building to a specific ground motion, a possible analysis method is the Capacity Spectrum Method (CSM; Freeman et al, 1975), in which the quantities in the building pushover curve are transformed into response measurements of an equivalent single-degree-of-freedom (SDoF) system (Figure 1). The SDoF is a virtual oscillator, which has the same natural frequency and elastic properties (e.g. stiffness) as that of the modeled 2D building. More precisely, the applied load is translated into spectral acceleration, and the lateral deformation is translated into spectral displacement.[1] The pushover curve represented by these two parameters is called the capacity curve. A building’s capacity curve reflects various seismic characteristics of the building, such as its stiffness, its material brittleness or ductility, and its strength. This curve correlates the lateral deformation of the building (in terms of spectral displacement) to a specific level of dynamic demand (expressed in terms of spectral acceleration).

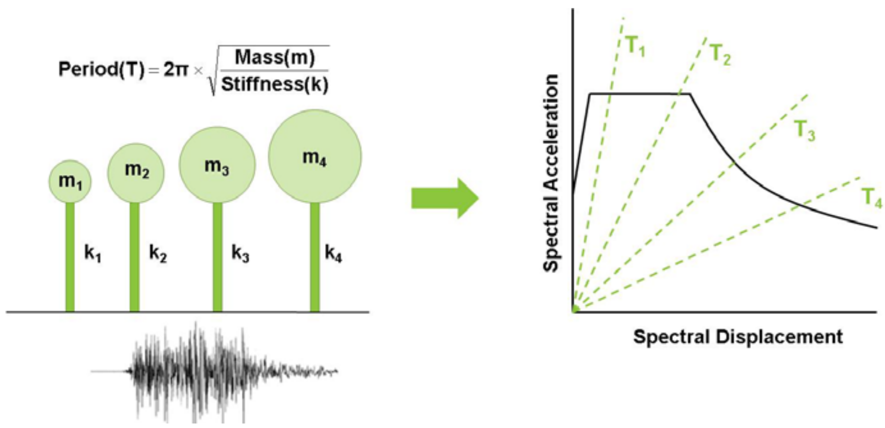
[1] Spectral acceleration and spectral displacement are two response measures of oscillators with given vibration period and damping.

Figure 1 Schematic Depiction of Static Pushover Analysis used in the Capacity Spectrum Method (excerpted from FEMA 440).



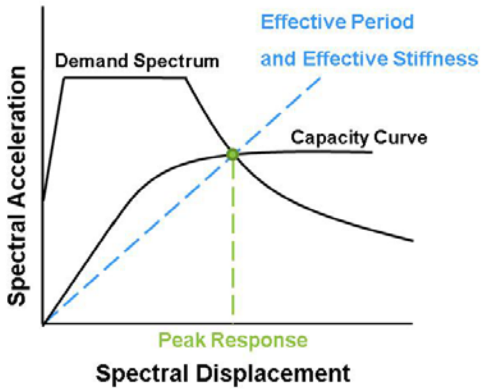
Any anticipated ground motion that may affect a building can be modelled in a more comprehensive form as a time-history of ground acceleration, i.e. by using recordings of past earthquakes (ground acceleration produced by an earthquake vs time). However, several simplified representations are also available, one of which is the elastic response spectrum (ERS). The elastic response spectrum representation is convenient to use in the framework of the Capacity Spectrum Method. In the ERS, the demand on a building imposed by ground motion is represented by the maximum acceleration and displacement of a series of SDoF oscillators characterised by different fundamental periods. The response of this collection of systems can be plotted as a curve of acceleration/displacement pairs known as the elastic response spectrum or the demand curve (Figure 2). The radial lines on the graph represent the periods of the oscillators. Note that a conventional (i.e. represented by a standardised analytical function) demand spectrum is usually used when implementing the CSM approach, generally specified by the relevant building code. Different reduction factors or indices are used to determine an equivalent inelastic spectrum from the elastic one.

Figure 2 Maximum Acceleration and Displacement of a Series of Oscillators.



The demand curve (i.e. spectrum) and the capacity curve are represented by the same parameters and can be plotted on the same graph. The intersection of the demand curve and the building capacity curve plotted on the spectral acceleration vs. spectral displacement plane corresponds to the performance point of the structure. The maximum roof displacement of the building relative to the ground in response to that ground motion can be then calculated from the performance point (Figure 3).

Figure 3 The Peak Response of a Structure Determined by its Capacity Curve.



A capacity curve representing a single building of a certain construction class will have a unique intersection (i.e. performance point) with different demand curves (i.e. response spectra) for different ground motion intensities. Similarly, different capacity curves representing different buildings of the same class will have unique intersections with the same response spectrum from a given ground motion intensity. These attributes provide the ability to distinguish between the responses of various building classes to different ground motion intensities.

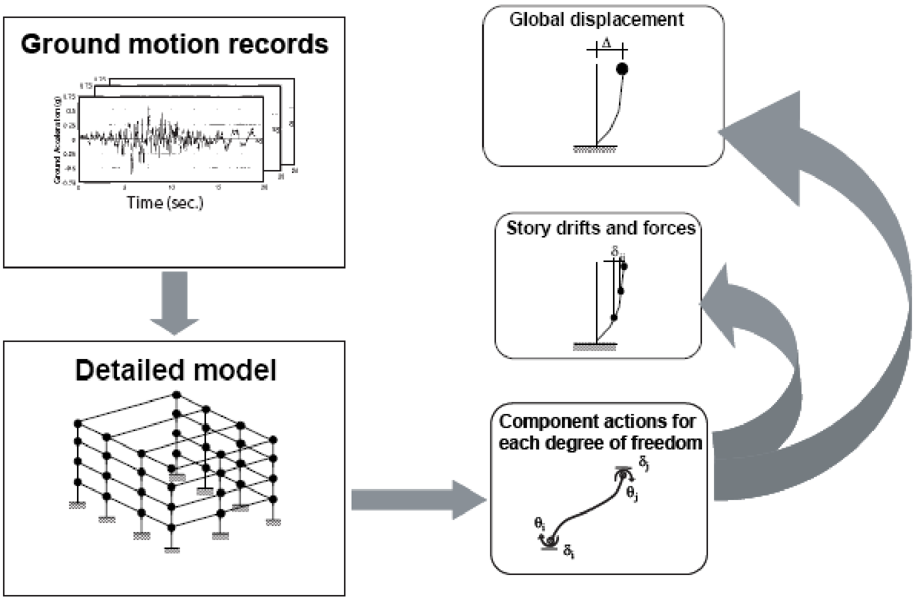
During ground shaking, the amount of deformation incurred by the different stories of a building can be derived, given certain assumptions, from the deformation at the roof level. The story deformations can be related to the damage suffered by all types of components, both structural (e.g. columns and beams) and non-structural (e.g. cladding, partitions, and ceiling tiles) at each story and therefore to the repair strategies that are expected due to the predicted damage.

2.3.2 Nonlinear Dynamic Analysis

The CSM, which uses pushover analysis for assessing responses of buildings to ground shaking, is a reliable analysis technique for addressing the inelastic response of buildings that respond predominantly in the fundamental mode of vibration. However, because of its inherent assumptions, CSM analysis may lose accuracy in predicting the seismic response of long-period buildings (e.g. tall buildings), whose higher modes of vibration need to be considered, and of other buildings with complex post-elastic behaviour or where floor accelerations are of interests (e.g. in hospitals when assessing damage to non-structural components).

Nonlinear dynamic analysis (NDA) is today considered the most accurate methodology for predicting building response to earthquake ground motion. As with CSM, the first step in NDA analysis is to create a computer model of the building that captures the nonlinear post-elastic behaviour of a building's structural elements that undergo damage (Figure 4). A large number of historical (where available) or simulated ground motion records of varying intensities are loaded into the software to perform a time-history (dynamic) analysis. Essentially, the virtual building is shaken (rather than pushed) using the recorded ground motions in the same way that it would be shaken by an actual earthquake. NDA allows higher modes of vibration to be captured as well as different failure modes.

Figure 4 Flow Chart Depicting the Use of NDA to Determine Building Response (Excerpted from FEMA 440).



Moreover, the use of time-history analysis allows an explicit consideration of the effects of the duration of the earthquake shaking on the cumulative damage of building components. In each analysis, the forces and deformations occurring in all structural members of the model are calculated and used to evaluate the global response measures such as maximum peak inter-story drifts and forces, roof displacement, and peak story accelerations. More specifically, the peak inter-story drift is the highest lateral displacement between two consecutive floors, normalised by the inter-story height. The maximum peak inter-story drift is the maximum drift among all stories that is observed over the entire duration of the earthquake. The peak floor acceleration (PFA) is the highest acceleration of a particular floor in response to ground shaking. Similarly, the *maximum* peak floor acceleration is the highest PFA found along the entire height of the building. This quantity is well correlated with damage to acceleration-sensitive nonstructural components (e.g. suspended ceilings), and to contents. As in the CSM approach, these parameters can be related to the damage suffered by all types of components and, therefore, to the repair strategies that are expected due to the predicted damage.

The use of ground motions from multiple earthquakes allows the model to obtain not only an estimate of the mean response given a certain level of ground shaking, but also allows it to account for the variability in the buildings' nonlinear response generated by different records of the same intensity (e.g. Jalayer and Cornell, 2009; Vamvatsikos and Cornell, 2004).

NDA directly provides, without any limiting assumptions, the force imposed on a building by ground motion. Deformation levels (or storey acceleration levels, when necessary) are then used to determine component damage and the associated repair strategy. The monetary loss for the entire building is estimated by combining component repair costs.

2.3.3 FRACAS (FRAgility through CApacity Spectrum assessment)

The CSM uses conventional and simplified demand spectra represented by a given analytical function described in the building codes. The variability of the demand spectra (and in general of actual ground motion inputs) due to actual earthquakes is not taken into account when applying the CSM. To overcome this limitation, a simplified capacity spectrum method that accounts for the actual ground motion variability has been developed. Similar to NDA, FRACAS (FRAgility through CApacity Spectrum assessment) allows the use of suites of scaled and/or unscaled ground motion records and delivers the immediate seismic response of the considered structure. Moreover, FRACAS does not rely on reduction factors or indices to determine the inelastic spectrum from the elastic one. Instead, for each target ductility and period, it carries out a simplified dynamic analysis on the idealised nonlinear SDoF model corresponding to the capacity curve. This process proves to be more time-consuming than the commonly-used static approaches (e.g. the CSM and its variations) but it is more robust and remains faster than performing full NDA on finite element models. This feature also has the advantage of permitting the use of various ground motion records that generate unsmoothed spectra as opposed to standardised design spectra. Therefore, the record-to-record variability can be directly introduced and the resulting cloud of performance points leads to seismic responses that account for the natural variability in the seismic demand.

Previous studies (e.g. Rossetto et al, 2014) have shown that FRACAS procedure outperforms CSM and its variants, particularly for the cases of low- and mid-rise RC regular frames of various vulnerability classes. This method is recommended in the recently published GEM Guidelines for Analytical Vulnerability Estimation (D'Ayala et al 2014); further details on the FRACAS methodology are also provided in Gehl et al (2014). Examples of FRACAS implementation on RC buildings, representative of European and Mediterranean/Italian stock can be found in Rossetto et al (2014) and Minas et al (2014).

2.4 Analytical Methods for Masonry Buildings

Analytical methods, which use numerical simulations to analyse the structural behaviour of buildings, are more sophisticated approaches than empirical methods. The data required for these approaches can be collected by visual inspections or extracted from construction drawings and/or laboratory tests. These approaches present the advantage of framing the problem of seismic vulnerability of masonry structures in structural engineering terms, defining their vulnerability as a direct function of construction characteristics, structural response to seismic actions and damage effects. The performance target, and hence damage thresholds, shall be selected according to the use of the building (private, public or strategic functions) and its occupancy levels.

Relatively few numerical approaches and corresponding software tailored to the seismic analysis of unreinforced masonry structures are available on the market or as open access. The seismic behavior of masonry walls can be classified as in-plane (i.e., within the plane of the wall) shear response and out-of-plane (normal to the plane of the wall) flexural response. The majority of numerical approaches performs essentially in-plane analysis of load bearing walls, while only a minority of them considers the response of walls both in plane and out of plane. The in plane mechanism is assumed as the main mode of response in buildings characterised by strong connections between walls and between walls and floors and hence responding to lateral action by way of a box behaviour. For the out of plane, this failure occurs in buildings with weak connections and/or poor fabric materials which trigger overturning of one or more adjacent load bearing walls when subjected to lateral action (see Figure 5).

Among the first group of approaches, it is worth mentioning the TREMURI software (Lagomarsino et al, 2013), which has been used in several applications reported in literature. It assumes that masonry walls behave essentially as equivalent frames and that the floor structures and connections are such that the out-of-plane failure is prevented. Capacity curves are obtained by incremental push-over analysis. A set of performance targets are proposed within the framework of the European FP7 Project PERPETUATE (www.perpetuate.eu), a collaborative project which has proposed guidelines for the seismic performance based assessment of masonry assets (D'Ayala, Lagomarsino, 2015).

The second group includes nonlinear analysis methods based on mechanical approaches, as recommended for instance by the Italian Building Code (CS.LL.PP., 2008). When thoroughly developed, they enable an estimate of the capacity of a structure for several different failure mechanisms and hence provide a more thorough assessment of its vulnerability. Mechanical methods are based on the application of kinematics models, which identify lateral collapse load multipliers of a given configuration of macro-elements and loads by imposing either energy balance or equilibrium equations. These methods present the advantage of requiring few input parameters to estimate the vulnerability and to identify the occurrence of possible mechanisms for a given building. Among these D'Ayala and Speranza (2003) developed the mechanical approach FaMIVE (Failure Mechanisms Identification and Vulnerability Evaluation) presented in more detail in the following sub-section.

2.4.1 FaMIVE

The FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) approach estimates the building performance both in terms of base shear and deformation capacity and identifies the most suitable strengthening and repair intervention by considering the possible collapse mechanisms which can occur given geometry, materials, loading conditions and constraints (see Figure 5). Both in-plane and out-of-plane behaviours are considered. The method has been applied to estimate the performance of buildings in several locations worldwide such as Nepal (D'Ayala, 2004), India (D'Ayala and Kansal, 2004), Italy, following the 2009 L'Aquila earthquake (D'Ayala and Paganoni, 2011) and recently in the Casbah of Algiers (Novelli and D'Ayala, 2014).

The FaMIVE method uses a nonlinear structural analysis method based on pushover analysis to estimate the performance of buildings by way of a variant of the N2 method (Fajfar & Gašperšič, 1996, included in EC8 part 3) as shown graphically in Figure 6. FaMIVE yields, as output, a collapse load factor λ_i, for each possible collapse mechanism. Thirteen different collapse mechanisms are considered as shown in Figure 5, determined by the different constraints conditions between a façade and the rest of the structure.

As shown in Figure 6, FaMIVE first calculates the collapse load factor for each façade in a building, and then identifies the one which is most likely to occur, taking into account geometric and structural characteristics and constraints. The mechanism can be triggered for either part of or the whole façade, involve the failure of one or more walls or the collapse of floors structures. Once the critical mechanism is identified, an equivalent non-linear single-degree-of-freedom (SDoF) oscillator is used to simulate the performance of the buildings for deriving the correspondent capacity curves. The performance point can then be computed following the procedure highlighted in section 2.2.1 as shown in Figure 6. FaMIVE has been applied to produce vulnerability functions for various unreinforced masonry typologies, from adobe to concrete blocks, for a number of reference typologies studied at sites in Italy, Spain, Slovenia, Turkey, Nepal, India, Iran and Iraq. The versatility of the system allows the consideration of different strengthening strategies and computes the new capacity curve and performance point once these are implemented.

Figure 5 Collapse mechanisms identified by FaMIVE for computing the limit lateral capacity of masonry façades

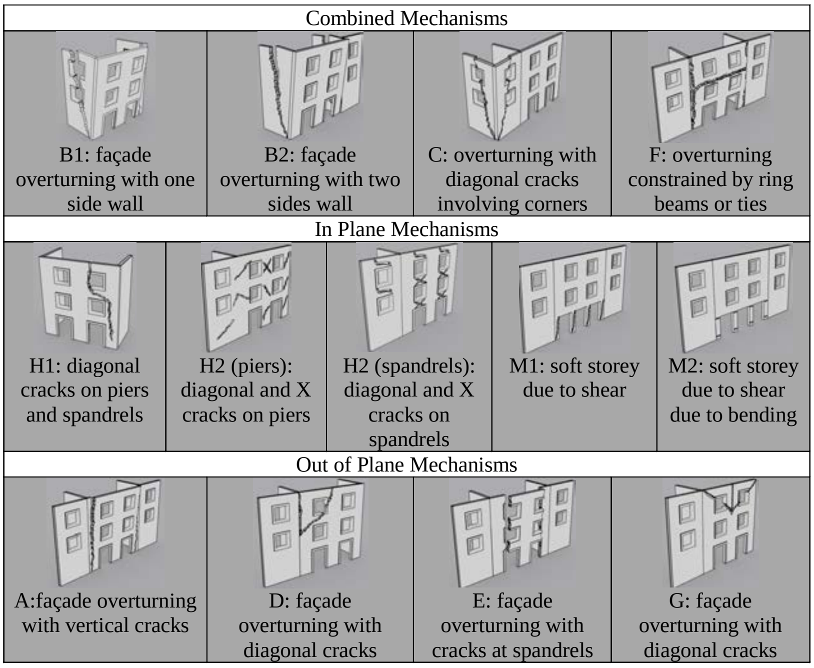
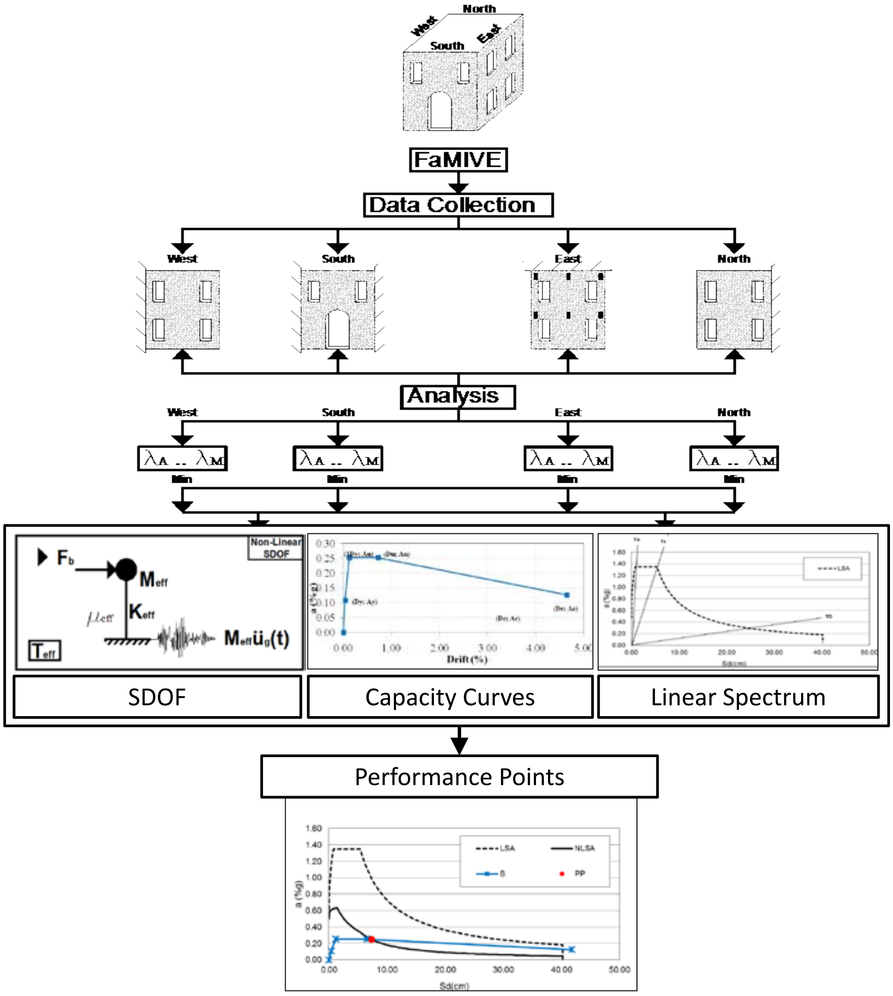


Figure 6 Flowchart setting out the rationale of the FaMIVE Procedure.



SECTION 3

Recommendations for the Nepalese Building Stock

In Nepal earthquakes have caused huge numbers of casualties and damage to structures. The Great Nepal-Bihar earthquake in 1934 reportedly killed 8519 persons and damaged 80,000 buildings in Nepalese territory. Though being a seismic country, earthquake-resistant standards have not been effectively applied and guidelines have not been published and practiced for hospital facilities in Nepal. The possibility of hospital buildings not being functional during a large seismic event is very high. The National Society for Earthquake Technology (NSET) conducted two studies, “Structural Assessment of Hospitals and Health Institutions of Kathmandu Valley” and “Non-structural Vulnerability Assessment of Hospitals in Nepal” in 2001 and 2003 respectively. A systematic approach towards seismic assessment of hospitals in Nepal was developed while carrying out those assessments in major hospitals of Nepal. In particular, a combination of both empirical and heuristic methods was used. The need to develop such a methodology is due to the fact that analytical methodologies used in other developed countries are not applicable in Nepal given the lack of detailed information on materials, geometry and structural design.

3.1 Overview of Existing Nepalese Portfolio of Hospitals and Medical Facilities

As a first step in the seismic vulnerability assessment of buildings an insight into the existing Nepalese building portfolio is required. According to previous studies conducted in the area of Nepal (Guragain et al, 2004), the main building typologies for hospitals and medical facilities can be divided into two main categories, namely reinforced concrete (RC) and masonry buildings, and can be further expanded to the following types:

- Type 1: Adobe, stone, adobe & stone, stone & brick-in-mud.
- Type 2: Un-reinforced masonry made of brick in lime, brick in cement, and well-built brick in mud, stone in cement
- Type 3: Reinforced concrete ordinary-moment-resistant-frames (OMRF)
- Type 4: Reinforced concrete intermediate-moment-resistant-frames (IMRF)
- Type 5: Reinforced concrete special-moment-resistant-frames (SMRF)
- Type 6: Other (must be specified and described)

Within each typology, it is important to consider the materials used, the building height, the year of construction, the lateral force resisting system and the floor diaphragm. It is noteworthy to mention that not all the existing structures satisfy the criteria defining each typology, therefore judgement may be required to carry out the classification process.

For the sake of simplicity, only generic structures, namely RC (low-rise, mid- to high-rise) and masonry (reinforced, unreinforced) structures will be discussed. For a synthetic overview see Table 1.

Table 1 Overview of Methodologies

Methodology	References	Building types	Context	Data collection method	Analysis method	Input data type	Approach	Level of resource for processing			Expertise		Results	Limitations of the results		Applications
								Time	Cost	Computing power	Local consultants	International experts		Vulnerability level	Retrofitting	
CSM	Freeman et al. (1975)	RC (and steel) buildings	single building, territorial scale	on site observation or systematic survey	analytical	geometric, mechanical properties,	structural analysis	low	low	low	x		vulnerability functions, capacity curve	detailed vulnerability of building sections	yes, detailed	Worldwide
FRACAS	Gehl et al. (2014); Rossettot al. (2014).	RC (and steel) buildings	single building, territorial scale	on site observation or systematic survey	analytical	geometric, mechanical properties,	structural analysis	medium	medium	medium	x	x	vulnerability functions, capacity curve, seismic demand distribution	detailed vulnerability of building sections	yes, detailed	Europe
NDA	Vamvatsikos and Cornell (2002); Jalayer et al. (2009).	RC (and steel) buildings	single building	detailed inspection, full documentation and plans, intrusive testing	analytical	geometric, mechanical properties,	structural analysis	high	high	high	x	x	vulnerability functions, seismic demand distribution	detailed vulnerability of building sections	yes, detailed	Worldwide
FaMIVE	D'Ayala et al. 2003, 2004, 2005; D'Ayala and Kansal 2004; D'Ayala and Paganoni 2011;	unreinforced masonry buildings, strengthened building	single building, territorial scale	on site observation or systematic survey	analytical	geometric, mechanical properties,	mechanical approach	low	low	low	x		vulnerability functions, collapse mechanisms, capacity curve	ranking of buildings, details output of vulnerability of building sections	yes, detailed	Nepal; Algieria; India; Iran; Italy; Slovenia; Spain; Switzerland; Turkey
TREMURI	Lagomarsino et al. 2013	unreinforced masonry buildings, reinforced masonry	single building	detailed inspection, full documentation and plans, intrusive testing	analytical	geometric, mechanical properties	structural analysis	high	medium/hi gh	medium	x	x	capacity curve, vulnerability functions	detailed vulnerability of building sections	yes	Europe, Algieria
VIM	Benedetti et al. 1988; Guragain et al. 2004; Lagomarsino et al. 2006; Oliveira et al. 2005, Barbat et	masonry and RC buildings	territorial scale	on site observation	empirical	geometric properties	parametric method	low	low	low	x		vulnerability functions	ranking of buildings	qualitative	Portugal; Italy, Spain, Latin America

3.2 Recommendations for Reinforced Concrete Buildings

3.2.1 Low-rise RC Buildings

Low-rise moment-resisting RC buildings represent a simple and popular structural methodology followed for constructing hospitals and medical facilities in Nepal. These structures are of regular plan and utilise a moment-resisting frame (MRF) approach as a lateral force resisting system (Guragain et al, 2004). For this structural typology, associated with low building heights and no irregularities in plan-view (predominant first-mode response), the CSM and FRACAS methods are recommended. The aforementioned methods are able to provide good estimates of response within the vulnerability assessment framework since they are able to accurately capture the first-mode effects of the building typology of interest. In general it has been shown that FRACAS provides better response estimates over other CSM approaches (Rossetto et al, 2014) but is more time consuming. It is noteworthy to mention that both CSM and FRACAS methods utilise as inputs the pushover/capacity curve associated with the building of interest. As discussed in Section 2.2.1, the pushover curves are generated by analysing building models that require numerous structural details. If these details are not available or difficult to obtain, one may use the generic capacity curves for the specific building typology from the available literature or, for example, from the HAZUS program (FEMA, 2010; https://www.fema.gov/hazus). HAZUS is a geographic information system-based natural hazard loss estimation software package developed and freely distributed by the Federal Emergency Management Agency (FEMA).

For the cases of low-rise RC buildings with irregular plan, the NDA method is recommended since it is able to capture the more complex dynamic behaviour due to the irregular distribution of mass, stiffness and strength within the building plan (and eventually along the height).

3.2.2 Mid-rise/High-rise Buildings

Similarly to the above building typology, mid- and high-rise RC buildings also follow regular plan arrangement and use moment-resisting framed lateral resisting system. However, the greater building height has an effect in the dynamic behaviour of the structures. The higher modes have a more significant contribution in the building's response, and therefore a structural analysis method that accounts for them should be considered. Furthermore, taller buildings that are characterised by highly nonlinear behaviour should be analysed using NDA. As a result, NDA is recommended as the appropriate analysis method for the current building class. It should be noted that FRACAS can be also implemented for the cases of regular mid-rise RC buildings. FRACAS is a more rapid approach but yields some accuracy issues comparing to NDA.

3.3 Recommendations for Masonry Buildings

3.3.1 Non-Reinforced Masonry Buildings

The analytical methods are recommended to estimate the vulnerability assessment of hospitals and medical facilities in Nepal. The two methods reviewed in section 2.3, TREMURI and FaMIVE, differ for the level of data required, level of training required and applicability to specific cases. TREMURI needs specific information on the strength characteristic of masonry, which might be acquired with in situ tests, and being a structural element based method, needs advanced computational analysis skills and might require some hours to conclude an analysis. Results are particularly meaningful if the structure shows good connections among walls and floors. The FaMIVE method has simpler data requirements which can be collected on site during a walk-through using the pre-defined form, requires modest level of pre-training and computational skills, and provides results for many alternative configurations in a few minutes. This feature also allows consideration of different constraint hypothesis when the information is not accurate or considers the beneficial effect of strengthening devices.

SECTION 4

Overview of International Guidelines and Building Codes for Seismic Vulnerability Assessment

International building codes do not usually provide specific recommendations or prescriptions on seismic vulnerability assessment and mitigation, and do not typically focus on hospitals or medical facilities. In more general terms, codes often do not deal with seismic vulnerability assessment of existing buildings and tend to focus on seismic design for new structures. The guidelines and building codes reviewed here have been developed for specific research projects (i.e. the Global Earthquake Model) or for a specific geographical area. As such they present the best practice available for the assessment of vulnerability of existing buildings to seismic events and form the focus of this section.

4.1 The Global Earthquake Model (GEM) Guidelines

The GEM Analytical Vulnerability Guidelines (D'Ayala et al, 2014) are developed for low/mid-rise buildings with a load bearing structure of reinforced concrete framed or unreinforced masonry construction. The Guidelines are one of the products of the Global Earthquake Model Initiative, whose objective is to bring together knowledge, data and resources for earthquake risk assessment worldwide in a collaborative environment. This is a critical step towards improved understanding and actions that both manage and reduce risk. The Guidelines, released in draft format in March 2014, and included in the OPENQUAKE platform (http://www.globalquakemodel.org/openquake/about/) are designed to enable users to create simplified nonlinear structural models to determine the vulnerability functions pertaining to structural response. Besides the approaches already reviewed in Section 2 of this document, sufficient flexibility is incorporated in the GEM guidelines to allow full exploitation of cutting-edge methods by knowledgeable users. This is obtained by defining a distinct hierarchy of complexity (and accuracy) levels for (a) sampling, (b) modeling and (c) analysing. Sampling is addressed at various levels of refinement in statistical terms, depending on size and diversification of the building population and resources available for the study. Structural representation of index buildings may be achieved via typical 2D/3D element-by-element models, simpler 2D story-by-storey (stick) models or an equivalent SDoF system with a user-defined capacity curve. Finally, structural analysis can be based on variants of nonlinear static procedures and NDA methods. The methods recommended in Section 3 fall squarely within the GEM guidelines. The definition of the index buildings and the corresponding number of cases to be analysed for each typology, can be decided after a thorough review of the entire hospital and medical facility building stock belonging to each typology.

It should be noted that for buildings with important contents and fixtures, such as main district hospitals, it might be necessary to carry out a vulnerability component approach, recommended in section F-2 of the GEM guidelines. This is developed along the ATC-58 framework (FEMA P-58-1), and requires fragility functions to be determined for structural and non-structural components and contents, such as equipment in surgical theatres or testing laboratory. Databases of such functions are available within the ATC-58 framework for US-based reference components. While these guidelines are not specific for hospital

buildings, it is noted that they represent the reference for the current state of the art in vulnerability assessment. GEM and NSET have in place an established collaboration for risk assessment and management in Nepal, including the development of scorecards to assess community resilience to earthquakes.
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4.2 FEMA Guidelines

The FEMA Guidelines reference for Hospital design and retrofit is the FEMA 577 (2007) document, 'Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds'. The information presented in this publication provides an exhaustive review of mitigation measures and design solutions that can improve the safety of hospitals in natural hazard events. It is presented in an intuitive way and is aimed at hospital managers as well as seismic engineering professionals. Chapter 2 examines specifically potential earthquake damage to hospitals, and how these facilities can most efficiently improve their performance. Typical seismic damages and the possible resulting effects on building functions or risk to occupants are of particular relevance and described and related to the standard damage states currently used in performance-based earthquake engineering design. The chapter provides a review of the best practices in seismic design and seismic retrofit of hospital facilities. Structural and non-structural performance targets are defined, in relation to the necessity of the hospital to be operational, after an otherwise highly damaging event. It provides an inventory of structural and non-structural components and, with reference to case studies, reviews common damage types and failures for each component, and classifies these in terms of damage level and hence performance categories. Histograms of expected damage distribution for level of expected spectral acceleration and level of seismic design are provided and can be used to benchmark hospital buildings in Nepal to decide whether and which type of strengthening might be necessary. Section 2.4.6 explicitly relates to mitigation measures for existing buildings and section 2.5 provides a checklist for assessment of seismic vulnerability of hospitals. Such a checklist can be used as a walk through reference to determine the specific need of a given building in terms of mitigation measures.

4.3 ASCE Guidelines

The ‘Seismic Evaluation of Existing Building’ standard by the American Society of Civil Engineers, or ASCE 31-03 (ASCE, 2003), now incorporated in the ‘Seismic Evaluation and Retrofit of Existing Buildings’ guidelines, or ASCE/SEI 41-13 (ASCE, 2013), provides a three-tiered process for seismic evaluation of existing buildings in any level of seismicity. Buildings are evaluated to either the Life Safety or Immediate Occupancy Performance Level. The design of mitigation measures is not addressed in this standard. All aspects of building performance are considered and defined in terms of structural, non-structural, and foundation/geological hazard issues. In a first stage, check lists related to structural, non-structural and foundation conditions can be selected and completed in accordance with the guidelines. In particular, the screening phase consists of three sets of checklists that allow rapid evaluation and quick identification of potential deficiencies of the structural, non-structural, and foundation/geologic hazard elements of the building and site conditions. If deficiencies are identified for a building using the checklists, the design professional may proceed to a second stage and conduct a more detailed evaluation of the building or conclude the evaluation and state that potential deficiencies were identified.

4.4 Eurocode 8/Italian Annex

The Eurocode 8 has no specific section for design or assessment of hospitals. However, relevant clauses are included in its Part 1 and Part 3. In Part 1, particular attention is paid to the behaviour, analysis and verification of non-structural elements. To determine the seismic action on non-structural element attention should be paid to their position within the building.

The Italian Ministry of Health in collaboration with the National Civil Protection and the Ministry for Infrastructure produced in 2003 a document of Recommendations for the improvement of the seismic safety of hospitals in Italy. This document is also known as ATC-51 and was developed in collaboration with the US Applied Technology Council. In reference to existing structures the document sets as objectives:

- Collapse prevention for a rare event (probability 2% in 50 years).
- Fully operational for a frequent event (probability 10% in 50 years).

The approach proposed focuses on the identification of deficiencies (structural and non-structural) and for the equipment. It also emphasises the necessity to identify priority, costs and timelines for the mitigation of the deficiencies while maintaining the hospital in service. The assessment is performance-based and along the same lines as identified in FEMA 577 discussed above. The document recommends different levels of screening and assessment and two phases of preliminary and detailed design of the necessary strengthening. The document covers both structures in RC and masonry, making reference to the Italian corresponding standard for these structural types. Building services and equipment are fundamental to the functionality of a hospital in the aftermath of an earthquake. Specific provisions are given to ensure their serviceability, by classifying the components in categories, more vulnerable to displacement or to acceleration, and ensuring that fixings and anchoring systems are properly designed.

The documents also highlight the necessity of ensuring that the access to the hospital and its facility is maintained in the aftermath of destructive events.

4.5 Indian Standards

No specific Indian Standard exists for seismic assessment and mitigation of hospital facilities, to our knowledge. However, the IS 13827:1993 - 'Improving Earthquake Resistance of Earthen Buildings' – Guidelines and the IS 13828:1993 - 'Improving Earthquake Resistance of Low Strength Masonry Buildings – Guidelines' and their updates might be specifically relevant as these construction types are very similar across the border. Moreover the IS 4326: 1993 'Earthquake Resistant Design And Construction Of Buildings – Code Of Practice' includes provisions for reinforced masonry in Chapter 8, Section 8.4, which covers seismic strengthening arrangements. The specification included in this section can be used as a checklist to verify whether existing masonry buildings comply with current code requirement or whether strengthening measures should be introduced to upgrade the structure and increase its resilience. It should be noted that measures are specific to masonry made of rectangular units, such as brickwork, squared stone or hollow concrete blocks.

SECTION 5

Examples of Implementation

5.1 Jigme Dorji Wangchuck National Referral Hospital, Thimphu, Bhutan

Jigme Dorji Wangchuk National Referral Hospital (JDWNRH) is the most important hospital in Bhutan, as well as the only major hospital providing medical care in Thimphu, the capital city. JDWNRH is located in a high earthquake hazard area.

In May-July 2012, GeoHazards International (GHI) performed an initial seismic vulnerability assessment of JDWNRH. The assessment was intended to provide the hospital, the Ministry of Health and the World Health Organization's Regional Office for Southeast Asia (SEARO) with an overview of the hospital's seismic vulnerabilities, and to recommend actions to improve the hospital's ability to deliver medical care following a major earthquake affecting Thimphu. The assessment was based on empirical and heuristic methods and consists of:

1) In-person evaluations of JDWNRH buildings and infrastructure over several days at the hospital site.
2) Review of available structural, architectural and utility service design drawings.
3) Interviews or discussions with the hospital's administration and engineering, maintenance and medical staff.
4) Technical support information from the United States Geological Survey (USGS), Royal Government of Bhutan Department of Geology and Mines (DGM) and relevant literature.

The evaluation team found that the hospital had a number of seismic vulnerabilities in its buildings, on-site utility infrastructure, medical equipment and emergency preparedness. However, this study simply classified, in a qualitative way, the damage potential of buildings and systems, in order to address consequences for three earthquake scenarios. Using engineering judgment and observations of damage to reinforced concrete and masonry buildings in previous earthquakes, the assessment team was able to estimate the potential levels of structural and architectural damage to the hospital's buildings. Damage to equipment, pipes and contents during the three considered scenario earthquakes was also assessed.

5.2 Kanti Children's Hospital, Kathmandu, Nepal

The 300-bed Kanti Children's Hospital is the only hospital for children in the Kathmandu Valley, for children up to the age of eighteen. The Advisory Group for the Nepal Risk Reduction Consortium (NRRC) Flagship Project 1 is tasked with improving hospital earthquake safety in Nepal and identified Kanti Children's Hospital as having high priority for assessment due to the critical paediatric services it provides. As part of the assessment process, GeoHazards International (GHI) sent a team to Kathmandu in May and June 2013 to assess the potential seismic vulnerabilities of building utility systems, equipment, architectural shell elements and nonstructural elements in Kanti Children's Hospital.

Similarly to the JDWNRH case-study, the assessment team obtained the necessary information by conducting in-person evaluations of building contents and utility systems over several days at the hospital; reviewing available technical reports and drawings; holding discussions with the hospital administration and engineering, maintenance, and medical staff; and obtaining technical information from the literature. This information was used to perform a seismic vulnerability assessment based on experts' judgment (i.e. a heuristic approach).

The study found that the hospital facility has some seismic vulnerability in its utility systems, equipment, architectural shell and contents, which should be addressed as part of a larger effort to improve the seismic performance and functionality of the facility.

5.3 Santa Maria Hospital, Lisbon, Portugal

The Santa Maria Hospital, in Lisbon, Portugal, is an example of a large, early reinforced concrete important building complex. It was built in the early 1950s before Portuguese structural codes considered earthquake resistant design related issues.

The seismic vulnerability assessment presented in Proença et al (2004) comprised of:

- On-site inspection, documental collection.
- Ambient vibration modal identification.
- Development of numerical models for seismic structural vulnerability assessment.
- Seismic vulnerability assessments of non-structural components such as basic facilities, equipment and architectural components.

In particular, the structural vulnerability assessment stages comprised of the development of linear dynamic and nonlinear static models performed according to the Capacity Spectrum Method (CSM), as discussed above.

The conclusions express the expected structural and non-structural seismic performance and point to damage reduction guidelines aimed at the structural retrofit strategy, as well as to the improvement of the connections of some basic facilities components.

5.4 San Salvatore Hospital, L'Aquila, Italy

The San Salvatore Hospital of Coppito is the critical component of the hospital system in the area of L'Aquila, Italy. It was completely evacuated during the 2009 L'Aquila earthquake due to the damage to various floors of the buildings. In terms of typology, the San Salvatore Hospital complex consists of a series of RC frame structures, with interior and exterior masonry walls, built in the mid-1970s onwards and put into service in the second half of the 1990s. The buildings differ in typology, materials and heterogeneous construction details depending on the different age of construction. A covered walkway connects the various blocks on four floors, two above ground and two underground.

Casarotti et al (2009) presented a thorough analysis of the seismic response of the San Salvatore Hospital during the L'Aquila earthquake. In particular, data on the geometric and instrumental surveys carried out in the emergency and post-emergency phases are presented together with the assessment of the damage and usability of the buildings. An example is presented of the vulnerability assessment of one of the hospital buildings, using a very simplified collapse mechanism-based procedure developed for the specific application. This case-study can be a very useful source for the Nepalese context.

5.5 The Ospedale del Mare, Naples, Italy

The Ospedale del Mare is a health care facility that is being built in Naples, Southern Italy. It is one of the largest base isolated structures in Europe (327 high-damping rubber bearings) and comprises a number of buildings with different functions. The planned layout of the main structure is about 150x150m and the total height is about 32m. The structural system utilised for the super-structure is a RC multi-storey framed system.

To assess the seismic response of the building, Di Sarno et al (2011) applied both CSM and full NDA on the three-dimensional (3D) finite element model (FEM) of the structure according to Eurocode 8; simplified NDAs were also conducted on SDoF systems.

5.6 Structural and non-structural seismic vulnerability assessment for hospitals based on questionnaire surveys: case studies in Central America and India.

This example (Lang et al; 2010) represents an application of the vulnerability index approach described in Section 2.2 for a fast and cost-effective assessment of structural and non-structural seismic vulnerability of hospitals and schools. Through the application of standardised questionnaires, both a structural and nonstructural vulnerability index (I_v) are derived which allow a priority ranking. Based on this ranking, the most vulnerable features can be identified and communicate to the responsible authorities. The structural vulnerability index is generated taking into account main design failures as well as the age of the building and its general state of maintenance. The non-structural vulnerability index covers all types of installations, secondary structural elements as well as their impact on the functionality of the building. The questionnaires have been successfully applied to numerous hospitals and school buildings in Northern India and the Central American countries, namely Guatemala, Nicaragua and El Salvador. The definition of reliable weighting factors for the different vulnerability-affecting aspects is also presented.

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Glossary

BASE ISOLATION: A method whereby a building superstructure is separated from its foundation using flexible bearings in order to reduce the earthquake forces. Special detailing is required to provide flexible connections for architectural components, building utilities, piping, etc. that cross the isolation plane into the building. This method can also be used to protect individual pieces of critical, sensitive, or expensive equipment, museum artefacts etc.

BASE SHEAR: The total design lateral force or shear at the base of a building structure or nonbuilding structure.

BASE: The portion of a building embedded in or resting on the ground surface. Seismic forces are delivered to the base of a building. This term is also used to describe the interface of a freestanding nonstructural component with the floor or roof of a building where it is supported. Seismic forces from the floor or roof level of the building are delivered to the base of the nonstructural component.

BEARING WALL: A concrete or masonry wall that supports a portion of the building weight, in addition to its own weight, without a surrounding frame.

BUILDING OR STOREY FRAGILITY CURVE/FUNCTION: A probability-valued function of the intensity measure that represents the probability of violating (exceeding) a given limit-state or damage state of the building or the storey given the value of the seismic intensity that it has been subjected to.

COLLAPSE PREVENTION: A performance level whereby a building is extensively damaged, has little residual stiffness and strength, but remains standing; any other damage is acceptable.

COST REPLACEMENT (NEW): The cost of replacing a component/group of components/an entire building. Since this is often compared to losses, demolition/removal costs may be added to it to fully represent the actual cost of constructing a new structure in place of the (damaged or collapsed) existing one.

DAMAGE: Physical evidence of inelastic deformation of a structural component caused by a damaging earthquake.

DAMPING: The rate at which natural vibration decays as a result of the absorption of energy. In buildings it is an inherent nature to resonate inefficiently to vibration depending on structural connections, kinds of materials, and nonstructural elements used. “Damping” design measures can reduce the magnitude of seismic forces.

DRIFT: The horizontal displacement of a building resulting from the application of lateral forces, usually forces from earthquake or wind. See also interstorey drift.

DUCTILITY: The characteristic of certain materials—steel in particular—to fail only after considerable distortion or deformation has occurred.

ENGINEERING DEMAND PARAMETER (EDP): A measure of structural response that can be recorded or estimated from the results of a structural analysis.

EXPOSURE: The characteristics of the ground roughness and surface irregularities in the vicinity of a building.

FOUNDATION: That part of a structure which serves to transmit vertical and lateral forces from the superstructure of a building to the ground.

FRAME: A type of structural system in which the loads are carried by a grid or framework of beams and columns, rather than by load-bearing walls. Special purpose frames built up from struts or steel shapes are used to support many types of nonstructural components such as piping, ducts, etc.

GROUND MOTION: The movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source, and travel through the earth and along its surface.

IMMEDIATE OCCUPANCY: A performance level whereby a building sustains minimal or no damage to its structural elements and only minor damage to its nonstructural components.

INTENSITY MEASURE (IM): Particularly for use within this document, IM refers to a scalar quantity that characterises a ground motion accelerogram and linearly scales with any scale factor applied to the record.

INTENSITY: See Shaking intensity.

INTERSTOREY DRIFT: The horizontal displacement that occurs over the height of one story of a building resulting from the application of lateral forces, usually forces from earthquake or wind. This is often expressed as an interstorey ratio; the ratio of the displacement to the height of the storey. Interstorey drifts from the structural design of a building are often needed in design calculations for nonstructural components such as glazing, pipe risers or precast panels that are attached to more than one floor.

LATERAL FORCE RESISTING SYSTEM: The elements of a structure that resist horizontal forces. These structural elements are typically frames, braces or shear walls.

LIFE SAFETY: A performance level whereby a building may experience extensive damage to structural and nonstructural components, but remains stable and has significant reserve capacity.

LOSS RATIO: The ratio of loss to the cost replacement new for a component/group of components.

LOSS: The actual monetary cost of repairing a component, a group of components, or an entire building.

MITIGATION: An action taken to reduce the consequences of a future earthquake. Other terms such as retrofit, rehabilitation or upgrade are also used to describe these actions.

NONLINEAR STATIC APPROACH/PROCEDURE: A structural analysis technique in which the structure is modelled as an lure assembly of components capable of nonlinear force-displacement behaviour and subjected to a monotonically increasing lateral load in a specific pattern to generate a global force-displacement capacity curve. The displacement demand is determined with a spectral representation of ground motion, using one of several alternative methods.

NONSTRUCTURAL COMPONENT: Any architectural element; mechanical, electrical, plumbing (MEP) equipment or systems or part thereof; any furniture, fixtures, equipment (FF&E) or building contents. This term is used to describe any and all components of a building or nonbuilding structure which are not an explicit part of the structural system.

REPAIR: An action taken to address a damaged building component.

RESPONSE SPECTRUM: A characterisation of ground motion (representing the suite of spectral ordinates) measuring the extent of shaking different structures will experience based on their natural period of vibration.

SHAKING INTENSITY: The amount of energy released by an earthquake as measured or experienced at a particular location. Intensity is subjectively measured by the effects of the earthquake on people and structures.

SPECTRAL ACCELERATION/DISPLACEMENT: The acceleration/displacement to be experienced by structures of different periods.

STIFFNESS: Rigidity, or resistance to deflection or drift. A measure of deflection or of staying in alignment within a certain stress.

STRUCTURAL COMPONENT: A structural member such as a beam, column, or wall that is an individual part of a structural element

VULNERABILITY CURVE/FUNCTION: A loss or loss ratio valued function of IM, that represents the distribution of seismic loss or loss ratio given the value of IM that a certain building or class of buildings has been subjected to.