Central America and the Caribbean

The Central America and the Caribbean Earthquake Hazard and Risk Model was developed within the scope of a regional programme supported by the United States Agency for International Development (USAID), in collaborations with over a dozen local institutions from the region. This project features the development of a probabilistic seismic hazard model, a uniform exposure dataset covering the residential, commercial and industrial building stock, and a set of vulnerability functions characterizing the likelihood of loss given a seismic hazard intensity. This initiative also covered a number of local events to improve the local capacity to assess earthquake hazard and risk in the region.

Regional Exposure

Reliable risk assessment requires an exposure model that features the size, spatial distribution, building classification and replacement cost of the building stock. To achieve a regional exposure model for Central America and the Caribbean additional challenges had to be overcome. Due to its size and tectonic configuration, it must contain all structures and their proximity to hazard sources found across the countries. In terms of building classification, the list of building classes should result from capturing regional variations of the characteristics that influence the dynamic behavior of the structures, like the occupancy, construction materials, level of seismic provisions and height. Finally, the economic value of the building stock should be estimated considering the difference in cost of building construction in each country. This section presents the procedure implemented to account for these variables and achieve a uniform exposure model for the residential, commercial and industrial building portfolios in the region.

Size and spatial distribution of the building portfolio

To determine the total number of structures and their spatial distribution first it was necessary to find common databases that could be accessed and analyzed. Naturally, cadastral and census databases containing all the buildings, structural attributes and location would be the best datasets to use. Across Central America, the most complete and up-to-date databases were the national population and household census. Every country in the isthmus provides information about household and population associated to a geographical variable that is publicly available online or upon request. Therefore, both population and household census were taken from the respective statistical offices to determine the number and location of residential dwellings. Commercial and industrial data are much less detailed and difficult to process. Nonetheless, all the countries keep an official directory of establishments containing the number of businesses dedicated to commercial or industrial activities. The following table summarizes the raw data found in the databases for each country in the region.

Country (ISO)	Population	Dwellings	Com	Ind	Sources
Guatemala (GTM)	16,176,133	2,574,908	226,352	49,595	www.ine.gob.gt
Cuba (CUB)	11,167,328	3,644,001	4,806	3,410	www.one.cu
Haiti (HTI)	10,291,060	N.A	N.A	N.A	www.ihsi.ht
Dom. Republic (DOM)	9,445,367	2,662,794	17,421	4,334	www.one.gob.do
Honduras (HND)	8,249,574	1,837,855	134,658	14,689	www.ine.gob.hn
Salvador (SLV)	6,377,195	1,372,831	140,872	21,079	www.digestyc.gob.sv
Nicaragua (NIC)	6,167,237	983,928	142,982	32,247	www.inide.gob.ni
Costa Rica (CRI)	4,301,006	1,360,625	37,829	10,190	www.inec.go.cr

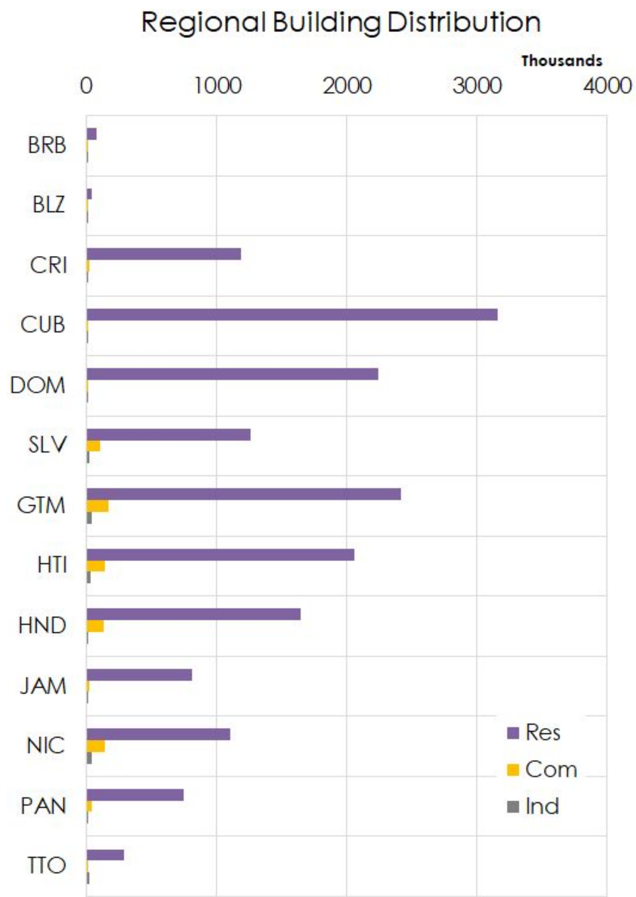
Panamá (PAN)	4,058,374	1,082,881	57,157	7,617	wwwcontraloria.gob.pa/inec
Jamaica (JAM)	2,697,053	881,021	34,547	16,221	www.statinja.gov.jm
Trinidad and Tobago (TTO)	1,114,777	313,032	9,532	20,042	www.cso.gov.tt
Belize (BLZ)	468,310	79,235	7,456	1,372	www.sib.org.bz
Barbados (BRB)	277,819	78,934	4,727	1,111	www.barstats.gov.bb

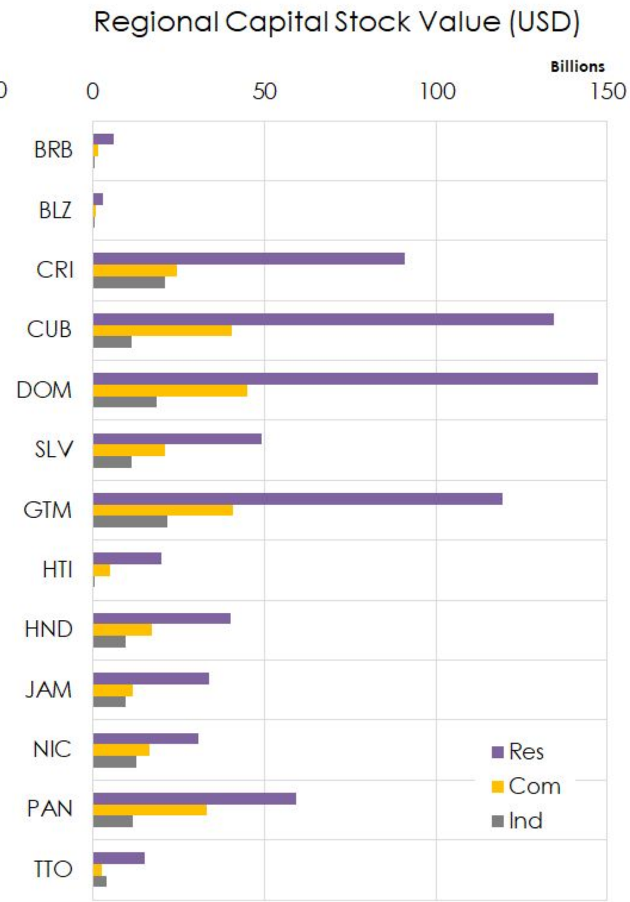
Identification of structure types

The first step in the characterization of the building stock is the review of the structural features consulting existing studies and databases. The World Housing Encyclopedia has reports that include the building materials, architectural drawings, construction process, socio-economic environment and even seismic performance of the common dwelling configurations found in the world. For Central America, there are over 14 reports covering several building types. Reinforced concrete frames and wooden structures are commonly found in the urban and rural centers of Belize and Panama. Guatemala, Honduras and Nicaragua have references specialized in adobe construction, that accounts for a significant percentage of the building stock and account for the most vulnerable class. Adobe and bahareque (wattle-daub) can also be found in El Salvador, whereas in Costa Rica adobe and bahareque structures are almost nonexistent at present, with the rest of the residential building stock composed mostly of confined masonry and wood. Nonetheless, the common factor across the seven countries is the widespread use of concrete block masonry and wood for residential dwellings, with steel excluded from single family houses but quite common on commercial and industrial establishments. It was consequently concluded that 1) bare reinforced concrete frames, 2) infilled concrete frames, 3) concrete walls, 4) wood panels, 5) adobe walls, 6) confined masonry walls, 7) reinforced masonry walls and 8) steel bare and infilled frames are the main structural types found in Central America. Since wattle-daub and waste materials are particular forms of informal construction, these buildings were classified together in a single 8) informal class.

Identification of height and ductility

On the second step of the process the structural types are further characterized into the final building classes by adding two more attributes: the building height and the probable level of ductility the structures will exhibit during intense ground shaking. Height is only indirectly registered by household databases. All consulted census made a separation of dwelling in individual houses (low rise structures) and apartment buildings (mid and high-rise structures). Taking advantage of such information, in this study adobe, wood and informal construction are considered 1 and 2 storey structures exclusively. On the other hand, reinforced concrete, masonry and steel buildings feature mid and high-rise classes ranging from 3 to 12+ storeys. Concerning the expected ductility level, a similar process is followed. Dwellings made of adobe, wattle-daub, stone and waste materials are classified as non-ductile classes, under the assumption that these would perform poorly regardless of construction date, structural system and material quality. On the contrary, reinforced concrete, confined masonry, reinforced masonry and steel present ductile and non-ductile typologies, depending on local construction practices, structural configurations and seismic provisions. The different combinations of structure types, height and ductility levels result in 73 building classes. These typologies are considered to be a comprehensive representation of the building stock in Central America and the Caribbean. The methodology used to distribute the 13 million dwellings and establishments into each typology is explained in the following section.





Building classes found in Central America and the Caribbean

Building Class	Material	LLRS	Ductility	Storeys
W+WLI/LWAL+DNO	Wood	Panels	Low	1 and 2
W+WLI/LWAL+DUM	Wood	Panels	Moderate	1 and 2
W+WWD/LWAL+DNO	Wood & Earth	Wall	Low	1
MATO	Waste / Others	Unknown	Low	1
W+WLI/LPB+DNO	Wood	Post and Beams	Low	1
MUR+ST/LWAL+DNO	Stone Masonry	Wall	Low	1 and 2
MUR+ADO/LWAL+DNO	Adobe Masonry	Wall	Low	1 and 2
MUR/LWAL+DNO	Unref. Masonry	Wall	Low	1 and 2
MR/LWAL+DNO	Reinf. Masonry	Wall	Low	1 to 3
MR/LWAL+DUM	Reinf. Masonry	Wall	Moderate	1 to 3
MR/LWAL+DUH	Reinf. Masonry	Wall	High	1 to 3

MCF/LWAL+DNO	Conf. Masonry	Wall	Low	1 to 3
MCF/LWAL+DUM	Conf. Masonry	Wall	Moderate	1 to 3
MCF/LWAL+DUH	Conf. Masonry	Wall	High	1 to 3
CR/LFM+DNO	Reinf. Concrete	Bare frame	Low	1 to 2
CR/LFM+DUM	Reinf. Concrete	Bare frame	Moderate	3 to 4
CR/LFM+DUH	Reinf. Concrete	Bare frame	High	3 to 4
CR/LFM+DNO/SOS	Reinf. Concrete	Soft storey	Low	2
CR/LFINF+DNO/SOS	Reinf. Concrete	Soft storey	Low	2
CR/LFINF+DNO	Reinf. Concrete	Infilled frame	Low	1 to 3
CR/LFINF+DUM	Reinf. Concrete	Infilled frame	Moderate	1 to 6
CR/LFINF+DUH	Reinf. Concrete	Infilled frame	High	4 to 6
CR+PCPS/LWAL+DUM	Post-Tension Concrete	Frame	Medium	1 to 3
CR+PC/LWAL+DNO	Precast Concrete	Wall	Low	1
CR+PC/LWAL+DUM	Precast Concrete	Wall	Moderate	1
CR/LDUAL+DUH	Reinf. Concrete	Wall & Frame	High	6 to 12
S+SR/LFBR+DUH	Steel - Hot Rolled	Braced Frame	High	6 to 12
S+SL/LFM+DNO	Steel - Cold Formed	Frame	Low	1
S+SR/LINF+DUM	Steel - Hot Rolled	Infilled frame	Moderate	1
S+SR/LFM+DUM	Steel - Hot Rolled	Frame	Moderate	1
S+SR/LFBR+DUH	Steel - Hot Rolled	Braced Frame	High	1
S+SR/LFM+DUH	Steel - Hot Rolled	Frame	High	1

Dwellings and establishments distribution

The final part of the procedure requires the dwellings and establishments to be distributed among the building classes. The household databases were parsed using the mapping scheme methodology. In this approach, the dwellings from the census databases are classified according to certain variables, such as the wall material, floor material, ceiling material and even household type. Crossing these variables allows segregating the dwellings into subgroups that are then subjected to a process of conditional selection. If a dwelling meets the criteria to belong to a certain building class, then it is assigned to that class. For example, regardless of the floor, ceiling material and household type, dwellings with wall variable equal to adobe will fall into the MUR-ADO typology. It is then assumed that these structures are only 1 and 2 storeys and have a low level of ductility. In the same manner, dwellings with wall variables equal to waste materials or light wood are assigned to MATO and WLI building classes, respectively.

A significant percentage of households in this region have walls made of masonry blocks. Because census enquiries may lack engineering knowledge, this subgroup could hold structures of unreinforced masonry, reinforced masonry, confined masonry or even infilled concrete frames. Additionally, these typologies present varying levels of ductility and height. To overcome this, additional variables, local judgement and socio-economic indexes are included in the selection criteria.

Dwellings that present both concrete blocks and ceramic pavement are subdivided into classes of concrete and masonry. The percentage of assets that fall in one or the other is defined based on local expert opinion, available literature and visual examination of the portfolio. The dwellings are then assigned to ductile or non-ductile classes based on the quality of the local seismic code and the percentage of informal construction. More than 140 professionals participated in the definition of dwelling distribution criteria for Central America and the Caribbean.

Dwelling to building conversion and replacement costs

Once the dwellings have been properly classified they are converted to buildings and assigned a replacement cost. Conversion from dwellings to buildings is necessary for mid- to high-rise structures that contain more than one household. Conversion factors are calculated based on the average number of households within apartment buildings, obtained from the official census and household databases. On the other hand, for average replacement costs, three different quality classes per building class were established. Based on the structural attributes discussed in the previous sections (i.e. floor, height and ductility), each building was assigned to a lower, middle or high quality class. Each class has an average size and cost of replacement per square meter, both determined based on official estimates by the country central bank. The average size and average cost of construction are then multiplied to obtain the final replacement cost for each building typology.

Regional exposure

As a result, 17 million structures were identified and classified in 73 vulnerability classes that comprise the residential, commercial and industrial building stocks of the countries. A total capital stock of 960 billion USD was estimated for the entire region with a population of 70 million people. The human and structural assets were spatially allocated at the smallest available administrative level.

<Dynamic map with the number of buildings at admin 1. Jeph and Armando will include a map with the data>

Vulnerability

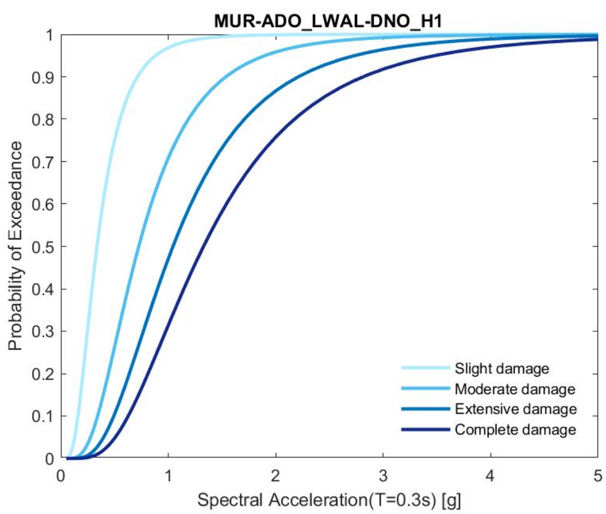
The vulnerability component characterizes the likelihood to suffer damage or loss given a hazard intensity. The relation between probability of loss and hazard intensity is expressed by a vulnerability function, whilst the relation between probability of damage and hazard intensity is represented by fragility functions. Despite the notable advances in regional seismic vulnerability modelling in the last three decades, a uniform set of vulnerability or fragility functions covering all of the building classes in Central America and the Caribbean were not available. Moreover, with a few exceptions, most of the existing vulnerability functions have not been tested against damage data from previous events or have not been applied within a probabilistic framework for earthquake loss assessment. To minimize some of these challenges, GEM and its partners collaborated within the Caribbean and Central America Risk Assessment (CCARA) project to develop a set of vulnerability functions for the most common building classes in the region, using a uniform and consistent derivation approach. In general, this approach relied in the following steps:

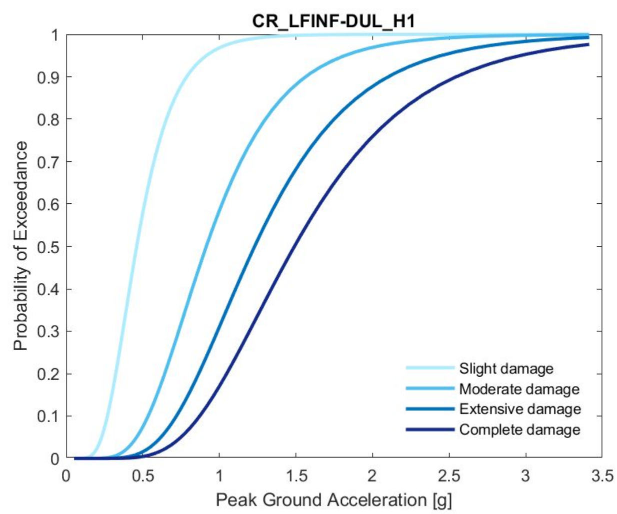
1. Identification of the most common building classes in the region, using peer-reviewed literature, web surveys (https://platform.openquake.org/building-class/), and World Housing Encyclopedia reports.
2. Development of simplified numerical models for each building class, using data from the literature and results from experimental campaigns (e.g. yield and ultimate global drift, elastic and yield period of the first mode of vibration, participation factor of the first mode of vibration, common failure mechanisms). Some of the building classes had to be explicitly modelled using complex 3D models due to the lack of information in the literature.
3. Selection of ground motion records using local strong motion databases, and considering the local seismicity and tectonic environment. To this end, seismic hazard disaggregation at the location of the most urbanized centers supported the identification of the combinations of magnitude and distance,

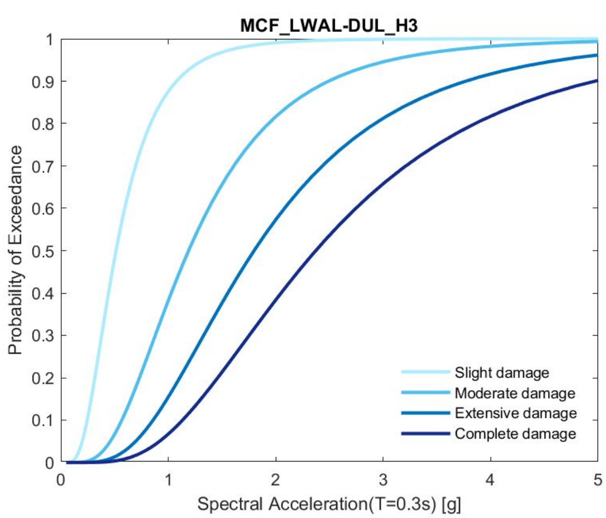
which contribute the most to the seismic hazard. The use of a large set of actual time histories aims at propagating the record-to-record variability to the vulnerability assessment.

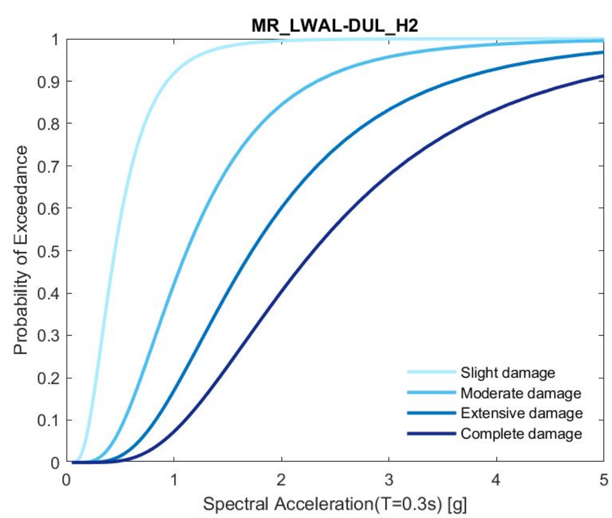
4. Performing nonlinear time history analysis to evaluate the structural response (i.e. engineering demand parameter (EDP) – maximum displacement and acceleration) of the simplified numerical model against the selected ground motion records. This step uses the open-source package for structural analysis OpenSees, and the Risk Modelers Toolkit supported by GEM.
5. Evaluation of the structural responses of the numerical models in order to evaluate the evolution of damage with increasing hazard intensities. In this process, the probability of exceeding a number of damage states for a set of intensity measure levels is defined (i.e. fragility functions).
6. The fragility functions can be converted into vulnerability functions (i.e. probability of loss ratio conditional on ground shaking) using a damage-to-loss model. Such functions can be used directly in the assessment of economic and human losses due to earthquakes.

A similar approach has been followed for the development of fragility and vulnerability functions within the scope of regional programs in South America, Sub-Saharan Africa and South-East Asia. This framework aims at being a dynamic tool which can be improved upon the release of new models and datasets. As an example, fragility models for the four most common building classes in Central America and the Caribbean are illustrated below.









Vulnerability Curves for CARA:

1) MUR-ADO_LWAL-DNO_H1
2) CR_LFINF-DLO_H1
3) MR_LWAL-DUM_H2
4) MCF_LWAL-DUH_H3

Seismic Hazard

The main components concerning the probabilistic seismic hazard model for the region can be found in the associated technical documentation at: https://hazard.pages.openquake.org/hazard-mosaic-docs/models/CCA The seismic hazard in terms of peak ground acceleration (PGA) for a probability of exceedance of 10% in 50 years (equivalent to approximately 475 years return period) is presented in the figure below.

<Include dynamic map produce by the hazard team>

Seismic Risk

Methodology

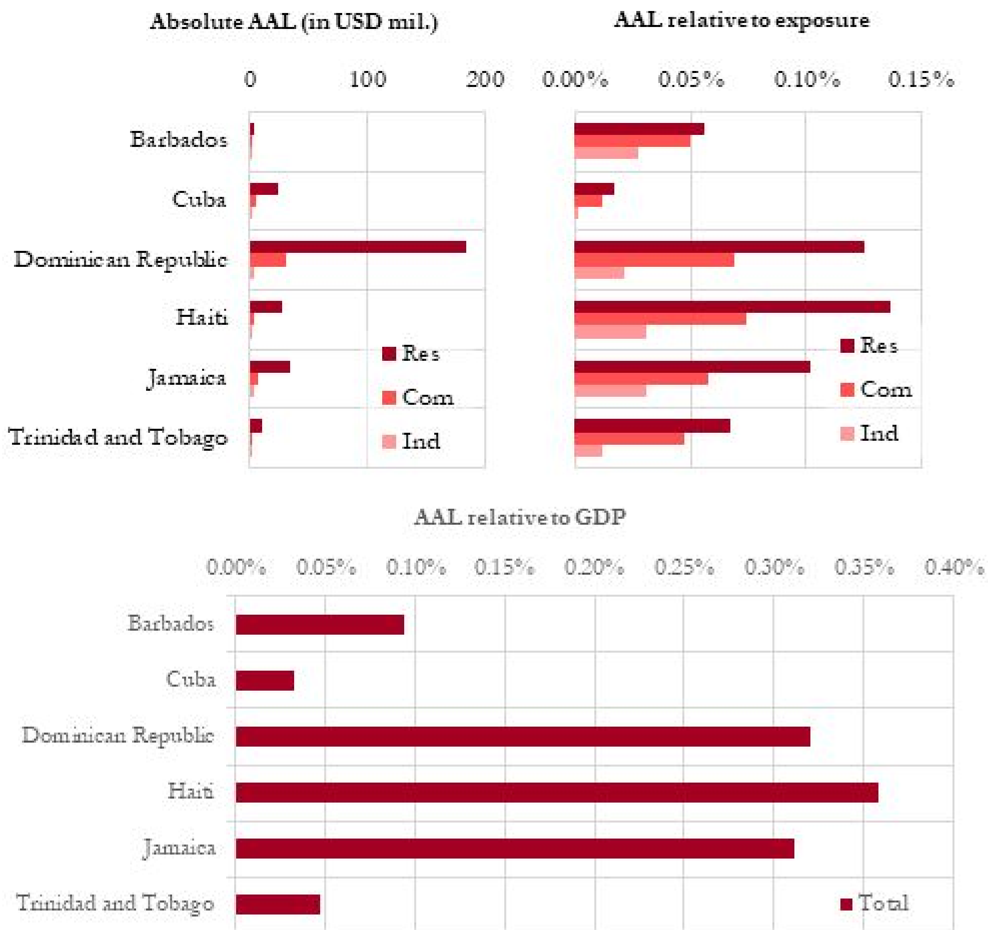
The seismic risk assessment for each building inventory was performed using the probabilistic event-based risk calculator of the OpenQuake-engine. In the process the recurrence laws within the seismic source model are used to generate possible realizations of seismicity conditional on a given interval of time (i.e. stochastic event sets - SES). Each earthquake in the stochastic event set is defined by a magnitude, upper and lower seismogenic depth, hypocenter, and dip, rake and strike angles. For each country in the region 100,000 SES with a 1-year duration were generated per logic three branch.This procedure was repeated several times in order to verify that each simulation produced negligible differences in the risk metrics of interest.

One ground motion field was generated for each event. The ground shaking amplification at each site is estimated by introducing Vs30 values directly into the ground motion prediction equations. The adjusted ground shaking intensities at each site and the vulnerability function assigned to each asset are used to compute the loss ratios. The final loss is obtained by multiplying this ratio by the associated replacement cost.

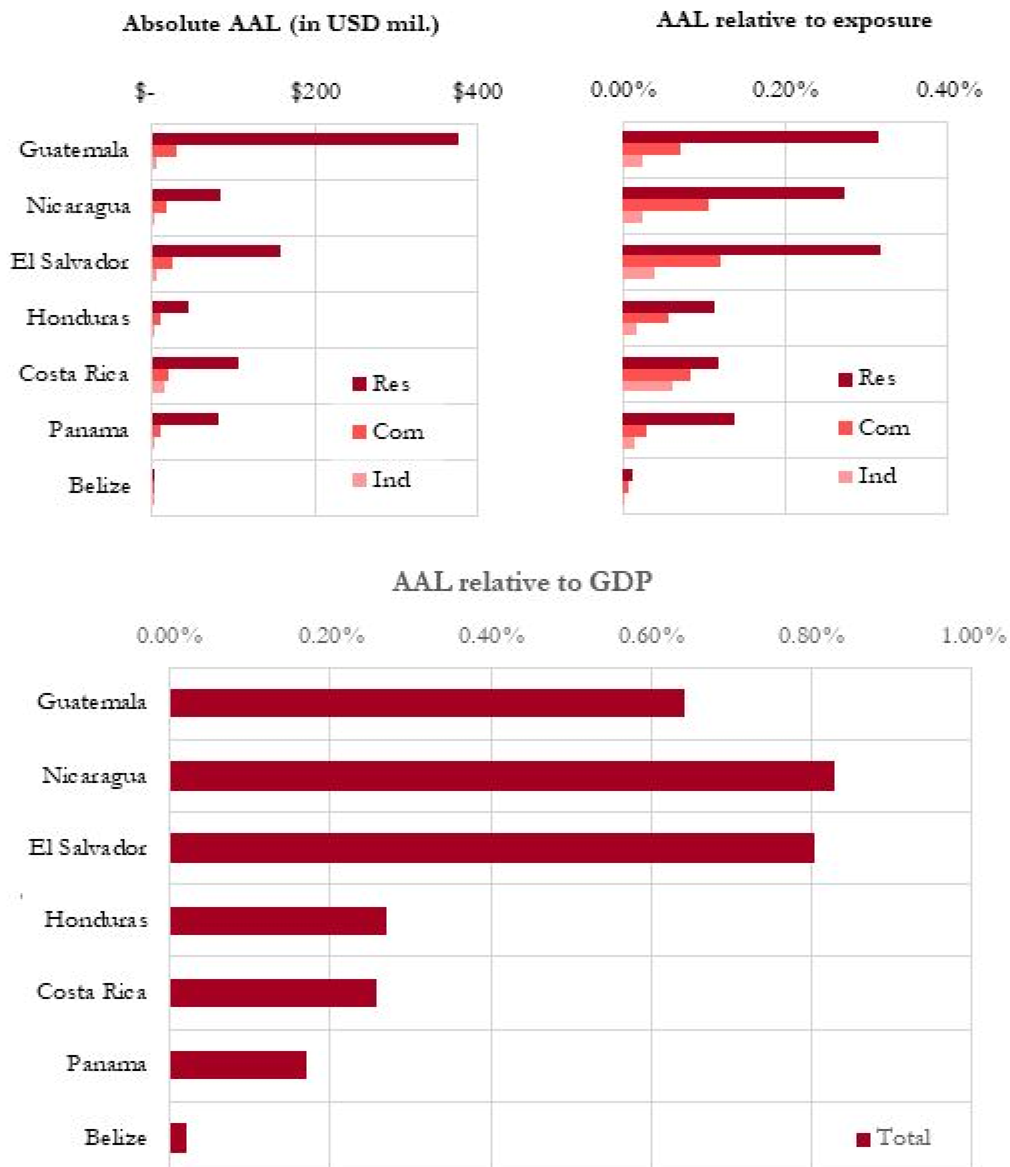
Average annualized losses

The average annualized economic losses are plotted in two forms: relative to the total exposed value and relative to the GDP (Indicator). In absolute terms, the countries with the highest risk are Guatemala and the Dominican Republic, both with an AAL of $375 and $184 million USD respectively. Together they account for more 49% of the total loss in the region. The rest is distributed primarily among the rest of the Central American (45%) countries, with a small contribution from the Caribbean (6%). However, in terms of risk indicator, the top risk country in the region is Nicaragua, losing over 0.8% of its GDP, followed by El Salvador, Guatemala, Haiti and the Dominican Republic.

Average annualized losses for the Caribbean



Average annualized losses for the Central America



<Include dynamic risk map produce of the risk at the hexagons - Luis and Vitor will produce this. We need Admin0 of all countries to do this- they have to follow same format as the other shapefiles in the name (for all countries>

Partners and collaborations

<Include a table of all contributors per country>

Middle East

<Brief description - Vitor to do>

Exposure

<Description of how the exposure model was developed - one paragraph)

Middle east exposure model is developed for 18 countries, the building stock comprises information for three occupancies, residential, commercial and industrial. The information include: number of buildings, dwellings and population with estimates of economic value available for urban and rural areas. The primary source used to model the portfolio is National census. The following steps illustrate the development process:

1. Identification of the predominant building typologies in accordance with GEM building taxonomy for each country. This step builds on the available information in the literature (local surveys, regional projects and other global initiatives including PAGER, GAR, WHE, GED and others). Moreover, The model involved several local experts and institutions.

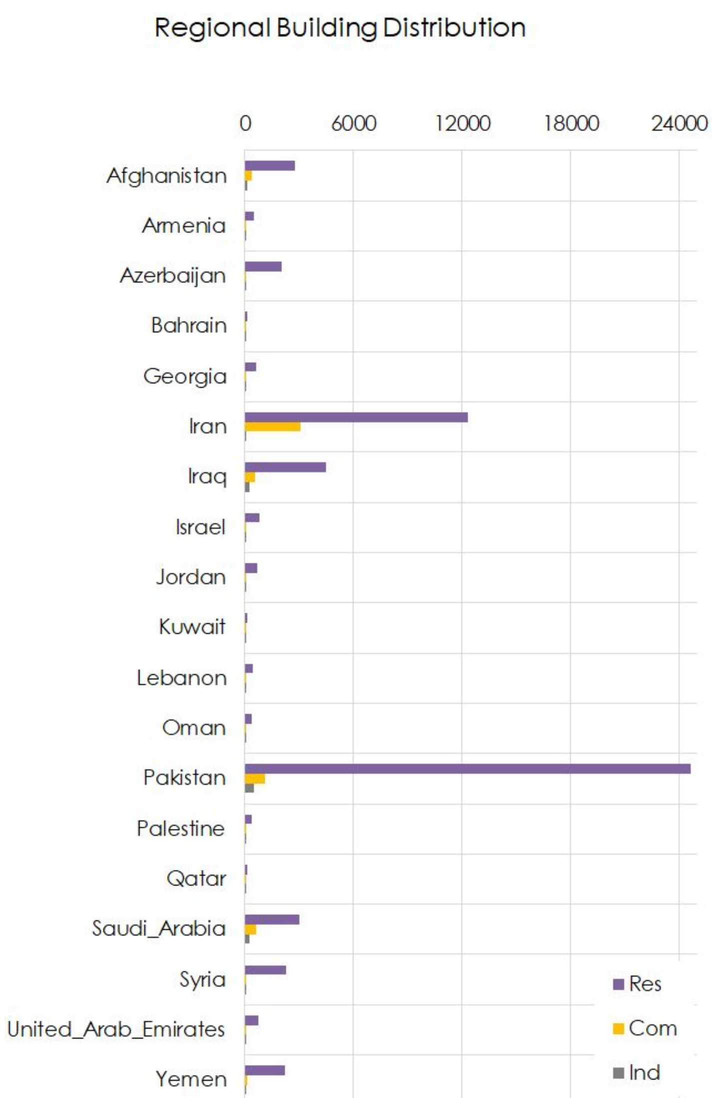
2. Assigning fractions for the predominant building classes using census variables (number of floors, wall material, construction age, ects). The fractions are assigned for the lowest available administrative level for each country.

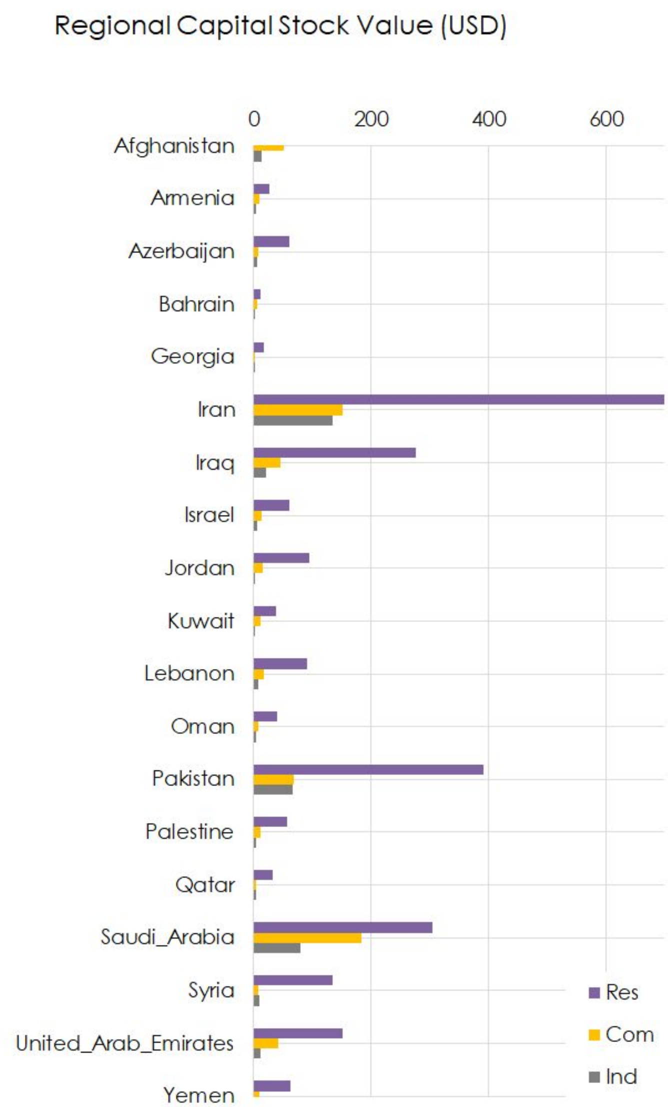
3. from dwellings to buildings. In this step the buildings are estimated based on the average dwellings size and floor number per building typology. Once the total built area is known replacement costs for different building typologies and occupancies are assigned.

<Table of census data and sources>

Country (ISO)	Population	Dwellings	Com	Ind	Sources
Afghanistan		3618503			http://www.cso.gov.af/
Armenia		786652			https://www.armstat.am/
Azerbaijan		3740756			https://www.stat.gov.az/
Bahrain		203298.8			http://www.data.gov.bh/
Georgia		1057164			http://www.geostat.ge/
Iran		0			https://www.amar.org.ir/
Iraq		5350444			http://www.cosit.gov.iq/
Israel		2314060			http://www.cbs.gov.il/
Jordan		1359930			http://www.dosweb.dos.gov.jo/
Kuwait		496159.7			https://www.csb.gov.kw/
Lebanon		1210786			http://www.cas.gov.lb/

Oman	551363.9	https://www.ncsi.gov.om/
Pakistan	33692282	http://www.pbs.gov.pk/
Palestine	834058.5	http://www.pcbs.gov.ps/
Qatar	280247.1	https://www.mdps.gov.qa/
Saudi_Arabia	4681528	https://www.stats.gov.sa/
Syria	3673134	http://www.cbssyr.sy/
United_Arab_Emirates	1176352	http://fcsa.gov.ae/
Yemen	2813414	http://www.catalog.ihsn.org/ http://www.cso-yemen.com/





<Regional Summary - w Catas script>
<Bar plot with capital stock - per occupancy>

<Dynamic map with the number of buildings at admin 1. We just need the QGIS project with the number of buildings at admin 1 - Jeph and Armando will include a map with the data>

Vulnerability

<Vitor and Luis will work on this>

<Author to select 4 building classes. Luis will generate the 4 plots>

Seismic Hazard

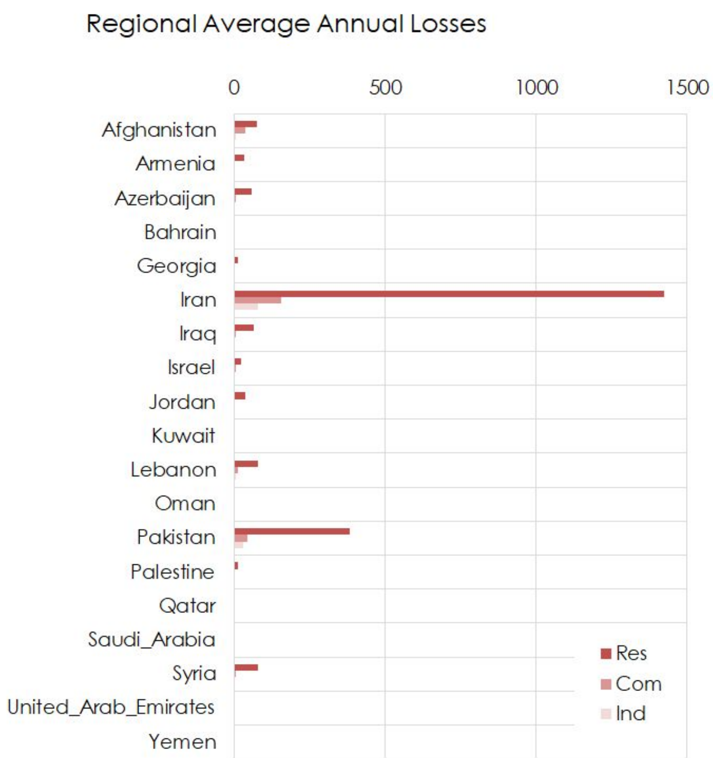
<Brief description - take from the hazard wiki>

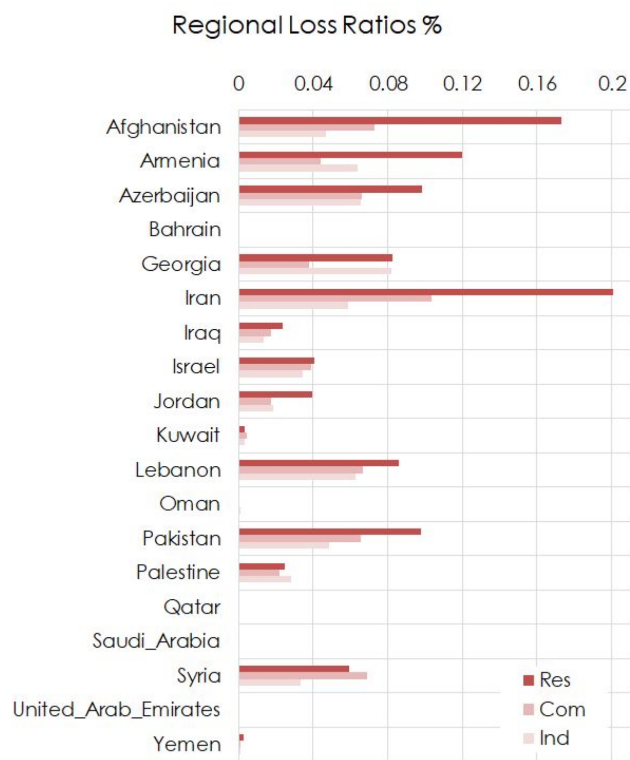
Link to the hazard wiki ()

<Include dynamic map produce by the hazard team>

Seismic Risk

<Brief description of the risk. For example, mentioning which countries have the highest risk and why - not more than a paragraph>





<Bar plot - AAL for top 10 countries >

<Bar plot - AALR for top 10 countries >

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Prepare a .zip
Adm0_Isle_of_Man

Partners and collaborations

<Include a table of all contributors per country>

North Africa and Sub Saharan Africa

Country (ISO)	Population	Dwellings	Sources
Algeria (DZA)	41,079,903	6,767,694	ONS http://www.ons.dz/
Ethiopia (ETH)	74,074,360	15,116,855	CSA - http://www.csa.gov.et/
Egypt (EGY)	94,798,827	21,818,718	CAPMAS - http://www.capmas.gov.eg/
Morocco (MAR)	33,610,071	7,264,869	NPC - http://www.hcp.ma/
Uganda (UGA)	45,690,140	7,348,287	UBOS - https://www.ubos.org/
Tunisia (TUN)	11,154,369	3,273,272	INS - http://www.ins.nat.tn/
Mozambique (MOZ)	21,943,708	4,835,898	INE - http://www.ine.gov.mz/
Tanzania (TAZ)	44,049,876	9,276,997	NBS - http://www.nbs.go.tz/
Rwanda (RWA)	10,378,019	2,424,898	NISR - http://www.statistics.gov.rw/
Malawi (MWI)	13,077,173	2,892,913	NSOMALAWI - http://www.nsomalawi.mw/
Eritrea (ERI)	NA	NA	NA
Kenya (KEN)	35,737,631	8,738,097	KBS - http://www.knbs.or.ke/
Zambia (ZMB)	13,059,747	2,675,035	ZAMSTATS - http://www.zamstats.gov.zm/
Burundi (BDI)	8,053,575	1,685,553	ISTEEBU - http://www.isteebu.bi/
Ghana (GHA)	24,675,398	5,883,868	GSS - http://www.statsghana.gov.gh/

Exposure

Within the Global Risk Model, exposure modelling was conducted for 56 countries including territories in Africa. The datasets represent the most complete source of information regarding elements exposed to seismic risk in Africa. Three main occupancy types, residential, commercial and industrial buildings were considered in the first phase of GRM. The primary sources of data were the latest population and housing census for each country. Other secondary sources of data include scientific publications, construction reports, housing surveys, UN-Habitat reports, local news websites etc. From each census, building attributes which describe the lateral load resisting system and the material of the lateral load were collected. Such attributes include exterior wall materials, roof materials and floor materials. Height of buildings, average floor area, and date of construction are sometimes reported per each household. In Africa, few statistical organizations presented the housing data as crossed variables while most are non-crossed. Also, some countries had very sparse or no data and as such, proxies were adopted to derive the exposed building stock based on average household size and estimated population. The main steps involved in estimating the number of buildings and capital stock are described below.

1. Pre-processing: While some census data were presented as crossed variable of two or three attributes, most information came as single non-crossed variables. One of the first steps adopted in this work was to cross all non-crossed attribute data. The pre-processing helped to understand the possible building class possible to be considered as the predominate building types in an area, whether rural, urban or in capital cities.
2. Defining building classes: Extensive literature review was conducted to understand the construction practices in each country. The existence of building code helped to describe more accurately the building classes in the formal sectors. Building types for each country was defined according to GEM's building taxonomies.
3. Mapping scheme: A very critical step in the exposure modeling when using authoritative data. It involves the transformation of the dwellings into building. In Africa, buildings were classified into the broad categories of concrete, masonry, wood, adobe, earthen and unknown buildings categories. This process involves transforming dwellings into buildings.
4. Area and cost: The final step we undertook was the area and cost/m2 estimate to quantify the building portfolio. Area and cost were assigned based on the building type, whether formal or informal, building location in a rural, urban or capital city and the cost of building materials in each country. Sources of such data include publications on housing finance, bills of quantification reports and reports of NGO's involved affordable housing, etc.