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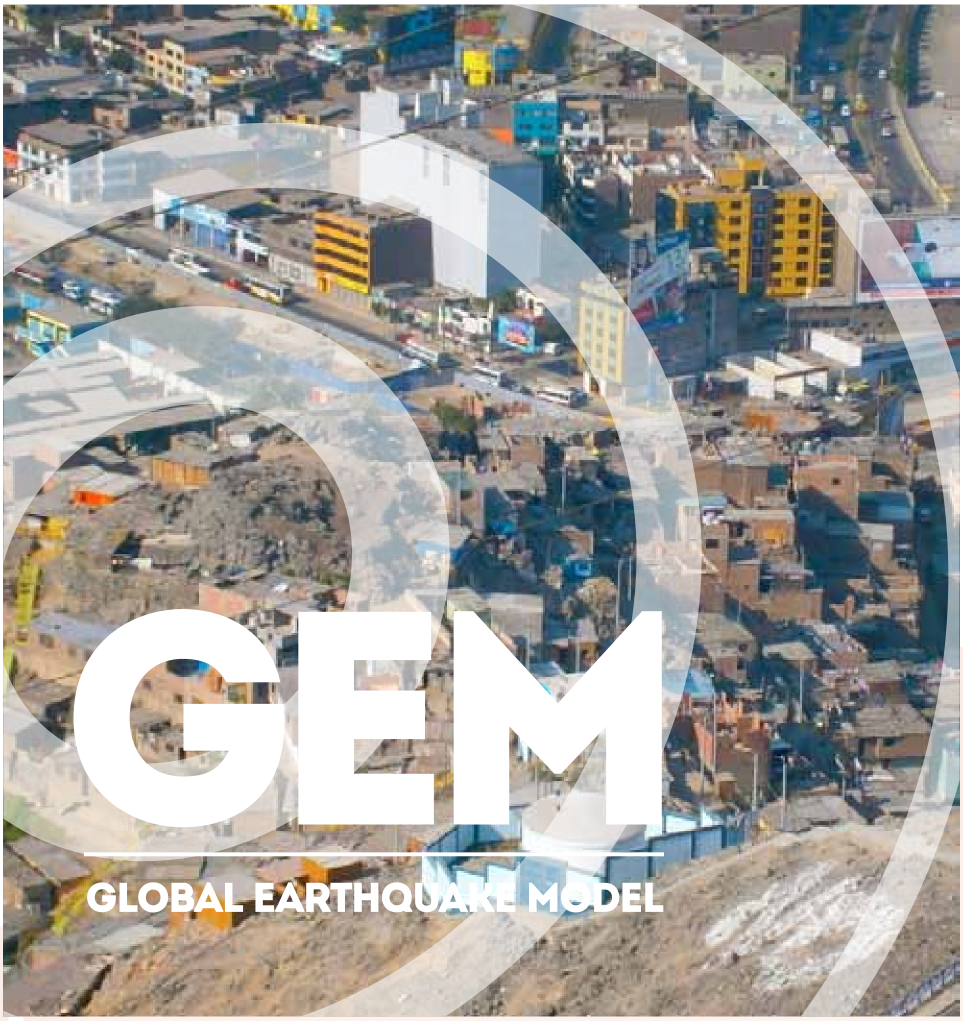
EXPOSURE
MODELLING

GEM Building Taxonomy Version 2.0

Brzev S., C. Scawthorn, A.W. Charleson, L. Allen, M. Greene, K. Jaiswal, V. Silva



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http://www.globalquakemodel.org/

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ABSTRACT

This report documents the development and applications of the Building Taxonomy for the Global Earthquake Model (GEM). The purpose of the GEM Building Taxonomy is to describe and classify buildings in a uniform manner as a key step towards assessing their seismic risk. Criteria for development of the GEM Building Taxonomy were that the Taxonomy be relevant to seismic performance of different construction types; be comprehensive yet simple; be collapsible; adhere to principles that are familiar to the range of users; and ultimately be extensible to non-buildings and other hazards. The taxonomy was developed in conjunction with other GEM researchers and builds on the knowledge base from other taxonomies, including the EERI and IAEE World Housing Encyclopedia, PAGER-STR, and HAZUS.

The taxonomy is organized as a series of expandable tables, which contain information pertaining to various building attributes. Each attribute describes a specific characteristic of an individual building or a class of buildings that could potentially affect their seismic performance. The following 13 attributes have been included in the GEM Building Taxonomy Version 2.0 (v2.0):

1. direction
2. material of the lateral load-resisting system
3. lateral load-resisting system
4. height
5. date of construction or retrofit
6. occupancy
7. building position within a block
8. shape of the building plan
9. structural irregularity
10. exterior walls
11. roof
12. floor
13. foundation system.

The report illustrates the practical use of the GEM Building Taxonomy by discussing example case studies, in which the building-specific characteristics are mapped directly using GEM taxonomic attributes and the corresponding taxonomic string is constructed for that building, with "/" slash marks separating attributes. For example, for the building shown at right, the GEM Building Taxonomy string is:

DX[1]/ MUR+CLBRS+MOCL[2] /LWAL[3]/ DY/MUR+CLBRS+MOCL/LWAL/YPRE:1939[4]/HEX:2[5]/RES[6] /[7]/[8]/IRRE[9]/10/RSH3+RWO+RWO2[11]/FW[12]/[13]/

which can be read as (1) **Direction** = [DX or DY] (the building has the same lateral load-resisting system in both directions); (2) **Material** = [Unreinforced Masonry + solid fired clay bricks + cement: lime mortar]; (3) **Lateral Load-Resisting System** = [Wall]; (4) **Date of construction** = [pre-1939]; (5) **Height** = [exactly 2 storeys]; (6) **Occupancy** = [residential, unknown type]; (7) **Building Position** =

[unknown = no entry]; (8) **Shape of building plan** = [unknown = no entry]; (9) **Structural irregularity** = [regular]; (10) **Exterior walls** = [unknown = no entry]; (11) **Roof** = [Shape: pitched and hipped, Roof covering: clay tiles, Roof system material: wood, Roof system type: wood trusses]; (12) **Floor** = [Floor system: Wood, unknown]; (13) **Foundation** = [unknown = no entry].

Mapping of GEM Building Taxonomy to selected taxonomies is included in the report – for example, the above building would be referenced by previous structural taxonomies as: PAGER-STR as UFB, UFB3 or UFB4, by the World Housing Encyclopedia as 7 or 8 and by the European Macroseismic Scale (98) as M5. The Building Taxonomy data model is highly flexible and has been incorporated within a relational database architecture.

Due to its ability to represent building typologies using a shorthand form, it is also possible to use the taxonomy for non-database applications, and we discuss possible applications or adaptation for Building Information Modelling (BIM) systems, and for the insurance industry.

The GEM Building Taxonomy was independently evaluated and tested by the Earthquake Engineering Research Institute (EERI), which received 217 TaxT reports from 49 countries, representing a wide range of building typologies, including single and multi-storey buildings, reinforced and unreinforced masonry, confined masonry, concrete, steel, wood, and earthen buildings used for residential, commercial, industrial and educational occupancy. Based on these submissions and other feedback, the EERI team validated that the GEM Building Taxonomy is highly functional, robust and able to describe different buildings around the world.

The GEM Building Taxonomy is accompanied by supplementary resources. All terms have been explained in a companion online Glossary, which provides both text and graphic descriptions. The Taxonomy is accompanied by TaxT, a computer application that enables a user to record information about a building or a building typology using the attributes of the GEM Building Taxonomy v2.0. TaxT can generate a taxonomy string and enable a user to generate a report in PDF format which summarizes the attribute values (s)he has chosen as representative of the building typology under consideration.

The report concludes with recommendations for future development of the GEM Building Taxonomy. Appendices provide the detailed GEM Building Taxonomy tables and additional resources, as well as mappings to other taxonomies.

Keywords

building taxonomy, attribute, building typologies, terminology, vulnerability

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LIST OF ABBREVIATIONS AND ACRONYMS

ATC	Applied Technology Council (list in alphabetical order)
BIM	Building Information Modelling
EERI	Earthquake Engineering Research Institute
FEMA	Federal Emergency Management Agency (US)
GEM	Global Earthquake Model
GIS	Geographic Information System
ISO	International Standards Organization
MBT	Model Building Types
TaxT	GEM Building Taxonomy Tester
USGS	U.S. Geological Survey
WHE	World Housing Encyclopedia
UNIFORMAT II	A building element taxonomy developed by NIST
NIST	National Institute of Standards and Technology (US)
ACORD	Association for Cooperative Operations Research and Development

1 Introduction

1.1. Purpose of the Project and this Report

This report documents a Building Taxonomy developed for the Global Earthquake Model over the last several years.

The term **taxonomy** derives from Greek, first appearing in French in 1813 and in English in 1819, and amalgamates *taxis,* meaning arrangement or order, and *nomy,* meaning study of. As generally used taxonomy refers simply to "A classification *of* something; a particular system of classification" [Oxford English Dictionary].

Why, for something as common as buildings, is a taxonomy needed? The taxonomy of animals, plants and minerals begun by Carl Linnaeus in his *Systema Naturae* [1735] created a framework which allowed scientists around the world to have assurance they were discussing the same thing, and to begin to see relationships between these things which had not previously been apparent. While Linnaeus' taxonomy was not the first, and has now been superseded by more modern systems, it was an important step towards creating order out of chaos. Today, for buildings, we don't have a system of classification; the GEM Taxonomy has been created to fill this need.

We don't have one unified or standardized system of classification, or rather we have numerous systems, each created to serve a special purpose. Examples of building classifications are those used for building codes, for fire protection, seismic design and energy efficiency. Many of these classifications are specific to only one country or region, are often overlapping and with much mixing of concepts. The City of New York's Building Classification [NYC, 2013] for example, combines in one system items such as ***A7****: Mansion or Town House,* ***G5****: Gas Station with Enclosed Workshop,* ***K5****: Diner - Franchised Type Stand,* ***K7****: Funeral Home,* ***M4****: Convent,* ***O2****: Office Building; 10+ Stories - Side Street Type,* ***Q7****: Tennis Court,* ***RP****: Outdoor Parking,* ***Z5*** *United Nations,* ***Z6****: Land Under Water, and* ***Z8****: Cemetery.*

The purpose of the GEM Building Taxonomy project therefore has been to develop a building taxonomy that, first and foremost, meets the needs of various GEM User Groups. These needs are daunting – to begin with, the Taxonomy is global in nature – it must be able to describe all building types in the world! Chapter 2 of this report provides a brief overview of global building types, as a glimpse of how challenging is this requirement. Given the open nature of GEM, the taxonomy should also meet the information needs of current users, as well as the needs of future users. The Taxonomy should be flexible, enabling users to collect information in the required detail (provided that such information is available) while at the same time be manageable – that is, it should accommodate both *breadth*, and *depth*.

Beyond meeting the needs of GEM, the vision for the Building Taxonomy has been to lay the foundation for a universal building description system that can grow to be used by many disparate groups, ranging from engineers, architects, builders ,and planners, scientists, economists and insurers, to parents, neighbourhood groups, social workers and artists.

Towards these goals, the GEM Building Taxonomy has been shaped by the following key considerations:

International in scope. As far as possible the Taxonomy should be appropriate for any region of the world. It should not favour any one region but rather be technically and culturally acceptable to all regions.

Detailed. The Taxonomy must include as many features as is feasible that are relevant to, initially, the seismic, and later other, performance objectives of a building located anywhere in the world. Initially, the Taxonomy will need to capture all aspects of the seismic performance and losses for an entire building, including structural and non-structural components (but we don't capture this in detail), the "before" and "after" states of common seismic retrofits and between "ductile and non-ductile" systems.
Collapsible. A taxonomy is collapsible if taxonomic groups can be combined and the resulting combination still distinguishes differences in seismic performance from other combinations, albeit with some loss of precision.
Extensible. All future data needs can't be foreseen, so the Taxonomy will also have to lend itself to future extensions – i.e., be 'growable'. In the future the Taxonomy if required should be able to grow to include hazards such as flood, wind, volcanoes, fire and explosion, hazardous material release, biohazards, and terrorism. Beyond such hazards, there are many other taxonomic needs, such as energy efficiency, interior pollutants, life-cycle considerations such as maintenance and recyclability, habitability, aesthetics and handicapped requirements, all of which could be addressed in theory by a unified Taxonomy.
User-friendly. The taxonomy should be straightforward, intuitive, and as easy to use as possible, by both those collecting data, those arranging for its analysis and those who are end users.

1.2. History of Project

As part of the Global Earthquake Model (GEM) initiative, several projects related to physical earthquake risk estimation were initiated in 2010. Each project covered a specific research component of the global earthquake risk estimation problem, such as, i) the development of a global exposure database (GED4GEM), ii) development of an earthquake consequence database of past earthquakes (GEMECD), iii) development of seismic vulnerability functions (Global Vulnerability Consortium) and iv) development of tools or a toolkit for inventory and vulnerability data collection (GEM IDCT). These four components have attempted to address several questions pertaining to understanding the global building stock, mapping the building stock inventory and their vulnerability characteristics, documenting their performance in past earthquakes, and developing tools to compile/document such characteristics using consistent processes worldwide.

The development of a global earthquake risk model requires a solid methodological foundation and terminology to achieve a shared understanding across the many fields and endeavours GEM addresses. The global building stock is highly heterogeneous in terms of design and construction practices, and its vulnerability to natural hazards. A common terminology or *taxonomy* is critical to document variations in building design and construction practices around the world, and has quickly been seen as vital to serving the needs of the various GEM Risk components, and for risk estimation in the GEM project. In order to develop the GEM Building Taxonomy, key tasks in the development process have been:

i. to review existing taxonomies,
ii. to develop the taxonomy, and
iii. to validate the taxonomy on a global level.

A preliminary version of the proposed GEM Building Taxonomy (Beta Version 0.1) was released in April 2011 [Brzev, Scawthorn, Charleson, and Langenbach, 2011], following the discussions and critique at the first Workshop held in Berkeley (March 3 and 4, 2011). The Taxonomy was substantially revised following the feedback received from the GEM Global Component project teams and participants at the second Workshop held in Pavia, Italy (May 25, 2011). Version 1.0 of the GEM Building Taxonomy was released in March 2012 and contained eight key attributes describing a building [Brzev, Scawthorn, Charleson, and Jaiswal, 2012]. The taxonomy was further revised and the current version 2.0 was created following feedback received from GEM researchers in September and October 2012. This report completes the final Version 2.0 of the GEM Building Taxonomy.

1.3. Organisation of Report

Chapter 2 of this report is a brief overview of the Global Building Environment – a discussion (necessarily limited) of the world-wide variety of buildings, in order to illustrate the great number of factors influencing seismic performance of buildings and environmental/climatic considerations that often govern building form and materials. Chapter 3 starts with a history of building classifications, followed by an overview of existing structural/building taxonomies and taxonomies from other fields. Chapters 2 and 3 are intended to lay the foundation for the reasoning that went into the development of the GEM Building Taxonomy, which is presented in Chapter 4. Chapter 5 discusses the process by which the GEM Building Taxonomy was validated, Chapter 6 discusses uses of the GEM Building Taxonomy, and Chapter 7 provides recommendations for future development. The report closes with a list of references and a rich appendix.

2 The Global Building Environment

The GEM Building Taxonomy is to be applicable worldwide. In order to provide background and understand the complexities of describing buildings worldwide, this chapter provides a brief overview of the development and variety of buildings around the world.

> **Building** (n): "a *usually roofed and walled structure built for permanent use (as for a dwelling)*" (Merriam-Webster Dictionary).
>
> **Building** (n): "a shelter comprising a partially or totally enclosed space, erected by means of a planned process of forming and combining materials" [ASTM E-631-06, 2006]

Basically, a building's primary purpose is to shelter (from direct harsh effect of weather like rain, wind and sun, and sometimes security from threats like animals or humans) things we value – humans, property of any kind, and things we hold sacred.

2.1. Earliest Beginnings

In the beginning, genus *Homo* probably took shelter in nests, caves and trees. What may be the oldest remains of a building have been found on a hillside north of Tokyo, and date from about 500,000 years ago[1], Figure 2.1. Prior to that discovery, the oldest remains of a building were believed to be in Terra Amata, France, dating from perhaps 400,000 years ago.

Homo Sapiens are believed to have developed about 200,000 years ago, and have left extensive evidence of shelter-building. However, the oldest existing buildings in the world are not shelters for the living, but were built as shelters for the dead. There are many such burial structures, with perhaps the oldest existing example being the Cairn of Barnenez in Brittany, France, dating from about 4800 BCE (BCE stands for Before Common Era; for Common Era dates, no acronym will be used - for reference, this report's year of preparation is 2013 Common Era), Figure 2.2. In the Americas, Sechin Bajo in Peru dates from about 3,500 BCE, while in Africa the first Egyptian pyramid (Pyramid of Djoser, 2700 BCE) is considered to be the earliest large-scale cut stone construction. In Asia, the remains of a well-planned town, including brick water reservoirs, were found at Dholavira, Gujarat, India (2600 BCE). By comparison, the Parthenon in Athens, Greece dates from 472 BCE (Figure 2.3).

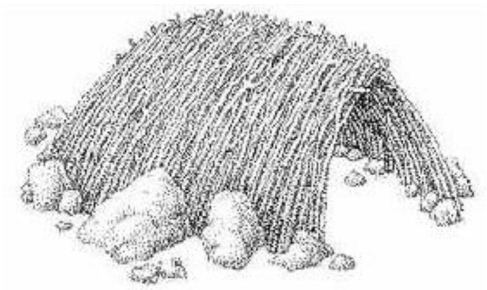


Figure 2.1 Artist's image of what may be the oldest remains of a building (perhaps 500,000 BCE)[2]

Figure 2.2 Cairn of Barnenez, Brittany, France (4800 BCE)[3]

[1] http://news.bbc.co.uk/2/hi/science/nature/662794.stm accessed 26 June 2013

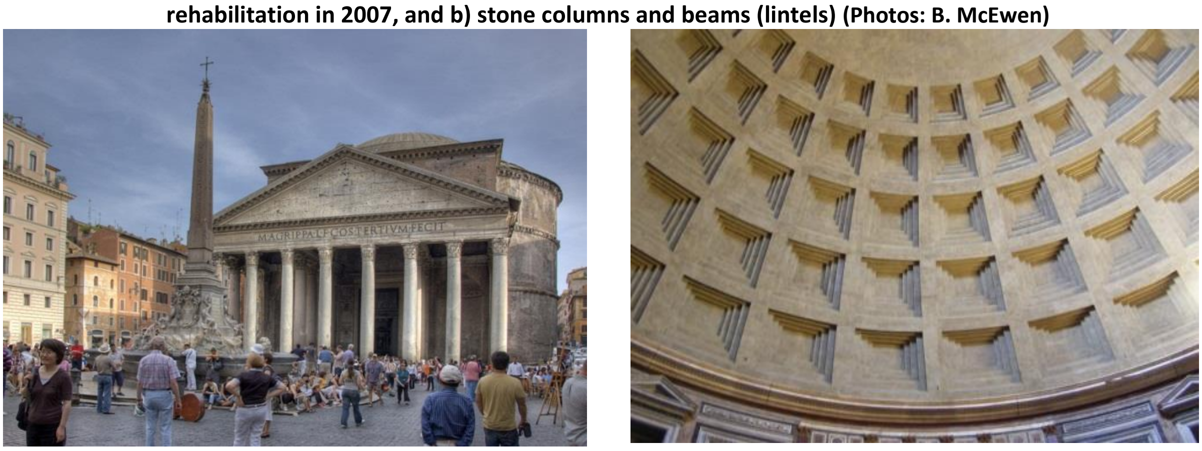
[2] http://news.bbc.co.uk/2/hi/science/nature/662794.stm

[3] http://en.wikipedia.org/wiki/File:Barnenez_front2.jpg

The oldest standing building still in regular use is the 43.3 m diameter domed Pantheon in Rome, Italy, dating from 125 (Figure 2.4a). The dome design was ingenious in that its thickness progressively decreases towards the top, and lighter materials were used in the upper part of the dome. Sunken panels (lacunari) in the interior of the dome were provided to reduce the overall weight, as shown in Figure 2.4b. Roman concrete, *opus caementicium*, made using pozzolana (volcanic ash) was used in the Pantheon construction.

a) b)

Figure 2.3 Ancient Greek temple Parthenon, Athens, Greece (500 BCE): a) a view of the temple during the structural rehabilitation in 2007, and b) stone columns and beams (lintels) (Photos: B. McEwen)



a) b)

Figure 2.4 Pantheon, Rome, Italy (built 125): a) an exterior view[4], and b) interior view showing dome (Photo: S. Brzev)

These and many similar surviving buildings that are thousands of years old typically owe their survival to their *sacred* nature. Sacred buildings – places of worship and tombs of venerated people – are typically the longest surviving types of structures, due both to the value placed in maintaining their existence, and also due to their being intended to endure – that is, being built of the most durable materials. All of the surviving ancient buildings mentioned above were built of stone or earth. It took more than two million massive stone blocks to build the Great Pyramid of Cheops at Giza, Egypt (2560 BCE), shown in Figure 2.5. At height of 147 m (equivalent to a 50-storey building) it was the world's tallest structure for 3,800 years, until surpassed by Lincoln Cathedral (England) in 1311. Ziggurats, terraced step pyramids made of sun-dried bricks, were sacred buildings typical for the ancient Mesopotamian valley and western Iranian plateau. The world's best preserved Ziggurat is Choga Zambil temple complex in Iran, built between 1275 to 1240 BCE (Figure 2.6). The main temple has plan dimensions of 105 m square and its original height was 52 m. Sacred, government and wealthier

[4] http://en.wikipedia.org/wiki/Pantheon,_Rome

residential buildings tend to be 'built to last', which in ancient times meant using earth and stone, however there are a few examples of other materials. The oldest surviving wood building, also a sacred building, is the pagoda of Horyu-ji Temple, Japan, dating from about 594 (Figure 2.7a), closely followed by the Jokhang Temple in Tibet (639). The Great Buddha Hall in Nara, Japan was originally built in 752 (the current building dates from 1709), Figure 2.7b, and, until a few years ago, was the world's largest wooden building.

Figure 2.5 The Great Pyramid of Cheops at Giza, Egypt (Photo: C. Scawthorn)

Figure 2.6 Chogha Zanbil Ziggurat, Iran

(Photo: S. Moarefi)

a)

b)

Figure 2.7 Japanese wooden buildings: a) Horyu-ji Temple, Japan[5], and b) Daibutsuden (Great Buddha Hall) at Todai-ji Temple, Nara, Japan, 752 (current building 1709), until recently world's largest wooden building[6]

The oldest surviving non-sacred building may be the Mousa Broch in Scotland, a fortification dating from about 100 BCE, Figure 2.8, although the Arg-e Bam, Iran, destroyed in the 2003 Bam earthquake had earlier origins (but primarily dated from the 7th~11th centuries).

Perhaps the best examples of early buildings are the reconstructions of structures preserved by the eruption of Mt. Vesuvius, Italy in 79, Figure 2.10 , some of which used timber frame and masonry infill construction, similar to vernacular buildings discussed later in this chapter. The oldest still-inhabited building is perhaps the thatch-roofed Kirkjubøargarður in the Faroe Islands, Denmark dating from about the 11th century, Figure 2.11.

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[5] http://en.wikipedia.org/wiki/File:Horyu-ji11s3200.jpg
[6]http://upload.wikimedia.org/wikipedia/commons/thumb/c/cd/Daibutsu-den_in_Todaiji_Nara02bs3200.jpg/300px-Daibutsu-den_in_Todaiji_Nara02bs3200.jpg

Figure 2.8 Mousa Broch (round tower), Scotland[7]

Figure 2.9 Arg-e Bam, Iran before the 2003 Bam earthquake[8]

Figure 2.10 Casa a Graticcio, Herculaneum, Italy, 79[9]

Figure 2.11 Kirkjubøargarður, Faroe Islands, Denmark[10]

2.2. Construction Materials, Climate, Building Forms, and Functions

Selection of construction material and building form are determined to a significant degree by climate. Climate drives a key requirement for a building: warmth in cold climates and ventilation in hot humid climates, and climate also determines the availability of building materials. Climates were first usefully classified by Wladimir Köppen in 1884, with several later modifications by Köppen and Geiger. Concurrently, a broader concept of "life-zones" was developed by C. Hart Merriam in 1889, which was later superseded by Holdridge [1947]. The Holdridge Life-Zones system is a global bioclimatic classification scheme for land areas. In general, this classification is well suited for tropical vegetation zones, Mediterranean zones, and boreal zones, and is less appropriate for cold oceanic or cold arid climates (moisture being the determining factor). The Life-Zones are arranged in a multi-dimensional scheme based on Precipitation (annual, logarithmic), Biotemperature (mean annual, logarithmic), Potential Evapotranspiration ratio (PET) and Mean Total Annual Precipitation. Further indicators incorporated into the system are humidity, latitude, and altitude. The scheme is shown in Figure 2.12, and, as used by the International Institute for Applied Systems Analysis (IIASA), has a total of 38 bioclimatic classes, shown in Figure 2.13. Because key determinants of the Life Zones are effectively temperature and humidity Figure 2.12 can be very approximately partitioned into three general zones – those where: i) wood is prevalent for building, ii) insulation is required against extremes of temperature (heat or cold), and iii) ventilation is required due to humidity. This partitioning is shown in Figure 2.14. In general, the

[7] http://en.wikipedia.org/wiki/File:Mousa_Broch_20080821_02.jpg
[8] http://en.wikipedia.org/wiki/Arg-%C3%A9_Bam
[9] http://en.wikipedia.org/wiki/File:Casa_a_Graticcio.jpg
[10] http://en.wikipedia.org/wiki/File:Faroe_Islands,_Streymoy,_Kirkjub%C3%B8ur_%281%29.jpg

closer to the lower right corner of the region in the Holdridge Life-Zone triangle, the less wall mass that region's buildings will have, while the closer to the other two corners, the more wall mass will be required against temperature extremes. The further left a region is in the triangle, the more recourse the population will have for earth and stone for building materials. Of course, while wood may be indicated as relatively prevalent, population may outstrip the demand for wood, requiring recourse to earth and stone.

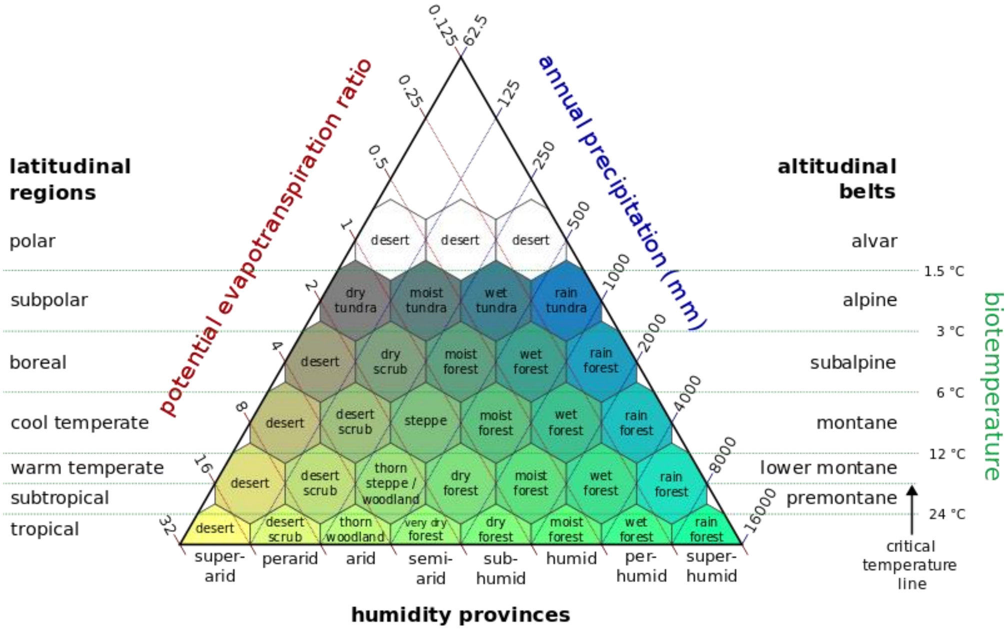

Figure 2.12 Holdridge Life-Zone Global System[11]

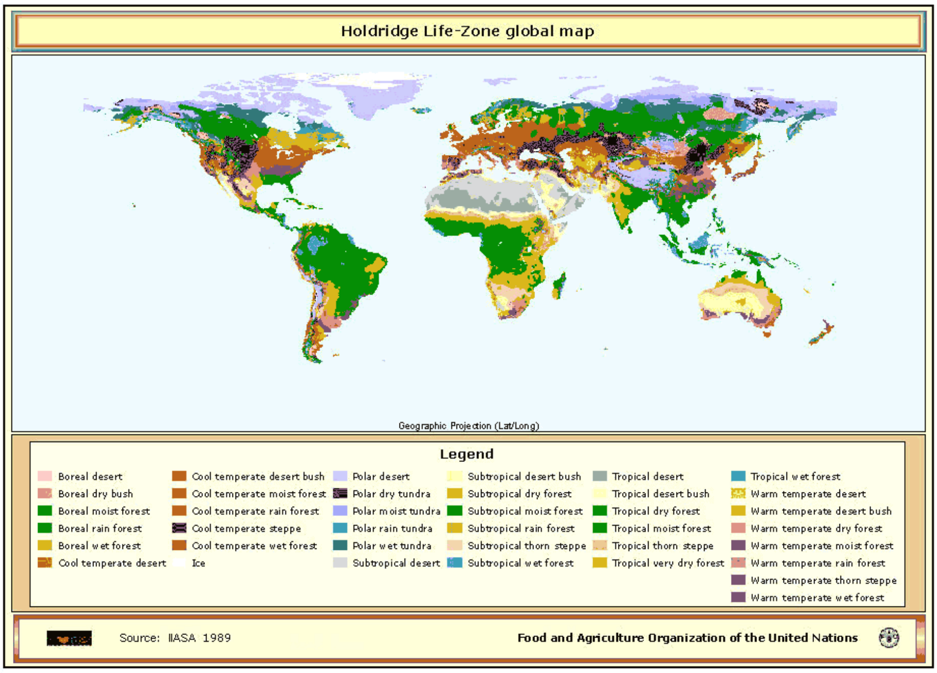

Figure 2.13 Holdridge Life-Zone Global Map[12]

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[11] http://en.wikipedia.org/wiki/File:Lifezones_Pengo.svg

[12] http://www.fao.org/geonetwork/srv/en/graphover.show?id=1006&fname=1006.gif&access=public

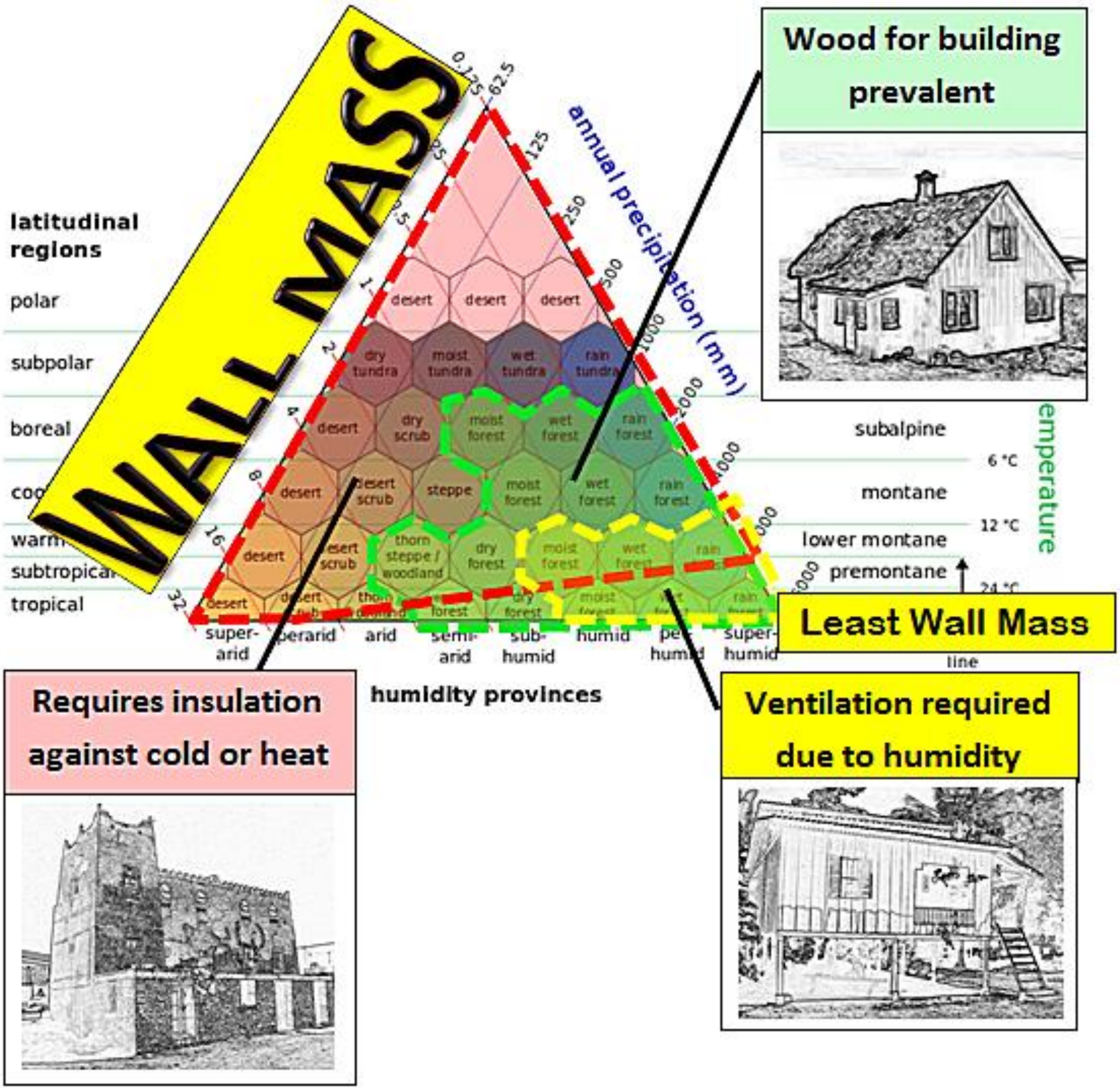

Figure 2.14 Holdridge Life-Zone Global System partitioned for impacts on Building Materials and Form

Using the materials at hand, a building's form usually derives from the function it serves in that society. Prior to the Industrial Revolution, most commerce and industry was farm- and cottage-based, so that the function of most buildings was residential, agricultural, government, military or religious. Residential buildings' size and organization reflect how the family and society are organized, from single-family rural housing in Chile, Figure 2.15, to communal long houses in Vietnam, Figure 2.16. Geography and economics play very important roles, as in the defensive cliff-side dwellings of Cappadocia, Turkey (Figure 2.17), the pueblos of the US southwest, (Figure 2.18), medium-rise apartment buildings in Denmark (Figure 2.19), or high density modern apartment towers in countries like China or India (Figure 2.20).

Figure 2.15 Rural single-family dwellings, Chile (Photo: S. Brzev)

Figure 2.16 A long house of E De people in Vietnam[13]

Figure 2.17 Cliffside dwellings, Cappadocia, Turkey (Photo: C. Scawthorn)

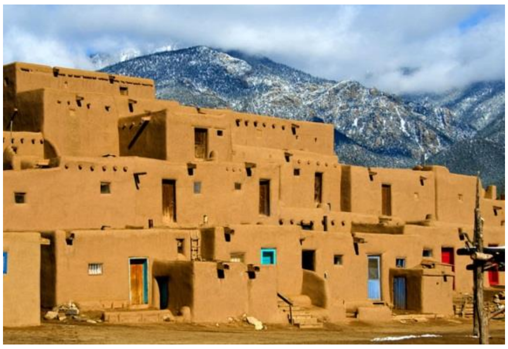

Figure 2.18 New Mexico, US, pueblo[14]

Figure 2.19 modern apartment block, Denmark (Photo: C. Scawthorn)

Figure 2.20 Modern apartment buildings, Beijing, China (Photo: S. Brzev)

Historically, government buildings often combined official and military functions, and were typically designed to communicate majesty and power, Figure 2.21. Structures primarily military in function typically feature layered defences (e.g., walls and moats) with actual buildings being a small part of the overall fortifications, Figure 2.22. With the rise of more representative and democratic governments, modern government buildings often display more open-ness while still also attempting to convey the gravity of government, Figure 2.23.

[13] http://commons.wikimedia.org/wiki/File:E_De_long_house.png
[14] http://santafe.org/Visiting_Santa_Fe/Indian_Pueblos/

Similarly, religious buildings' form is typically strongly driven by a message, as well as that they are typically large assembly halls.

Figure 2.21 Older government buildings: Hall of Supreme Harmony, Forbidden City, Beijing, China (1406, rebuilt 1695) (Photo: S. Brzev)

Figure 2.22 A monumental government building complex: Osaka Castle, Japan[15]

Figure 2.23 A modern government building: Palace of Assembly Chandigarh, India[16]

With the advent of the Industrial Revolution, the need to shelter large machinery and massive increases in goods resulted in new industrial buildings of various forms, including power plants (Figure 2.24), factories (Figure 2.25), and warehouses. Administering these enterprises required larger and larger office buildings (Figure 2.26), and larger and larger transportation hubs to bring workers to these buildings (Figure 2.27).

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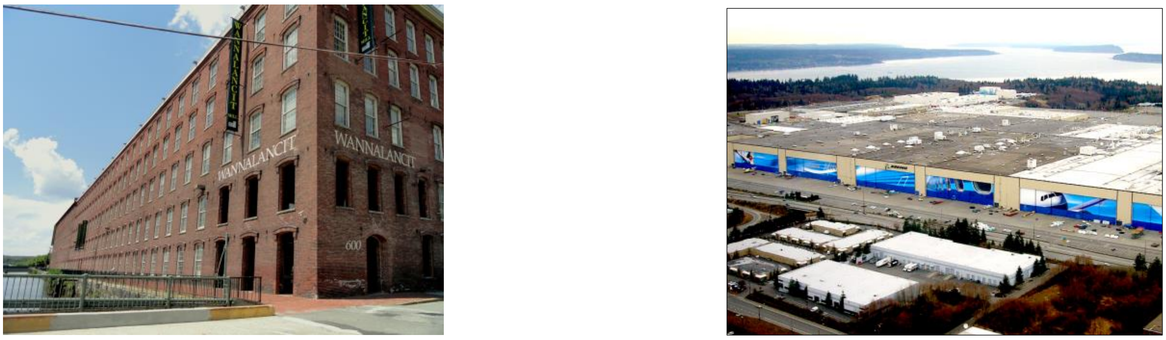
[15] http://commons.wikimedia.org/wiki/File:Osaka_Castle_02bs3200.jpg
[16] 16 http://commons.wikimedia.org/wiki/File:Palace_of_Assembly_Chandigarh_2006.jpg

a) b)

Figure 2.24 Power plants: a) Dutch wind mill, and b) Battersea Power Station, London (Photos: C. Scawthorn)



a) b)

Figure 2.25 Factories: a) Wannalancit Mill, Lowell MA, c. 1830[17], and b) Boeing Factory, Everett WA (world's largest building, by volume)[18]

a) b)

Figure 2.26 Office buildings: a) Equitable Life Assurance Building, 1870, New York – first building to use elevators[19]; and b) Woolworth Building, 1912, New York[20]

[17] http://commons.wikimedia.org/wiki/File:Wannalancit_Mills_-_University_of_Massachusetts_Lowell_-_DSC00092.JPG
[18] http://en.wikipedia.org/wiki/Boeing_Everett_Factory

a)

b)

Figure 2.27 Transportation hubs: a) Hamburg Main Station, Germany1906[21], and b) Aerium, Brand-Briesen Airfield, Germany, 2000, largest freestanding hall in the world[22]

2.3. Vernacular Buildings

Since the aim of the GEM project is global coverage it is necessary to ensure vernacular buildings are included in the building taxonomy. Vernacular architecture refers to architecture based on localized needs and construction materials, and reflecting local traditions[23]. It can be described as "architecture of the people, and by the people, but not for the people" [Oliver, 2003]. Vernacular buildings are generally constructed by homeowners or builders without technical training and are often referred to as non-engineered buildings. The majority of vernacular buildings are residential buildings (dwellings). This type of building cannot be ignored because it comprises more than 90% of the world's building stock [Vellinga et al., 2007]. Oliver [2003] believes that a very small fraction (1 %) of all dwellings in the world (estimated as 1 billion in total) were designed by architects. According to Vellinga et al. [2007], vernacular buildings are mainly confined to developing countries and are inhabited by people from over 2000 different cultures. Houses in informal or squatter settlements are included in this building type, and in 2001 they provided shelter for some 32% of the urban population, or 20% of the world's population. A detailed overview of vernacular buildings around the globe is presented in Oliver [1997, 2003]; Vellinga, Oliver, and Bridge [2007]; and Langenbach [2009]. EERI and IAEE World Housing Encyclopedia [EERI, 2000, 2004] offers a wealth of information related to global vernacular housing, including their socio-economic, architectural, structural and seismic features, as summarized by Sassu [2004].

Vernacular dwellings are usually designed keeping in mind economic and social needs, protection from the elements, and a need to provide a liveable atmosphere for the occupants. Seismic safety of these buildings is often not among the key design considerations. In some areas of the world, such as Maharashtra, India, heavy earthen roofs and thick stone walls have been used for traditional housing construction (Figure 2.28a) despite the implications for seismic vulnerability – roof type was primarily a response to day-to-day comfort

[19] https://en.wikipedia.org/wiki/File:Equitable_Life_Assurance_Building_1870.jpg
[20] http://commons.wikimedia.org/wiki/File:Woolworth_bldg_nov2005c.jpg
[21] http://en.wikipedia.org/wiki/File:Hamburger_Hauptbahnhof.jpg
[22] http://upload.wikimedia.org/wikipedia/commons/thumb/0/04/Brand_Cargolifter_Halle.jpg/220px-Brand_Cargolifter_Halle.jpg
[23] http://en.wikipedia.org/wiki/Vernacular_architecture

(considering warm climate where seasonal temperatures exceed 40° C) and functional needs [INTERTECT, 1984].

Most vernacular buildings are low-rise (one- or two-storey high); this is due to limitations in construction materials and techniques and also social needs, since most of these buildings are providing shelter for single families. Vernacular buildings usually have a simple plan shape (square, rectangular, or circular) and structural layout. Buildings with circular plan shape have demonstrated good performance in past earthquakes. *Bhonga,* vernacular construction practice from Gujarat, India, has a circular plan shape, earthen walls and bamboo reinforcing bands at the lintel and collar level, Figure 2.28b [Choudhary, Jaiswal, and Sinha, 2002]. *Bhonga* construction has been practiced for several hundred years in the Kutch area of Gujarat, India, which is characterized by high seismicity, and showed very good performance in the 2001 Bhuj earthquake (M 7.6).

a) b)

Figure 2.28 Vernacular buildings and seismic resilience: a) traditional stone masonry dwellings in Maharashtra, India are at risk due to heavy timber roofs with earthen overlay, and b) traditional *Bhonga* construction in Gujarat, India has shown good seismic performance due to circular plan shape and light roof (Photos: a) S. Brzev and b) K. Jaiswal)

Spaces in a building are created by the enclosing walls and roof, which must resist the downward force of gravity on their mass, as well as resist lateral and other forces due to wind, earthquake and other phenomena. Bearing walls are the most common structural system for vernacular buildings. Materials used for vernacular building construction are predominantly stone, earth, and wood.

Stone masonry is a traditional form of construction that has been practiced for centuries in regions where stone is a locally available material. Buildings of this type range from cultural and historical landmarks, often built by highly skilled stonemasons, to simple owner-built dwellings built in developing countries where stone is an affordable and cost-effective building material for housing construction. Stone masonry buildings can be found in many earthquake-prone regions and countries including Mediterranean Europe, North Africa, the Middle East, and Southeast Asia, as illustrated in the World Housing Encyclopedia [EERI, 2000] and Bothara and Brzev [2011]. Stone masonry is considered to be one of the most seismically vulnerable types of masonry; this is due to the heavy mass of stone masonry buildings and limited strength of stone masonry. Seismic performance of vernacular stone masonry buildings can be improved by providing horizontal reinforcement in the form of wooden members; this practice has been followed in countries like India, Pakistan, Nepal, Turkey, Algeria, etc.

a) b)

Figure 2.29 Stone masonry construction: a) typical random rubble stone masonry dwellings in Marrakesh, Morocco, and b) a stone masonry building with horizontal timber reinforcement, Pakistan (Photos: a) C. Scawthorn, and b) J. Bothara)

Earth (often referred to as mud) is used for the construction of a large fraction of vernacular buildings. An example of earthen construction is rammed earth, where earth is compacted by hand or mechanically into formwork that is then removed and the wall is allowed to dry[24], Figure 2.30a. Alternatively, earth is used for masonry construction, which involves the use of masonry units (stone boulders, bricks, or blocks); mortar as a binding agent, and reinforcement (when provided). The first masonry units were sun-dried bricks (adobe), with the oldest examples being from about 8000 BCE [Houben and Guillard, 1994]. Use of adobe is very common in some of the world's most hazard-prone regions, such as Latin America, Africa, Indian subcontinent and other parts of Asia, Middle East and Southern Europe. Around 30% to 50% of the world's population (approximately three billion people) lives or works in earthen buildings [Rael, 2009].

Traditional unreinforced adobe wall buildings (Figure 2.30) are considered to be one of the most seismically vulnerable building typologies that have caused significant human and economic losses in past earthquakes in Latin America (e.g. 1970 Peru and 2001 El Salvador) and Middle East (2003 Bam, Iran earthquake). Seismic performance of adobe buildings is influenced by roof type; buildings with lighter roofs tend to perform better in earthquakes, while adobe buildings with heavy earthen roofs caused significant fatalities in the 2003 Bam, Iran earthquake[25] (Figure 2.43b). Several viable approaches for reinforcing adobe buildings were outlined by Scawthorn [1986] and Blondet et al. [2011].

a) b)

Figure 2.30 Earthen construction: a) a rammed earth houses in Afghanistan, and b) an adobe house in Peru (Photos: a) Aga Khan Development Network, and b) N. Tarque).

[24] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/rammed-earth--etr

[25] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/vaulted-earthen-roofs--re1

Burnt (fired) clay bricks have also been widely used for vernacular construction. “Firing” brick – that is, heating it to high temperatures – causes fusing of the clay and silica and greatly increases resistance to wind and rain. The earliest instances of fired brick are from about 4500 BCE in the Indus Valley. The fabrication process ranges widely depending on the available technology – from simple kilns found in rural areas of developing countries to highly industrialized continuous process. The size of bricks is dictated by the human hand – the width should be no more than can be picked up using the thumb and fingers of one hand. The standard size of bricks varies with the climate – larger bricks are better insulation for colder climates – and vary from about 92 mm width in the US to 110 mm in countries like Russia and India; other dimensions typically being in an approximate ratio of 4:2:1 (length:width:depth). Brick masonry has been used for construction of vernacular buildings for many centuries, particularly in Mediterranean Europe, Latin America, and Asia. An example of medieval unreinforced masonry building in Italy is shown in Figure 2.31a. Seismic performance of these buildings is influenced by building plan configuration, building height, and masonry strength which is in turn influenced by the type of mortar. In most instances, vernacular brick masonry walls do not contain any form of external or internal reinforcement. However, there is an example of timber-laced masonry bearing wall construction known as *Taq* in Kashmir, India and *Bhatar* in Pakistan, Figure 2.31b. It is a composite structural system with a modular layout of loadbearing brick masonry piers and window bays tied together with horizontal timbers in a ladder-like arrangement; the timbers are embedded in the masonry walls at each floor level and window lintel level [Langenbach, 2009].

Several vernacular building typologies utilize both timber and masonry components. For example, *Dhajji Dewari* construction from Kashmir (India and Pakistan) has a brick masonry wall structure confined with horizontal, vertical, and diagonal (cross) timber members, Figure 2.32a. The term is derived from a Persian word meaning “patchwork quilt wall”, which is reflective of its appearance [Langenbach, 2009]. A similar building typology is known as *Himiş* in Turkey and neighbouring countries influenced by the Ottoman Empire. Another similar building typology is known as *Pombalino* in Lisbon, Portugal (Figure 2.32b). These historic masonry buildings with wooden bracing members were built after the devastating 1755 Lisbon earthquake [Cardoso, Lopes, Bento, and D’Ayala, 2002]. It should be noted that similar vernacular construction practices exist in a few other European countries, e.g. *Colombage* in France, *Fachwerk* in Germany and “half-timber” in Great Britain [Langenbach, 2009].

a) b)

Figure 2.31 Brick masonry construction: a) a typical historic single-family house in Italy, and b) *Taq* construction in Kashmir, India (Photos: a) D’Ayala, E. Speranza, and F. D’Ercole, and b) D.C. Rai and C.V.R. Murty)

a) b)

Figure 2.32 Composite timber and brick masonry construction: a) *Dhajji Dewari*, Kashmir, India, and b) a *Pombalino* building, Lisbon, Portugal (Photos: a) D. Rai, and b) S. Brzev)

A form of composite earth and timber construction, known as *Quincha* in Peru, has been practiced for centuries in Central and South America, where *Quincha* walls are built using wooden sticks or reeds plastered with mud (Figure 2.33a). In Britain this construction practice is known as *Wattle and Daub* [26]. A similar construction, known as *Taquezal* or *Bahareque* in some other Latin American countries, consists of a bamboo or split-lath enclosed basket between timber studs filled with loose earth and stone [Langenbach, 2009]. *Wattle and Daub* construction is common in African countries, mostly in the form of "cone-and-cylinder" huts, such as *Kipsigis* hut in Kenya [Oliver, 2003]. A similar construction in Malawi, known as *Yamata*, consists of reinforced earthen walls and lightweight bamboo and thatched roof, Figure 2.33b [Sassu and Ngoma, 2002].

a) b)

Figure 2.33 Composite wood and earthen construction: a) *Quincha* construction, Peru, and b) *Yamata* construction, Malawi (Photos: a) S. Brzev and b) Ngoma and Sassu)

In general, these composite timber and masonry buildings demonstrated good performance in past earthquakes. In fact, it is believed that these construction practices have emerged based on the good performance of buildings in earthquake-affected regions. For example, traditional Assam construction (India) consists of small-sized wood columns and beams braced by lightweight ikra walls and light roofs, Figure 2.34a [Malladi et al., 2012]. Seismic resilience of Assam building construction was confirmed in the 1897 Assam

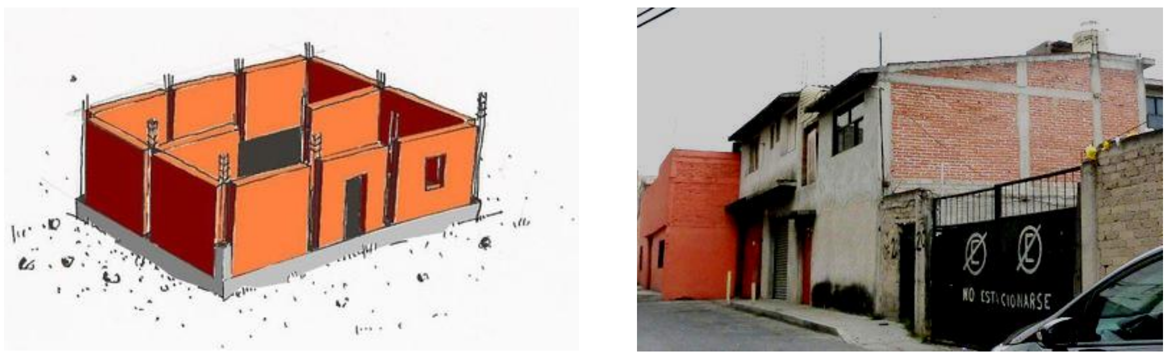
[26] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/wattle-and-daub--wwd

earthquake (M 8.1). Bamboo frame[27] is another form of lightweight earthquake-resistant vernacular construction found in earthquake prone areas of the world, such as Assam (India) and Costa Rica (Figure 2.34b).

a) b)

Figure 2.34 Lightweight vernacular buildings: a) Assam type building, India, and b) bamboo frame construction, India (Photos: People in Centre)

A relatively recent vernacular construction practice is confined masonry[28], a composite masonry and concrete construction practice where masonry walls are first laid and then horizontal and vertical reinforced concrete confining elements are cast, Figure 2.35a. Its concept is similar to that found in some vernacular construction practices mentioned above, such as the Assam type construction (India) and *Taq/Bhatar* (India/ Pakistan). Confined masonry construction has evolved through an informal process based on its satisfactory performance in past earthquakes. The first reported use of confined masonry was in the reconstruction of buildings destroyed by the 1908 Messina, Italy earthquake (M 7.2), which killed more than 70,000 people. Subsequently, its first application in Latin America took place in Chile after the 1928 Talca earthquake (M 8.0) that affected a significant number of unreinforced brick and adobe masonry buildings. In the 1940s the practice was introduced in Mexico (Figure 2.35b) and subsequently in other Latin American countries. Confined masonry has also been practiced in Mediterranean Europe (Italy, Slovenia, Serbia, and Greece), the Middle East (Iran), South Asia (Indonesia), and the Far East (China). In many countries, design provisions for confined masonry buildings have been included in national building codes and standards.



a) b)

Figure 2.35 Confined masonry construction: a) construction sequence, and b) a confined masonry building in Mexico City, Mexico (Illustrations: a) T. Schacher, and b) S. Brzev)

Wood (timber) has been used for low-cost vernacular housing construction for centuries. However, in many regions of the world wood is no longer available or its use for construction is restricted; as a result, some

[27] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/bamboo--wbb

[28] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/masonry-confined--mcf

vernacular wood construction practices are being discontinued. Wooden buildings are usually characterized by frame structural system, which is usually braced to provide lateral load resistance; this can be achieved either by wooden braces, or these frames may be infilled with masonry walls. The latter type of bracing was discussed earlier in this section (e.g. *Taq/Bhatar* system). Wooden buildings are usually lightweight, ductile, and strong, and generally suitable for construction in regions of high seismicity. *Yurta*, a traditional dwelling in Kyrgyzstan, Figure 2.36a, is an example of earthquake-resistant wood construction; its lateral load-resisting system consists of wooden poles forming a frame enclosed by felt tension cloth. These dwellings have circular plan shape and are extremely lightweight [Begaliev and Uranova, 2002]. Wooden buildings may be light weight but have heavy roofs; this increases their seismic vulnerability, as shown by in the 1995 Kobe earthquake. Figure 2.36b is a traditional Japanese house under construction – note the heavy tile roof (weight good for typhoon, bad for earthquake) supported on very few walls with modest bracing; large openings and few partitions promote ventilation during hot humid summers. Seismic performance of wooden buildings is significantly influenced by the roof weight (buildings with heavy roofs are more vulnerable) and the strength of connections. Wooden elements are susceptible to decay due to elements and insects, and may be less durable compared to other materials (e.g. masonry).

a)

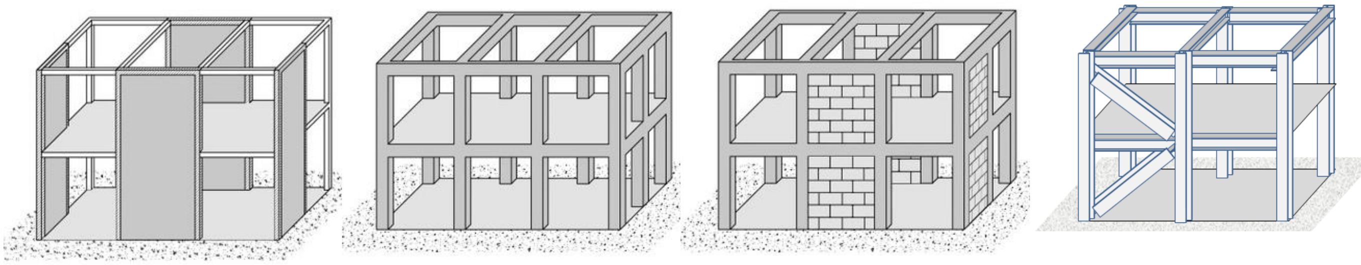
b)

Figure 2.36 Examples of vernacular wood housing: a) *Yurta*, Kyrgyzstan[29], and a) a traditional Japanese house under construction (Photo: C. Scawthorn)

2.4. An Overview of Structural Systems for Buildings

Because the purpose of buildings is to shelter, interior spaces are intrinsic to buildings. The spaces are created by the enclosing walls and roof. A building's structural system must be able to resist the downward force of gravity (due to its own weight, and possibly snow or other loads) and lateral forces due to wind, earthquake and other phenomena. The set of vertical and horizontal components of the structural system that provides resistance against horizontal forces is referred to as the Lateral Load-Resisting System (LLRS). Vertical components of a building's LLRS include columns, bracing, and walls, while horizontal components are beams, floors and roof. There are several common LLRSs, however the basic systems are Wall and various frame systems: Post and Beam, Moment Frame, Infilled Frame, Figure 2.37.

[29] http://commons.wikimedia.org/wiki/File:Kyrgyz_yurt.jpg



a) b) c) d)

Figure 2.37 Lateral load-resisting systems: a) Wall; b) Moment Frame, c) Infilled Frame and d) braced frame (adapted from: A. Charleson, *Seismic Design for Architects*, Architectural Press 2008, p. 64, Fig. 5.2).

Hybrid (mixed) LLRS[30] exists when there is more than one LLRS within a building; this happens to be the case with many buildings in the world, as illustrated in Figure 2.38.

a) b)

Figure 2.38 Hybrid lateral load-resisting systems: a) stone walls with arches below, wood framing with brick or wattle and daub above in a medieval house, Alsace, France, and b) an old loadbearing brick masonry at the ground floor overlaid by new reinforced concrete frame construction above damaged in the 1999 Athens, Greece earthquake (Photos: a) http://commons.wikimedia.org/wiki/File:Riquewihr_029.jpg; b) A. Pomonis)

The earliest structural system most likely involved a combination of Wall and Post and Beam[31] which created a void by supporting a beam (the lintel) on two or more posts, Figure 2.39 . An early example of Post and Beam construction is the Parthenon temple in Athens, Greece (Figure 2.3b). The forces of gravity on the beam above the void are resisted by the posts at the side with the beam resisting downward forces by bending, creating tension forces towards the bottom of the beam and compression forces towards the top. If the posts are held in place by an exterior wall such as in Figure 2.40, or portions of the walls are filled in with for example "wattle and daub", Figure 2.33, the structure may be stable. However, a simple post and beam structure lacking walls has a tendency to 'rack' (i.e., deform and ultimately collapse sideways in a *sidesway* mechanism). This undoubtedly soon led to the development of bracing, whether 'knee-braces' or full storey bracing. The

[30] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/hybrid-lateral-load-resisting-system--lh

[31] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/post-and-beam--lpb

horizontal beam in a Post and Beam structure is subject to bending and must be rather large to span a significant space so that, given the idea of bracing, the concept of a Truss probably soon emerged, Figure 2.40. In a Truss, the individual members can be lighter although some must be able to resist tension (i.e., cannot be earth or stone).

Alternatively, particularly where only materials weak in tension but strong in compression (e.g., stone, masonry) are available, the concept of the Arch emerged, in which materials need to only resist compression. An arch differs from a beam in that primarily only compression forces exist within the "voussoirs" (i.e., the wedge-shaped elements) of the arch, Figure 2.39. Arches seem to have been first built about 1800 BCE, but were first extensively utilized by the Romans. The Colosseum in Rome, Italy (built from 70 to 82) was the first permanent amphitheatre built by ancient Romans, with a 50,000 seating capacity and around 80 entrances (Figure 2.41a). The plan is a vast ellipse, measuring externally 188 m by 156 m. The façade contains 3 tiers of arches and an attic storey – 48 m high (equivalent to a 12 to 15 storey building). Romans used circular and flat arches for buildings, bridges and aqueducts; similar arches continue to be used today. Other types of arches, such as Arabic arches, have been used in many countries with Arabic cultural heritage (Figure 2.41b).

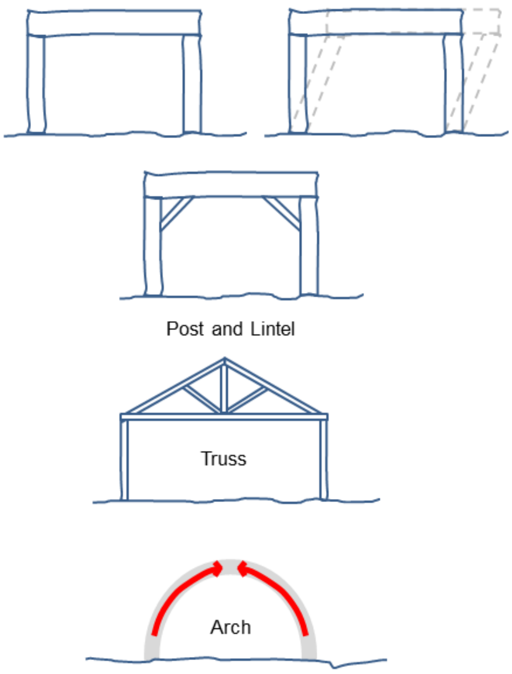


Figure 2.39 Structural systems: Post and Beam, Truss, and Arch

Figure 2.40 Lion Gate at Mycenae, Greece, 13th C. BCE, illustrating Post and Beam construction with lateral support (Photo: S. Brzev)

a) b)

Figure 2.41 Arch structures: a) circular arches in Colosseum, Rome, and b) Arabic arches, Bara Gumbad Mosque, New Delhi, India (Photos: S. Brzev)

Ancient Romans also employed masonry wall construction; the walls were constructed using bricks and/or stone. Examples of Roman wall construction that involves an early application of fired bricks and pozzolana-based mortar can be seen at the Forum Romanum site in Rome, Italy (Figure 2.42).

a) b)

Figure 2.42 Early wall structures: a) Forum Romanum, Rome, Italy, and b) wall detail.

Extension of the arch concept to three dimensions – that is, the dome – occurred in the Ancient Rome, Pantheon Temple (Figure 2.4). The period from the fall of the Roman Empire until the Renaissance in Europe saw great structures built in Europe in the Gothic style, e.g. the Florence Cathedral (Duomo), Italy (constructed in the period from 1296 to 1462). It consists of two brick masonry domes (inner and outer) with the total height 114 m. The dome was constructed without formwork due to a special herringbone brick pattern used in the construction. Taller and taller heights in cathedrals eventually required buttresses, e.g. Notre Dame Cathedral in Paris, France. Domed roofs have also been used for housing in some countries - for example, earthen domed roofs were used in the area affected by the 2003 Bam, Iran earthquake.

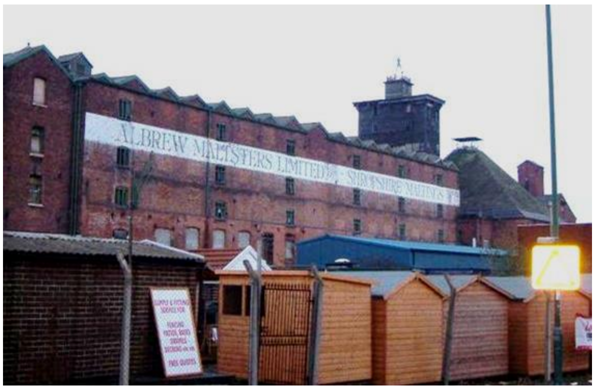
a) b)

Figure 2.43 Dome structures: a) Florence Cathedral (Duomo), Italy , and b) earthen dome roof in a house, Bam, Iran (Photos: a) B. McEwen and b) F. Naeim)

2.5. Modern Engineered Buildings

The early building concepts – mound/pyramid, post and beam, truss and arch/dome, implemented in earth, masonry and timber – remained the only structural systems for buildings until the emergence of new materials in the Industrial Revolution. The early Industrial Revolution only affected mechanical methods for production, which continued to be sheltered in traditional buildings, typically masonry, Figure 2.25. By the 1800s however, a number of innovations were occurring:

- Cast iron emerged as a material for building columns and facades, although the structural system was still Post and Beam. The oldest iron-framed building in the world is the Ditherington Flax Mill in Shropshire, UK, dating from 1797, Figure 2.44a.
- Modular construction was applied to buildings, as exemplified in Paxton's astonishing 1851 Crystal Palace, Figure 2.45.
- The increase in building height necessitated the invention of the elevator. The 'safety elevator' was first demonstrated by Otis in 1854 at New York's Crystal Palace (built in emulation of the larger one in London). The first building with a working elevator was 488 Broadway in New York in 1857, Figure 2.44b, although the Cooper Union building had earlier (1853) been built with an elevator shaft (circular, based on the greater efficiency of that shape) in anticipation of the invention of a safety elevator.
- Inexpensive machine-made nails together with the availability of inexpensive standard sized sawn lumber ("2x4") led to the extensive use of modular wood-framed buildings in North America. "Balloon" framing was introduced in Chicago in the 1830s, and was largely supplanted by platform framing by the 1940s, Figure 2.54a.



a)

b)

Figure 2.44 Cast iron buildings: a) Ditherington Flax Mill, United Kingdom (1797) – oldest iron-framed building[32], and b) 488 Broadway, New York (1854) - first building to have an elevator[33]

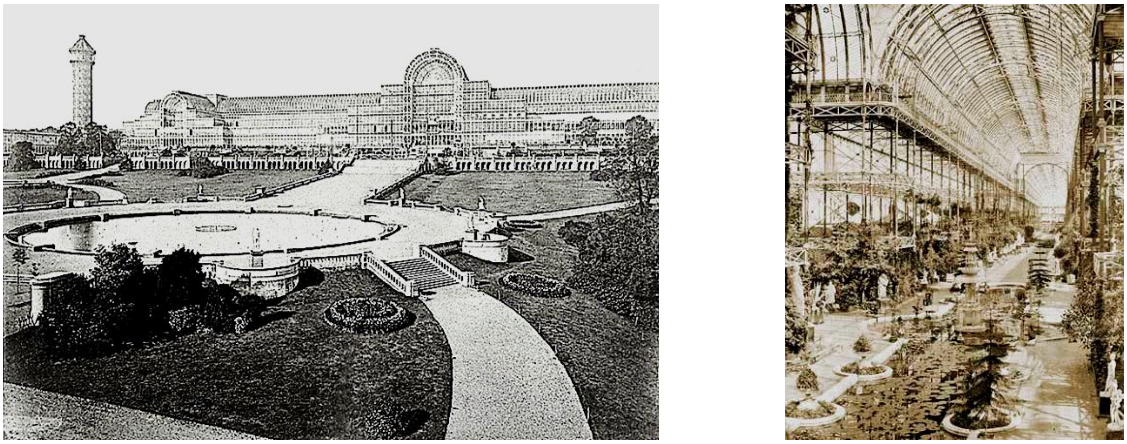
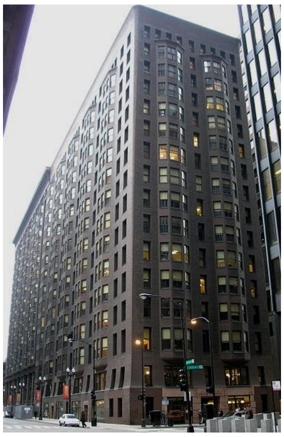


Figure 2.45 Crystal Palace, London, UK (1851)[34]

[32] http://commons.wikimedia.org/wiki/File:Ditherington_Flax_Mill_-_geograph.org.uk_-_295465.jpg
[33] http://en.wikipedia.org/wiki/File:Haughwout_Building_from_west.jpg

Tall residential buildings, as high as ten stories, had apparently existed in antiquity and through the Middle Ages, such as the *insulae* of Rome, tower houses in Bologna, Italy, and high-rise apartments in Yemen[35], but these were all bearing wall construction. Innovations that emerged during the Industrial Revolution combined with rapid urban growth to lead to the demand and potential for significantly taller buildings, which by the 1880s had evolved into a new structural form – the "skyscraper". The Monadnack Building (Chicago, USA) at 17 storeys represented the economical limit that load-bearing masonry could achieve (above this height, the walls simply consumed too much of the floor plan), and the Home Insurance Building, termed the first "skyscraper", avoided this problem by using "curtain" walls supported by a skeletal metal frame, Figure 2.46. As such buildings quickly grew in height, from the 'tallest building in the world' going from 21 stories to 55 stories in just 16 years, Figure 2.47, and have continued albeit at a generally slower pace, Figure 2.48.

a)



b)

Figure 2.46 Skyscrapers - the beginnings: a) Home Insurance Building, Chicago, USA (1884) first 'skyscraper' at 10 stories (later 12)[36], and b) Monadnack Building, Chicago (1889), tallest load bearing masonry building in the world (17 storeys)[37]

[34] Sources: http://en.wikipedia.org/wiki/File:Crystal_Palace_General_view_from_Water_Temple.jpg
http://viewfinder.englishheritage.org.uk/search/reference.aspx?uid=81310&index=0&form=advanced&collection=P%20H%20Delamotte

[35] http://en.wikipedia.org/wiki/Skyscraper#Pre-19th_century

[36] http://en.wikipedia.org/wiki/File:Home_Insurance_Building.JPG

[37] http://en.wikipedia.org/wiki/File:Monadnock.jpg

a) b) c) d)

Figure 2.47 Early New York City skyscrapers: a) American Surety Building (1896, 21 stories); b) Park Row Building (1899, 30 stories); c) Singer Building (1908, 47 storeys), and d) Woolworth Building (1912, 55 storeys)[38]

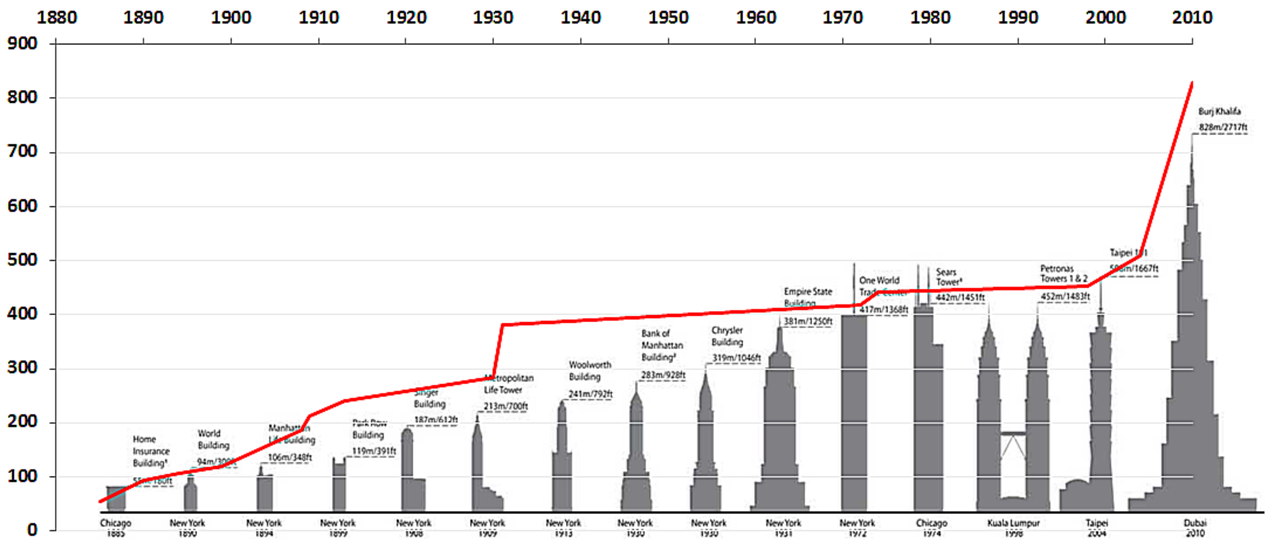


Figure 2.48 Progression of "world's tallest building" 1885-2010[39]

As buildings grew taller, new structural systems were required. The fundamental problem was not gravity loading – that increased approximately linearly with added floors – rather, the problem was lateral loading,

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[38]http://www.officemuseum.com/American_Surety_Bldg_NYC_completed_1896_21_stories.jpg
http://www.officemuseum.com/Park_Row_Building_postmarked_1916.jpg
http://www.officemuseum.com/1908_Singer_Building_highest_office_building_in_the_world.jpg
http://www.officemuseum.com/1913_Woolworth_Bldg_1.jpg
[39] http://www.e-architect.co.uk/images/stories/worlds_tallest_buildings_c110310tb.jpg

which increased approximately as the square of the height so that, for a typical high rise building, the load per column due to wind begins to exceed gravity load above about 15 to 20 stories.

The initial solution was steel and the rigid moment-resisting frame (referred to as Moment Frame in the GEM Building Taxonomy) – a column and beam type frame where however the joint resisted bending forces (“moments”) causing angular deformation of the joint, Figure 2.37b. While only “semi-rigid” connections were first possible, due to the lack of rigidity of riveted construction, a combination of the moment-resistance of beam-column joints together with the resistance of infill to racking allowed taller buildings. As experience was gained, new analytical techniques as well as the emergence of welding for steel, which permitted more rigid connections, led to the development of the rigid connection (Figure 2.49). As shown in Figure 2.50, various systems have evolved to permit ever taller buildings – bracing allowed heights to about 60 stories, and ‘tube’ concepts emerged in the 1960s and 70s which allowed buildings to reach over 100 stories, Figure 2.51.

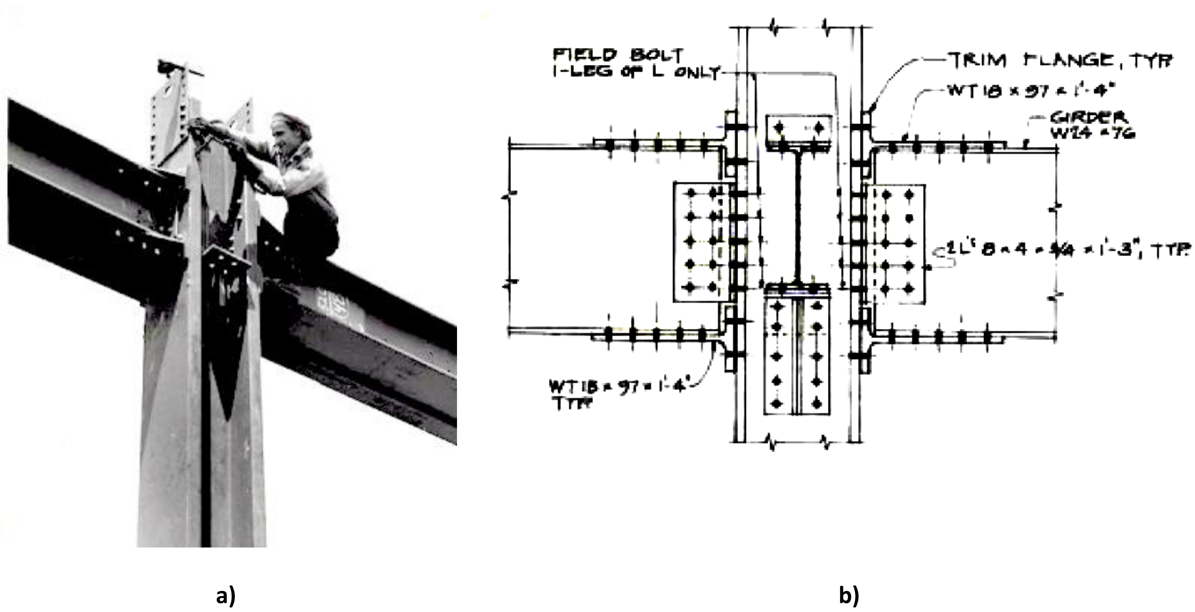


Figure 2.49 Steel moment frame construction: a) Empire State Building rigid frame beam-column connection being assembled – note the flange plate connectors top and bottom of the beam[40]; b) drawing of typical 1930s beam-column moment connection[41]

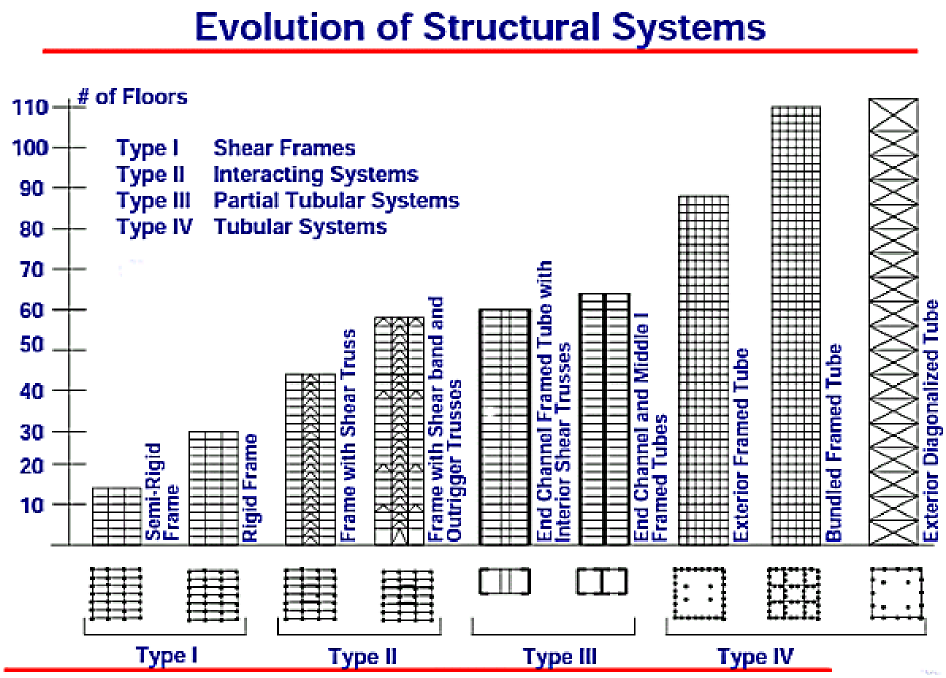


Figure 2.50 Evolution of structural systems[42]

[40] http://www.spicx.com/2012/09/rare-photos-of-empire-state-building.html#axzz2Z0TDjOej
[41] FEMA 355e, 2000
[42] http://en.wikipedia.org/wiki/File:Skyscraper_structure.png

a)

b)

Figure 2.51 Construction of tall buildings: a) World Trade Center, New York, under construction 1971 showing exterior "tube" columns[43], and b) high-rise under construction in Seattle, showing reinforced concrete shear wall around elevator core (Photo: C. Scawthorn)

Concurrently, reinforced concrete emerged as a viable alternative to steel for buildings. Concrete had been known since the time of the Romans, and in fact plain concrete forms the dome of the Pantheon, Figure 2.4b, but after the fall of Rome the techniques for its production were generally forgotten and its use all but disappeared until the 19th century when Portland cement was invented in 1824. Reinforced concrete was invented (1849) by Joseph Monier in France, and the first iron reinforced concrete building was built by Coignet in Paris in 1853. Reinforced concrete, due to its lower use of steel and plastic freedom of form, early found widespread applications – Schussler built the 43 m high concrete gravity-arch dam at Crystal Springs CA in 1888 (placed only 200 m from the San Andreas fault, it survived the 1906 earthquake with no damage) and Ransome built one of the world's first reinforced concrete bridges in San Francisco in 1884 and the first reinforced concrete high-rise building in 1903 (Ingalls Building, Cincinnati OH, 15 stories, Figure 2.52). From this period on, reinforced concrete became a common material for buildings worldwide and was quickly used in many innovative structures, Figure 2.51b. The primary structural systems for reinforced concrete buildings are the moment resisting (rigid) frame, and the shear wall, Figure 2.37. The current world's tallest building, the 828 m Burj Khalifa in Dubai, utilizes a reinforced concrete structural system.

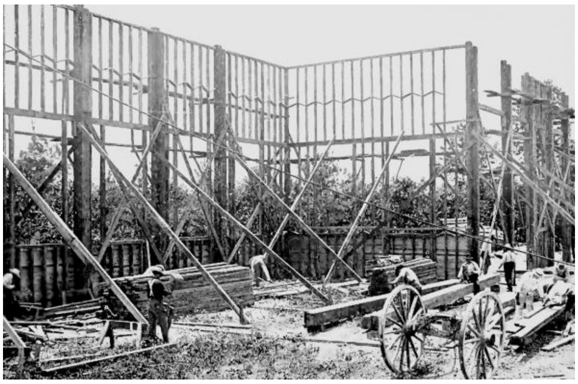
Another innovation that emerged in the late 19th century was the concept of *pre-stressing* concrete – that is, rather than placing steel bars passively in the concrete structure and waiting for the loads to place these bars in tension, the pre-stressing concept takes advantage of the high compressive strength of concrete and the high tensile strength of steel to actively place the concrete in compression by inducing a clamping force transferred to the concrete via steel cables or rods placed in tension within the concrete structure. The concept of pre-stressed concrete was introduced in 1888 by P.H. Jackson in the US but it was only due to the pioneering work of Freyssinet in Europe in the early 20th C. and then Magnel and T.Y. Lin in the US in the 1950s that it caught on as a major structural material.

[43] http://wirednewyork.com/forum/showthread.php?t=21249&page=14

Figure 2.52 Ingalls Building, Cincinnati, OH, USA (1903), 15 stories, first reinforced concrete high-rise building (Photo: C. Scawthorn)

The growth of the US western wood industry together with the invention of a waterproof adhesive in the 1930s led to the introduction of plywood on an industrial scale, which was given great impetus by its use in WW2 for housing, boats and aircraft construction. The post-war demand for housing combined with modular 2x4 wood stud construction led to enormous amounts of wood housing construction in North America, Figure 2.53a. Light wood frame construction is referred to as pre-engineered construction, because its structural systems and components are designed by engineers. This information is communicated to builders via non-technical codes or guidelines so that the engineering requirements of this relatively simple construction can be achieved without any further involvement of engineers.

Recently, metal studs have emerged as an alternative to wood studs, Figure 2.53b. Wood remains a widely used material for construction of single-family housing and apartment buildings (up to six storeys high) in some regions, including North America (particularly US and Canada), Scandinavia, Japan, New Zealand, etc. Modern North American and Japanese low-rise wood frame construction are presented in Figure 2.54.



a)

b)

Figure 2.53 Modular housing construction: a) early North American wood frame construction - balloon framing, 1907[44], and b) steel stud framing, 2000s[45]

[44] http://gluedideas.com/content-collection/Radfords-cyclopedia-of-construction-Vol-3-Framing/House-Framing_P1.html
[45] http://www.manusteelcn.com/2013/01/steel-framing.html

a) b)

Figure 2.54 Modern wood frame construction: a) North American platform framing[46], and b) Japanese house under construction, showing full story diagonal bracing (note, some bracing is only temporary) (Photo: C. Scawthorn)

The use of tension structures was developed in Russia in the late 19th C. by Shukhov but had to wait until the 1960s for better materials, typically fabric membranes, in order to emerge as a new low-cost way to enclose large spaces, and is now widely used for halls and stadia, Figure 2.55.

Figure 2.55 Tension fabric roof – Canada Place, Vancouver, Canada (Photo: S. Brzev)

2.6. Evolution of Earthquake Engineering and Seismic Design

The key problem that GEM addresses is lateral loads due to earthquake. For most of the history of buildings, however, lateral or earthquake loads were not in fact explicitly understood. The downward thrust of mass was used to resist lateral loads, although earthquake after earthquake demonstrated that, while added mass might be useful to resist wind, it was actually counterproductive for earthquake. Because earthquakes were relatively infrequent, the lessons were forgotten time after time, as following the 1755 Lisbon earthquake, when the *Pombalino* building system that was developed following that disaster, Figure 2.32, was not employed elsewhere in Europe.

The early beginnings of seismology and earthquake engineering are discussed elsewhere [Ben-Menahem, 1995; Scawthorn, 2007]. In summary, an explicit understanding of seismic loads required the development of instruments to measure earthquake ground motions, which first occurred in Europe and Japan in the 1880s.

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[46] https://upload.wikimedia.org/wikipedia/commons/5/50/Wood-framed_house.jpg;

These instruments were however teleseismic instruments (i.e., weak motion) which at first provided little information for the design of buildings for earthquakes. Nevertheless, while the 1906 San Francisco earthquake in the US and the 1908 Messina earthquake in Italy spurred some interest in seismic design, the 1891 Nobi earthquake in Japan actually led to more integrated development in earthquake engineering, which was demonstrated by the good performance of engineered buildings in the 1923 Tokyo earthquake. These developments were concurrent with the development of tall steel framed buildings, and reinforced concrete framed buildings, particularly in the US, which lead to greater wind loading. This motivated Japan to adopt a rational seismic design procedure in its building code, using the Equivalent Lateral Force (ELF) method developed by Sano early in the century (and independently, by Italians). Combined with the development of strong motion instruments in California in the late 1920s, which gave engineers the first real measured basis for rational design for earthquake forces, there developed recognition that braced frames, moment resisting frames, and shear wall buildings, could be rationally designed for seismic forces. The 1925 Santa Barbara earthquake, combined with a seminal series of papers in 1923-24 by Stanford professor Bailey Willis in the Bulletin of the Seismological Society of America, lead to adoption in 1927 of a similar provision in the first Uniform Building Code. The Italians, Japanese and American engineers all agreed that an ELF of about 10%, adjusted for soils and transient stresses, should suffice.

Thus, from the early 20th Century through the 1970s, the key concept was *resistance* to lateral loads via systems as shown in Figure 2.50. Buildings were built with bracing, moment connections or shear walls sized to resist lateral loads. Dynamics developed as a tool to understand the response of structures to transient loads, and lateral loads were recognized to be a function of the natural period and other dynamic properties of the building. Earthquake engineering developed as an art of designing the lateral load resisting systems to be strong enough to resist the lateral loads, but as flexible as possible so as not to attract too much lateral load. The importance of unity of construction emerged – that the building had to move “together” under a ground excitation, and that plan and vertical irregularities created portions of the building that responded separately (and often separated).

Starting in the 1970s, the concept of *avoiding* lateral loads, rather than *resisting* them, has emerged. This is accomplished by changing, or *controlling*, the dynamics of the building, in either passive or active ways. Passive control refers primarily to two techniques:

- Base isolation, which consists of introducing a flexible joint between upper and lower portions of a building. The flexible joint permits the lower portion of the building to move with the ground, while the upper portion responds to movement at its base much more slowly, thereby reducing inertial forces on the building. First utilized in 1982 in New Zealand and 1985 in the US, base isolation is now a standard technique applied to selected buildings in high seismic regions.
- Energy dissipation, primarily via enhanced damping. Dampers of various kinds such as oil-filled cylinders or restrained buckling steel braces permit lateral deformation of the building but at a slower rate than would otherwise occur, thereby reducing dynamic response and lateral forces on the building. Energy dissipating systems are now also a standard technique applied to selected buildings in high seismic regions.

Active control refers primarily to two techniques:

- Tuned mass dampers (TMD), which are relatively large masses (hundreds of tons) typically at or above the mid-height of a high rise building. When dynamic lateral loads are detected, the TMD is forced to vibrate in a fashion contrary to the dynamic lateral load, in effect partially ‘cancelling’ the lateral loads.

TMDs were first installed in the John Hancock building in Boston in 1970 and are employed in the 101 story Taipei 101 (tallest building in the world 2004~2010), for both seismic and wind effects mitigation.

- Active tendon and bracing systems, which apply forces contrary to the forces induced in a building due to the dynamic lateral loads. This technique has seen only very limited application to date.

2.7. Summary

In summary, the variety of building types and forms in the world is perhaps exceeded only by the variety of types and forms of people. For most of humankind's history the global building environment has been constructed using four basic structural systems – mound, post and beam, truss and arch/dome – and, dependent on the particular life-zone, materials at hand – primarily earth, stone, wood, and various plant materials. From such simple beginnings has emerged a myriad of building types. The Industrial Revolution led to needs and materials so that steel and other metals, concrete, glass and fabrics were used in new structural systems, the most prominent of which has been the rigid or moment-resisting frame, the braced frame, and the shear wall. Technologically advanced systems such as base isolation, tuned mass dampers and energy dissipation have emerged in recent decades, as have tensile structures in a variety of shapes and applications. Today, advanced computational methods for analysis and fabrication allow innovation as astonishing as Paxton's Crystal Palace was in 1851, with imagination being the only limit to a building's material and shape, Figure 2.56.

A framework that can capture the key attributes of this variety, in a simple way that is yet useful for describing buildings and capturing their earthquake-relevant properties, is a significant challenge. Chapter 4 presents a taxonomy developed for that purpose.

a)

b)

Figure 2.56 Modern buildings: a) Guggenheim Museum, Bilbao Spain (1997)[47], and b) HSB Turning Torso Malmö, Sweden, 2005, aluminum cladding (Photo: C. Scawthorn)

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[47] http://upload.wikimedia.org/wikipedia/commons/1/1d/Guggenheim_Museum,_Bilbao,_July_2010_%2806%29.JPG

3 An Overview of Existing Taxonomies

3.1 Background

A literature review of existing taxonomies was performed at the initial development stage of the GEM Building Taxonomy. The review revealed a significant number of existing structural/building taxonomies, which were mostly developed in the context of earthquake-related projects and initiatives. Most of these taxonomies have a regional or a country-based focus, and only two taxonomies (PAGER-STR and WHE) have the intent of describing global building stock. Taxonomies from other fields, such as the insurance or construction industries, are also relevant for development of the GEM Building Taxonomy. A brief overview of the history of building classifications, and the key features of relevant existing taxonomies are presented in this chapter.

3.2 History of Building Classifications

This section reviews selected building classification systems to show the roots of current building seismic classification. The origin of most modern building classifications begins with the 1666 Great Fire of London and the subsequent rapid growth of the insurance industry in London:

> *By the end of the 18th C., insurance maps and plans originated in London in response to the need felt by large fire insurance companies and underwriters for accurate, current, and detailed information about the buildings they were insuring…In 1835 a major conflagration in New York City caused losses of more than 20 million dollars and wiped out most of the nation's smaller insurance companies, which had little or no reserve funds. In the reorganization of the industry larger companies were formed, and states and cities passed laws requiring reserve funds and issued other regulations. Solicitation areas were expanded by the larger companies, which maintained agents in various cities. Personal inspection of properties under consideration for insurance became impossible and a demand for maps giving essential risk information developed. During the period 1865 to 1900 a number of surveyors and map publishers prepared fire insurance maps and atlases, but these were principally of urban areas in their immediate locale. In 1867, D. A. Sanborn founded the National Insurance Diagram Bureau in New York City, which grew into a specialized company that compiled and published maps for the fire insurance industry for more than a hundred years.*

Adapted from *Introduction to the Sanborn Map Collection*[48]

What emerged in the US was a relatively simple classification of buildings for fire protection purposes, based primarily on the flammability of the structural materials, Table 3.1:

Table 3.1 Typical US Building Code Types of Construction

TYPE I:	Fire Resistive Non-combustible
TYPE II-A:	Protected Non-Combustible
TYPE II-B:	Unprotected Non-Combustible
TYPE III-A:	Protected Combustible
TYPE III-B:	Unprotected Combustible
TYPE IV:	Heavy Timber
TYPE V-A:	Protected Wood Frame (no exposed wood visible)
TYPE V-B:	Unprotected Wood Frame

[48] http://www.loc.gov/rr/geogmap/sanborn/san4a1.html

Sometime around the mid-20th century, this system was adapted by US West Coast Insurers [California Department of Insurance] for earthquake insurance rating purposes, Table 3.2:

Table 3.2 California Department of Insurance Building Classes

Class	Type of Building
1A	Single through four family dwellings. No limitations on story height, area, and construction materials.
1B	"Homeowners".
1C	**Habitational**: Wood frame and frame stucco habitational buildings which do not exceed 2 stories in height, regardless of area. **Non-habitational**: Wood frame and frame stucco, except buildings (1) > 3 stories; and (2) > 3,000 sq. ft. in ground floor area.
1D	Wood frame and frame stucco buildings not qualifying under Class 1C.
1E	Mobile homes and contents.
All-metal Buildings	
2A	All-metal buildings one story in height and 20,000 sq. ft. or less in ground floor area. Wood or cement-asbestos are acceptable alternatives to metal roofing and/or siding.
2B	Buildings which would qualify as Class 2A except for exceeding area or height limitations.
Steel Frame Buildings	
3A	Buildings with a complete steel frame carrying all loads. Floors and roofs must be of cast-in-place (CIP) reinforced concrete (RC) or of concrete fill on metal decking welded to the steel frame (open web steel joists excluded). Exterior walls must be non-load bearing and of CIP RC or of reinforced unit masonry. Buildings having column-free areas greater than 2,500 sq. ft. (such as auditoriums, theatres, public halls, etc.) do not qualify.
3B	Buildings with a complete steel frame carrying all loads. Floors and roofs must be of CIP RC, metal, or any combination thereof, except that roofs on buildings over three stories may be of any material. Exterior and interior walls may be of any non-load bearing material.
3C	Buildings having a complete steel frame with floors and roofs of any material (such as wood joist on steel beams) and with walls of any non-load bearing materials.
RC Buildings **Combined RC and Structural Steel Buildings**	
Note	Class 4A and 4B buildings must have all vertical loads carried by a structural system consisting of one or a combination of the following (a) CIP RC frame, (b) CIP RC bearing walls, (c) partial structural steel frame with (a) and/or (b). Floors and roofs must be of CIP RC, except that materials other than RC may be used for the roofs of buildings over 3 stories.
4A	Buildings with a structural system as defined by the note above with CIP RC exterior walls or reinforced unit masonry exterior walls. Not qualifying are buildings having column-free areas greater than 2,500 sq. ft. (such as auditoriums, theatres, public halls, etc.).
4B	Buildings having a structural system as defined by the note above with exterior and interior non-bearing walls of any material.

Class	Type of Building
4C	Buildings having (a) partial or complete load carrying system of precast concrete, and/or (b) RC lift-slab floors and/or roofs, and (c) otherwise qualifying for Class 4A and 4B.
4D	Buildings having a RC frame, or combined RC and structural steel frame. Floors and roofs may be of any material (such as wood joist on RC beams) while walls may be of any non-load bearing material.
Mixed Construction	
5A	Buildings having load bearing exterior walls of (a) CIP RC, and/or (b) precast RC (such as "tilt-up" walls), and/or (c) reinforced brick masonry, and/or (d) reinforced hollow concrete block masonry. Floors and roofs may be of wood, metal, CIP concrete, precast concrete, or other material. Interior bearing walls must be of wood frame or any one of a combination of the aforementioned wall materials. (Note: No class distinction is made between newer highly earthquake resistive buildings and older moderate earthquake resistive buildings having these construction materials. ISO Classes 5A and 5AA shall be combined and considered as Class 5A.)
5B	Buildings having load bearing walls of unreinforced brick or other types of unreinforced solid unit masonry, excluding adobe.
5C	Buildings having load bearing walls of hollow tile or other hollow unit masonry construction, adobe, and cavity wall construction. Also included are buildings not covered by any other class.
Earthquake Resistive Construction	
6	Any building with any combination of materials so designed and constructed as to be highly earthquake resistant and also with superior damage control features in addition to the minimum requirements of building codes.
Miscellaneous	
7	Bridges, tunnels, dams, piers, wharves, tanks, tank contents, towers of all types, and the like. Time-element coverage for these structures to be included.

This system was then adapted for a project that developed a consistent set of building and infrastructure vulnerability functions [ATC, 1985] for 78 different types of structural systems using abbreviated descriptors, Table 3.3.

Table 3.3 Selected ATC-13 Facility Classes and Descriptors [ATC, 1985]

No.	Facility Class	ATC-13
1	Low Rise Wood Frame	W/F/LR
2	Low Rise Metal Frame	M/F/LR
3	Low Rise RC Shear Wall (w/ MRF)	RC/SW-MRF/LR
…	…	…
7	Med Rise RC Shear Wall (w/o MRF)	RC/SW-0/MR
…	…	…
14	High Rise Braced Steel Frame	S/BR/HR
…	…	…
89	Moment Resisting Non-ductile RC Distributed Frame, High-rise	RC/MR-D/ND/HR

This system was relatively quickly standardized into what became referred to as the “FEMA Model Building Types” in a number of seismic design documents sponsored by the US Federal Emergency Management Agency, e.g. FEMA 154 [1988] (originally developed in 1988 and updated in 2002), as shown in Table 3.4. Even though very US-specific in their building descriptions, these “Model Building Types” have influenced seismic-related building classifications in many countries and remain to this day more or less the defacto global building seismic classification system. Recently, the concept was extended by the US Geological Survey to a global seismic building classification system PAGER-STR [Jaiswal and Wald, 2008].

Table 3.4 FEMA Model Building Types [FEMA 154, 2002]

Descriptor	Description
W1	Light wood-frame residential and commercial buildings smaller than or equal to 5,000 square feet
W2	Light wood-frame buildings larger than 5,000 square feet
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frames with cast-in-place concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear-wall buildings
C3	Concrete frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing-wall buildings

3.3 Structural/Building Taxonomies

This section reviews several existing structural taxonomies as part of the process of developing a building taxonomy for the GEM project. Before commencing the review it must be noted that each building type has to be defined adequately to satisfy the information and analysis requirements of GEM. Therefore the structural taxonomy is just one of several taxonomies that together will contain all the relevant data about a particular building. For example, in addition to the pivotal structural taxonomy, other taxonomies need to cover issues related to: general building information including age of construction, non-structural elements, occupancy type, construction aspects affecting earthquake performance, retrofit work, etc. Given the possibility of extending GEM beyond buildings to include other built forms, the GEM Building Taxonomy needs to be able to be expanded to include bridges, tunnels, dams, wharves, tanks, towers, and other non-building construction.

Most of the taxonomies reviewed in this section cover just structural aspects. They have in general been developed to describe and classify building structures in terms of seismic resistance and response and been developed since 1985. It can be expected that more recent taxonomies have improved upon earlier similar taxonomies. Note that the taxonomies are presented in chronological sequence.

A number of (other) country-specific structural/building taxonomies have also been developed. Several of these have been reviewed, e.g. [IIT, 2012], but are not included below due to their limitations in terms of their ability to address the range of permutations and combinations encountered world-wide. Several building taxonomies have been developed in Europe, both at a country level and a regional level. A regional Europe-based building taxonomy is included in the AeDES post-earthquake damage assessment field manual [Pinto and Taucer, 2007]. Another building taxonomy comprising of 23 principal classes grouped by the structural type, material of construction, height class, and building design code level, was used in the RISK-UE project focused on developing seismic risk scenarios for seven European cities [Mouroux et al., 2004]. INSPIRE Direction, currently under development in Europe, also contains a building taxonomy [INSPIRE, 2012].

The approach taken in this section follows that of Porter [2005] whose review of existing taxonomies focused on those addressing non-structural components. In his review, Porter evaluated each taxonomy against a range of criteria in order to identify the most appropriate taxonomy to build upon.

The criteria by which the existing taxonomies are assessed are listed below:

1. Distinguishes differences in seismic performance. The taxonomy distinguishes earthquake-resistant versions of structural systems from non-earthquake-resistant versions, including the “before” and “after” states of common seismic retrofits and between “ductile and non-ductile” systems.

2. Observable. Two individuals examining the same structural system in the field or using data obtained from the field should independently assign it to the same taxonomic group based solely on the text definition of the taxonomic group.

3. Complete. The taxonomy must include all engineering features relevant to the global seismic performance of a building structure. As mentioned above, it is recognized that there will be a need for additional taxonomies to capture all aspects of the seismic performance and losses for an entire building, including building dimensions and non-structural components. The structural taxonomy must contain sufficient attributes to meet the needs of the GEM end users.

4. Simple and collapsible. The taxonomy should have as few groups as possible, while still meeting the other requirements. It is also desirable to define common combinations and relative quantities of structural systems so that fragility or vulnerability functions can be created by aggregating the fragilities or vulnerabilities of detailed components, while still distinguishing, for example, differences in ductility, design or retrofit alternatives. A taxonomy is judged to be collapsible if taxonomic groups can be combined and the resulting combinations still distinguish differences in seismic performance.

5. Nearly exhaustive. Within practical limits, almost every structural system can be sensibly assigned to a taxonomic group.

6. Familiar to engineering practitioners and architects. It is desirable that engineers and architects be familiar with the taxonomic system, particularly to readily and accurately identify structural attributes. If the new taxonomic system corresponds readily to an existing taxonomic system, it can give users access to existing data. Engineers and architects should be familiar with the nomenclature to be defined to avoid ambiguity.

7. Treats non-buildings. Built forms other than buildings need to be included in the taxonomy sometime in the future. These include structures such as dams, bridges and tunnels.

8. Extensible to other hazards. It is unlikely that the GEM model will include other natural hazards such as floods, hurricanes and volcanic eruptions, however similar models could be developed by other communities with regards to these hazards.

9. User-friendly. The taxonomy should be straightforward, intuitive, and as easy to use as possible by those collecting data, those arranging for its analysis and the end users.

10. International in scope. As far as possible the taxonomy should be appropriate for any region of the world. It should not favour any one region but be technically and culturally acceptable to all regions.

Table 3.5 shows the extent to which each of the reviewed taxonomies meets the above criteria. The value of this comparison is to identify the taxonomy with the greatest potential for development in order to satisfy GEM requirements. If a simple scoring system is used the SYNER-G taxonomy emerges as the one with the greatest potential to be further developed. Following that tabular summary, each taxonomy is briefly commented upon.

Table 3.5 Comparisons of various structural taxonomies against stated criteria

	1. Differentiates seismic performance	2.Observable	3. Complete	4. Simple and collapsible	5. Nearly exhaustive	6. Familiar	7. Treats non-buildings	8. Extensible to other hazards	9. User-friendly	10. International in scope	Score	Comments
ATC-13	s	s	s	s	u	t	t	u	t	u	10	California-focused
FEMA 154 (ATC-21)	s	s	u	s	u	t	u	u	t	u	7	For US construction
EMS-98	s	s	u	s	u	t	u	u	t	t	9	Too broad
WHE	s	s	t	s	t	t	u	u	t	t	13	More than structural
Coburn & Spence	s	s	s	t	t	t	u	u	t	t	13	Both engineered and non-engineered buildings
HAZUS	t	s	s	s	u	t	u	t	t	u	11	For US construction
Gunel and Ilgin	s	s	s	s	u	s	u	u	t	u	7	Tall buildings only
CEQID	t	s	s	s	s	t	u	u	s	t	11	EQ damage database
PAGER -STR	t	s	t	t	t	t	u	u	t	t	15	Most comprehensive to date
SYNER-G	t	s	t	t	t	s	t	s	t	t	17	Best potential

Notes: t = true (2 points), s = somewhat true (1 point) and u = untrue (0 points)

ATC-13 [ATC, 1985]

- A pioneering effort to develop a facility classification scheme for California, including engineering classification and social function classification.
- Key engineering characteristics considered in developing the classification include construction material, soil conditions, foundation, height, structural framing system, configuration, structural continuity, design and construction quality, age, and proximity to other structures.
- The engineering classification contains 78 classes of structures, 40 of which are buildings and 38 are other structure types (bridges, storage tanks, towers, etc.); 11 structure categories contain two or three height ranges. It would be advantageous to uncouple height from the structural taxonomy.
- Not collapsible.
- Uses a labelling scheme which consists of letters and symbols (slash "/" and dash "-") to identify facility classes
- California-focused and embedded assumptions that are often not valid nor relevant internationally (similar to HAZUS).

FEMA 154 [FEMA, 1988]

- One of the advantages of FEMA 154 is its simplicity, consisting of only 15 structure types. However, the disadvantage is that most of the structure type definitions are too broad. For example, there are only 2 classes for wood buildings, 5 classes for steel buildings, 3 classes for reinforced concrete, 2 classes for precast concrete, and 3 classes for masonry buildings.
- Most classes address only the vertical structural system - type of diaphragm (rigid/flexible) was considered only for reinforced masonry buildings.
- Description of structural classes is very detailed and includes illustrations of structural systems and their components, which is very helpful for sidewalk surveys of buildings.
- US-focused.

EMS-98 [Grünthal, 1998]

- One of the advantages of EMS-98 is its simplicity, consisting of only 15 structure types. However, the disadvantage is that most of the structure type definitions are too broad.
- Only variation in the seismic performances of RC frames and walls are able to be distinguished. They are defined as “without earthquake-resistant design”, “with moderate level of earthquake resistant design” and “with high level of earthquake-resistant design”.
- All steel and timber structures are covered under a single type which does not afford the opportunity to distinguish between, for example, ductile and non-ductile steel structures.

World Housing Encyclopedia [1]

- The World Housing Encyclopedia (WHE) database captures structural information about a building, and also architectural, socio-economic, vulnerability, construction, insurance and strengthening aspects.

- Detailed structural information can be selected from 14 house construction types and 45 sub types. Gravity and lateral load resisting systems can be independently assigned to a building.
- There are 20 options for floors and roofs, and 18 for foundations.
- Some structural types without seismic-resisting features, such as RC frames, are itemized but others such as shear walls and braced frames are not, so there is a certain lack of rigour. Also, as designed it is not collapsible.
- A lot of the information is entered in a descriptive manner rather than through pick lists.
- One very attractive feature is that it contains photographs of each building type.
- It contains a lot of non-structural information pertinent to seismic performance.

Coburn and Spence [2002]

- Divided into non-engineered and engineered buildings. So not clear where pre-engineered buildings fall (see Section 2.5 for a description of pre-engineered buildings).
- Building types are listed beginning with the most vulnerable through the least vulnerable.
- Many vulnerability parameters, other than the main structural classification and building type, are listed, but are not included in the classification.

HAZUS [FEMA, 2003]

- Building types are based on the classification system of FEMA 178 (FEMA 1992) and the classes are divided into height ranges.
- Contains 36 structural categories in total, including 9 with three height ranges to choose from (low-rise, mid-rise and high-rise). It would be advantageous to uncouple height from the structural taxonomy and capture it in a general building taxonomy.
- Relatively simple but not designed to be collapsible.
- US-focussed and embedded assumptions are often not valid internationally. For example, assumptions made of concrete strengths and ductility capabilities are based on US conditions.
- Some materials and construction technologies are missing, e.g. earthen or stone construction.
- Extending the taxonomy to include, for example, configuration aspects and revealing assumptions like the degree of ductility etc. would require many more structural types, making the taxonomy very cumbersome.

Gunel and Ilgin [2007]

- For modern high-rise buildings only
- Six structural systems form the classification system of which five are not included in any other taxonomies.
- Just three materials, including composite (RC + steel) construction

PAGER-STR [Jaiswal and Wald, 2008]

- Most comprehensive taxonomy developed to date

- Captures most of the key structural aspects that affect seismic performance but there are some missing. For example, factors like concrete strength, provision of ductile detailing, and configuration irregularities are very important in predicting seismic behaviour. To some extent the way it differentiates between ductile and non-ductile frames makes allowance in a generic fashion for the factors above.
- Simple and collapsible.
- International coverage. It contains a breadth of structural types that are found outside the more developed countries.
- Difficulty in extending the taxonomy. If it is desirable to be more specific about ductility and configuration issues then the number of possible structural types increases rapidly and the taxonomy quickly becomes cumbersome.
- The more modern structural systems, like RC structures are subdivided into three building heights; 1-3 story, 4-7 storey and 8+ storey. It could be possible to simplify the taxonomy if the building height or number of storeys were uncoupled from the structural taxonomy.

SYNER-G (2011)

- This taxonomy was developed for European buildings.
- The only taxonomy reviewed that is non-hierarchical. It consists of fifteen facets or lists of categories. The number of facets will need to be increased in order to capture all the vulnerabilities and other data which GEM requires, but this can be easily achieved.
- The existing structure of the database would benefit from some reorganisation.
- Has a potential to treat non-buildings because of the way it is structured.
- The taxonomy with the potential for greatest degree of completeness and the most flexibility.

CEQID [Lee, Pomonis, So, and Spence, 2011]

- The Cambridge Earthquake Impact Database (CEQID) which contains damage data from more than 70 studies covering more than 600 locations in 53 earthquakes that occurred in the 20th century, has accumulated almost 300 building classes in its system.
- The building class descriptions in the CEQID include the following parameters: i) main construction material (e.g. adobe, brick, reinforced concrete); ii) structural system (e.g. steel moment resisting frame, shear wall); secondary attribute details (e.g. walls, floors, roofs); age or age reference (e.g. 1941-56, pre-1941, post-1976, pre-code, modern code); height (e.g. 2 to 3 floors, 4 to 10 stories), and occupancy type (e.g. rural, residential).
- Across all regions, the current building classification in CEQID exhibits three types of inconsistencies: across the format of the building class label, or how the descriptor components are shorthanded; between building class descriptions and building class labels; and in how the descriptor components are delimited.

Several relevant structural classification systems were each rated for their suitability for the GEM project. The SYNER-G taxonomy is considered the most appropriate given its inclusion of all the features that GEM requires.

Some additional structural types and other factors affecting seismic performance may need to be added and reorganisation of the order of the facets and the contents within them is required.

3.4 Taxonomies from Other Fields

This section reviews existing taxonomies from other (non-earthquake related) fields which are considered to be relevant for the GEM Building Taxonomy. This review is not exhaustive, and it is limited to selected taxonomies from the insurance industry, construction industry, and architecture.

3.4.1. *Insurance Industry*

The insurance industries of some countries have also developed their own taxonomies for insurance premium rating purposes. An early example of a taxonomy developed for the insurance industry was presented in Section 3.2. The California Earthquake Zoning and Probable Maximum Loss Evaluation Program is a more recent example from California [Garamendi, 2003; CEZ, 2003]. The taxonomy was developed for the Californian insurance industry with an emphasis on fire performance and is focused on US construction types, and provides no differentiation between gravity and lateral load-resisting systems. A more advanced system is the ACORD data standard V1, which is discussed in some detail.

ACORD [2011]

ACORD (Association for Cooperative Operations Research and Development) is the insurance industry's non-profit standards developer and a resource for information technology and electronic commerce in the US and abroad, most exemplified by the publication and maintenance of a large library of standardized forms for the insurance industry data exchange. Most claims in the US and other countries are recorded or transmitted on ACORD forms. This review is focused on ACORD's data standard V1. Key features of ACORD data standard V1 are summarized in Table 3.6.

Key Features

- It is a new standard (doesn't have a previous user history).
- The standard addresses the needs of insurance industry and contains asset classes.
- The standard attempts to address the needs of non-technical users and the low granularity of data which the insurance industry is able to capture; the information captured by insurance industry is not detailed and is inconsistent.
- The approach taken in developing the standard is pragmatic, and the goal is that the standard is implementable. It is difficult for the insurance industry to capture data like roof information (possible for a very small fraction of entries - on the order of 0.5%).
- The goal is to replace the many individual EXCEL sheets in use with a common form or an XML approach but NOT to replace any frequently used, detailed standardized data formats.
- The taxonomy codes are intuitive - for example, RESGEN999 indicates RESidential GENeral construction, and "999" indicates "Unspecified".
- An "unspecified" category is included to describe low-granularity (high uncertainty) entries.
- Definitions (glossary) for several parameters like disasters (perils), occupancy, and structure type, are included in the standard.

Table 3.6 ACORD Taxonomy: Summary

Parameter	Total number of classes	Minimum/collapsed number	Comments
Construction codes (structure types)	19 • Wood (1) • Masonry (5) • Concrete (5) • Steel (3) • Mobile home (3) • Glass (1)	6 • Masonry unspecified • Concrete unspecified • Steel unspecified • Mobile home unspecified • 6. Glass (greenhouse)	• The classification is somewhat rough - for example, unreinforced masonry includes stone, brick and block masonry; • Each class is accompanied by a text description; some descriptions may not be sufficient for non-technical users (for example, difference between precast and cast-in-situ concrete construction)
Occupancy	346 • Residential (11) • Commercial (43) • Industrial (257) • Agriculture (12) • Marine, aviation and transport (5) • Motor (2) • Infrastructure (16)	7 • Residential (RES) • Commercial (COM) • Industrial (IND) • Agriculture (AGR) • Marine, aviation and transport (MAT) • Motor (MO) • Infrastructure (INF)	• A very detailed list of asset classes • Text description is very brief because the categories are expected to be self-explanatory
Hazard Zone Scheme Codes	6	-	Includes two US-based codes (FEMA and State of California), one UK-based code (Pool Re), Czech Republic, Austria and Germany
Peril codes	59	11 • Earthquakes (EQ) • Tropical Cyclone (TC) • Flood (FL) • Storm (ST) • Volcanic Eruption (VO) • Extreme Weather (EW) • Earth Movement (EM) • Terror (TE); Fire (FI); Social Risk (SR)	Includes a comprehensive list of natural and man-made perils (disasters)

3.4.2. *Construction Industry*

Several classification systems have been developed for construction industry in North America, including MasterFormat, UniFormat, and OmniClass. MasterFormat™ was initially published in 1963 and it provides a master list of numbers and titles classified by work results as a part of a construction specification. UNIFORMAT™ (first published in 1998) provides a standard method for arranging construction information, organized around the physical parts of a facility called systems and assemblies. OmniClass, the most recent and most comprehensive North American construction classification system, draws from MasterFormat™ for work results, UNIFORMAT™ for elements, and Electronic Product Information Cooperation (EPIC) for products. The Unified Classification for the Construction Industry (UNICLASS), a faceted classification system designed using ISO standards as a legacy, is the UK's equivalent of OmniClass. This section provides an overview of the UniFormat and OmniClass classification systems.

UNIFORMAT

During the 1990s the US National Institute of Standards and Technology developed UNIFORMAT II [Charette and Marshall, 1999], a standard for classifying building elements for specifications, cost estimating, and cost analysis in the US and Canada. The elements are major components common to most buildings, which are summarized (and compared with systems in several other countries) in Table 3.7.

OmniClass [2006]

The OmniClass Construction Classification System (OmniClass) provides a standardized basis for classifying information created and used by the North American architectural, engineering and construction industry. Its development started in 2000, and the first version was issued in 2006, followed by several subsequent updates. The development was jointly sponsored by Construction Specifications Canada and the US-based Construction Specifications Institute.

OmniClass consists of 15 hierarchical tables, each of which represents a different facet of construction information. Each table can be used independently to classify a particular type of information; alternatively, entries from different tables can be combined to classify more complex subjects. OmniClass can be used for a variety of applications, from organizing library materials, product literature and project information, to providing a classification structure for electronic databases. It has been used in the area of Building Information Modeling (BIM) and it has been incorporated into Autodesk's REVIT software. The key facets composing the OmniClass system of relevance to the GEM Building Taxonomy are summarized in Table 3.8.

Key Features

- A relatively new standard (initial version released in 2006).
- A very detailed (granular) classification for each facet (each table represents one facet), however critical facets for seismic vulnerability of building structures and associated losses missing (e.g. structural system, type of floor/roof).
- Focused on North American terminology and practice, however U.K. and international standards were used in its development; compatible with appropriate international classifications and standards (e.g. ISO standards).
- An open and extensible standard; developed and updated with industry participation - industry as a whole governs development and dissemination of the standard.
- OmniClass concept and data model considered relevant for the GEM Building Taxonomy.

Table 3.7 UNIFORMAT II Element Classification

UNIFORMAT General Services Administration (GSA)	CANADIAN INSTITUTE OF QUANTITY SURVEYORS (CIQS)	THE ROYAL INSTITUTION OF CHARTERED SURVEYORS (RICS-UK)	CONSTRUCTION ECONOMICS EUROPEAN COMMITTEE (CEEC)
01 FOUNDATIONS	A1 SUBSTRUCTURE	1.0 SUBSTRUCTURE	(1) SUBSTRUCTURE
011 Standard foundations	A11 Foundations	2.0 SUPERSTRUCTURE	SUPERSTRUCTURE
012 Special foundations	A12 Basement excavation	2.1 Frame	(2) Frame
02 SUBSTRUCTURE	A2 STRUCTURE	2.2 Upper floors	(3) External walls
021 Slab on grade	A21 Lowest floor construction	2.3 Roof	(4) Internal walls
022 Basement excavation	A22 Upper floor construction	2.4 Stairs	(5) Floors
023 Basement walls	A23 Roof construction	2.5 External walls	(6) Roofs
03 SUPERSTRUCTURE	A3 EXTERIOR ENCLOSURE	2.6 Windows and exterior doors	(7) Stairs
031 Floor construction	A31 Walls below grade	2.7 Interior walls & interior partitions	(8) Windows & external doors
032 Roof construction	A32 Walls above grade	2.8 Interior doors	(9) Internal doors
033 Stair construction	A33 Windows & entrances	3.0 INTERNAL FINISHES	FINISHES
04 EXTERIOR CLOSURE	A34 Roof covering	3.1 Wall finishes	(10) Internal wall finishes
041 Exterior walls	A35 Projections	3.2 Floor finishes	(11) External wall finishes
042 Exterior doors & windows	B1 PARTITIONS & DOORS	3.3 Ceiling finishes	(12) Floor finishes
05 ROOFING	B11 Partitions	4.0 FITTINGS AND FURNITURE	(13) Ceiling finishes
06 INTERIOR CONSTRUCTION	B12 Doors	4.1 Fittings and furnishings	(14) EQUIPMENT AND
061 Partitions	B2 FINISHES	5.0 SERVICES	FURNISHINGS SERVICES
062 Interior finishes	B21 Floor finishes	5.1 Sanitary appliances	(15) Plumbing
063 Specialties	B22 Ceiling finishes	5.2 Services equipment	(16) Heating
07 CONVEYING SYSTEMS	B23 Wall finishes	5.3 Disposal installations	(17) Ventilating & air-
08 MECHANICAL	B3 FITTINGS & EQUIPMENT	5.4 Water installations	conditioning
081 Plumbing	B31 Fittings & equipment	5.5 Heat source	(18) Internal drainage
082 HVAC	B32 Equipment	5.6 Space heating & air treatment	(19) Electrics
083 Fire Protection	B33 Conveying systems	5.7 Ventilation systems	(20) Communication
084 Special mechanical systems	C1 MECHANICAL	5.8 Electrical installation	(21) Lifts, escalators, etc.
09 ELECTRICAL	C11 Plumbing & drainage	5.9 Gas installation	(22) Protective installations
091 Distribution	C12 Fire protection	5.10 Life & conveyor installation	(23) Miscellaneous services
092 Lighting & power	C13 HVAC	5.11 Protective installations	inst.
093 Special electrical systems	C14 Controls	5.12 Communication installations	EXTERNAL SITE WORKS
10 GENERAL CONDITIONS & PROFIT	C2 ELECTRICAL	5.13 Special installations	(24) Site preparation
11 EQUIPMENT	C21 Services & distribution	5.14 Builders work in connection with	(25) Site enclosure
111 Fixed & moveable equipment	C22 Lighting, devices & heating	services	(26) Site fittings
112 Furnishings	C23 Systems & ancillaries	5.15 Builders profit & attendance on	(27) Site services
113 Special construction	D1 SITE WORK	services	(28) Site Buildings
12 SITE WORK	D11 Site development	6.0 EXTERNAL WORKS	(29) Hard and soft landscaping
121 Site preparation	D12 Mechanical site services	6.1 Site works	(30) PRELIMINARIES
122 Sit improvements	D13 Electrical site services	6.2 Drainage	
123 Site utilities	D2 ANCILLARY WORK	6.3 External services	
124 Off-Site work	D21 Demolition	6.4 Minor building work	
	D22 Alterations		

Source:Bowen, B. and Charette, R.P., "Elemental Cost Classification Standard for Building Design,"1991 American Association of Cost Engineers (AACE) Transactions, Seattle, Washington, 1991, p. H2-1 to H2-5.

OmniClass Data Model

- Each table number designated by a pair of digits (e.g. 11, 12).
- There is an increasing depth related to the level of classification from left to right.
- Additional pairs of digits can be added to represent each additional level of classification.
- The plus sign "+" indicates the conceptual intersection of two or more construction subjects. For example, a "high-rise residential apartment building" can be represented as the intersection of "High-Rise Free-Standing Building" and "Large Complex Multiple Family Residence" construction entries, that is, 11-16 21 21 + 12-11 17 11.
- The slash sign "/" is used to indicate a broad range of consecutive classes within a single table that are applicable to an object's classification. For example, work results related to mechanical and electrical construction are shown as 22-21 00 00/22-28 46 29.
- The less-than and greater-than symbols "<" and ">" are used to indicate that one construction object is a part of another. For example, 13-15 11 34 11 < 11-13 24 11 (office space < hospital).
- The OmniClass notation is hierarchical; this means that if full detail of the entries presented at the OmniClass tables is not required, lower level digits can be omitted and classification can be performed at a higher (broader) level in the hierarchy. For example, an object could be classified at a broader level by using 11-13 instead of 11-13 27 11.

An illustration of the OmniClass data model is provided in Figure 3.1, which shows an excerpt from Table 21 Elements.

Table 3.8 OmniClass Taxonomy: Summary

Parameter	Total number of classes	Minimum/collapsed number	Comments
Construction entities by function (Table 11)	> 230 • Assembly facilities (13) • Learning facilities (34) • Public service facilities (32) • Cultural facilities (19) • Recreation facilities (20) • Residences (22) • Commercial facilities (18) • Production facilities (40) • Storage facilities (15) • Water management facilities (24) • Energy management facilities (27) • Waste management facilities (6) • Information management facilities (9) • Transportation terminals (27) • Transportation routes (20) • Mixed-use facilities (1)	16 • Assembly facilities • Learning facilities • Public service facilities • Cultural facilities • Recreation facilities • Residences • Commercial facilities • Production facilities • Storage facilities • Water management facilities • Energy management facilities • Waste management facilities • Information management facilities • Transportation terminals • Transportation routes • Mixed-use facilities	• Definable units of the built environment comprised of elements and interrelated spaces and characterized by function. • A construction entity is complete and can be viewed separately rather than as a constituent part of a larger built unit. • Function is the purpose or use of a construction entity. It is defined by primary occupancy, and not necessarily by all activities that can be accommodated by the construction entity.
Construction entities by form (Table 12)	34 (buildings) Plus additional 100 for other categories	6 (buildings) • Low-rise buildings • Mid-rise buildings • High-rise buildings • Submerged buildings • Mixed-form buildings	• Significant, definable units of the built environment comprised of elements and interrelated spaces and characterized by form. • Besides buildings, the table includes non-building structures

		• Other buildings	(bridges, tanks, etc.), movable structures, land forms, water forms, construction entity groupings (campus, districts, municipalities) • Level 2 and 3 items for buildings may not be directly useful for the GEM Taxonomy without a mapping scheme (see section 12-11 11 00 Low-rise Buildings as example)
Elements (Table 21)	>600	3 • Substructure • Shell • Interiors • Plus a few other categories	• Detailed list of all elements in the building, particularly non-structural elements • Based on UniFormat II
Materials (Table 41)	>200	4 • Chemical elements • Solid compounds • Liquids • Gases	• Substances or other items used in construction or to manufacture products. These substances may be raw materials or refined compounds, and are considered subjects of this table irrespective of form. • For example, concrete is not included in the table, but its constituent materials are (cement, sand, etc.).

21-41 31 00 Superstructure and Enclosure

21-41 31 11	**Floor Construction**	
21-41 31 11 11	Supported Basement Floors	
21-41 31 11 21	Structural Floors	
21-41 31 11 31	Vertical Shaft Structure	
21-41 31 11 41	Balconies	
21-41 31 11 51	Mezzanines	
21-41 31 11 61	Ramps	
21-41 31 13	**Stairs and Ladders**	
21-41 31 13 11	Stairs	
21-41 31 13 21	Landings	
21-41 31 13 31	Fire Escapes	
21-41 31 13 41	Ladders	
21-41 31 15	**Conveying Systems**	
21-41 31 15 11	Vertical Transportation	(Includes: Elevators and Wheel-Chair Lifts)
21-41 31 15 21	Horizontal Transportation	(Includes: Moving Walkways)
21-41 31 15 31	Sloped Transportation	(Includes: Escalators and Wheel-Chair Lifts)
21-41 31 15 41	Materials Handling Containers	
21-41 31 15 51	Turntables	
21-41 31 15 61	Operable Scaffolding	
21-41 31 17	**Roof Construction**	
21-41 31 17 11	Roof Framing	
21-41 31 17 21	Sloped Roof Framing	
21-41 31 17 31	Vaulted Roof Framing	
21-41 31 17 41	Canopy Framing	
21-41 31 17 51	Fabric Roof Framing	
21-41 31 17 61	Dome Framing	
21-41 31 17 71	Air Supported Framing	

Figure 3.1 An example of OmniClass Table 21-Elements related to structural framing [OmniClass, 2006]

3.4.3. *Architecture*

There are numerous classification systems in architecture, however this section is limited to review of the GreatBuildings taxonomy, which is relevant for the GEM Building Taxonomy due to its global scope.

GreatBuildings [2]

GreatBuildings is a web-based database of over 1,000 classics of world architecture. The database covers architecture around the world and across history, and documents one thousand buildings, and hundreds of leading architects, with photographic images and architectural drawings, integrated maps and timelines, 3-D building models, commentaries, bibliographies, web links, etc. The database was developed in 1997 by the UK-based Architecture Week journal. Key features of the GreatBuildings database are summarized in Table 3.9.

Table 3.9 GreatBuildings Taxonomy: Summary

Parameter	Total number of classes	Comments
Building types (function)	34 Small houses, large houses, multi-family housing, etc.	The list includes non-buildings, e.g. bridges
Construction types	10 Bearing masonry, brick, concrete, curtain wall, fabric & tensile, geodesic, glass, light wood frame, steel, timber	• The classification includes materials and some structural systems • The classification is not very exhaustive
Architectural styles	32 Hindu, Islamic, vernacular, etc.	
World architecture time periods	14 1800s, 1900-1949, 1950-1975, etc.	The classification narrows down in the 20th century to 25 year period
American architecture time periods	1700s 1800s 1900-1909 etc.	The classification narrows down to 10 year period in 20th century
Climates	9 Desert, temperate, mild, cold, warm, hot	
Contexts	10 Urban, suburban, rural, hill or cliffside	

3.5 Summary

A review of existing taxonomies for earthquake-related and other applications has been an important step in developing the GEM Building Taxonomy. An overview of the history of building classifications has shown how and why the concept of taxonomy emerged in the 17th century. A review of structural/building taxonomies has confirmed existence of several taxonomies which were developed in different countries and for different stakeholders, however none of them fully satisfies needs of GEM users. PAGER-STR taxonomy was identified as the most comprehensive of all reviewed taxonomies. Taxonomies from other fields (e.g. construction industry, insurance industry) were also considered to be relevant for the development of GEM Building Taxonomy. In particular, OmniClass taxonomy was found to be most relevant in terms of its organization and data model.

4 GEM Building Taxonomy v2.0: An Overview

4.1 Vision for the GEM Building Taxonomy

The vision of the GEM Building Taxonomy team is to create a unique description (code) for a building or a building typology - something like a genetic code (genome), as shown in Figure 4.1. This *building genome* is defined by several attributes. Each attribute corresponds to a specific building characteristic that affects its seismic performance. Typical attributes include material, lateral load-resisting system, building height, etc. The proposed taxonomy scheme is flexible and provides an opportunity for adding and/or modifying attributes depending upon the level of detail required and the new knowledge gained through the data collection process; this is an advantage over alternative taxonomy models considering the global scope of the GEM initiative. This taxonomy is different from the majority of existing structural taxonomies used for seismic risk assessments and is seen as the next generation taxonomy. The taxonomy data model is in line with modern Building Information Modeling (BIM) approaches and taxonomies used in the construction industry, e.g. OmniClass (see Section 3.4).

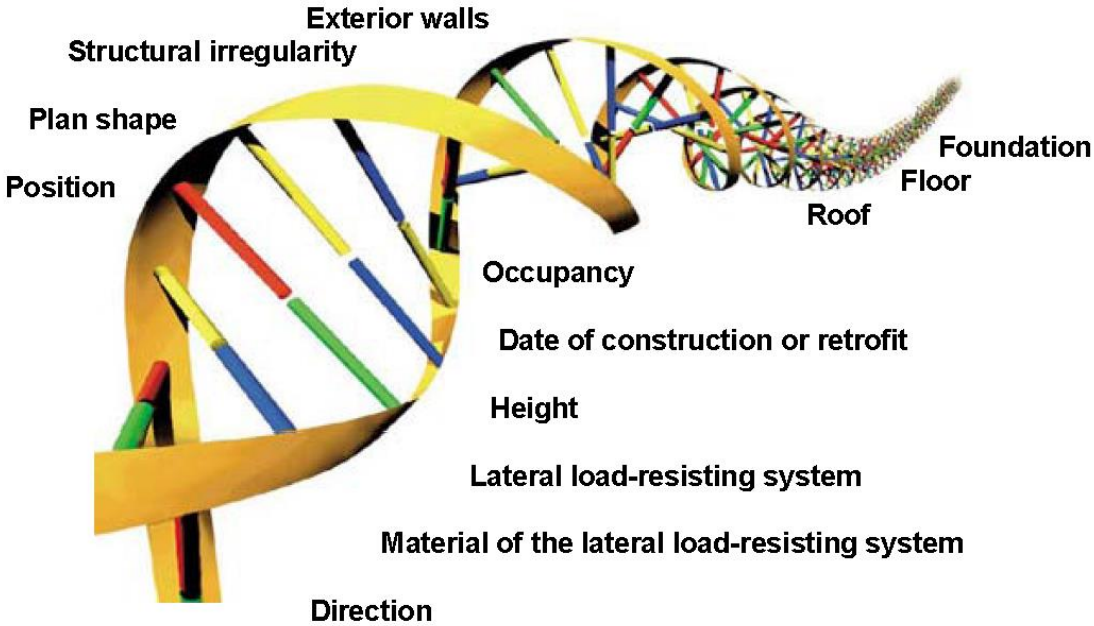

Figure 4.1 Building genome

4.2 Building Attributes

One of the challenges associated with taxonomy development is the selection of key attributes which are required to describe building characteristics. The required number of attributes or the depth of information to be captured for a building depends on the specific use/application of the taxonomy, available data sources, and the type of data collection. The initial (Beta 0.1 version) of the taxonomy had approximately 60 attributes.

A rather complete description of a unique building can be generated when all attributes are populated with data. However, such a taxonomy was perceived as too detailed for its intended purposes. The subsequent version (V1.0) had 8 basic attributes required by all GEM Risk components: i) material of the lateral load-resisting system, ii) lateral load-resisting system, iii) roof, iv) floor, v) height, vi) date of construction, vii) structural irregularity, and viii) occupancy. Five additional attributes were proposed as a result of the application of the V1.0 taxonomy by GEM researchers: direction, building position within a block, shape of the building plan, exterior walls, and foundation.

The GEM Building Taxonomy v2.0 therefore describes a building or a building typology through the following 13 attributes which are associated with specific building characteristics that can potentially affect seismic performance:

1. **Direction** - this attribute is used to describe the orientation of building(s) with different lateral load-resisting systems in two principal horizontal directions of the building plan which are perpendicular to one another.
2. **Material of the lateral load-resisting system** - e.g. "masonry" or "wood".
3. **Lateral load-resisting system** - the structural system that provides resistance against horizontal earthquake forces through vertical and horizontal structural components, e.g. "wall", "moment frame", etc.
4. **Height** - building height above ground in terms of the number of storeys (e.g. a building is 3-storeys high); this attribute also includes information on number of basements (if present) and the ground slope.
5. **Date of construction or retrofit** - identifies the year when the building construction was completed.
6. **Occupancy** - the type of activity (function) within the building; it is possible to describe a diverse range of occupancies - for example, residential occupancies include informal housing (slums) as well as high-rise apartment buildings.
7. **Building position within a block** - the position of a building within a block of buildings (e.g. "detached building" is not attached to any other building).
8. **Shape of the building plan** - e.g. L-shape, rectangular shape, etc.
9. **Structural irregularity** - a feature of a building's structural arrangement, such as one story significantly higher than other stories, an irregular building shape, or change of structural system or material that produces a known vulnerability during an earthquake. Examples: re-entrant corner, soft storey, etc. In recognition of the fact that a building can have more than one irregularity, the user is able to identify primary and secondary irregularity.
10. **Exterior walls** - material of exterior walls (building enclosure), e.g. "masonry", "glass", etc.
11. **Roof** - this attribute describes the roof shape, material of the roof covering, structural system supporting the roof covering, and roof-wall connection. For example, roof shape may be "pitched with gable ends", roof covering could be "tile", and roof system may be "wooden roof structure with light infill or covering".
12. **Floor** - describes floor material, floor system type, and floor-wall connection. For example, floor material may be "concrete", and the floor system may be "cast in-place beamless reinforced concrete slab".
13. **Foundation system** - that part of construction where the base of the building meets the ground. The foundation transmits loads from the building to the underlying soil. For example, a shallow foundation supports walls and columns in a building for hard soil conditions, and a deep foundation needs to be provided for buildings located in soft soil areas.

A detailed discussion on the rationale behind the selection of these attributes is beyond the scope of this report. The decision was made based on the collective experience of the GEM Building Taxonomy team and other GEM Risk researchers, and is supported by numerous references, ranging from research papers and reports to evidence from past earthquakes. A brief explanation is presented below.

Numerous research studies and evidence from past earthquakes have shown that seismic performance of a building is significantly influenced by the type of its **lateral load-resisting system** and the prevalent **material** (e.g. masonry, reinforced concrete, steel). In general, unreinforced masonry buildings, in particular stone and adobe masonry in developing countries, have shown the worst performance and have caused significant fatalities in past earthquakes. Some forms of reinforced concrete construction have also experienced significant damage and caused fatalities in several earthquakes, including the 1999 Turkey earthquakes, 1999 Chi Chi, Taiwan earthquake, 2001 Bhuj, India earthquake, etc. Lateral load-resisting system in these buildings is reinforced concrete frame with masonry infill walls[49]. Reinforced concrete buildings with shear walls[50] performed well in past earthquakes, however several reinforced concrete high-rises suffered significant damage in the 2010 Maule, Chile earthquake. Steel frame buildings have generally shown good performance, however some medium- to high-rise steel buildings were severely damaged in the 1994 Northridge, California earthquake due to inadequate connections. In general, wood buildings have shown good performance in past earthquakes. It should be noted that wood frame apartment buildings with open ground floor (parking space) suffered severe damage both in the 1989 Loma Prieta, California and the 1994 Northridge earthquake[51]. Single-family wood buildings have performed well, except for the buildings with cripple walls[52].

In many instances, buildings are characterized by different lateral load-resisting systems in two orthogonal directions of a building plan. The purpose of the **Direction** attribute is to enable users to identify these different systems (if present), since they might show different seismic performance.

R**oof** and **floor** (also known as diaphragms) are the key horizontal components of a lateral load-resisting system, and have a significant influence upon seismic performance of a building. Distribution of seismic forces in a building is significantly affected by the type of diaphragm (rigid or flexible). In general, buildings with rigid diaphragms have superior integrity and perform better than buildings with flexible diaphragms. For example, older unreinforced masonry buildings often have wood floors and roof, which act as flexible diaphragms; this has an adverse effect upon their seismic performance. Type of roof system and roof covering also has an implication upon the building weight; buildings with heavy roofs often show poor earthquake performance, irrespective of the type of lateral load-resisting system and its material. For example, single-family wood dwellings with heavy roofs suffered significant damage and caused about 5,000 fatalities in the 1995 Kobe, Japan earthquake.

Building **height** affects the fundamental period of vibration, an important dynamic property of a building which influences its seismic performance. The fundamental period of vibration depends on building height, its weight, and the type of lateral load-resisting system. In general, taller buildings are usually more flexible and are characterized by longer periods. Also, the heavier a building, the longer its period. Finally, the type of lateral load-resisting system significantly influences the period. For example, a masonry wall building will have a significantly shorter period than a steel frame building with the same height. It is difficult to predict whether a taller building is going to experience more substantial damage than a low-rise building; this strongly depends on earthquake characteristics, type of soil, and other factors. However, since taller buildings are more flexible,

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[49] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/infilled-frame
[50] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/wall
[51] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/soft-story
[52] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/cripple-wall-light-timber-construction

these buildings may experience larger lateral deformations than otherwise similar low-rise buildings; this may cause non-structural damage. For example, modern reinforced concrete high-rises in Mexico City were severely damaged in the 1985 earthquake. This was due to amplified vibration in soft soil deposits and because the predominant frequency of shaking corresponded to 2 sec period; this caused modern high-rise buildings with similar periods to resonate. It should be noted that many adjacent low-rise unreinforced masonry buildings suffered only minor damage in the same earthquake, although this type of construction is seismically vulnerable and has shown poor performance in many other earthquakes.

Influence of architectural configuration of a building upon its seismic performance has been recognized by earthquake engineering community [Guevara-Perez, 2008]. **Shape of the building plan** influences seismic performance of a building: in general, buildings with regular plan shapes show better performance than those with irregular ones. **Structural irregularity** is one of the most critical attributes in terms of the expected seismic performance of a building. A study of 21 damaging earthquakes which took place from 1980 to 2003 confirmed that the extent of damage was strongly correlated with the presence of structural irregularities (plan or vertical) in the affected buildings [Gonzáles Herrera and Gómez Soberon, 2008].

Building position within a block may influence its seismic performance. Buildings in densely populated urban centres are at risk of pounding[53] with adjacent buildings unless adequate seismic gaps are provided. Research studies have shown that for buildings within a row/block, the ones situated at the end of a row are always more prone to pounding damage than the ones situated in the middle, which most of the times, even benefit from pounding [Azevedo and Bento, 1996]. This finding is supported by the evidence from several past earthquakes, including the 1985 Mexico, 1994 Northridge and the 1995 Kobe earthquake. A survey after the 1978 Thessaloniki, Greece earthquake showed that corner buildings suffered more damage than other buildings within the same block [Penelis et al., 1988].

The remaining attributes (exterior walls, occupancy, date of construction or retrofit) are not directly related to expected seismic performance of a building, but they provide information relevant for other critical parameters. For example, information related to the material of **exterior walls** may be useful to determine the type of lateral load-resisting system and other characteristics of a building which are accessible only from the exterior. Also, the material of exterior walls may influence the risk of non-structural building damage. Information on building **occupancy** may be used to determine prevalent construction type for a given city or a region within a country. For example, majority of single-family dwellings in the Province of British Columbia, Canada are of wood frame construction.

Information related to **date of construction or retrofit** of a building may be important for assessing its seismic risk. Older existing buildings usually show inferior seismic performance compared to otherwise similar buildings of more recent construction. For example, reinforced concrete frame buildings in the USA and Canada (and most other countries) of pre-1970 construction are more vulnerable than buildings of more recent vintages due to the absence of ductile detailing provisions. Date of construction may also be used to identify the building code according to which the building was designed.

Finally, type of **foundation system** may influence the seismic performance of a building. However, it is also necessary to have information on the characteristics of the underlying soil, because the choice of foundation system depends on soil conditions. The type of underlying soil is one of the key factors influencing intensity of ground shaking at the given location. There is substantial evidence that earthquake damage is more pronounced in soft soil areas.

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[53] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/pounding-potential--pop

Each attribute has been described by one or more levels of detail, which will be referred to as Level 1, 2, 3, etc., in this document. Attributes and associated details included in the GEM Building Taxonomy are presented in Figure 4.2. It can be seen from the diagram that some attributes (e.g. Direction, Building Position within a Block, etc.) have only one level of detail, while others (e.g. Roof) have five levels. Number of levels depends on the complexity of specific building attribute. A brief description of each attribute level is outlined in Table 4.1, and additional information and illustrations are provided in the online Glossary (see Section 4.7.2).

It should be noted that a few attributes provide information useful for other natural hazards. For example, roof connections level in the Roof attribute may be useful for assessing risk of hurricane damage, and height of ground floor level above grade (Height attribute) may be useful for assessing flooding risk.

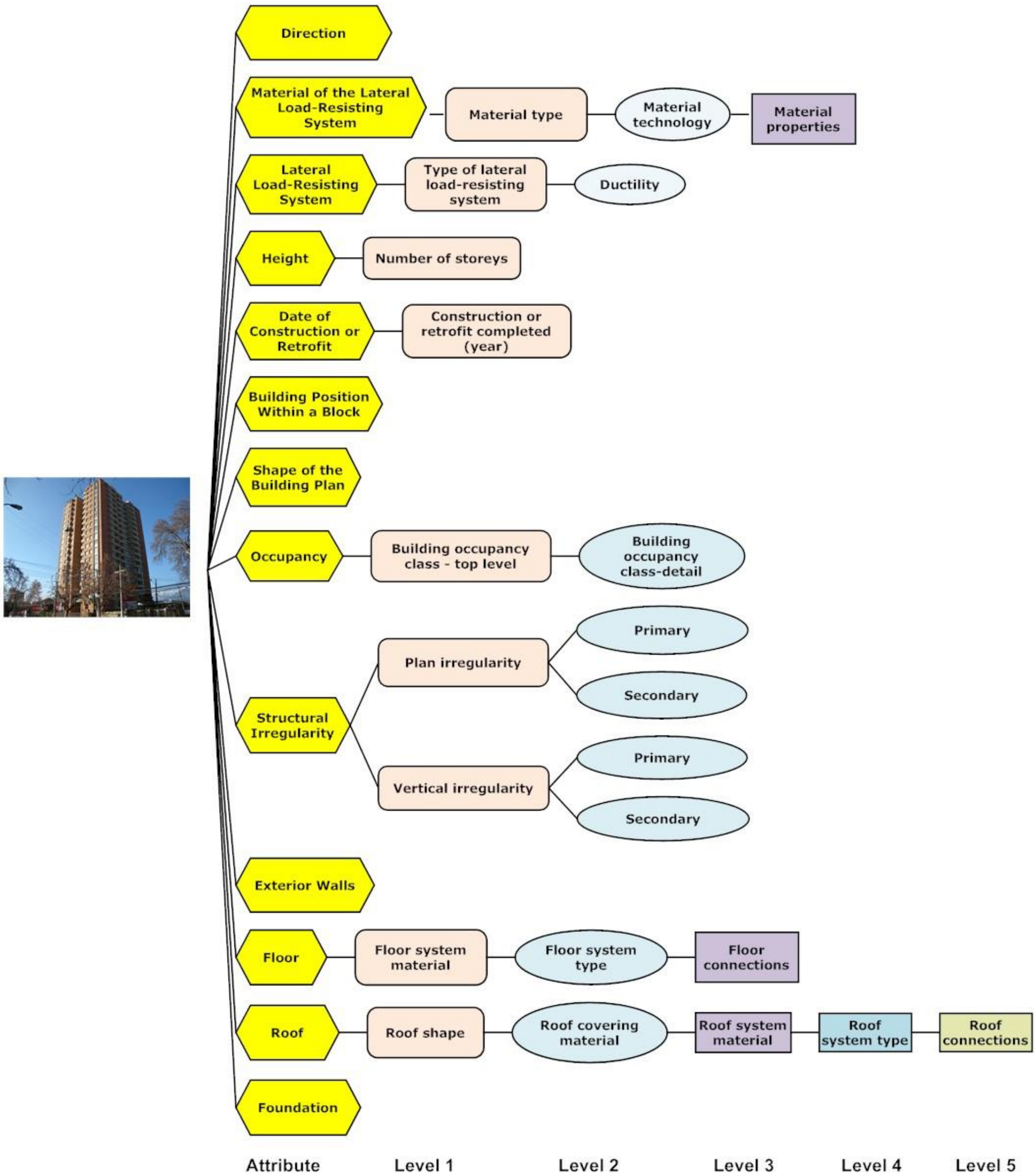


Figure 4.2 GEM Building Taxonomy v2.0: attributes and associated levels of detail

Table 4.1 GEM Building Taxonomy - Attribute Levels

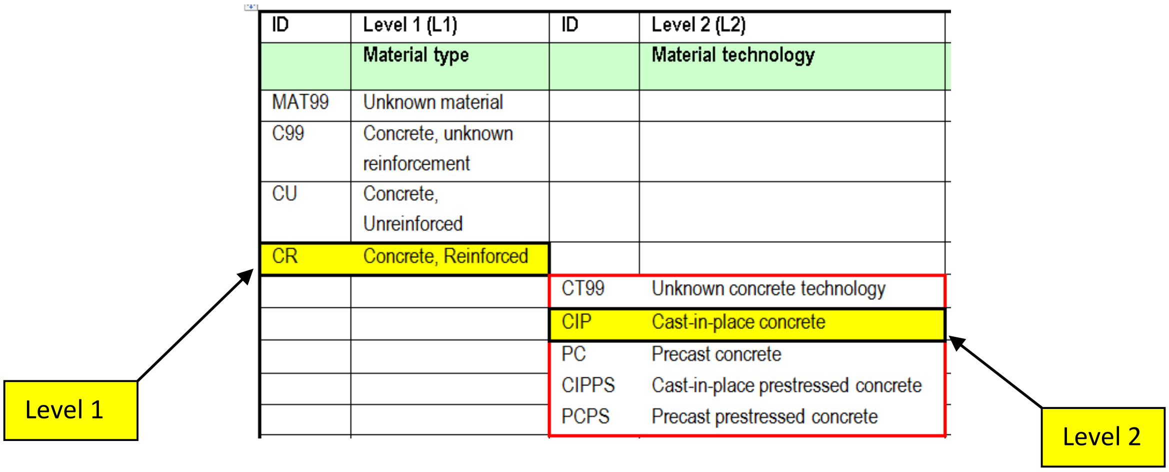
#	Attribute	Attribute levels	Description
1	Direction	Direction of the building	
2	Material of the Lateral Load-Resisting System	Material type (Level 1)	The material of the structural members that resist lateral loads and are the part of the Lateral Load-Resisting System
		Material technology (Level 2)	A more detailed description of the material type
		Material properties (Level 3)	Detailed information related to material technology, such as steel connections, types of stone masonry and mortar
3	Lateral Load-Resisting System	Type of lateral load-resisting system (Level 1)	Lateral load-resisting system is the structural system that provides resistance against horizontal earthquake forces through vertical and horizontal components.
		System ductility (Level 2)	A building can be classified as ductile or non-ductile, depending on its expected seismic performance before an earthquake, or its observed performance after an earthquake. Alternatively, a building can be equipped with base isolation and/or energy dissipation devices.
4	Height	Height	
5	Date of Construction or Retrofit	Construction completed (year)	
6	Occupancy	Building occupancy class - general (Level 1)	The main overall type of occupancy
		Building occupancy class - detail (Level 2)	A more detailed occupancy description than the Building occupancy class - general
7	Building Position within a Block		
8	Shape of the Building Plan	Plan shape (footprint)	
9	Structural Irregularity	Regular or irregular (Level 1)	Does the building possess structural irregularities from a seismic perspective?
		Plan irregularity or vertical irregularity (Level 2)	An indication as to whether a plan structural irregularity and/or a vertical structural irregularity are present
		Type of irregularity (Level 3)	Detailed description of a type of irregularity identified in plan irregularity or vertical irregularity
10	Exterior Walls	Exterior walls	

#	Attribute	Attribute levels	Description
11	Roof	Roof shape (Level 1)	The shape and angle of the roof on the building
		Roof covering material (Level 2)	The material that covers the roof. In most cases, this is different to the material of the roof system, but in some cases the roof covering will be the same as the roof system.
		Roof system material (Level 3)	The general classification of the material of the roof system
		Roof system type (Level 4)	Detailed classification of the type of roof system
		Roof connections (Level 5)	Includes connections that enable the roof diaphragm to transfer horizontal shear forces induced by an earthquake or wind to the lateral load-resisting structure of the building and to prevent walls from falling away from the diaphragm, as well as the connections that prevent wind uplift or lift-off.
12	Floor	Floor system material (Level 1)	The material is that from which the floor is primarily constructed
		Floor system type (Level 2)	Classifies the floor structural systems according to materials and methods of construction
		Floor connections (Level 3)	Classifies floor connections that transfer in-plane forces of floor diaphragms to the lateral load-resisting structure of the building, and also restrain outward wall displacements.
13	Foundation system	Foundation system	

GEM Building Taxonomy is presented in Appendix A in the form of 14 tables, which contain various attributes presented at several levels of detail. Table G1 summarizes all attributes while Tables 1 to 13 contain detailed content for each attribute. Each attribute table contains several columns which include unique identifying characters/codes (IDs) in alphanumeric format, which are used to associate specific attribute details to the corresponding text descriptions.

An example illustrating the attributes and the associated levels of detail is presented in Figure 4.3. The material of the lateral load-resisting system is an attribute, and the details are presented in Table 2 of Appendix A. There are three levels of detail associated with the material, as follows:

1. Level 1 (L1) - Material Type: describes material type - a typical detail is CR and a corresponding description is "concrete, reinforced" (CR).
2. Level 2 (L2) - Material Technology: expands characteristics of L1 details - in this case the attribute level relates to Material Technology. For example, L1 detail CR (concrete, reinforced) can be associated with one of the following L2 details: CT99 (unknown concrete technology), CIP (cast-in-place concrete), PC (precast concrete), CIPPS (cast-in-place prestressed concrete), or PCPS (precast prestressed concrete).
3. Level 3 (L3) - Material Properties: further expands the characteristics of the L2 details, and provides information associated with the specific material technology. For example, various types of mortar and stone are available for masonry technologies, and type of connections (welded, bolted, etc.) for steel construction technologies.



ID	Level 1 (L1)	ID	Level 2 (L2)
	Material type		Material technology
MAT99	Unknown material		
C99	Concrete, unknown reinforcement		
CU	Concrete, Unreinforced		
CR	Concrete, Reinforced		
		CT99	Unknown concrete technology
		CIP	Cast-in-place concrete
		PC	Precast concrete
		CIPPS	Cast-in-place prestressed concrete
		PCPS	Precast prestressed concrete

Figure 4.3 An example of a Level 1 detail (CR = concrete, reinforced) and a Level 2 detail (e.g. CIP = cast-in-place concrete) (Source: Table 2, Appendix A)

Additional background related to Direction and Material attributes is provided in Appendix B. This information is expected to be of interest to users of the GEM Building Taxonomy. It would be useful to provide additional background for the remaining attributes and produce a User Manual for the GEM Building Taxonomy, as an additional supplementary resource (see discussion in Chapter 7).

4.3 Key Rules Defining Relationships between the Attributes

4.3.1 General Rules

It is expected that the taxonomy will be mostly used in computer-based applications where a user will be able to describe a building by picking and choosing attributes and details from drop-down menus. A number of these tools have been created during the Taxonomy and Inventory Data Capture Tools Risk Global Components (GCs): The TaxT tool was created to allow engineers to validate the work of the Taxonomy GC and to generate taxonomy strings for building types. The IDCT GC has created two open-source field data capture tools for Windows and Android hardware (the Mobile Tools) that are available for immediate collection of structural data and ancillary project data and media.

For non-database applications, a building can be described by a string of characters (referred to as a string in this document); this provides a building description in a shorthand form. Rules for defining relationships between attributes in the GEM Building Taxonomy that need to be followed to create taxonomy strings are summarized in Table 4.2.

Table 4.2 GEM Building Taxonomy – Rules

Rule #	Description	Examples
1	**Details – General**	
1a	A detail for each attribute is defined by an identifier (ID). All IDs are outlined in the tables included in Appendix A.	S= steel (Level 1 detail associated with the Material attribute in Table 1) SL= light-weight steel members - a Level 2 detail associated with the steel (S) Level 1 attribute in Table 1
1b	Details which require numerical input (height and date of construction) are specified by a text ID, the colon sign ":", and a number (integer).	H:3 H=height and 3= number of stories (see Table 5) YN:1999, where YN= exact date of construction and 1999=year (see Table 6)
1c	When information about a detail is not available, a "99" entry will be assigned. Entries with unknown properties are labelled "99". Note that "99" entries may be omitted from a taxonomy string.	L99 in Table 2 refers to an unknown lateral load-resisting system. MUN99= unknown type of masonry unit in Table 1 (Level 2 detail)
2	**Attribute Sequence**	
2a	Attributes need to be entered in the same sequence as listed in Table G1.	See Table G1
3	**Level 1, 2, and 3 Attribute Details**	
3a	Level 1 details for Material (Table 1) and Lateral Load-Resisting System (Table 2) must be provided.	See Example 1 – a building typology is described using a combination of a material and a lateral load-resisting system, e.g. M99/LWAL/
3b	Level 2 and Level 3 details are optional.	Provision of Level 2 and Level 3 details depends on available data (see Example 1).
3c	For specific Level 1 attribute detail, it is possible to assign more than one Level 2 detail.	Material attribute (Table 1): Example of masonry: rubble stone masonry (STRUB) reinforced with timber (RW), that is, MR+ RW+ STRUB Where MR is Level 1 detail (Masonry, Reinforced), while RW (Wood reinforced) and STRUB (Rubble (field stone) or semi-dressed stone) are Level 2 details. Refer to Example 1.
4	**Slash Sign "/"**	

Rule #	Description	Examples
4a	The slash sign "/" is used as a separator (to separate the attributes).	See Example 2. Record B contains values for all attributes of the Building Taxonomy: DX:D99/ MUR+CLBRS+MOCL /LWAL/DY:D99/ MUR+CLBRS+MOCL /LWAL /HEX:2//RES+RES99///IRRE// RSH3+RMT99+RWO+RWO99 /FW+FW99//
4b	When information about an attribute is not available, place a slash sign ("/") without a blank space after the previous attribute. The objective is to insert placeholders for the missing attributes. This rule is optional for database applications (it may be possible to identify the missing attributes in an alternative way).	See Example 2. Record A has assigned values for six attributes, and the missing attributes are identified by slash signs (no values). DX:D99/MUR/LWAL/DY:D99/MUR/LWAL/HEX:2//RES+ RES99///// RSH3+RMT99+RWO+RWO99///
5	**Plus Sign "+"**	
5a	The plus sign "+" is used to include Level 2 and Level 3 details which describe properties of the Level 1 detail.	Masonry example (see Example 1): **MR**+RW+STRUB+MOM **MR** = Level 1 detail STRUB and RW = Level 2 details MOM = Level 3 detail

4.3.2 Constraints

Developing a relational database of building typologies by combining attributes and their details compiled through drop-down lists is a challenge. There is a chance that user(s) might try to use infeasible combinations of values; for example a "skyscraper or a very tall building" may be associated with a wood construction type. This problem can be addressed by imposing certain "constraints" which are based on an acceptable range of attribute values for various materials and lateral load-resisting systems.

The proposed approach for developing the constraints is as follows:

1. Set a material (Table 1 in Appendix A) as the key (anchor) point. The following five materials have been considered: concrete, masonry, steel, earth, and wood.
2. Identify acceptable details from Table 2 (Lateral Load-Resisting System) and Table 5 (Height), that is, combinations of lateral load-resisting system and height entries, which are "acceptable" in general engineering practice as plausible in combination with the specific material.

This approach can be applied to more than three attributes; however, it is deemed reasonable to set the constraints for the combinations of material, lateral load-resisting system, and building height.

These constraints have been presented in a tabular form in Appendix C. There are two tables for each material. The first table shows a relationship between the specific material and various lateral load-resisting systems. Unacceptable values for lateral load-resisting systems associated with specific materials are highlighted in yellow. The second table shows building height limits (expressed in terms of the maximum number of storeys), for example H:10 means that the maximum building height is 10 storeys.

Building height constraints associated with different materials have been developed based on the common knowledge of existing building typologies in various parts of the world. However, note that the recommended height limits are somewhat arbitrary. Database users should be able to review the constraints identified for a specific application and bypass them if they so desire. In other words, these constrains should serve as alerts (a message like "Please check whether this input is correct" should appear if a constraint limit has been exceeded).

4.4 Data Model

GEM Building Taxonomy has been coded in the form of a SQLite relational database by the IDCT Global Component. This forms a standardised basis for the IDCT Mobile Tools software for Windows and Android operating systems. This Data Model includes attributes from the Taxonomy alongside additional tables storing data on project and user metadata, location attributes and associated media captured by the Mobile Tools. The Data Model is expansible to include future modifications to the Taxonomy, however it is designed to limit selection of single, not multiple, variables for each building and metadata parameter. Creation of this Data Model has facilitated the standardised collection of building attributes and associated photographic, sketch, voice and video media in a digital form for use on multiple hardware platforms. A paper collection form that mirrors the data model has also been provided by IDCT. The Data Model is also aligned to the GED4GEM and GEMECD data structures and so the IDCT Mobile Tools can be used to directly populate both the GEM exposure and consequences databases (associated with the GEMECD and GED4GEM projects respectively). A diagram showing the complex data model structure developed by GEM IDCT team is presented in Figure 4.4, and a similar diagram showing data model structure developed by GEMECD team is shown in Figure 4.5.

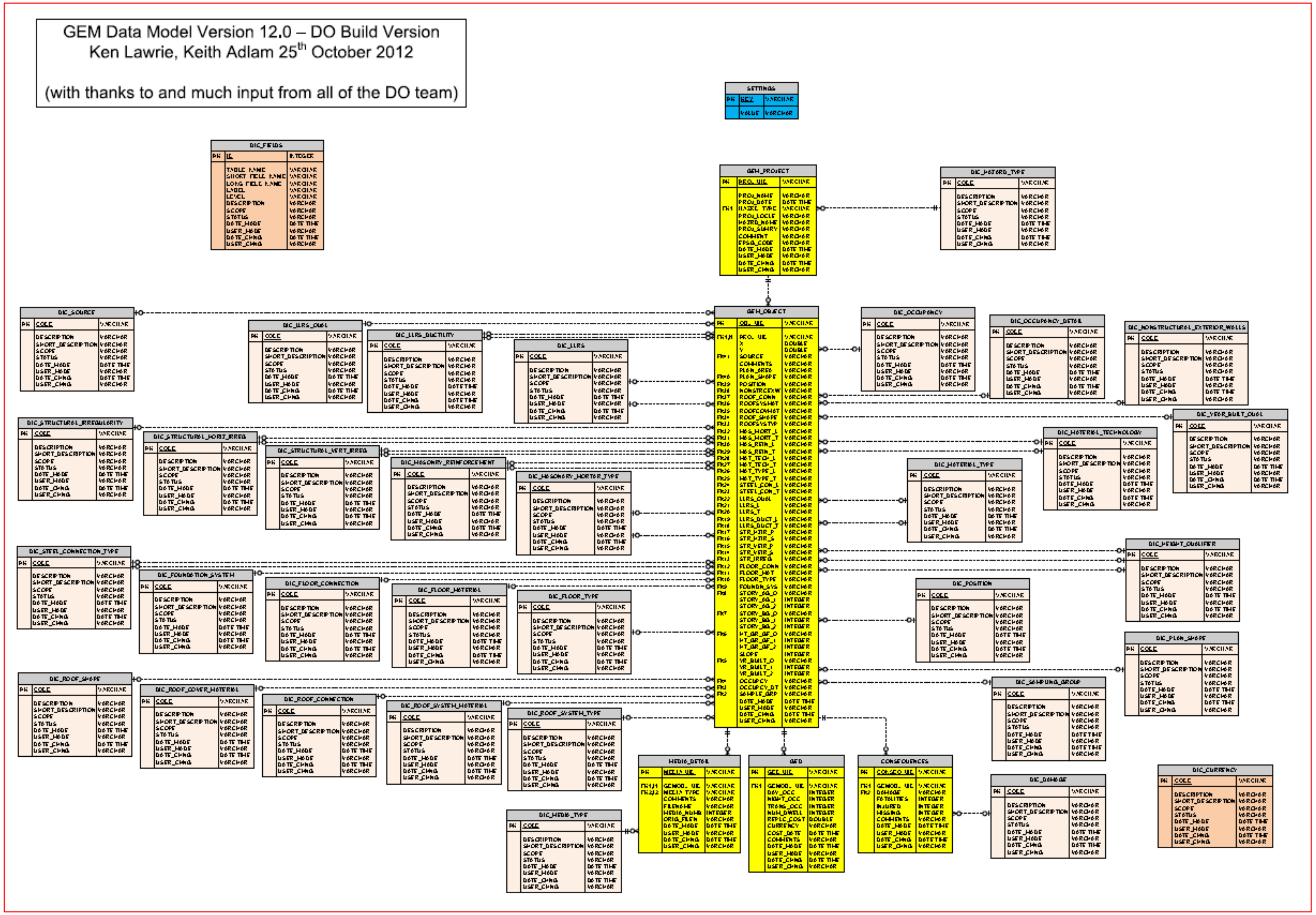


Figure 4.4 GEM Data Model Version 12.0 [GEM IDCT]

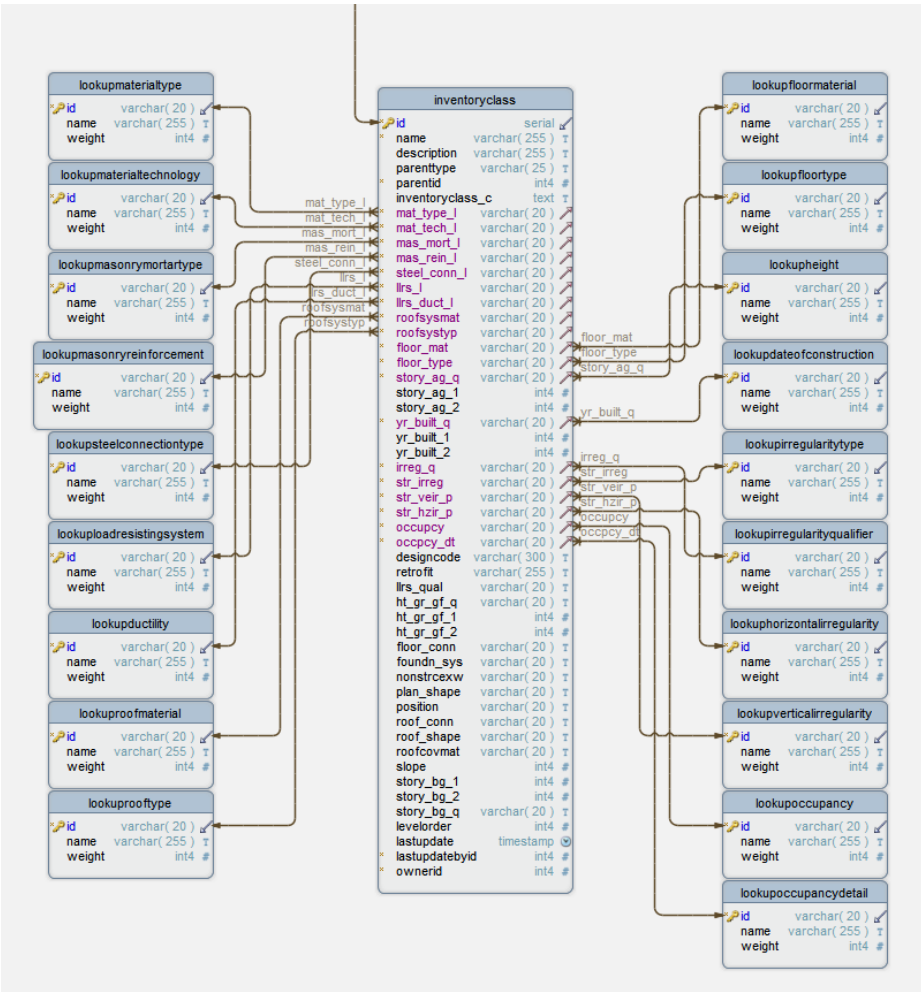


Figure 4.5 GEMECD data model for inventory classes which uses the GEM Building Taxonomy [Ruffle and Smith, 2013]

4.5 Applications and Examples

The user can describe a building typology in two ways: i) manually - by referring to the taxonomy tables included in Appendix A, or ii) by using a computer-based tool such as TaxT [Silva, 2013] where a user can select attribute values and the process is facilitated through drop-down menus, as shown in Figure 4.6.

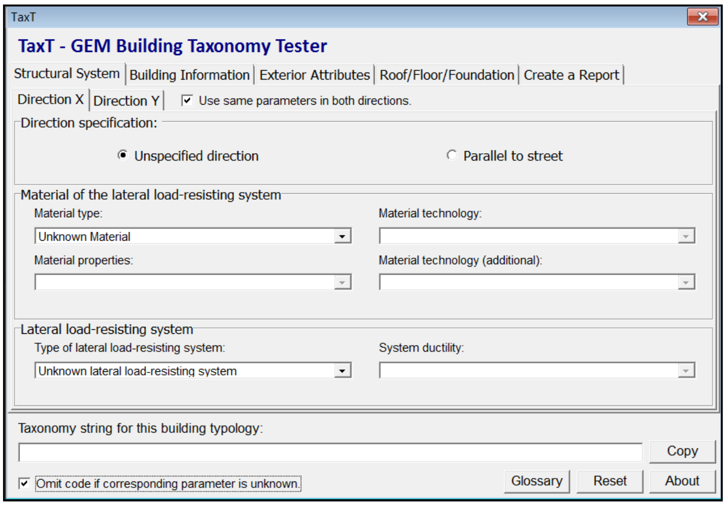


Figure 4.6 GEM Building Taxonomy tester TaxT v4.0 - a screen display

Once the user identifies all attributes/features of a building typology using the taxonomy tables, a taxonomy string can be created as a shorthand description of that typology. A taxonomy string can be compared to a bar code or QR code[54] used to identify merchandise in stores. A mud hut with a thatch roof from an African country is shown in Figure 4.7, with its corresponding GEM Building Taxonomy string, also provided as a QR code.

Figure 4.7 The taxonomy string is equivalent to a bar or QR code for a building. Photo: Rural Taxonomy mud wall building [Sassu and Ngoma, WHE Report 43]

The string represents a combination of unique IDs for selected attributes and attribute details and delimiters. Key rules for creating taxonomy strings are summarized below (see also Section 4.3):

1. Attributes need to be entered in the same sequence as presented in Table G1 of Appendix A.

[54] http://en.wikipedia.org/wiki/QR_code

2. Each attribute value is defined by an identifier (ID) and the corresponding text description (see tables in Appendix A).
3. Attribute values which require numerical input (height and date of construction) are specified by a text ID, the colon sign ":", and a number (integer).
4. Entries with unknown properties are labelled "99".
5. Slash sign "/" is used to separate the attributes.
6. Plus sign "+" is used to include Level 2, Level 3, etc. attribute details with the Level 1 attribute.

Applications of the GEM Building Taxonomy v2.0 will be illustrated with six examples. Note that the attributes for which information is not available are not discussed in these examples and they are omitted from the taxonomy strings.

EXAMPLE 1: A reinforced rubble stone masonry wall building

A reinforced rubble stone masonry wall building with horizontal timber elements shown in Figure 4.9 is a type of construction found in South-East Asia (India, Nepal, and Pakistan), Turkey, Greece, etc. [Bothara and Brzev, 2011].

Figure 4.8 Reinforced rubble stone masonry with horizontal timber elements, Pakistan (Photo: T. Schacher)

This building typology can be described in several ways. Three different options are described below.

Option 1: direct coding

Direct "coding" of the description "a reinforced rubble stone masonry building with horizontal timber elements" can be described by the following string:

/MR+RW+STRUB/LWAL/

Where

MR - a Level 1 detail for the Material attribute with the description "Masonry, Reinforced" (see Table 2 of Appendix A),

RW - denotes timber-reinforced masonry, a Level 2 detail associated with the "Masonry, Reinforced" (see Table 2 of Appendix A), STRUB - denotes rubble stone masonry, a Level 2 detail associated with the Masonry Level 1 details (see Table 2 of Appendix A), and

LWAL - denotes that the lateral load-resisting system is a shear wall (see Table 3, Appendix A).

Option 2: a more detailed description

A user familiar with this type of stone masonry construction would likely assume that buildings of this type are usually built using mud mortar. Therefore, (s)he could specify the type of mortar (MOM in this case) as a Level 3 detail.

/MR+RW+STRUB+MOM/LWAL/

Note that the Level 3 detail (MOM), shown underlined in the above string, is associated with the Level 2 detail (STRUB). Alternatively, the user could specify the type of stone as a Level 3 detail, but it would then not be possible to specify the type of mortar. For example, if granite stone boulders are used (SPGR in Table 2, Level 3 detail for masonry), the taxonomy string is as follows:

/MR+RW+STRUB+SPGR/LWAL/

Option 3: least detailed (aggregated) description

A user with limited expertise associated with building construction practices and/or less information available related to the same building class could define this as “a masonry building”. This implies that resistance to lateral seismic forces is provided by walls. The following string could be used to describe this building:

/M99/LWAL/

where M99 refers to “Masonry, unknown reinforcement” in Table 2. This represents an example of low-detail (aggregated) building typology description.

EXAMPLE 2: Load bearing masonry, mostly residential, built before World War II

Another example of a building typology is related to older unreinforced masonry buildings from the beginning of the 20th century common in many European countries. A typical building is shown in Figure 4.10 (the photo was taken in Ljubljana, Slovenia). The typology description was provided by the GEMECD group, and it is taken from the Earthquake Consequences Database which is currently under development [Lee, Pomonis, So, and Spence, 2011]. Two different records/strings have been created (Record A and Record B), depending on the available information, as illustrated in Figure 4.9.

Figure 4.9 A loadbearing brick masonry building, Ljubljana, Slovenia (Photo: S. Brzev)

Record A describes the typology in an aggregated form, assuming that only general information is available. Only a few basic attributes are used for this record, and the level of detail is low, that is, information on Level 2 and Level 3 attribute details is not available. For example, some users would not be able to determine which type of masonry units were used in this building (because the exterior walls are overlaid with plaster).

Record B describes the same building typology in more detail, but within the structure available in the Building Taxonomy. All attributes have been used in this case. Users familiar with regional construction practices would be able to determine that the masonry walls were not reinforced (MUR is a Level 1 detail in Table 2 of Appendix A), and that fired clay solid bricks were used for wall construction (CLBRS is a Level 2 detail in Table 2). For buildings in that region of Europe built before World War II, cement-lime mortar was used for masonry construction (MOCL is a Level 3 detail in Table 2). The user can refer to the Building Taxonomy Glossary descriptions for mortar terms if in doubt, since there is an option to use either low-strength or regular strength mortar. Lime and cement mortar is identified as regular strength mortar per the Glossary document. The user could also provide more information about the roof system. It is likely that wood trusses were used as a roof system. It is obvious that the roof is pitched and that clay tiles were used as a roof covering. A wooden floor system was likely used.

Finally, since the building was built before World War II, which started in 1939, the user should specify YPRE (latest date prior to the date of construction) as 1939 (see Table 5 in Appendix A), that is, YPRE:1939. However, if the user happens to know that the building was retrofitted in the 1990s, that is, between 1990 and 2000, the taxonomy description should be YBET:2000,1990. It is believed that, if a building was retrofitted, the information related to the retrofit (including lateral load-resisting system and date of retrofit) is more important than the information related to the original construction. When the year of retrofit is known, the user can track the vintage of the building code that was likely used to design the retrofit solution.

It should be noted that it is possible to omit unknown attribute values which contain number "99" in the attribute ID, e.g. D99 (Unspecified direction) for Direction attribute, RES99 (Residential, unknown type) for the Occupancy attribute, etc. This enables the user to create a shorter taxonomy string.

Development of taxonomy strings for different records is summarized in Figure 4.11.

1. Load bearing masonry, mostly residential, built before the World War II

References from other structural taxonomies:
PAGER-STR (UFB, UFB3, UFB4) EERI WHE (7,8) EMS-98 (M5)

Description

Residential buildings found in several European countries (Italy, Greece, Hungary, former Yugoslavia, etc.). By and large, these buildings were built at the beginning of the 20th century before World War II. The main gravity and lateral load resisting systems consist of unreinforced masonry walls, usually built using fired clay bricks in cement: lime mortar. The walls are usually plastered. These buildings usually have wood floors, and clay tile roofing covering a sloped wood roof.

RECORD A: Basic information available (aggregated record)

Direction *(Table 1)*	*Material* *(Table 2)*	*Lateral Load-Resisting System* *(Table 3)*	*Height* *(Table 4)*	*Date of construction or retrofit* *(Table 5)*	*Occupancy* *(Table 6)*	*Structural Irregularity* *(Table 9)*	*Roof system* *(Table 11)*	*Floor system* *(Table 12)*
Unspecified **DX+D99** **or** **DX** **(omit D99)** **DY+D99** **or** **DY** **(omit D99)**	Masonry, unreinforced (not sure of exact type - brick or block due to plaster) **MUR**	Wall **LWAL**	Exactly two-storey high **HEX:2**		Residential, unknown type **RES+RES99** **or** **RES** **(omit RES99)**		Roof shape: pitched and hipped Roof covering: unknown Roof system material: wood Roof system: unknown **RSH3+RWO**	

DX/MUR/LWAL/DY/MUR/LWAL/HEX:2//RES///// RSH3+RWO///

RECORD B: Detailed information available (when the user is more familiar with the regional construction practices, and the exact year of construction)

Direction *(Table 1)*	*Material* *(Table 2)*	*Lateral Load-Resisting System* *(Table 3)*	*Height* *(Table 4)*	*Date of construction or retrofit* *(Table 5)*	*Occupancy* *(Table 6)*	*Structural Irregularity* *(Table 9)*	*Roof system* *(Table 11)*	*Floor system* *(Table 12)*
Unspecified **DX+D99** **or** **DX** **(omit D99)** **DY+D99** **or** **DY** **(omit D99)**	Unreinforced Masonry+solid fired clay bricks+cement: lime mortar **MUR+CLBRS+** **MOCL**	Wall **LWAL**	Exactly two-storey high **HEX:2**	Built before World War II (before 1939) **YPRE:1939**	Residential, unknown type **RES+RES99** **or** **RES** **(omit RES99)**	Regular structure **IRRE**	Roof shape: pitched and hipped Roof covering: clay tiles Roof system material: wood Roof system type: wood trusses **RSH3+RMT1** **+RWO** **+RWO2**	Wood, unknown **FW+FW99** **or** **FW (omit FW99)**

DX/ MUR+CLBRS+MOCL/LWAL3/DY/ MUR+CLBRS+MOCL/LWAL/YPRE:1939/HEX:2/RES///IRRE// RSH3+RWO+RWO2/FW//

Figure 4.10 An example of a building typology description using the GEM Building Taxonomy

EXAMPLE 3: Two different Lateral Load-Resisting Systems in two principal horizontal directions

In this example, the user would like to describe a reinforced concrete building with two different lateral load-resisting systems. Direction X parallel to the street façade is characterized by cast in-place reinforced concrete flat plate system, and Direction Y is characterized by a cast-in-place reinforced concrete wall system. Direction Y is perpendicular to Direction X. A sample building of this type is shown in Figure 4.11, and a drawing showing vertical sections and plans is presented in Figure 4.12.

Figure 4.11 A reinforced concrete building with flat plate system in one direction and the wall system in other direction (Photo: S. Brzev)

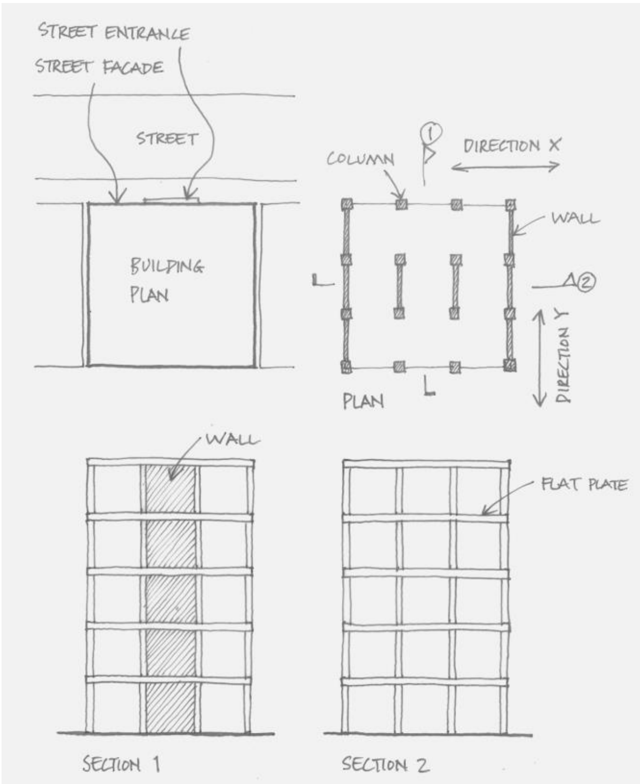


Figure 4.12 A building with different lateral load-resisting systems in directions X and Y

The taxonomy string for attributes 1 to 3 is as follows:

/DX+PF/CR+CIP/LFLS/DY+OF/CR+CIP/LWAL/

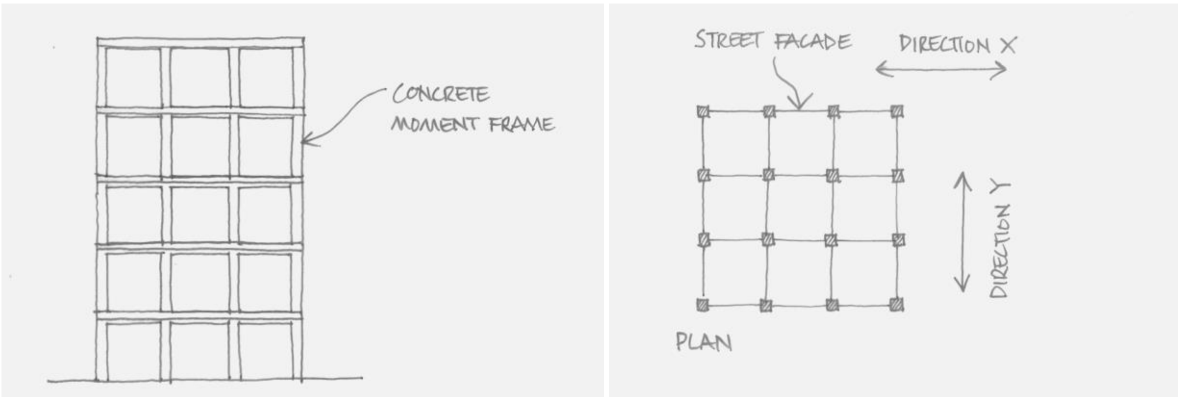
where (see Tables 1 to 13 in Appendix A)

DX - Direction X
PF - Parallel to street
CR - Concrete, reinforced
CIP - Cast in place
LFLS - Flat plate lateral load-resisting system
DY - Direction Y
OF - Perpendicular to street
LWAL - Wall lateral load-resisting system

EXAMPLE 4: A building with the same lateral load-resisting system in both directions

A building with cast-in-place reinforced concrete Moment Frame (LFM) in both directions (DX and DY) is illustrated in Figure 4.13. A drawing showing a vertical section and floor plan for reinforced concrete moment frame building is shown in Figure 4.14.

Figure 4.13 Reinforced concrete moment frame building, New Zealand (Photo: A. Charleson)



A

Figure 4.14 A building with the same lateral load-resisting system in both directions

The taxonomy string for attributes 1 to 3 is as follows:

/DX+PF/CR+CIP/LFM/DY+OF/ CR+CIP/LFM/

where (see Tables 1 to 13 in Appendix A)
DX - Direction X
PF - Parallel to street
CR - Concrete, reinforced

CIP - Cast in place
LFM - Moment frame lateral load-resisting system
DY - Direction Y
OF - Perpendicular to street

EXAMPLE 5: A building with multiple entrances

Consider the building plan with the same LLRS as Example 3 shown in Figure 4.16. The building is a part of a residential development (building complex) and it has more than one main entrance. In this case, Direction X and Direction Y cannot be associated with the street (main) façade. An example of such building is shown in Figure 4.15, and illustrative drawings are shown in Figure 4.16.

Figure 4.15 A building with multiple entrances: street entrance plus entrances to individual apartment units at ground floor level (Photos: S. Brzev; Map data ©2013 Google, Province of British Columbia, DigitalGlobe, IMTCAN)

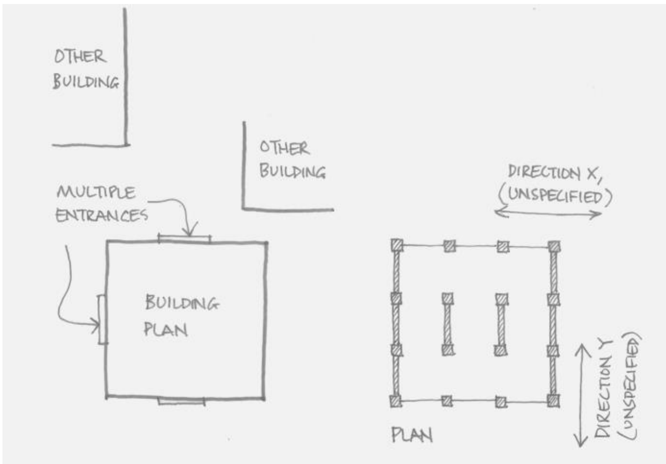


Figure 4.16 An example of a building with unspecified directions

However, it is still possible to record two different LLRSs in two principal directions by using the attribute value Direction Unspecified (D99) for both directions. The taxonomy string for attributes 1 to 3 is as follows:

/DX+D99/CR+CIP/LFLS/DY+D99/CR+CIP/LWAL/

EXAMPLE 6: Buildings with structural irregularities

Example 6a) The building has principal and secondary irregularities in both directions

Let us consider an example where a building has two plan irregularities: torsion eccentricity (TOR) as the primary irregularity and re-entrant corner (REC) as the secondary irregularity. There are also two irregularities in the vertical direction: soft storey (SOS) as the primary irregularity and pounding potential (POP) as the secondary irregularity. The resulting taxonomy string is as follows:

/IR+IRPP:TOR+IRPS:REC+IRVP:SOS+IRVS:POP/

Example 6b) The building has one irregularity in plan and vertical direction each

Consider the same building, but include only information about primary irregularities for plan and vertical directions. The taxonomy string is as follows:

/IR+IRPP:TOR+IRPS:IRN+IRVP:SOS+IRVS:IRN/

In this case, the ID IRN (no irregularity) should be assigned to both secondary plan irregularity (IRPS) and secondary vertical irregularity (IRVS).

Example 6c) The building has only plan irregularities

Consider the same building, but include only information about plan irregularities. The taxonomy string is as follows:

/IR+IRPP:TOR+IRPS:REC+IRVP:IRN+IRVS:IRN/

In this case, the ID IRN (no irregularity) should be assigned to vertical irregularities.

Example 6d) The building has only vertical irregularities

Consider the same building, but include only information about vertical irregularities. The taxonomy string is as follows:

/IR+IRPP:IRN+IRPS:IRN+IRVP:SOS+IRVS:POP/

In this case, the ID IRN (no irregularity) should be assigned to plan irregularities.

4.6 Mapping the GEM Building Taxonomy to Other Taxonomies

It is expected that the GEM Building Taxonomy will be used to collect information on thousands of buildings found around the world, including many previously classified according to other taxonomies, such as PAGER-STR [Jaiswal and Wald, 2008; USGS & WHE, 2008] and HAZUS [FEMA, 2003]. Mapping of the GEM Building Taxonomy to the PAGER-STR and HAZUS taxonomies is presented in Appendix D. An example illustrating the mapping of the GEM Building Taxonomy to the PAGER-STR taxonomy is presented below.

EXAMPLE 7: Mapping the GEM Building Taxonomy to the PAGER-STR Taxonomy

A user desires to describe light timber frame construction (wood-stud frame), a common housing practice in North America shown in Figure 4.17. This corresponds to typology W1 in the PAGER-STR taxonomy, according to the following description:

> *Wood stud-wall frame with plywood/gypsum board sheathing. Absence of masonry infill walls. Shear wall system consists of plywood or manufactured wood panels. Exterior is commonly cement plaster ("stucco"), wood or vinyl planks, or aluminium planks (in lower cost houses). In addition, brick masonry or stone is sometimes applied to the exterior as a non-load-bearing veneer. The roof and floor act as diaphragms to resist lateral loading. (US & Canadian single family homes).*

This building typology can be described in the GEM shorthand form as follows:

/W+WLI/LWAL/RWO+RWO3/

where W - denotes Wood (Level 1 Material), WLI - light wood members (Level 2 detail associated with W), LWAL - wall system (since wood-stud frame can be treated as an equivalent wall for lateral load purpose), RWO - wooden roof, and RWO3 - wood-based sheets on rafters and purlins (this is a roof type associated with RWO).

Figure 4.17 Light timber frame construction, USA (Photos: Arnold, WHE Report 65)

4.7 Supplementary Resources

4.7.1 GEM Building Taxonomy Tester (TaxT)

It is expected that the Taxonomy will be primarily used in computer applications. TaxT is a computer application developed by a GEM researcher Vitor Silva [Silva, 2013]. TaxT Version 4.0 enables a user to record information about a building or a building typology using the 13 attributes of the GEM Building Taxonomy v2.0. The attributes are divided into four groups, as shown in Table G1 in Appendix A: structural system (attributes 1 to 3), building information (4 to 6), exterior attributes (7 to 10), and roof/floor/foundation (11 to 13). TaxT screen display is shown in Figure 4.6. TaxT also generates a taxonomy string corresponding to the information entered by the user for each building typology. In addition, TaxT enables a user to generate a report in PDF format which summarizes the attribute values (s)he has chosen as representative of the building typology under consideration. The report may also include a photo of the building typology, and a text box where comments can be entered. An electronic version of TaxT is posted on GEM NEXUS web site (www.nexus.globalquakemodel.org/gem-building-taxonomy/posts/apply-the-gem-building-taxonomy-v2.0-using-taxt).

4.7.2 Glossary

All terms of the GEM Building Taxonomy have been explained in the companion *Glossary for the GEM Building Taxonomy* which is available at the NEXUS website [3]. The Glossary comprises more than 370 terms containing text descriptions and more than 760 illustrations (photographs and drawings). A sample glossary term Infilled Frame[55] is presented in Figure 4.18.

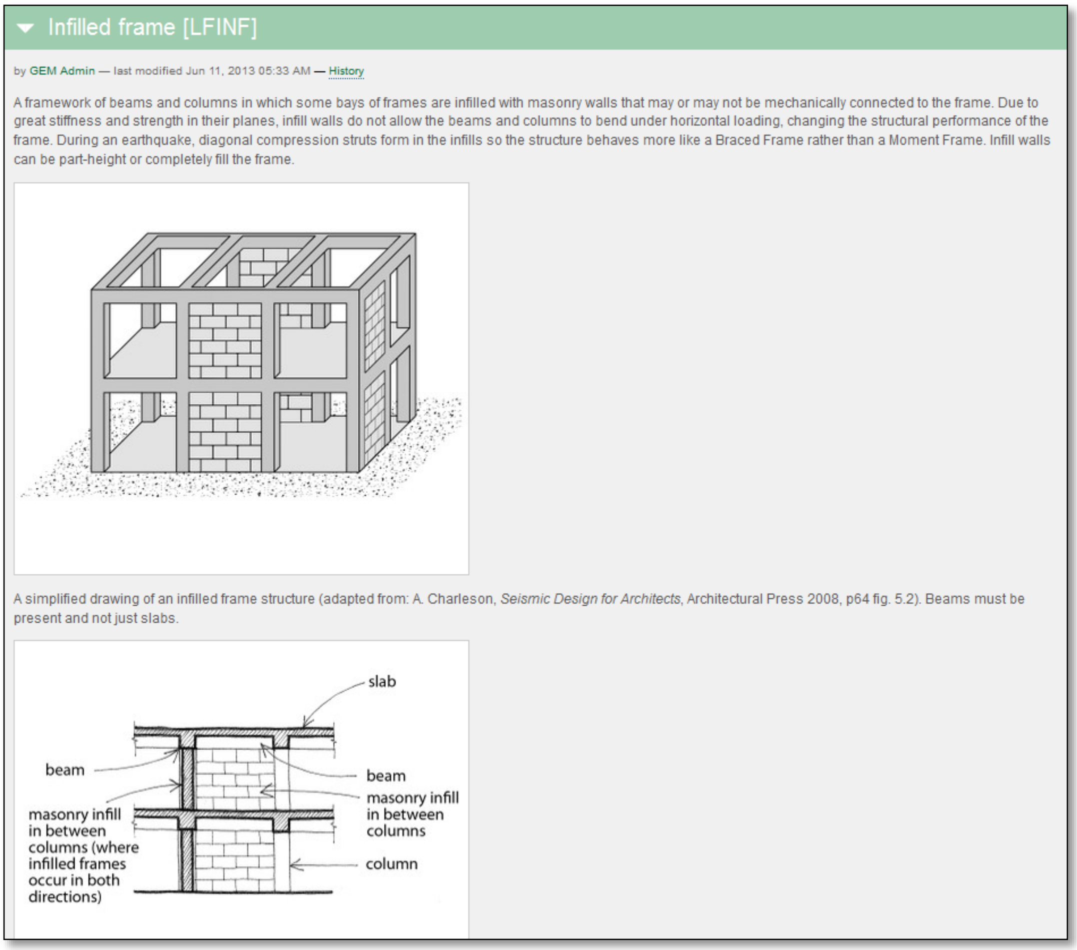


Figure 4.18 A glossary description for Infilled Frame (LFINF)

It has been acknowledged that earthquake engineering professionals in different countries may use different terms for the same attributes. The Glossary anticipates this and has a section called Variants, which is used to

[55] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/infilled-frame—lfinf

identify synonyms for attributes and attribute values used in the GEM Building Taxonomy. For example, the term Moment Frame[56] in Table 2 (Lateral Load-Resisting System) has five variants, as shown in Figure 4.19.

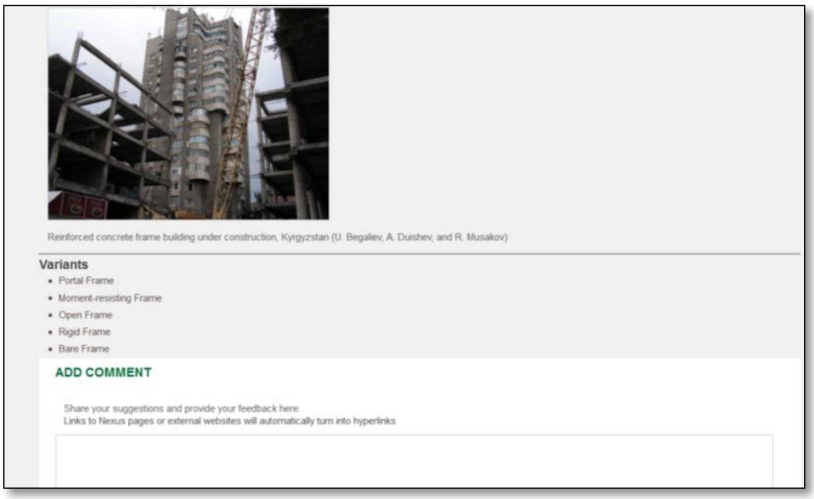


Figure 4.19 Variants for the attribute value Moment Frame (Lateral Load-Resisting System attribute)

4.8 Summary

Chapter 4 outlined the vision and key concepts of the GEM Building Taxonomy v2.0. Thirteen main attributes have been explained, along with the rules for creating taxonomy strings. Taxonomy is mostly going to be used in computer-based applications, and the relational database model has been briefly explained in this chapter. A few building examples have been used to illustrate taxonomy applications. Supplementary resources are important for successful taxonomy application. TaxT Building Taxonomy Tester is an online tool that enables the user to describe a building using GEM Building Taxonomy and generate a taxonomy string. Glossary is a very important supplementary resource, which provides text explanations and graphical illustrations for all taxonomy terms.

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[56] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/moment-frame--lfm

5 Evaluation and Testing of GEM Building Taxonomy

5.1 Background

The Earthquake Engineering Research Institute (EERI), through its World Housing Encyclopedia (WHE) project and its network of international members and colleagues, assisted GEM with the evaluation and testing of the GEM Building Taxonomy. The evaluation and testing process was designed to be interactive, user-friendly and to include international participation. EERI staff and members of the GEM Taxonomy team conducted the evaluation and testing, which is documented in detail by Gallagher et al. [2013].

The purpose of the evaluation was to test the functionality and robustness of the GEM Building Taxonomy. The evaluation process sought to answer the following questions:

- Can the Taxonomy be used to describe construction types that can be found in various countries?
- Does the Taxonomy include all of the most important features relevant to the seismic performance of a building located in various countries?
- Is the Taxonomy user-friendly? Are the Glossary explanations of terms clear, and is there a need to introduce improvements?

This section describes the evaluation and testing approach and its implementation, and summarizes key results relevant for the GEM Building Taxonomy.

5.2 Evaluation and Testing Tools

The two primary means of receiving feedback regarding the GEM Building Taxonomy were:

i. TaxT reports and feedback forms, and
ii. Online survey.

TaxT Reports and Feedback Forms

Participants were asked to first briefly review the GEM Building Taxonomy and then download the interactive TaxT Tester to fill out and submit a report on a specific building typology with which they were familiar. By using TaxT participants were able to describe a specific building using the GEM Building Taxonomy without having to get familiar with the taxonomy by reviewing the taxonomy overview report and tables. EERI staff and the Taxonomy team hypothesized that if participants from various countries were able to describe a specific building in their country/region using TaxT, that would indicate that the Taxonomy was complete and functional. A sample TaxT report is presented in Figure 5.1.

GEM Building Taxonomy Report

The complex building of the Yingxiu secondary school in Yingxiu town

Sun Baitao

Taxonomy string:
DX+PF /CR+CIP /LFINF+DUC /DY+OF /CR+CIP /LFINF+DUC /YEX:2005 /HEX:5+HBEX:0+HFEX:3.60 /EDU+EDU2 /BP1 /PLFR /IRRE /BWMA /RSH1+RMN+RC /FC+FC2 /FOSSL

Material type (direction 1): Concrete, reinforced	Material technology (direction 1): Cast-in-place concrete
Material properties (direction 1):	Material techonology (additional, direction 1):
Lateral load-resisting system (direction 1): Infilled frame	System ductility (direction 1): Ductile
Material type (direction 2): Concrete, reinforced	Material technology (direction 2): Cast-in-place concrete
Material properties (direction 2):	Material techonology (additional, direction 2):
Lateral load-resisting system (direction 2): Infilled frame	System ductility (direction 2): Ductile
Foundations: Shallow foundation, with lateral capacity	Plan shape: Rectangular, solid
Type of Irregularity: Regular structure	Building position within a block: One adjacent building
Plan structural irregularity - primary:	Vertical structural irregularity - primary:
Plan structural irregularity - secondary:	Vertical structural irregularity - secondary:
Roof shape: Flat	Roof covering: Concrete roof, no covering
Roof system material: Concrete	Roof system type: Concrete, unknown
Roof connections: Roof-wall diaphragm connection unknown	
Floor system material: Concrete	Floor system type: Cast-in-place beam-supported RC floor
Floor connections: Floor-wall diaphragm connection, unknown	
Exterior walls material: Masonry	
Date of constrution: Exact date of construction or retrofit 2005	
Number of storeys above the ground: Exact number of storeys 5	Number of storeys below the ground: Exact number of storeys 0
Height of the grade above ground floor: Exact height above grade 3.60	Slope of the ground (for buildings on slopes): Unknown slope
Occupancy type - general: Education	Occupancy type - detail: School
Country: China, Peoples Republic of	Region (province, state, etc.): Hei Longjiang

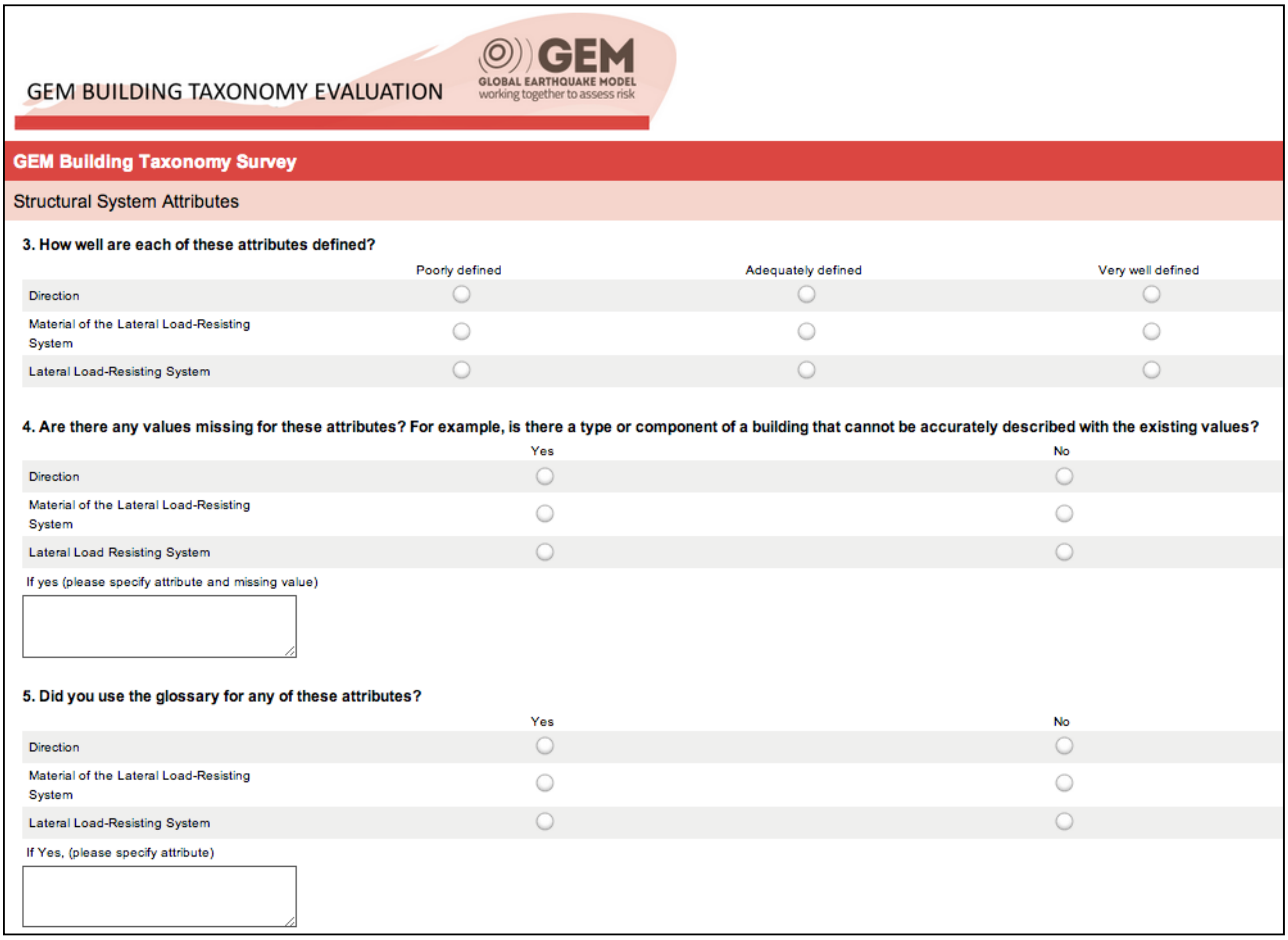
Summary:

Reinforced concrete frame structure is comprised by floors,beams,columns and foundations.Firstly,the plane frame is comprised by beams,columns and foundations.Secondly,Spatial structure system is comprised by the plane frames connecting with continuous beams.The structure would be able to provide large space,and the plane arrangement is flexible. E-35

Figure 5.1 A TaxT report that describes a school building in China (Author: Baitao Sun)

Online Survey

In addition to the website, EERI created a ten-minute web-based survey using a facility [4] to further evaluate the functionality and robustness of the GEM Taxonomy. The survey included a set of 19 basic questions (see sample in Figure 5.2) about the taxonomy and its attributes. The questions were related to the content of the taxonomy (whether any relevant attributes or values were missing), clarity and level of complexity (whether attributes were easy to use), the Glossary explanations, and general comments. A complete list of survey questions is included in the report by Gallagher et al. [2013].



GEM BUILDING TAXONOMY EVALUATION

GEM GLOBAL EARTHQUAKE MODEL working together to assess risk

GEM Building Taxonomy Survey

Structural System Attributes

3. How well are each of these attributes defined?

	Poorly defined	Adequately defined	Very well defined
Direction	○	○	○
Material of the Lateral Load-Resisting System	○	○	○
Lateral Load-Resisting System	○	○	○

4. Are there any values missing for these attributes? For example, is there a type or component of a building that cannot be accurately described with the existing values?

	Yes	No
Direction	○	○
Material of the Lateral Load-Resisting System	○	○
Lateral Load Resisting System	○	○

If yes (please specify attribute and missing value)

5. Did you use the glossary for any of these attributes?

	Yes	No
Direction	○	○
Material of the Lateral Load-Resisting System	○	○
Lateral Load-Resisting System	○	○

If Yes, (please specify attribute)

Figure 5.2 Sample questions used in the survey

5.3 Evaluation and Testing Process

The Evaluation and Testing was conducted in five main steps: i) review of the GEM Building Taxonomy, ii) developing of evaluation and testing materials, iii) Beta-testing, iv) data collection, and v) analysis of results.

Step 1: Review of the GEM Building Taxonomy

EERI staff critically reviewed the GEM Taxonomy materials including the Interim Overview Report [Brzev et al., 2012a], Glossary, TaxT online tester and the PowerPoint tutorial available on how to use the taxonomy. EERI staff and the GEM Taxonomy team worked together to make sure the taxonomy materials were clear to participants who had not been involved in the taxonomy development.

Step 2. Developing of Evaluation and Testing Materials

EERI staff created a series of multi-media interactive materials to test and evaluate the GEM Building Taxonomy. These materials were crafted to reach a wide range of participants from various professional backgrounds and countries. The materials included a website that hosted all of the evaluation and testing materials, a Survey to gather feedback on the taxonomy, an email message to invite participation in the evaluation and testing, a short presentation describing the rationale for the evaluation and testing, and two short videos that described the attributes used in the GEM Building Taxonomy and a typical building typology. The EERI team spent two months on the content development (researching, writing, gathering, organizing and editing information from the Taxonomy materials listed above) for this site, trying to create a website that was informative, interactive and user-friendly.

A highlight of the web site were two videos prepared by EERI interns Hannah Gallagher and Jonathon Tai. They prepared a cartoon-style video to explain each of the Taxonomy attributes, using simple drawings and a bit of humour [http://vimeo.com/54881667]. The other video described a particular building and each of its attributes [http://vimeo.com/54875387#]. The videos were filmed using an iPhone5 and edited with iMovie software.

Step 3. Beta-Testing

The GEM Building Taxonomy was first tested by a select group of experts from various countries around the world. This group of beta-testers included members of the World Housing Encyclopedia Editorial Board, the GEM Building Taxonomy team, and select professionals working in the field of earthquake engineering. These participants were sent an email that briefly described the evaluation and testing process and linked them to the website (Figure 5.3). In addition to being asked to participate in the evaluation and testing process (which provided expert feedback on the functionality of the GEM Building Taxonomy) these participants helped EERI revise testing materials. They were asked the questions like: Is the email message clear? Are the instructions on how to participate clear? Is the survey clear and comprehensive (does it capture their comments)?

As can be seen in the figure, the participants were asked to complete four steps—each step led to a separate web page where additional information was provided. Only three or four participants even attempted to complete these steps and found the directions confusing and the expectations overwhelming.

Step 4. Widespread Data Collection

Based on the results of the beta-testing, EERI staff decided to completely redesign the initial web pages and worked to greatly simplify the needed steps for participants to follow in order to review and provide feedback for the GEM Building Taxonomy. All instructions were combined into one web page[57], which was hosted on the World Housing Encyclopedia website (see Figure 5.4).

Blast emails were broadcast to World Housing Encyclopedia network and all EERI members. The evaluation and testing process was also advertised on social media sites (Facebook and LinkedIn). In addition, EERI staff and the Taxonomy team reached out to colleagues in particular countries with unique or not well-publicized construction technologies, or countries that may have not yet participated actively in either GEM or WHE activities. EERI encouraged participation in the testing from as many countries as possible with a significant seismic risk.

[57] www.world-housing.net/related-projects/share-your-knowledge-of-buildings

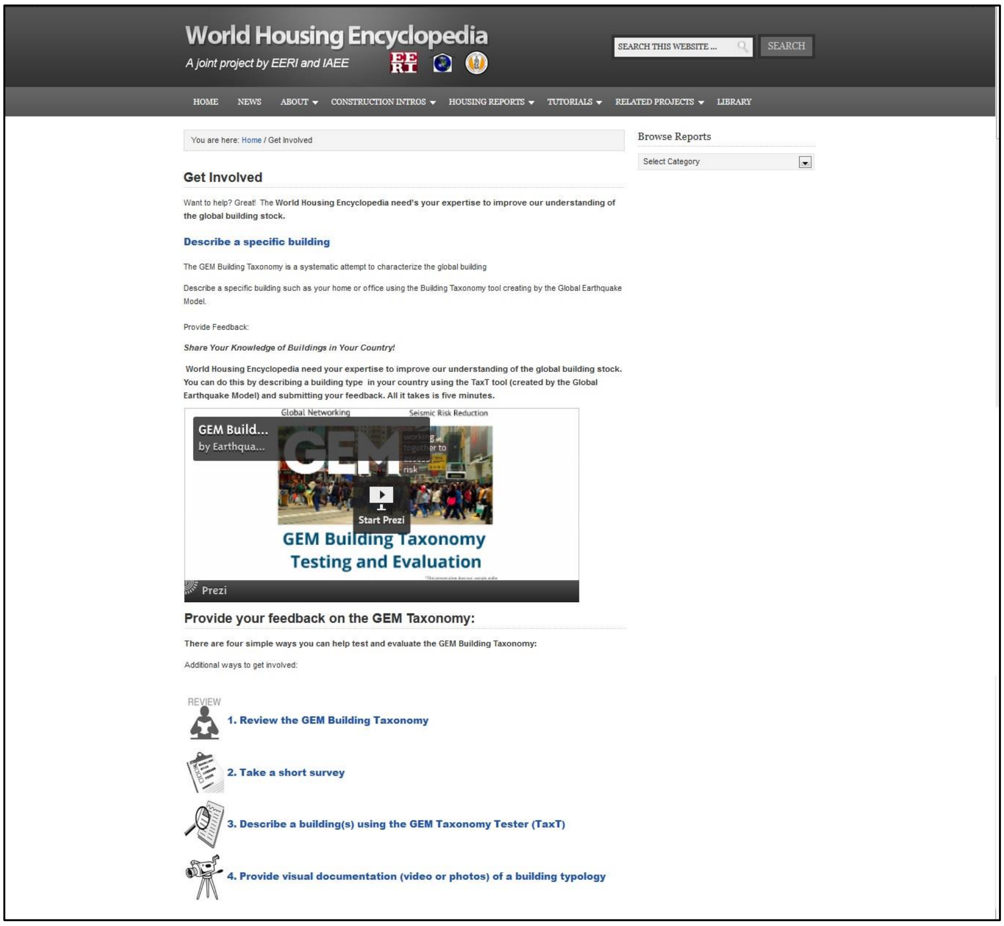


Figure 5.3 Original web site developed for the beta-testing of the GEM Building Taxonomy

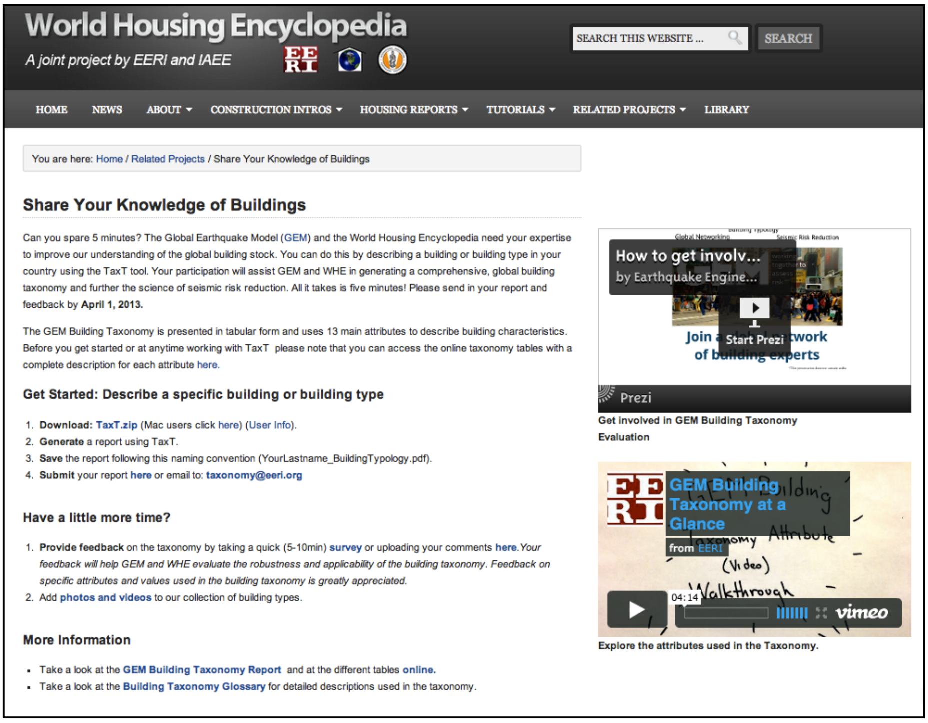


Figure 5.4 Evaluation and Testing Website Screen Shot

5.4 Results: TaxT Reports

By May 2nd, 2013, EERI had received 217 TaxT reports with good geographic representation: 49 different countries in 6 continents (see Figure 5.5 and Table 5.1). The reports represent a wide range of building typologies including single- and multi-storey, reinforced and unreinforced masonry, confined masonry, concrete, steel, wood, and earthen buildings used for residential, commercial, industrial and educational purposes. All of the reports (organized by country) are included in the report by Gallagher et al. [2013] and also posted online[58].

Figure 5.5 TaxT reports - contributions by country

Participants in the Evaluation and Testing of the GEM Building Taxonomy in general were able to submit reports that were complete (all of the attributes were used to describe the building). However, EERI received a handful of incomplete reports where a few attributes are missing and/or failed to describe the building type. This could be because participants did not take the time, were unfamiliar with the terminology, the attribute was irrelevant to their building or they couldn't find a way to describe their building using the values included in the TaxT tester or Taxonomy itself. Because few participants provided specific feedback when they did have trouble it is hard to conclude which of these reasons primarily led to the incomplete reports.

During data collection EERI also found that many participants were unaware or did not understand that they needed to submit both their report and their feedback as two separate PDF documents. This could be one of the reasons that of the 217 reports received, less than a dozen submitted feedback that related to the GEM Taxonomy. It is important to separate out problems with the procedures—the need to submit files separately after completing them rather than as an automatic upload, the fact that TaxT runs only on computers with Windows platform — from issues with the Taxonomy itself. The intention of the Evaluation and Testing task was to evaluate the Taxonomy. Based on the feedback received, there were very few issues with the Taxonomy itself. There were a few specific changes suggested that could be made to the GEM Building Taxonomy to better describe a building's seismic performance. In the feedback there are suggestions on how to characterize buildings with seismic protection such as including values for seismic isolation or energy dissipation devices and soil type.

[58] www.world-housing.net/related-projects/share-your-knowledge-of-buildings/building-taxonomy-summary-reports

Table 5.1 GEM Building Taxonomy (TaxT) Reports by Continent

Africa (9)	Europe (43)	Asia (137)	North America (17)	South America (9)	Oceania (2)
Algeria (3) Ethiopia (1) Ghana (1) Kenya (1) Malawi (1) South Africa (1) Uganda (1)	Bulgaria (1) Germany (2) Greece (2) Hungary (1) Italy (3) Ireland (1) Portugal (6) Romania (17) Slovenia (2) Spain (5) Switzerland (2) United Kingdom (1)	Afghanistan (8) Bhutan (1) China (2) India (3) Indonesia (9) Iran (10) Japan (11) Kyrgyzstan (10) Nepal (3) Pakistan (59) Saudi Arabia (1) Singapore (1) Tajikistan (2) Thailand (1) Central Asia (14) Uzbekistan (1) Turkmenistan (1)	Barbados (1) Haiti (2) Jamaica (1) Mexico (2) Trinidad & Tobago (1) United States (10)	Argentina (1) Brazil (1) Chile (3) Colombia (1) Peru (2) Venezuela (1)	New Zealand (2)

Notes: number of forms per country shown in parentheses

It is of interest to understand the range of reports and building types that were submitted. Figure 5.6 shows details for the occupancy (use) for each building; note that large majority of buildings were single-unit residential buildings. Figure 5.7 indicates that the majority of the buildings for which reports were prepared were one storey high. Figure 5.8 indicates the range of years when the buildings were constructed; for many of the buildings the year of construction was unknown, but for those buildings where this date is known, almost half were constructed since 1980.

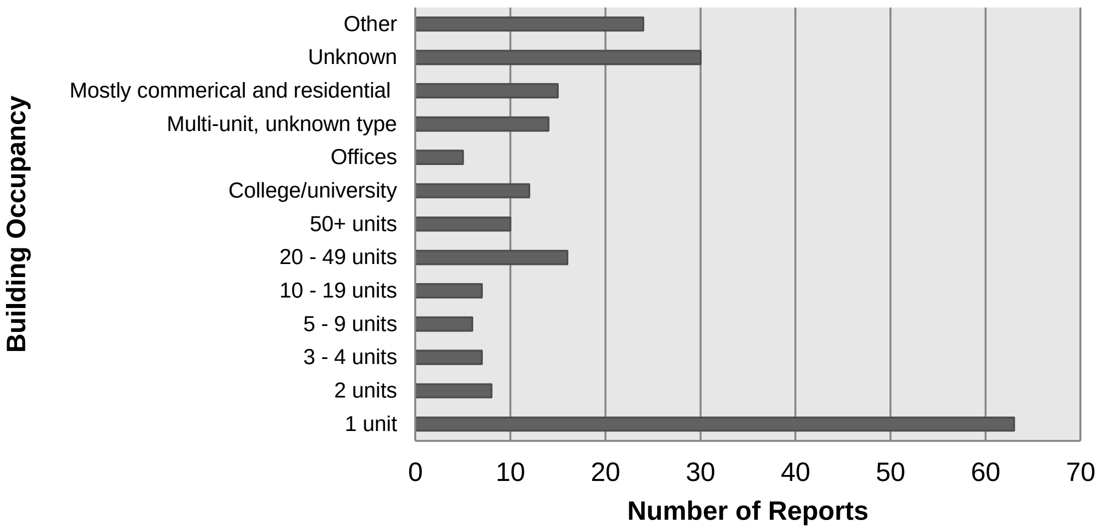


Figure 5.6 Building Occupancy

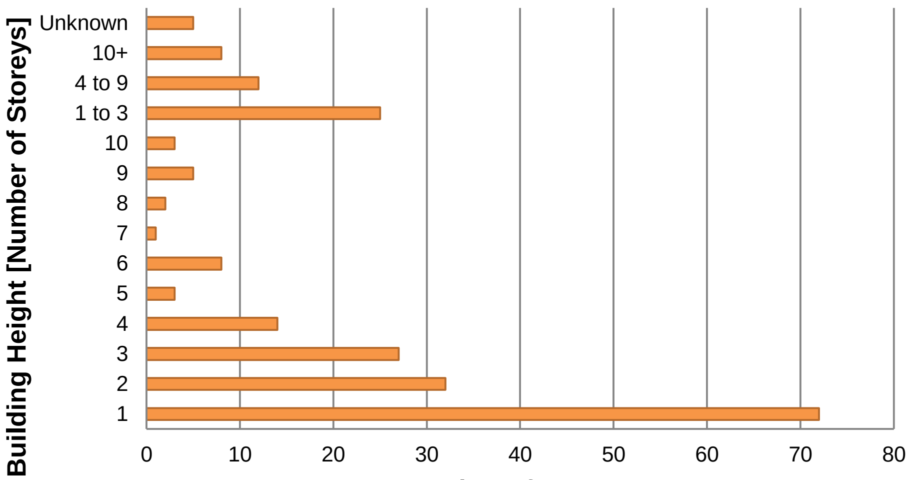


Figure 5.7 Building height (number of storeys)

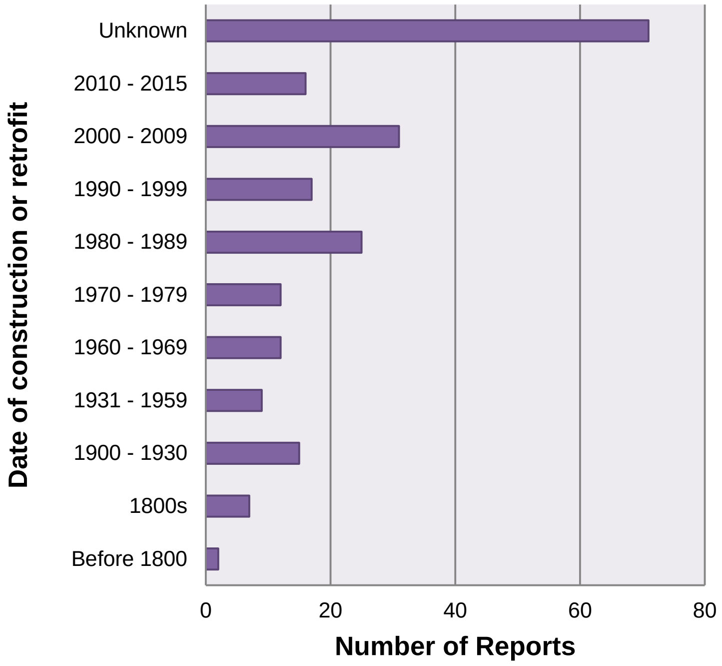


Figure 5.8 Date of construction or retrofit

Detail about the construction material and lateral load-resisting system for each of the buildings reported are presented in Figures 5.9 and 5.10. The majority of reports received described concrete or unreinforced masonry buildings, an indication of the prevalence of these building types around the world.

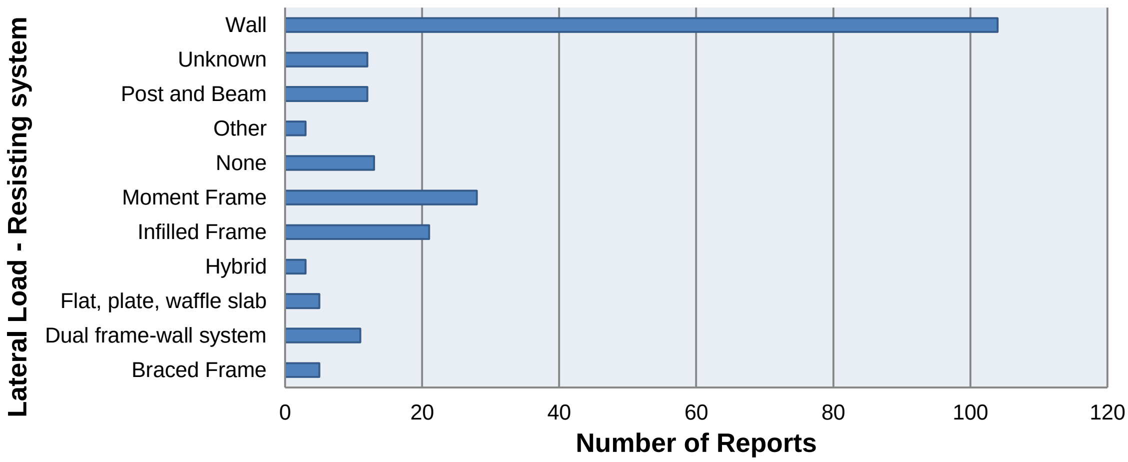


Figure 5.9 Lateral load-resisting system

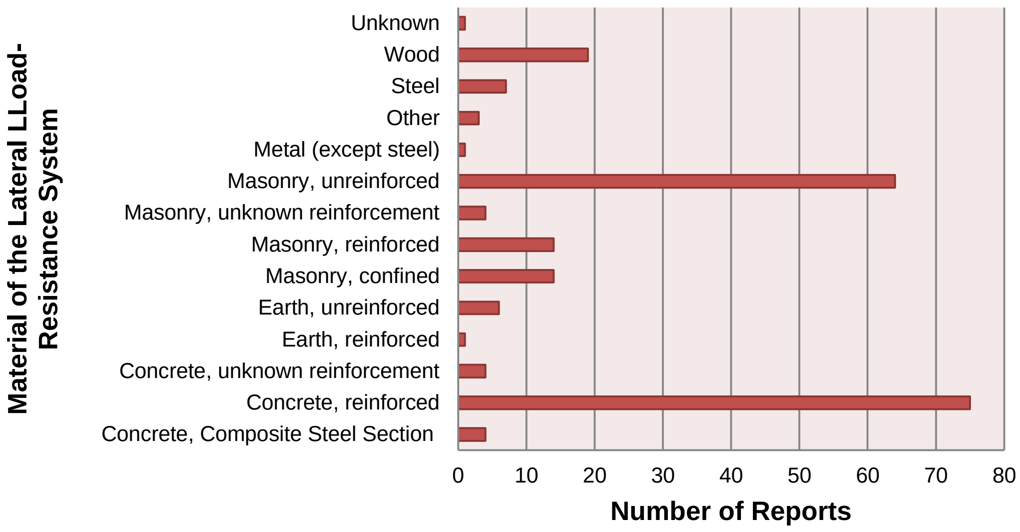


Figure 5.10 Material of the lateral load-resisting system

5.5 Results: Survey

As opposed to the 217 TaxT reports respondents provided, the web-based survey generated fewer responses – 21 individuals participated in the survey. This lower response could be because the survey was relatively long and very detailed, or because the instructions on how to participate and why were not clearly explained to participants.

One of the key questions (#2) in the survey was: *Is the concept of a building taxonomy clear?* A large majority of participants (19 out of 21) responded positively, as shown in Figure 5.11.

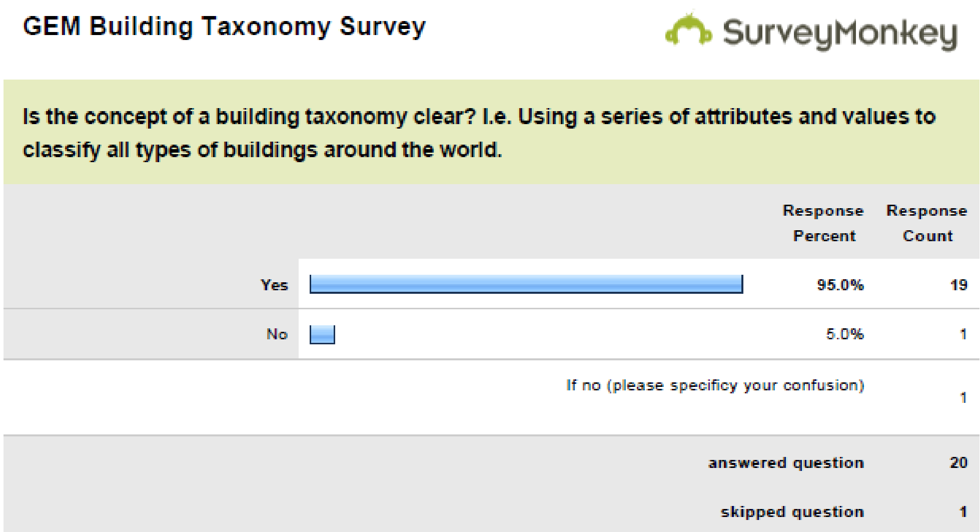
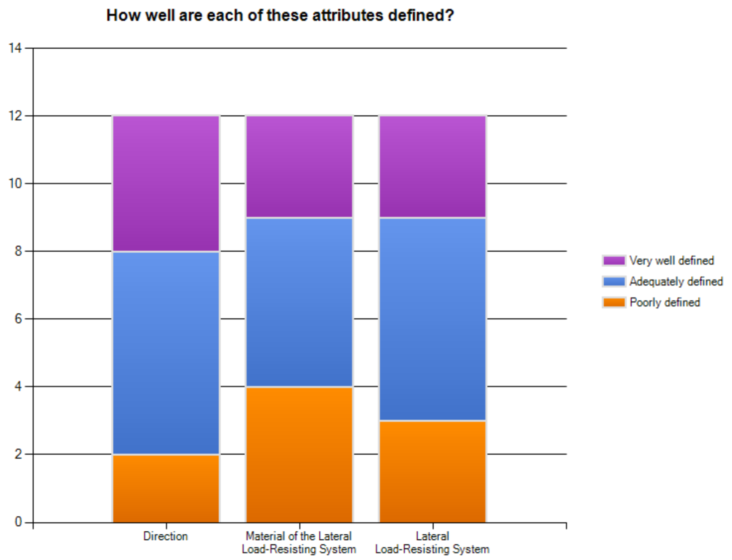
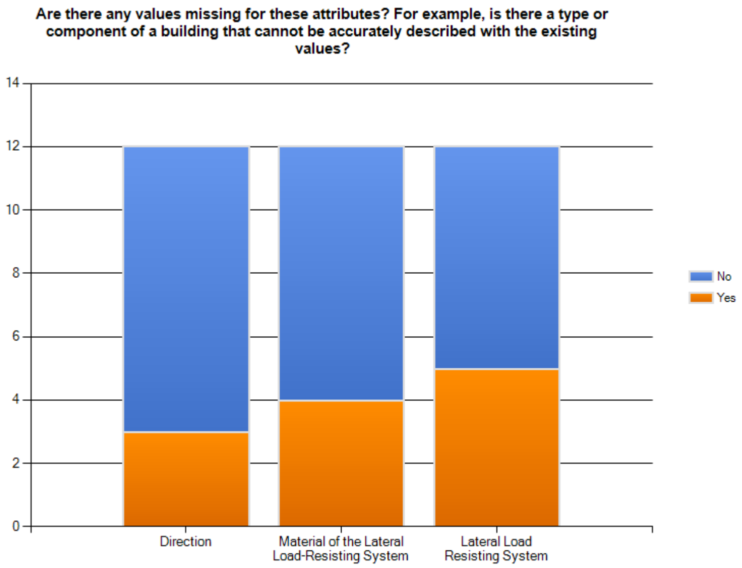


Figure 5.11 A summary of the responses to survey question 2

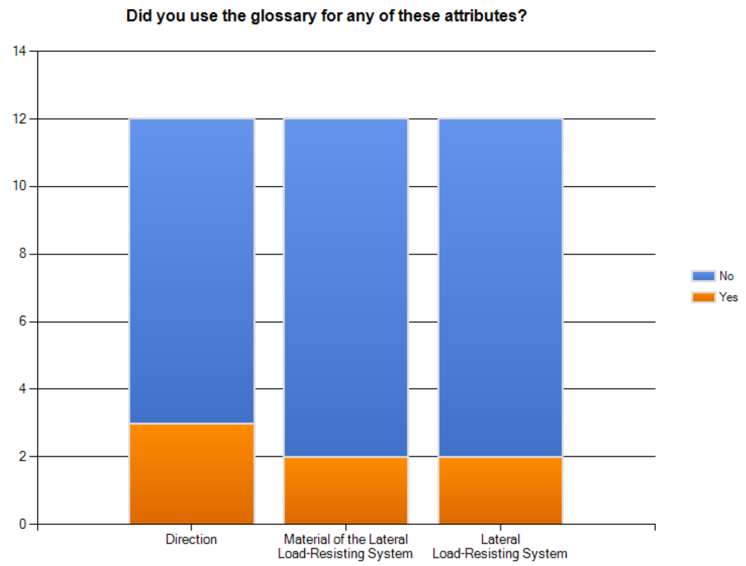
Subsequent survey questions were related to the taxonomy attributes. For example, questions 3, 4, and 5 were related to the first three attributes: direction, material of the lateral load-resisting system, and lateral load-resisting system. The responses are shown on the charts below. It can be seen that majority of responses are positive, that is, most participants responded that the attributes are well defined (adequately defined or very well defined) and that no values are missing (questions 3 and 4). Most participants did not use Glossary to clarify these attributes (question 5).



a)



b)



c)

Figure 5.12 Sample responses to survey questions: a) Question 3; b) Question 4, and c) Question 5.

The feedback that was received from TaxT reports and the survey responses is compiled in Table 5.2. Overall, the feedback was related to a specific value or attribute that was either missing in the taxonomy or poorly defined and thus participants had a hard time describing their building.

Table 5.2 GEM Building Taxonomy Feedback

Attribute Group	#	Attribute Name	Survey Feedback	Response by the GEM Building Taxonomy Team
Structural System	1	Direction	Feedback not provided	
	2	Material of the Lateral Load-Resisting System	The material technology (additional) button didn't work. I wanted to clarify that interior walls were made of solid artisan bricks and that only exterior walls are made of hollow clay brick.	It is possible to make a distinction between interior and exterior walls. Interior walls can be described using Material attribute, while exterior walls can be described using Exterior Walls attribute.
			Not clear how to use the two columns 'material technology' and 'material properties', or rather, why I cannot mark 'lime mortar' plus 'granite'. (This feedback came from using the Mac PDF).	In the current version of the taxonomy, the user needs to choose between defining type of mortar and the type of stone. For stone masonry construction it is considered more relevant to specify the type of stone than the type of mortar. For other masonry technologies, the user needs to specify the type of mortar only (since information on the type of stone does not apply).

Attribute Group	#	Attribute Name	Survey Feedback	Response by the GEM Building Taxonomy Team
Building Information	3	Lateral Load-Resisting System (LLRS)	It is not possible to describe a lateral load-resisting system which includes original masonry structure and retrofit with steel braces.	In case of a retrofitted structure the user needs to enter information about LLRS for the retrofit.
			Missing buckling-restrained braced frames	It is possible to specify LLRS as "Braced Frame" (LFBR) as Level 1 attribute, and "Equipped with base isolation and/or energy dissipation devices" (DBD) as Level 2 attribute.
	4	Height	Feedback not provided	
	5	Date of Construction or Retrofit	It is difficult to explain original construction and retrofit in the same description	For a retrofitted building the user is expected to enter the date of construction for the retrofit (it is not possible to enter information about both the original construction and the retrofit).
	6	Occupancy	Missing 'Residential dwelling above a shop unit', a very popular 'occupancy' in a lot of countries	The participant missed to note the attribute value "Mostly residential and commercial" (MIX1) which is available in Occupancy table.
Exterior	7	Building Position within a Block	Feedback not provided	
	8	Shape of the Building Plan	Building plans vary significantly; taxonomy needs to include L-Shaped and H-Shaped plans.	These plan shapes are included in the taxonomy, that is, "L-shape" (PLFL) and "H-shape" (PLFH).
	9	Structural Irregularity	Not actually sure what this is relating to, suggests an irregular structure?	If the user is not sure which type of irregularity applies in specific case, (s)he can either choose "Unknown structural irregularity (IR99), or "Other plan irregularity" (IRHO) or "Other vertical irregularity" (IRVO)
	10	Exterior Walls	Feedback not provided	
Interior	11	Floor	Feedback not provided	
	12	Roof	Roof material: stone slabs as roofing material is missing.	"Stone slab roof covering" (RMT5) is available in the Roof table.
			For the roof, I struggled with a simple duo-pitched roof	The participant in the survey was likely not able to identify "duo-pitched roof" in Roof table. The term is called "Pitched with gable ends" (RSH2).

Attribute Group	#	Attribute Name	Survey Feedback	Response by the GEM Building Taxonomy Team
	13	Foundation	Missing ‘piled’ option	The Foundation table includes two terms which could be used to describe pile foundations: "Deep foundation, with lateral capacity" (FOSL) and "deep foundation, no lateral capacity" (FOSDN).

5.6 Summary

As a result of the Evaluation and Testing, EERI team received 217 TaxT reports from 49 countries, representing a wide range of building typologies, including single and multi-storey buildings, reinforced and unreinforced masonry, confined masonry, concrete, steel, wood, and earthen buildings used for residential, commercial, industrial and educational occupancy. The EERI team also received feedback from 21 participants through an online survey. Based on the analysis of results, the EERI team validated that the GEM Building Taxonomy is highly functional, robust and able to describe different buildings around the world. However, evaluation and testing process could be expanded to other countries and regions. TaxT reports received to date could be cross-referenced against a global seismic hazard map to identify missing countries of medium or high seismic risk. Also, additional reports could be collected from 49 countries that have been included in the current evaluation and testing.

6 Using the GEM Building Taxonomy

The GEM Building Taxonomy was designed first of all for use within the GEM, but also with a wider vision of defining a "building genome" that potentially could have universal application. The questions exist:

- How does one use the GEM Building Taxonomy, in GEM?
- Similarly, how might the GEM Building Taxonomy be used for applications beyond the immediate needs of the GEM?
- How might the GEM Building Taxonomy integrate with emerging building information systems, as used in the design and construction field (i.e., BIMS, OmniClass) and in the finance, insurance and asset management fields (e.g., ACORD), both discussed in Chapter 3?

This section addresses these questions.

6.1 GEM Applications of the GEM Building Taxonomy

With regard to the GEM, applications for the GEM Building Taxonomy relate to defining building classes and their attributes for use in the following components:

- Global Exposure Database (GED4GEM) project
- Global Vulnerability Estimation Methods (GEM VEM) project
- Global Consequences Database (GEMECD) project
- Inventory Data Capture Tools (GEM IDCT) project

The next sections briefly summarize how the GEM Building Taxonomy is being utilized in each of these components.

6.1.1 GED4GEM

The aim of the Global Exposure Database (GED4GEM) project is to develop a publicly available global database of buildings. Such an "exposure" database is necessary to understand what is at risk and to support the development of vulnerability data appropriate to specific countries, structures, or building classes. To do this, buildings and their attributes need to be consistently defined across and within regions – to do this, GED4GEM is utilizing the GEM Building Taxonomy.

The development of GED4GEM fully incorporates the latest GEM Building Taxonomy specifications, as exemplified in a recent project in Bishkek, Kyrgyzstan where detailed exposure data is being captured and databased, Figure 6.1.

6.1.2 GEMECD

The aim of the GEMECD project is to develop a publicly available global database of information on earthquake consequences. Such a consequences database is useful to inform potential users of consequences from past events, as a benchmarking tool for analytical loss models and to support the development of tools to create vulnerability data appropriate to specific countries, structures, or building classes. In short, GEMECD becomes for the earthquake research community a context for analysis and presentation of results against a standardised base. To do this, buildings and their attributes need to be consistently defined across and within events – to do this, GEMECD is utilizing the GEM Building Taxonomy.

The development of GEMECD fully incorporates the latest GEM Building Taxonomy including its building descriptions in drop down menus. A typical taxonomy record (referred to as Inventory Class by GEMECD) is shown in Figure 6.2. As well, GEMECD team has been supportive and active in helping with the development of the GEM Building Taxonomy.

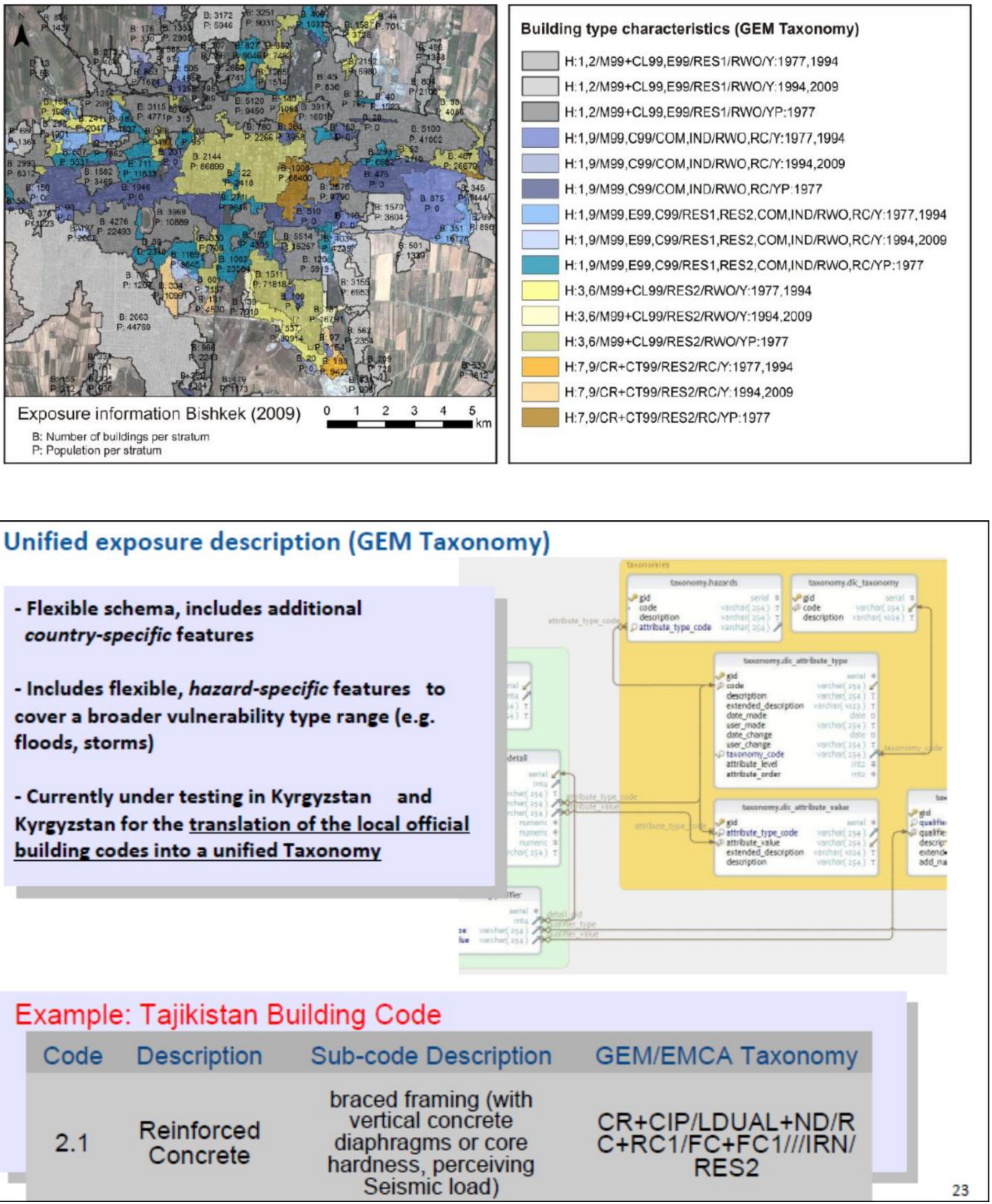


Figure 6.1 Use of GEM Building Taxonomy by GED4GEM project [Wieland, 2013]

Reinforced Concrete Frame with Brick or Hollow Concrete Block Infill Walls (3-7 storeys) & Masonry with RC bottom frame (3-5 storeys)

back to Guo et al 2010 Remote Sensing Damage Survey

Inventory class name		Reinforced Concrete Frame with Brick or Hollow Concrete Block Infill Walls (3-7 storeys) & Masonry with RC bottom frame (3-5 storeys)
Material type		Concrete, reinforced
Material technology		Cast-in-place concrete
Type of lateral load-resisting system		Infilled frame
System ductility		Ductility unknown
Roof system material		Concrete
Floor material		Concrete
Height qualifier		Range of no. of storeys above ground
Upper bound of height range	*storeys*	7
Lower bound of height range	*storeys*	3
Date of construction or retrofit qualifier		Upper and lower bound date of construction or retrofit
Upper bound of date of construction or retrofit range	*year*	2009
Structural irregularity type		Irregular structure
Vertical irregularity description		Change in vertical structure (includes large overhangs)
Occupancy		Mixed use

Figure 6.2 A typical record in the GEMECD online database - this entry describes reinforced concrete frame buildings damaged in the 2010 Southern Qinghai, China earthquake (M 6.9) [gemecd.org]

6.1.3 GEM IDCT

The Inventory Data Capture Tools (IDCT) global risk component is developing a set of open-source tools to allow GEM users to populate the Global Exposure Database (GED) of the analytical model, at city-wide scale (GED Level 2) to per-building scale (GED Level 3), and the Earthquake Consequences Database with post-disaster impact data. The tools developed by IDCT utilize the GEM Building Taxonomy to generate building inventories within a study area, essential for an improved understanding of seismic exposure and vulnerability. The most recent version of the IDCT tools were tested in Bishkek, Kyrgyzstan in 2013, and the following information is drawn from Fousler-Piggot et al. [2013].

For data collection, once the building of interest is identified, on-screen data collection forms with each attribute option for a structure, as described in the GEM Building Taxonomy, can be completed by the user. These forms present a series of drop-down menus or textboxes with values contextual to the relative field, Figure 6.3. Photographs, video, voice recordings and sketches can also be input into the tools and associated with the location and building attributes of the surveyed structures.

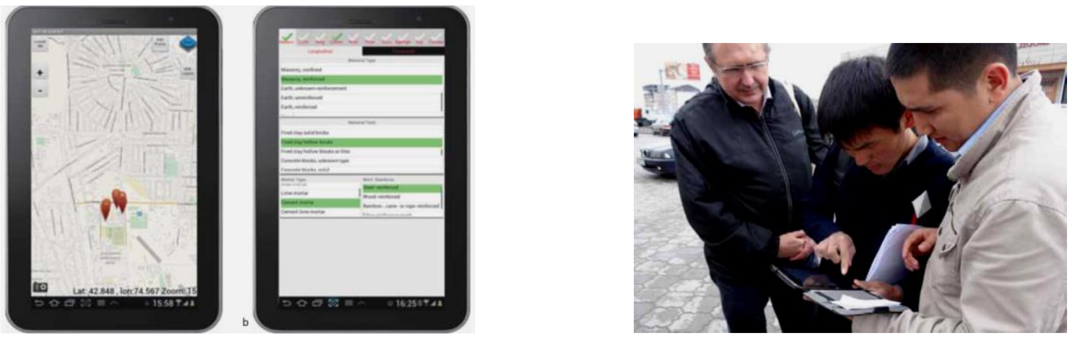


Figure 6.3 A IDCT field collection tools and use, Bishkek Kyrgyzstan [Fousler-Piggot et al., 2013]

Figure 6.4 shows some of the GEM Building Taxonomy attributes as displayed on an IDCT tool (paper form), while Table 6.1 shows the GEM Building Taxonomy attributes most commonly collected in the 2013 Bishkek, Kyrgyzstan field test. Note that attribute names correspond to Attribute_Type_Code used by data modellers and shown in the taxonomy tables in Appendix A. The table shows the three most common values for each attribute.

Table 6.1 Most commonly collected building attributes in the 2013 Bishkek, Kyrgyzstan field test [Fousler-Piggot et al., 2013]

Attribute	Common Values		
PLAN_SHAPE	Rectangular, solid	Square, solid	Irregular shape
POSITION	Detached building	Detached building	Detached building
NONSTRCEXW	Masonry	Concrete	Unknown material
ROOFSYSMAT	Unknown roof material	Wood	Metal
ROOFCOVMAT	Unknown roof covering	Metal or asbestos sheets	Metal or asbestos sheets
ROOF_SHAPE	Unknown roof shape	Pitched and hipped	Pitched and hipped
ROOFSYSTYP		Wood, unknown	Metal beams or trusses supporting light roofing
MAT_TECH_L	Fired clay solid bricks	Concrete blocks, hollow	Concrete, unknown
MAT_TYPE_L	Masonry, unreinforced	Masonry, unreinforced	Concrete, reinforced
LLRS_T	Wall	Wall	Moment frame
LLRS_DCT_T	Non-ductile	Non-ductile	Ductile
STR_HZIR_P	No irregularity	No irregularity	Other horizontal irregularity
STR_HZIR_S	No irregularity	No irregularity	Torsion eccentricity
STR_VEIR_P	No irregularity	No irregularity	Other vertical irregularity
STR_VEIR_S	No irregularity	No irregularity	
STR_IRREG	Regular structure	Regular structure	Irregular structure
FLOOR_MAT		Unknown floor material	Concrete
FLOOR_TYPE			Concrete, unknown
STORY_AG_Q	Exactly	Exactly	Approximately
STORY_AG_1	5	1	2
STORY_AG_2	0	0	0
STORY_BG_Q	Approximately	Exactly	Approximately
STORY_BG_1	0	0	1
STORY_BG_2	0	0	0
HT_GR_GF_Q	Approximately	Approximately	Approximately
HT_GR_GF_1	0	0	0
HT_GR_GF_2	0	0	0
YR_BUILT_Q	Pre	Approximately	Approximately
YR_BUILT_1	0	0	0
YR_BUILT_2	2000	2010	2010
YR_RETRO	0	0	0
OCCUPCY	Residential	Residential	Commercial and public
OCCUPCY_DT	Residential	Residential	Commercial and public

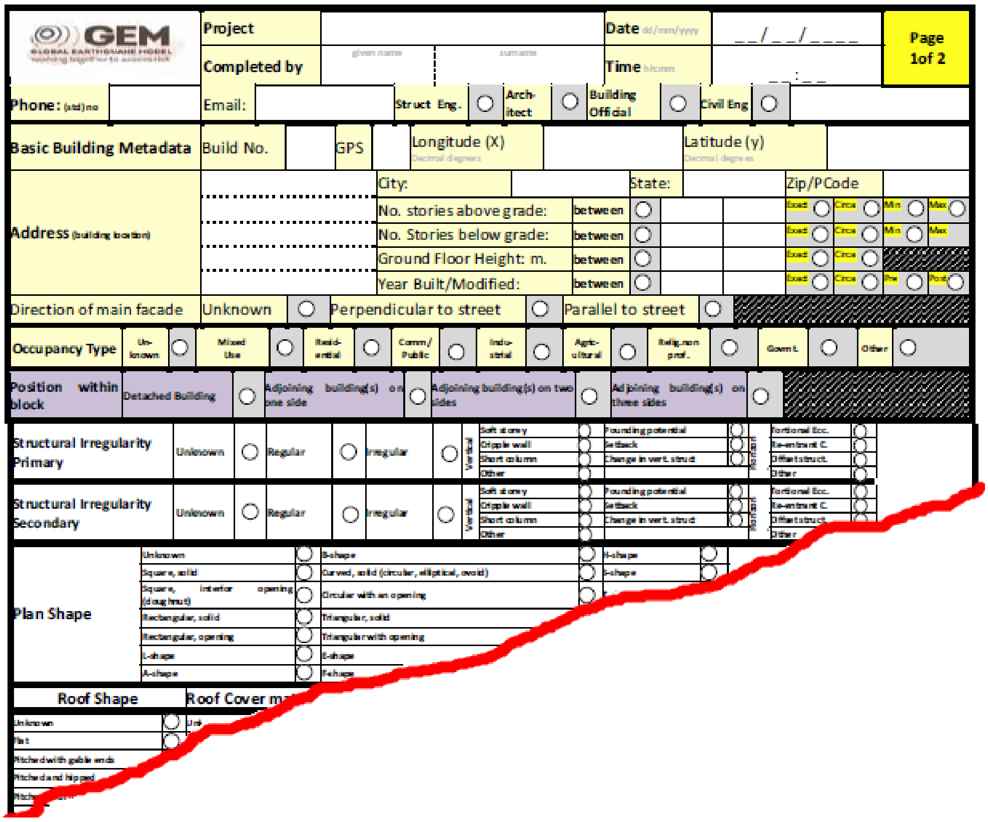


Figure 6.4 GEM Building Taxonomy as implemented in IDCT tool (paper form) [Fousler-Piggot et al., 2013]

6.1.4 GEM VEM

The Vulnerability Estimation Methods (VEM) global risk component is focussing on developing standard guidelines for the creation of new seismic vulnerability/fragility functions to allow GEM users to estimate vulnerability of buildings given earthquake ground motions. The project utilizes analytical, empirical and expert judgment-based approaches in parallel. Building classification needs for these approaches are analogous to, and need to be consistent with, the approaches employed for classifying buildings in other components (i.e., GED4GEM, GEMECD and GEM IDCT). In this regard, GEM VEM requires use of GEM Building Taxonomy as a standardized scheme in order to allow its users to select existing functions from the repository or submit new seismic vulnerability functions into GEM's Physical Vulnerability database [Jaiswal, 2013; Rossetto et al., 2013]. Similarly GEM Building Taxonomy also helps in defining index buildings for use in analytical development of seismic vulnerability functions [Porter et al., 2013].

6.2 Broader Applications of the GEM Building Taxonomy

The GEM Building Taxonomy may have broader applications beyond the GEM. Buildings are a very large fraction of the total human-created environment – in the US in 2011 for example, the total value of buildings is about USD 32 x 10^{12}, or about 72% of all fixed assets[59] – so that a consistent framework for defining and identifying buildings is fundamental to managing this large asset class. We discuss applications of the GEM Building Taxonomy for two of the world's largest building-industries – the Building Industry, and the Finance,

[59] http://stats.oecd.org/BrandedView.aspx?oecd_bv_id=na-data-en&doi=data-00368-en

Insurance and Real Estate (F.I.R.E.) industries – and an important industry that is rapidly growing, "green" energy.

6.2.1 Building industry

By Building Industry we refer not simply to the segment of the industry that constructs new buildings, but to the larger industry that designs, builds, maintains and, eventually, disposes of buildings. Collectively these activities are the "building supply chain" or building life-cycle and may be illustrated by the following simple example of one building component – a light bulb:

- While planning a building, the architect decides that a particular part of the building will have a specific use – for example, a reading room in a library.
- Based on the occupancy, the lighting engineer determines the pattern and size of lighting fixtures, including the specific number and size of the light bulbs.
- The cost estimator determines the number and cost of the light bulbs, on behalf of the owner for use in contract negotiations.
- The contractor similarly determines the number and cost of the light bulbs, for bidding and negotiation.
- During construction, the contractor purchases the necessary light bulbs.
- The light bulb supplier manages the logistics of getting the light bulbs to the construction site.
- The contractor manages the logistics of storing and installing the light bulbs at the site.
- The owner's representative checks the light bulbs are correctly installed.
- The building opens – someone turns the lights on.
- After some time, the maintenance department estimates the light bulbs are at the end of their useful life, and replaces them (rather than replacing them on a one-by-one basis).
- The used light bulbs are recycled or otherwise disposed of.

Such is the life of a light bulb, passing through many people's thoughts and hands, as are all the other parts of a building. Until recently, most of the above eleven steps, for every part of a building, involved duplicate data lookup and input, with opportunity for error with each input. In recognition of this opportunity for improved efficiencies, the concept of Building Information Modeling (BIM) has recently emerged:

> *Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition*[60].

BIM is a new technology – it is to buildings what in some ways Geographic Information Systems (GIS) is to maps, navigation, social networking, consumer preferences and any other location-relevant activity. It offers similar opportunities for efficiency and innovation. Many people have a stake in BIMs, as shown in Table 6.2.

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[60] https://en.wikipedia.org/wiki/Building_information_modeling#cite_note-3

Table 6.2 Stakeholders in BIM Use and Information [NIBS, 2007]

Stakeholders	Information Needs
Owners	High level summary information about their facilities.
Planners	Existing information about physical site(s) and corporate program needs.
Realtors	Information about a site or facility to support purchase or sale.
Appraisers	Information about the facility to support valuation.
Mortgage Bankers	Information about demographics, corporations, and viability.
Designers	Planning and site information.
Engineers	Electronic model from which to import into design and analysis software.
Cost and Quantity Estimators	Electronic model to obtain accurate quantities.
Specifiers	Intelligent objects from which to specify and link to later phases.
Attorneys and Contracts.	More accurate legal descriptions to defend or on which to base litigation
Construction Contractors	Intelligent objects for bidding and ordering and a place to store gained information.
Sub-Contractors	Clearer communication and same support for contractors.
Fabricators	Can use intelligent model for numerical controls for fabrication.
Code Officials	Code checking software can process model faster and more accurately.
Facility Managers	Provides product, warranty, and maintenance information.
Maintenance and Sustainment	Easily identify products for repair parts or replacement.
Renovation and Restoration	Minimizes unforeseen conditions and the resulting cost.
Disposal and Recycling	Better knowledge of what is recyclable.
Scoping, Testing, and Simulation	Electronically build facility and eliminate conflicts.
Safety and Occupational Health	Knowledge of what materials are in use and MSDS.
Environmental and NEPA	Improved information for environmental impact analysis.
Plant Operations	3D visualization of processes.
Energy and LEED	Optimized energy analysis more easily accomplished allows for more review of alternatives, such as impact of building rotation or relocation on site.
Space and Security.	Intelligent objects in 3D provide better understanding of vulnerabilities
Network Managers	3D physical network plan is invaluable for troubleshooting.
CIOs	Basis for better business decisions and information about existing infrastructure.
Risk Management	Better understanding of potential risks and how to avoid or minimize.
Occupant Support	Visualization of facility for wayfinding (building users often cannot read floor plans).
First Responders	Minimize loss of life and property with timely and accurate information.

BIMs are also a global development (with, however, differing standards emerging in different countries[i]). The key to BIMS, as with the GEM, is a standardized terminology, so that ‘everyone is speaking the same language’ and a Tower of Babel is avoided. Recognition of the need for such a standardized terminology emerged in the 1990s:

> *The building community needs a classification framework to provide a consistent reference for the description, economic analysis, and management of buildings during all phases of their life cycle. This includes planning, programming, design, construction, operations, and disposal. The elemental building classification UNIFORMAT II meets these objectives. Elements are major components, common to most buildings that usually perform a given function regardless of the design specification, construction method, or materials used. Examples of elements are foundations, exterior walls, sprinkler systems, and lighting.* [Charette and Marshall, 1999].

As with its predecessor, treatment of structural systems leaves much to be desired, an area that the GEM Building Taxonomy may supplement. OmniClass for example is very good at describing a space's function (Table 13), materials (Table 41) and properties (Table 49), but does not appear to describe the lateral load-resisting system or other attributes needed for loss estimation for natural hazards. In this regard, the GEM Building Taxonomy and Glossary may be adapted for use in OmniClass.

6.2.2 Finance, Insurance and Real Estate (F.I.R.E.) industries

Industries with an even greater interest in natural hazards than the Building Industry are the Finance, Insurance and Real Estate industries, collectively termed the "F.I.R.E. industry". Their interest stems almost entirely from the risk perspective – the finance industry invests in buildings and wishes to protect its investment, typically in part through the insurance industry while the real estate industry performs the investment transaction and can bear significant liability.

The real estate industry addresses earthquake and other natural hazards risks through the 'due diligence' process, which typically requires a Property Condition Assessment (PCA) for a property prior to final closure. Seismic risk for such PCAs are quantified according to relatively standard procedures, as exemplified by [ASTM E-2026-07, 2007; ASTM E-2557-07, 2007]. However, these standard guides and practices do not provide standardized terminology for buildings or structural systems, but rather refer to documents such as [ASCE 7-10, 2010; ASCE 31-03, 2003; ASCE 41-06, 2006] regarding technical analysis procedures. The terminologies employed in these documents are those discussed in Section **3.2** and presented in **Table 3.4**. That is, after wending through the guides, practices, standards and other documents, one finds only the same model building types that have been in place since the 1970s and earlier, and a lack of standards for describing a building with any specificity. *Voila*, a need that can be filled by the GEM Building Taxonomy.

Also as discussed in Section **3.2**, the genesis of the early standardized building terminology was the insurance industry. More recently, the insurance industry has sought to develop much more detailed and standardized systems and terminologies, as exemplified by ACORD system discussed in Section 3.4.1. While the ACORD library of standardized forms is very extensive, and it does include a very limited terminology with regard to structures and earthquakes, **Table 3.6**, the terminology is too limited to be of much use, so that another opportunity exists for application of the GEM Building Taxonomy in this area. The GEM Building Taxonomy offers the opportunity for integrating loss estimation on a consistent basis with the many other activities the insurance industry engages in.

6.2.3 Green Energy

An industry unrelated to natural hazards but important for the environment and the economy is that of "green" energy – that is, renewable energy and energy conservation. The current GEM Building Taxonomy can be used by building energy conservation technologists, to identify the orientation of the building, its wall mass, roof shape and covering, wall materials and other attributes that directly influence the energy use of a building. The GEM Building Taxonomy can be enhanced to capture additional energy-relevant attributes, such as "R" rating (i.e., the insulation value of walls and roof) and mechanics of building heating/cooling.

7 Recommendations for Future Development

At this stage, the GEM Building Taxonomy v2.0 meets the needs of GEM users. The Taxonomy has been employed in the field satisfactorily by the GEM IDCT team [Foulser-Piggot et al., 2013], used by the GEMECD team for post-earthquake damage surveys, by the GED4GEM team as the basis for inventory development and by the GEM VEM team as the basis for defining index buildings for use in developing vulnerability functions. Additionally, the taxonomy is being implemented in Central Asia and Latin America through the GEM Regional Programmes. The Taxonomy was also internationally validated through the Evaluation and Testing exercise described in Chapter 5.

The GEM Building Taxonomy team has identified the following recommendations for future development related to the taxonomy:

1. Create a Global Building Taxonomy community
2. Develop a User Manual
3. Expand the Taxonomy
4. Maintain and grow the online Glossary

1. Create a Global Building Taxonomy community

Development of the GEM Building Taxonomy is an open-ended process. As GEM evolves, the need for more specificity and accuracy will require elaboration of the current attributes, and creation of new attributes. These development needs will emerge via feedback from users around the world, though large-scale field applications. The management of such global feedback, and maintaining the GEM Building Taxonomy's usefulness and meeting the criteria of being *International in scope, Detailed, Collapsible, Extensible and User-friendly*, will be very challenging and can easily tax GEM's resources. The only way we see to achieve these goals is to develop an open forum, akin to the management of Wikipedia, in which the GEM Building Taxonomy grows into a Global Building Taxonomy community, self-governing and self-sustaining. The nurturing of such a community is the crucial next step in the development of the GEM Building Taxonomy, and our most important recommendation. How this is to be accomplished will require careful thought and some work. Useful first steps might be the linkage of the current GEM Nexus Building Taxonomy Glossary and other sites, to a broader community, such as Wikipedia, and the holding of a Workshop on a Global Building Taxonomy, with participation by representatives of analogous initiatives in the Building, F.I.R.E. and other industries. **Again, our recommendation is to encourage the creation of a Global Building Taxonomy community.**

2. Develop a User Manual

We believe that it would be useful to develop a **User Manual** for the GEM Building Taxonomy. The purpose of the manual would be to i) supplement the information provided in the Glossary in more detail, and ii) provide illustrative examples. GEM Building Taxonomy has 13 main attributes and numerous attribute values (373 in total) which have been explained in the Glossary. Most of the taxonomy terms are easy to understand, and additional text and graphic explanations are provided in the Glossary. However, there are a few challenging attributes which would require additional explanation, particularly for inexperienced users. Lateral Load-

Resisting System (LLRS) is one such attribute. Glossary offers descriptions of various LLRSs[61], and provides illustrations (diagrams and photos). However, in many cases it is difficult to identify LLRS from the facade (exterior view). Since LLRS is one of the key attributes it is very important for the user to be able to identify it correctly. Also, some of the LLRSs, e.g. Hybrid Lateral Load-Resisting System[62], are more complex and users would benefit from case study examples for these systems. A guideline accompanied by case studies on different LLRSs would be helpful to the users. Other attributes that would benefit from additional explanations and case studies are Direction, Material, Roof, and Floor. Case studies could be supplemented by short videos. The manual could also include a section Frequently Asked Questions (FAQ), where common questions regarding the application of GEM Building Taxonomy would be answered. A repository of FAQs is expected to grow over time. The User Manual would be made available to users of IDCT field tools, and it would be used as a resource for the orientation before using the tools.

3. Expand the Taxonomy

Our other recommendations have to do with several attributes that are currently absent from the Taxonomy, but which have been identified by the Taxonomy team and/or GEM collaborators. These are: i) code compliance, ii) seismic code version, iii) quality of construction, iv) hybrid lateral load-resisting systems, and v) attributes required for analytical vulnerability studies, which we discuss next.

The ***Code Compliance*** attribute was included in Beta V0.1 of the GEM Building Taxonomy [Brzev et al., 2011]. This attribute is intended to identify whether a building had been designed according to a building code, and whether seismic design provisions were considered in its design and construction. Based on this information, a user would be able to differentiate buildings designed and constructed in compliance with a building code from non-engineered buildings, which were designed and constructed without involvement of qualified professionals. Non-engineered buildings constitute a significant portion of the global building stock. This category includes most buildings in rural areas, as well as buildings in urban areas of countries where compliance with building codes is not mandatory. Some building taxonomies, for example HAZUS [FEMA, 2003], specify level of code compliance: high-code, moderate-code, low-code, or pre-code (non-engineered). It is expected that code compliance could be assessed for specific buildings only if additional information is available, including construction drawings and possibly familiarity with local building design and construction practices. In the current Taxonomy it is possible to use the Date of Construction attribute to infer whether a building was designed according to seismic provisions of the building code. For example, for buildings in the CIS countries (territory of the former Soviet Union) the first seismic code was issued in 1957, therefore pre-1957 buildings in the CIS countries are not expected to have been designed with seismic considerations. As another example, New Zealand buildings designed post-1976 can be expected to incorporate ductile detailing. Older buildings are expected to be non-ductile. A possible Code Compliance classification, as proposed in Beta V1.0 of the Taxonomy, is presented in Table 7.1.

The ***Seismic Code Version*** is related to the Code Compliance attribute, and it refers to identifying the version (edition) of the seismic code used for the design of a specific building. In general, once the Date (year) of Construction is known, it may be possible to infer the version of seismic code for the region/country in which a building is located. A correct application of this attribute would require knowledge of local building codes and legislation. For example, when a new edition of the National Building Code of Canada (NBCC) is issued, it

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[61] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/system

[62] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/hybrid-lateral-load-resisting-system--lh

is not required to apply its provisions in building designs until provinces issue their building codes which reference the latest NBCC. The Taxonomy team believes that the Seismic Code Version should not be a part of the taxonomy, but the information about it (if known) could be entered as a reference using tools developed by the IDCT group.

Quality of Construction, including quality of building materials and workmanship, significantly influences the seismic performance of a building, possibly more than the design complexity and code provisions applied in the design. This is confirmed by past earthquakes. Poorly constructed reinforced concrete buildings can show inferior performance compared to unreinforced masonry buildings, which are generally more vulnerable to seismic effects. This attribute Quality of Construction was not included in the taxonomy, because it is difficult to classify within a global taxonomy. It is recognized that the quality of construction is related to economic factors and governance, and it may be possible to relate quality of construction to a national GDP or other economic indicators for a country or a region. It should be noted that quality of construction was addressed in housing reports contained in the World Housing Encyclopedia [EERI, 2000]. Some building codes recognize the impact of quality of construction upon load-bearing capacity of new masonry buildings. For example, the New Zealand masonry design standard NZS 4230:2004 [NZS, 2004] classifies masonry structures into observation types (A, B, or C) depending on the level of construction supervision by a qualified professional. Similarly, Eurocode 6 [CEN, 2004] prescribes different values for partial factors for materials (masonry and steel) γ_M, depending on the type of masonry units, mortar, and execution control (quality of workmanship and level of construction supervision). A possible taxonomy classification related to the quality of construction is presented in Table 7.2.

Table 7.1 Code Compliance Attribute (proposed)

ID	Description	Definition	Comments
CC	**Code Compliance**		
CC99	Code compliance unknown	It is not known if this building was designed according to a seismic Code.	
CCN	No code	A non-engineered building, not complying with a seismic code.	
CCY	Code compliant	Either specifically designed to comply with a seismic code, or pre-engineered. This means that although there was no or very little direct professional engineering input, this building complies with a code that includes seismic considerations.	If a building has been engineered we can assume it has been designed to a code. Pre-engineered is intended to cover construction that conforms with standards that provide seismic resistance. For example, 95% of New Zealand houses are not designed by an engineer but comply with a New Zealand standard which ensures a minimum standard of resistance.

Table 7.2 Quality of Construction Attribute (proposed)

ID	Description	Definition	Comments
QC	**Construction quality**		
QC99	Construction quality unknown	Quality of construction for this building is not known	
QCN	Construction quality poor	Quality of detailing and building materials are considered to be inadequate (per the requirements of national codes and standards); quality of workmanship is considered to be poor (per local construction standards)	
QCY	Construction quality adequate	Quality of detailing and building materials are considered to be adequate (per the requirements of national codes and standards); quality of workmanship is considered to be good (per local construction standards)	

Hybrid (mixed) lateral load-resisting systems are usually encountered in one of the following two cases: a) there is more than one Lateral Load-Resisting System (LLRS) in the building along one or more principal directions (X/Y) or up the building height, or b) there is only one LLRS in the building, but two or more materials of the LLRS are used in different portions of the building. Hybrid LLRSs can be found in many countries, as illustrated in the Glossary for the GEM Building Taxonomy[63]. Researchers from the GEMECD group have identified several hybrid LLRSs while performing post-earthquake damage surveys [Pomonis, 2012]. For example, buildings with a reinforced concrete frame at the ground floor level and masonry walls above were found in the area affected by the 2008 Wenchuan, China earthquake [Su et al., 2011]. Hybrid LLRS is listed as a type of lateral load-resisting system in GEM Building Taxonomy v2.0 (Table 3 in Appendix A). However, it is not possible to identify a combination of LLRSs and/or materials that constitute a hybrid LLRS. A list of hybrid LLRSs is presented in Table 7.3. Considering that buildings with hybrid LLRSs are found around the world, it would be desirable to include a classification of hybrid LLRSs in future version of the GEM Building Taxonomy.

Table 7.3 Hybrid Lateral Load-Resisting Systems

ID		**ID**		
	Type of lateral load-resisting system		**Detail**	**Examples**
LH	Hybrid lateral load-resisting system			
		H99	Unknown hybrid lateral load-resisting system	
		H1	RC frame at lower floors supporting masonry wall structure above	China
		H2	Stone or brick masonry walls with vertical and/or horizontal RC	Greece, Italy (5% of building stock in Greece falls into this

[63]http://www.nexus.globalquakemodel.org/gem-building-taxonomy/overview/glossary/hybrid-lateral-load-resisting-system--lh

ID		ID		
	Type of lateral load-resisting system		Detail	Examples
			structural elements not designed to perform as moment frames	category); RC floor usually constructed above an existing URM building.
		H3	Masonry wall structure at lower floors supporting wooden structure above	Chile, India
		H4	Masonry wall structure at the exterior with interior RC frames	China
		H5	Exterior masonry walls and interior timber frame at the lower floors; this interior frame supports upper floors made of timber	Greece, Lefkas island, system called pontelarisma
		H6	RC frame at the exterior with SRC columns in the interior	Japan, low-rise buildings
		H5	SRC at lower floors and RC frame at upper floors	Japan, medium-rise buildings
		H7	RC frame in the basement and steel frame with SRC columns above ground level	Japan, high-rise buildings
		H8	RC frame in the basement and SRC columns linked with steel beams above ground level	Japan, medium- and high-rise buildings
		H9	RC frame in the basement and light-weight steel frame above	North America, medium-rise commercial buildings
		H10	RC frame in the basement and wood stud structure above	North America, medium-rise apartment buildings
		HO	Other hybrid lateral load-resisting system	

A number of ***attributes required for analytical vulnerability studies*** have not been included in GEM Building Taxonomy v2.0. The Taxonomy was developed to address the needs of various GEM seismic risk studies. Due to its flexible data model and a comprehensive content, it is able to describe characteristics of global building stock at an aggregated level. It is acknowledged that the goal of the Global Vulnerability Consortium (GVC) is to provide methods and standards for vulnerability assessment that can be applied to a wide taxonomy of structures, and to derive sample vulnerability functions that can be applied at a global scale. GVC has been working on three different approaches for vulnerability assessment: empirical, analytical, and expert opinion. In the initial phase of the taxonomy development (Beta 0.1 Version), the Taxonomy team developed a comprehensive taxonomy structure and content which was intended to meet the needs of all vulnerability assessment approaches [Brzev et al., 2011]. However, based on the feedback provided by GEM collaborators the decision was made at the May 2011 Pavia workshop to reduce the scope of the taxonomy to building attributes that are of common interest to all GEM Risk components: GEMECD, GED4GEM, GEM IDCT, and GVC.

As a result, subsequent taxonomy development was directed to a smaller set of attributes (13 in total). It is believed that the current Taxonomy meets the needs of the empirical vulnerability assessment, however it is not able to address the needs of analytical vulnerability assessment [D' Ayala and Meslem, 2011]. It appears that detailed building information is required for the analytical vulnerability assessment, including i) building configuration and dimensions, ii) detailed information on structural and non-structural elements (e.g. dimensions and material properties), and iii) load information. In fact, the type and extent of information is equivalent to the information needed for computer-based structural analysis of a building. D' Ayala and Meslem [2012] have illustrated the needs of an analytical structural vulnerability assessment with an example of a reinforced concrete frame building with masonry infills. Building information required for an analytical vulnerability assessment includes building geometry and configuration (storey heights, number and dimensions of baylines in each direction); material properties (modulus of elasticity, yield strength, etc.); dimensions of beams, columns, and slabs; reinforcement details, etc. Considering the broad focus of the GEM Building Taxonomy, both in terms of lateral load-resisting systems and materials, it is impractical to develop detailed taxonomic classifications at the level required for the analytical vulnerability assessment. In terms of non-structural analytical vulnerability, the GEM team could benefit from the output from the ATC-58 (FEMA P-58) project [ATC, 2013], which has produced a comprehensive classification of non-structural building components suitable for analytical vulnerability assessment.

4. Maintain and grow the online Glossary

Our final recommendation is related to the **Glossary** for the GEM Building Taxonomy. Glossary is a living document and it is expected to grow in future, particularly in terms of illustrations, that is, photographs illustrating features of global building stock. GEM collaborators should be actively encouraged to provide photographs of buildings in their countries and regions which would be posted in the Glossary. Also, Variants (synonyms) section within the current Glossary will need to be expanded to include terms used in various countries. The GEM Building Taxonomy team has recognized a diversity of technical terminology used to describe the Glossary terms - an example is the term Moment Frame which currently has five variants (see Section 4.7.2). This task can only be accomplished with active participation of the GEM community.

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APPENDIX A GEM Building Taxonomy Attributes

Table G1 GEM Building Taxonomy: Attributes

TaxT Attribute Group	#	Attribute	Reference	Attribute levels	Type	Example
Structural System	1	Direction	Table 1	Direction of the building		
	2	Material of the Lateral Load-Resisting System	Table 2	Material type (Level 1)	Text	Steel
				Material technology (Level 2)		
				Material properties (Level 3)		
	3	Lateral Load-Resisting System	Table 3	Type of lateral load-resisting system (Level 1)	Text	Braced frame
				System ductility (Level 2)		
Building Information	4	Height	Table 4	Height	Integer	4
	5	Date of Construction or Retrofit	Table 5	Construction completed (year)	Integer	1925
	6	Occupancy	Table 6	Building occupancy class - general (Level 1)	Text	Residential
				Building occupancy class - detail (Level 2)		
Exterior Attributes	7	Building Position within a Block	Table 7		Text	
	8	Shape of the Building Plan	Table 8	Plan shape (footprint)	Text	
	9	Structural Irregularity	Table 9	Regular or irregular (Level 1)	Text	Re-entrant corner
				Plan irregularity or vertical irregularity (Level 2)		
				Type of irregularity (Level 3)		
	10	Exterior Walls	Table 10	Exterior walls	Text	Wood

TaxT Attribute Group	#	Attribute	Reference	Attribute levels	Type	Example
Roof/Floor/ Foundation	11	Roof	Table 12	Roof shape (Level 1)	Text	Tile (clay, concrete)
				Roof covering (Level 2)		
				Roof system material (Level 3)		
				Roof system type (Level 4)		
				Roof connections (Level 5)		
	12	Floor	Table 11	Floor system material (Level 1)	Text	Concrete
				Floor system type (Level 2)		
				Floor connections (Level 3)		
	13	Foundation System	Table 13	Foundation system	Text	Shallow foundation, with lateral capacity

Table 1: Direction

ID	Level 1 (L1)	ID	Level 2 (L2)
	Direction of building under consideration		**Description of the direction**
DX	Direction X		
		D99	Unspecified direction
		PF	Parallel to street
DY	Direction Y		
		D99	Unspecified direction
		OF	Perpendicular to street

Table 2: Material of the Lateral Load-Resisting System

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Material type		**Material technology**		**Material properties**
Attribute_ Type_Code	**MAT_TYPE**		**MAT_TECH**		
MAT99	Unknown material				
C99	Concrete, unknown reinforcement	CT99	Unknown concrete technology		
CU	Concrete, unreinforced	CIP	Cast-in-place concrete		
CR	Concrete, reinforced	PC	Precast concrete		
SRC	Concrete, composite with steel section	CIPPS	Cast-in-place prestressed concrete		
		PCPS	Precast prestressed concrete		
S	Steel			**STEEL_CONN**	
		S99	Steel, unknown	SC99	Steel connections, unknown
		SL	Cold-formed steel members	WEL	Welded connections
		SR	Hot-rolled steel members	RIV	Riveted connections
		SO	Steel, other	BOL	Bolted connections
ME	Metal (except steel)				
		ME99	Metal, unknown		
		MEIR	Iron		
		MEO	Metal, other		

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Material type		Material technology		Material properties
Attribute_Type_Code	MAT_TYPE	MAT_TECH		MAS_MORT	
M99	Masonry, unknown reinforcement	MUN99	Masonry unit, unknown	MO99	Mortar type unknown
MUR	Masonry, unreinforced	ADO	Adobe blocks	MON	No mortar
MCF	Masonry, confined	ST99	Stone, unknown technology	MOM	Mud mortar
MR	Masonry, reinforced	STRUB	Rubble (field stone) or semi-dressed stone	MOL	Lime mortar
		STDRE	Dressed stone	MOC	Cement mortar
		CL99	Fired clay unit, unknown type	MOCL	Cement:lime mortar
		CLBRS	Fired clay solid bricks	SP99	Stone, unknown type
		CLBRH	Fired clay hollow bricks	SPLI	Limestone
		CLBLH	Fired clay hollow blocks or tiles	SPSA	Sandstone
		CB99	Concrete blocks, unknown type	SPTU	Tuff
		CBS	Concrete blocks, solid	SPSL	Slate
		CBH	Concrete blocks, hollow	SPGR	Granite
		MO	Masonry unit, other	SPBA	Basalt
		MASS_REIN		SPO	Stone, other type
		MR99	Masonry reinforcement, unknown		
		RS	Steel-reinforced		
		RW	Wood-reinforced		
		RB	Bamboo-, cane- or rope-reinforced		
		RCM	Fibre reinforcing mesh		
		RCB	Reinforced concrete bands		

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Material type		**Material technology**		**Material properties**
Attribute_Type _Code	**MAT_TYPE**		**MAT_TECH**		
E99	Earth, unknown reinforcement	ET99	Unknown earth technology		
EU	Earth, unreinforced	ETR	Rammed earth		
ER	Earth, reinforced	ETC	Cob or wet construction		
		ETO	Earth technology, other		
W	Wood				
		W99	Wood, unknown		
		WHE	Heavy wood		
		WLI	Light wood members		
		WS	Solid wood		
		WWD	Wattle and daub		
		WBB	Bamboo		
		WO	Wood, other		
MATO	Other material				

Table 3: Lateral Load-Resisting System

ID	Level 1 (L2)	ID	Level 2 (L2)
	Type of lateral load-resisting system		**System ductility**
Attribute_Type_Code	**LLRS**		**LLRS_DUCT**
L99	Unknown lateral load-resisting system	DU99	Ductility unknown
LN	No lateral load-resisting system	DUC	Ductile
LFM	Moment frame	DNO	Non-ductile
LFINF	Infilled frame	DBD	Equipped with base isolation and/or energy dissipation devices
LFBR	Braced frame		
LPB	Post and beam		
LWAL	Wall		
LDUAL	Dual frame-wall system		
LFLS	Flat slab/plate or waffle slab		
LFLSINF	Infilled flat slab/plate or infilled waffle slab		
LH	Hybrid lateral load-resisting system		
LO	Other lateral load-resisting system		

Table 4: Height

ID	Level 1 (L1)	ID		Definition	Examples
	Height				
Attribute_Type_Code					
H99	Number of storeys unknown				
Attribute_Type_Code	**STORY_AG**				
H	Number of storeys above ground				
		HBET	Range of number of storeys above ground	HBET:a,b = range of number of storeys (a=upper bound and b= lower bound)	Range HBET:3,1 (height range from 1 to 3 storeys)
		HEX	Exact number of storeys above ground	HEX:n = maximum number of storeys above ground level	Fixed number (integer) HEX:2 (two storeys)
		HAPP	Approximate number of storeys above ground	HAPP:n = approximate number of storeys above ground level	Fixed number (integer) HAPP:2 (two storeys)

ID	Level 1 (L1)	ID		Definition	Examples
	Height				
Attribute_Type_Code	**STORY_BG**				
HB	Number of storeys below ground				
		HB99	Number of storeys below ground unknown		
		HBBET	Range of number of storeys below ground		Range (meters) HBBET: 3,1 (between 1 and 3 levels of basement)
		HBEX	Exact number of storeys below ground		Fixed number (integer) e.g. HBEX:2 (two levels of basement)
		HBAPP	Approximate number of storeys below ground		
Attribute_Type_Code	**HT_GR_GF**				
HF	Height of ground floor level above grade				
		HF99	Height of ground floor level above grade unknown		
		HFBET	Range of height of ground floor level above grade	HFBET: a,b (a= upper bound and b=lower bound)	Range (meters) HFBET: 1.0,0.5 (between 0.5 m and 1.0 m)
		HFEX	Exact height of ground floor level above grade		HFEX: 0.75 (exactly 0.75 m)

ID	Level 1 (L1)	ID		Definition	Examples
	Height				
		HFAPP	Approximate height of ground floor level above grade		HFAPP: 0.5 (approximately 0.5 m)
Attribute_Type_Code	**SLOPE**				
	Slope of the ground				
		HD99	Slope of the ground unknown		
		HD	Slope of the ground	HD:a	Integer (degrees) e.g. HD:10 (10 degrees)

Table 5: Date of Construction or Retrofit

ID	**Level 1 (L1)**	**Definition**	**Examples**
	Date of construction or retrofit		
Attribute_Type_Code	**YR_BUILT**		
Y99	Year unknown		
YEX	Exact date of construction or retrofit	Year during which the construction was completed or retrofitted.	YEX:1936
YBET	Upper and lower bound for the date of construction or retrofit	The construction likely took place between 1930 and 1940.	YBET:1940,1930
YPRE	Latest possible date of construction or retrofit	The construction was completed before the World War II, thus the year entered is 1939.	YPRE:1939
YAPP	Approximate date of construction or retrofit	The construction was completed approximately in 1935	YAPP:1935

Note: There is a possibility of entering information related either to the date of original construction or the retrofit - whichever occurs later. For example, if a building was constructed in 1936 and it was retrofitted in 1991, the user should enter 1991.

Table 6: Occupancy

ID	Level 1 (L1)		ID	Level 2 (L2)
	Building occupancy class - general	**Definition**		**Building occupancy class - detail**
Attribute_ Type_Code	OCCUPCY			OCCUPCY_DT
OC99	Unknown occupancy type			
RES	Residential			
			RES99	Residential, unknown type
			RES1	Single dwelling
			RES2	Multi-unit, unknown type
			RES2A	2 Units (duplex)
			RES2B	3-4 Units
			RES2C	5-9 Units
			RES2D	10-19 Units
			RES2E	20-49 Units
			RES2F	50+ Units
			RES3	Temporary lodging
			RES4	Institutional housing
			RES5	Mobile home
			RES6	Informal housing
COM	Commercial and public			
			COM99	Commercial and public, unknown type
			COM1	Retail trade

ID	**Level 1 (L1)**		**ID**	**Level 2 (L2)**
	Building occupancy class - general	**Definition**		**Building occupancy class - detail**
			COM2	Wholesale trade and storage (warehouse)
Attribute_ Type_Code	**OCCUPCY**			**OCCUPCY_DT**
			COM3	Offices, professional/technical services
			COM4	Hospital/medical clinic
			COM5	Entertainment
			COM6	Public building
			COM7	Covered parking garage
			COM8	Bus station
			COM9	Railway station
			COM10	Airport
			COM11	Recreation and leisure
MIX	Mixed use			
			MIX99	Mixed, unknown type
			MIX1	Mostly residential and commercial
			MIX2	Mostly commercial and residential
			MIX3	Mostly commercial and industrial
			MIX4	Mostly residential and industrial
			MIX5	Mostly industrial and commercial
			MIX6	Mostly industrial and residential

ID	Level 1 (L1)		ID	Level 2 (L2)
	Building occupancy class - general	**Definition**		**Building occupancy class - detail**
IND	Industrial			
			IND99	Industrial, unknown type
			IND1	Heavy industrial
			IND2	Light industrial
AGR	Agriculture			
			AGR99	Agriculture, unknown type
			AGR1	Produce storage
			AGR2	Animal shelter
			AGR3	Agricultural processing
ASS	Assembly			
			ASS99	Assembly, unknown type
			ASS1	Religious gathering
			ASS2	Arena
			ASS3	Cinema or concert hall
			ASS4	Other gatherings
GOV	Government			
			GOV99	Government, unknown type
			GOV1	Government, general services
			GOV2	Government, emergency response
EDU	Education			
			EDU99	Education, unknown type

ID	Level 1 (L1)		ID	Level 2 (L2)
	Building occupancy class - general	**Definition**		**Building occupancy class - detail**
			EDU1	Pre-school facility
			EDU2	School
			EDU3	College/university, offices and/or classrooms
			EDU4	College/university, research facilities and/or labs
OCO	Other occupancy type			

Table 7: Building Position within a Block

ID	Level 1 (L1)
	Building Position within a Block
Attribute_Type_Code	**POSITION**
BP99	Unknown building position
BPD	Detached building
BP1	Adjoining building(s) on one side
BP2	Adjoining buildings on two sides
BP3	Adjoining buildings on three sides

Table 8: Shape of the Building Plan

ID	Level 1 (L1)
	Shape of the Building Plan
Attribute_Type_Code	**PLAN_SHAPE**
PLF99	Unknown plan shape
PLFSQ	Square, solid
PLFSQO	Square, with an opening in plan
PLFR	Rectangular, solid
PLFRO	Rectangular, with an opening in plan
PLFL	L-shape
PLFC	Curved, solid (e.g. circular, elliptical, ovoid)
PLFCO	Curved, with an opening in plan
PLFD	Triangular, solid
PLFDO	Triangular, with an opening in plan
PLFP	Polygonal, solid (e.g. trapezoid, pentagon, hexagon)
PLFPO	Polygonal, with an opening in plan
PLFE	E-shape
PLFH	H-shape
PLFS	S-shape
PLFT	T-shape
PLFU	U- or C-shape
PLFX	X-shape
PLFY	Y-shape
PLFI	Irregular plan shape

Table 9: Structural Irregularity

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Regular or irregular		**Plan irregularity or vertical irregularity**		**Type of irregularity**
Attribute_Type_Code	**STR_IRREG**				
IR99	Unknown structural irregularity				
IRRE	Regular structure				
IRIR	Irregular structure				
		Attribute_Type_Code	**STR_HZIR_P**		
		IRPP	Plan irregularity-primary	IRN	No irregularity
				TOR	Torsion eccentricity
				REC	Re-entrant corner
				IRHO	Other plan irregularity
		Attribute_Type_Code	**STR_HZIR_S**		
		IRPS	Plan irregularity-secondary	IRN	No irregularity
				TOR	Torsion eccentricity
				REC	Re-entrant corner
				IRHO	Other plan irregularity

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Regular or irregular		**Plan irregularity or vertical irregularity**		**Type of irregularity**
		Attribute_Type_Code	STR_VEIR_P		
		IRVP	Vertical structural irregularity - primary	IRN	No irregularity
				SOS	Soft storey
				CRW	Cripple wall
				SHC	Short column
				POP	Pounding potential
				SET	Setback
				CHV	Change in vertical structure (includes large overhangs)
				IRVO	Other vertical irregularity
		Attribute_Type_Code	STR_VEIR_S		
		IRVS	Vertical structural irregularity - secondary	IRN	No irregularity
				SOS	Soft storey
				CRW	Cripple wall
				SHC	Short column
				POP	Pounding potential
				SET	Setback
				CHV	Change in vertical structure (includes large overhangs)
				IRVO	Other vertical irregularity

Table 10: Exterior Walls

ID	Level 1 (L1)
	Exterior Walls
Attribute_Type_Code	**NONSTRCEXW**
EW99	Unknown material of exterior walls
EWC	Concrete exterior walls
EWG	Glass exterior walls
EWE	Earthen exterior walls
EWMA	Masonry exterior walls
EWME	Metal exterior walls
EWV	Vegetative exterior walls
EWW	Wooden exterior walls
EWSL	Stucco finish on light framing for exterior walls
EWPL	Plastic/vinyl exterior walls, various
EWCB	Cement-based boards for exterior walls
EWO	Material of exterior walls, other

Table 11: Roof

ID	Level 1	ID	Level 2	ID	Level 3 (L3)	ID	Level 4 (L4)	ID	Level 5 (L5)
	Roof shape		**Roof covering**		**Roof system material**		**Roof system type**		**Roof connections**[1]
Attribute_Type_Code	**ROOF_SHAPE**		**ROOFCOVMAT**		**ROOFSYSMAT**		**ROOFSYSTYP**		**ROOF_CONN**
RSH99	Unknown roof shape	RMT99	Unknown roof covering	R99	Roof material, unknown			RWC99	Roof-wall diaphragm connection unknown
RSH1	Flat	RMN	Concrete roof without additional covering					RWCN	Roof-wall diaphragm connection not provided
RSH2	Pitched with gable ends	RMT1	Clay or concrete tile roof covering	RM	Masonry roof			RWCP	Roof-wall diaphragm connection present
RSH3	Pitched and hipped	RMT2	Fibre cement or metal tile roof covering			RM99	Masonry roof, unknown	RTD99	Roof tie-down unknown
RSH4	Pitched with dormers					RM1	Vaulted masonry roof	RTDN	Roof tie-down not provided
RSH5	Monopitch	RMT3	Membrane roof covering			RM2	Shallow-arched masonry roof	RTDP	Roof tie-down present
RSH6	Sawtooth	RMT4	Slate roof covering			RM3	Composite masonry and concrete roof system		
RSH7	Curved	RMT5	Stone slab roof covering	RE	Earthen roof				
RSH8	Complex regular	RMT6	Metal or asbestos sheet roof covering			RE99	Earthen roof, unknown		
RSH9	Complex irregular	RMT7	Wooden or asphalt shingle roof covering			RE1	Vaulted earthen roof		

ID	Level 1	ID	Level 2	ID	Level 3 (L3)	ID	Level 4 (L4)	ID	Level 5 (L5)
	Roof shape		**Roof covering**		**Roof system material**		**Roof system type**		**Roof connections**[1]
RSHO	Roof shape, other	RMT8	Vegetative roof covering	RC	Concrete roof				
		RMT9	Earthen roof covering			RC99	Concrete roof, unknown		
		RMT10	Solar panelled roofs			RC1	Cast-in-place beamless reinforced concrete roof		
		RMT11	Tensile membrane or fabric roof			RC2	Cast-in-place beam-supported reinforced concrete roof		
		RMTO	Roof covering, other			RC3	Precast concrete roof with reinforced concrete topping		
						RC4	Precast concrete roof without reinforced concrete topping		
				RME	Metal roof				
						RME99	Metal roof, unknown		
						RME1	Metal beams or trusses supporting light roofing		
						RME2	Metal roof beams supporting precast concrete slabs		
						RME3	Composite steel roof deck and concrete slab		
				RWO	Wooden roof				
						RWO99	Wooden roof, unknown		
						RWO1	Wooden structure with light roof covering		

ID	Level 1	ID	Level 2	ID	Level 3 (L3)	ID	Level 4 (L4)	ID	Level 5 (L5)
	Roof shape		**Roof covering**		**Roof system material**		**Roof system type**		**Roof connections**[1]
						RWO2	Wooden beams or trusses with heavy roof covering		
						RWO3	Wood-based sheets on rafters or purlins		
						RWO4	Plywood panels or other light-weight panels for roof		
						RWO5	Bamboo, straw or thatch roof		
				RFA	Fabric roof				
						RFA1	Inflatable or tensile membrane roof		
						RFAO	Fabric roof, other		
				RO	Roof material, other				

Table 12: Floor

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Floor system material		**Floor system type**		**Floor connections**
Attribute_Type_Code	**FLOOR_MAT**		**FLOOR_TYPE**		**FLOOR_CONN**
FN	No elevated or suspended floor material (single-storey building)				
F99	Floor material, unknown			FWC99	Floor-wall diaphragm connection unknown
FM	Masonry floor			FWCN	Floor-wall diaphragm connection not provided
		FM99	Masonry floor, unknown	FWCP	Floor-wall diaphragm connection present
		FM1	Vaulted masonry floor		
		FM2	Shallow-arched masonry floor		
		FM3	Composite cast-in-place reinforced concrete and masonry floor system		
FE	Earthen floor				
		FE99	Earthen floor, unknown		
FC	Concrete floor				
		FC99	Concrete floor, unknown		
		FC1	Cast-in-place beamless reinforced concrete floor		
		FC2	Cast-in-place beam-supported reinforced concrete floor		
		FC3	Precast concrete floor with reinforced concrete topping		

ID	Level 1 (L1)	ID	Level 2 (L2)	ID	Level 3 (L3)
	Floor system material		**Floor system type**		**Floor connections**
		FC4	Precast concrete floor without reinforced concrete topping		
FME	Metal floor				
		FME99	Metal floor, unknown		
		FME1	Metal beams, trusses, or joists supporting light flooring		
		FME2	Metal floor beams supporting precast concrete slabs		
		FME3	Composite steel deck and concrete slab		
FW	Wooden floor				
		FW99	Wooden floor, unknown		
		FW1	Wooden beams or trusses and joists supporting light flooring		
		FW2	Wooden beams or trusses and joists supporting heavy flooring		
		FW3	Wood-based sheets on joists or beams		
		FW4	Plywood panels or other light-weight panels for floor		
FO	Floor material, other				

Table 13: Foundation System

ID	Level 1 (L1)
	Foundation System
Attribute_Type_Code	**FOUNDN_SYS**
FOS99	Unknown foundation system
FOSSL	Shallow foundation, with lateral capacity
FOSN	Shallow foundation, no lateral capacity
FOSDL	Deep foundation, with lateral capacity
FOSDN	Deep foundation, no lateral capacity
FOSO	Foundation, other

APPENDIX B GEM Building Taxonomy Attributes: Additional Background

B.1 Direction

The Direction attribute (Table 1 of Appendix A) enables the users to enter orientation of the lateral load-resisting system of a building and its material. It has been assumed that every building has two principal horizontal directions (X and Y) orthogonal (perpendicular) to one another. It is possible to specify different Lateral Load-Resisting Systems (LLRS) and the corresponding Material of the Lateral Load-Resisting System in Directions X and Y (see Figure B.1).

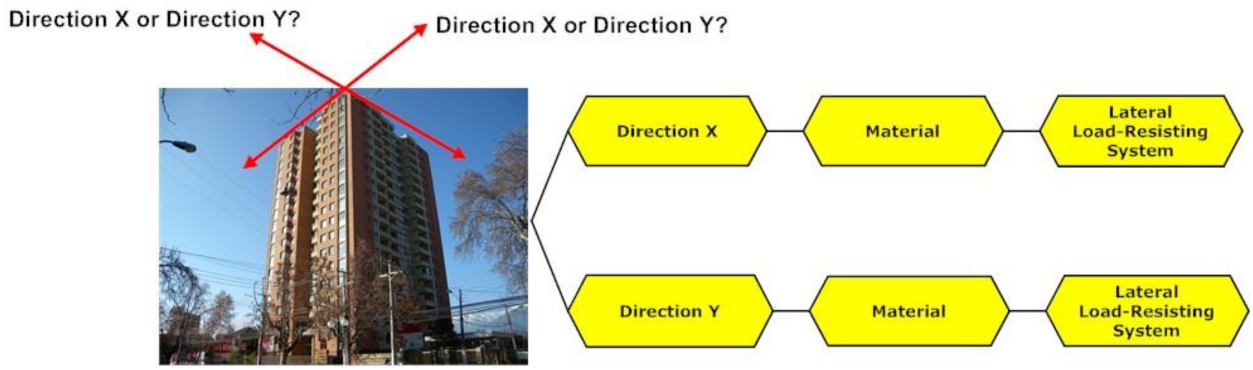

Figure B.1 Direction attribute

Application of the Direction attribute is explained for a building within a building block, with the main entrance facing the street in Figure B.2. The building has two different LLRSs: reinforced concrete flat plate (slab and column system) parallel to street façade, and reinforced concrete wall system perpendicular to street façade. In this case, Direction X (parallel to street façade) is associated with a flat plate system (LFLS) (see Section 2), while Direction Y (perpendicular to street façade) is associated with a wall system (LWAL) (see Section 1).

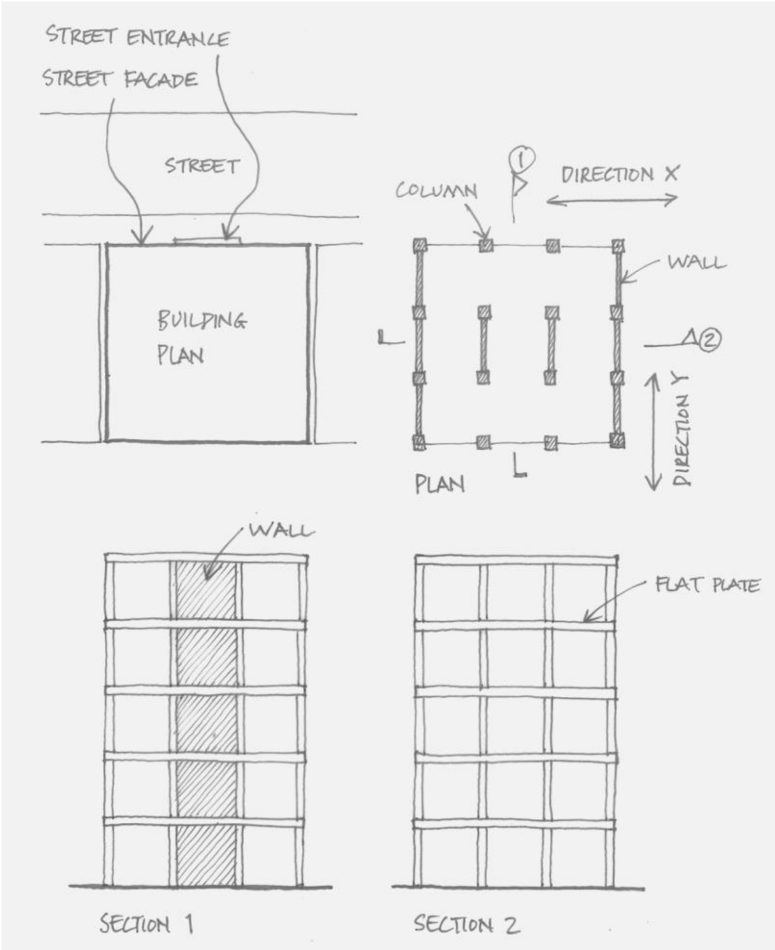

Figure B.2 An application of the Direction attribute

In some cases it is difficult to specify principal directions for a building. An example is a building with a circular plan shape, such as shown in Figure B.3. The user can choose Unspecified Direction (D99) to describe orientation of Directions X and Y.

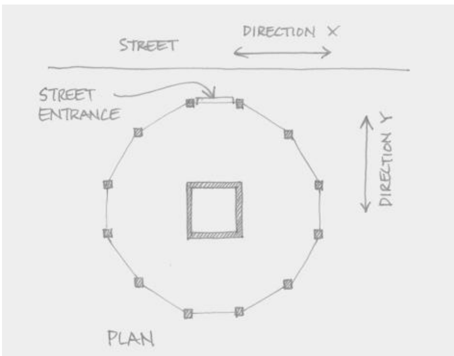

Figure B.3 Direction attribute for a building with circular plan shape

B.2 Material of the Lateral Load-Resisting System

This section explains the relationship between Level 1, Level 2, and Level 3 details associated with the Material attribute (refer to Table 1 in Appendix A).

Some construction materials such as steel, wood, and metal are described using only Level 1 detail, i.e., using S, W and ME identifiers. However, concrete has three possible Level 1 details (C99, CU, and CR). Note that only CR (Concrete, reinforced), shown with a blue frame (solid line) in Figure B.4 can be associated with any of the following Level 2 details (CT99, CIP, PC, CIPPC, and CIPPS), as shown by a red frame (dashed line). Note that each Level 2 detail is associated with a single Level 1 detail.

Level 1

ID	Level 1 (L1) Material type	ID	Level 2 (L2) Material technology
MAT99	Unknown material		
C99	Concrete, unknown reinforcement		
CU	Concrete, unreinforced		
CR	Concrete, reinforced		
		CT99	Unknown concrete technology
		CIP	Cast-in-place concrete
		PC	Precast concrete
		CIPPS	Cast-in-place prestressed concrete
		PCPS	Precast prestressed concrete

Level 2 details

Figure B.4 Relationship between Level 1 and Level 2 details

Masonry is characterized by complex relationships between attribute details. There are several Level 1 details (M99, MUR, MR, and MCF); these details are shown with a blue framed box (solid line) in Figure B.5. Any Level 1 attribute detail may be associated with a unique Level 2 detail (MUN99, ADO, etc.), as shown with a red box (dashed line). This relationship is illustrated on a diagram presented in Figure B.6. For the sake of clarity, relationships between Level 1 and Level 2 details have been shown only for two Level 1 details: i) Masonry, unknown reinforcement and ii) Masonry, reinforced.

Level 1

ID	Level 1 (L1) Material type	ID	Level 2 (L2) Material technology
M99	Masonry, unknown reinforcement	MUN99	Masonry unit, unknown
MUR	Masonry, unreinforced	ADO	Adobe blocks
MCF	Masonry, confined	ST99	Stone, unknown type
MR	Masonry, reinforced	STRUB	Rubble (field stone) or semi-dressed stone
		STDRE	Dressed stone
		CL99	Fired clay unit, unknown type
		CLBRS	Fired clay solid bricks
		CLBRH	Fired clay hollow bricks
		CLBLH	Fired clay hollow blocks or tiles
		CB99	Concrete blocks, unknown type
		CBS	Concrete blocks, solid
		CBH	Concrete blocks, hollow
		MO	Masonry unit, other

Level 2 details

Figure B.5 Relationship between Level 1 and Level 2 details for masonry

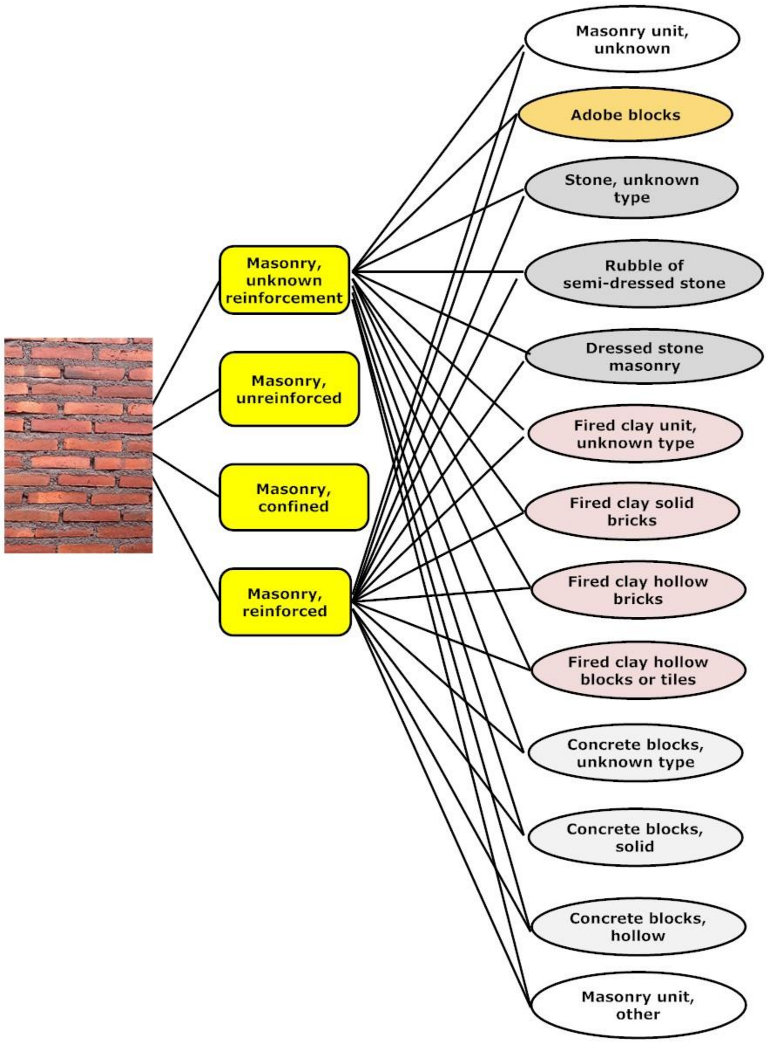

Figure B.6 An illustration of relationships for Level 1 and Level 2 masonry details

In most cases, there is only one Level 2 detail associated with specific Level 1 detail. However, in the case of masonry, a single Level 1 detail can be associated with two Level 2 details (see Rule 3c in Table 4.2). For example, Level 1 detail MR (Masonry, reinforced) can be associated with an appropriate masonry unit (Level 2a), and also a type of reinforcement (RS, RW, RB, RCM, and RCB) (Level 2b), as shown in Figure B.7.

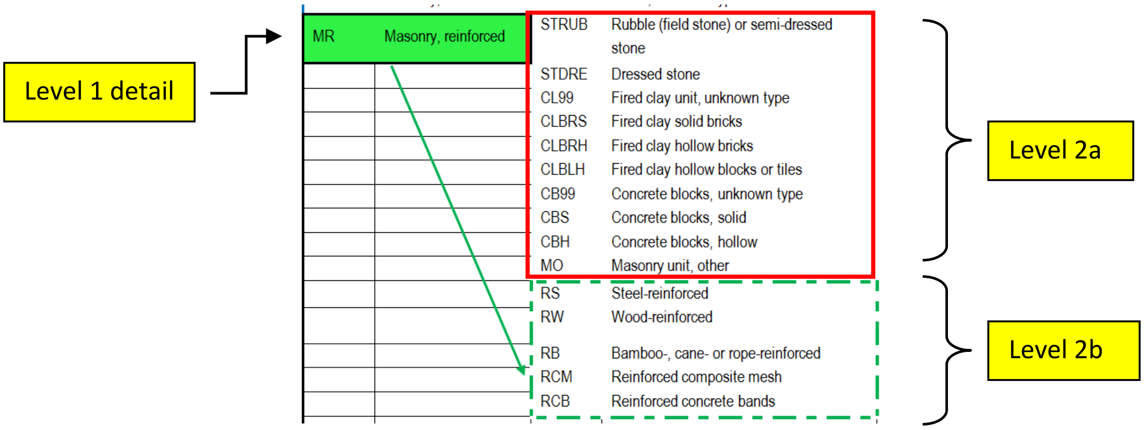

Figure B.7 Level 1 detail MR (Masonry, reinforced) and Level 2 details related to type of reinforcement

The relationship between Level 2 and Level 3 attribute details associated with masonry is shown in Figure B.8. Each Level 2 detail, that is, masonry unit (MUN99, ADO, ST99, STRUB, etc.) contained within the red frame (dashed line) can be associated with one Level 3 detail contained within the purple frame (solid line). Possible Level 3 details include type of mortar (MO99, MON, MOM, etc.) and type of stone (SP99, SPLI, SPSA, etc.). Note that the user needs to make the choice - there is no distinction between the type of mortar and the type of stone (green line shown in the figure).

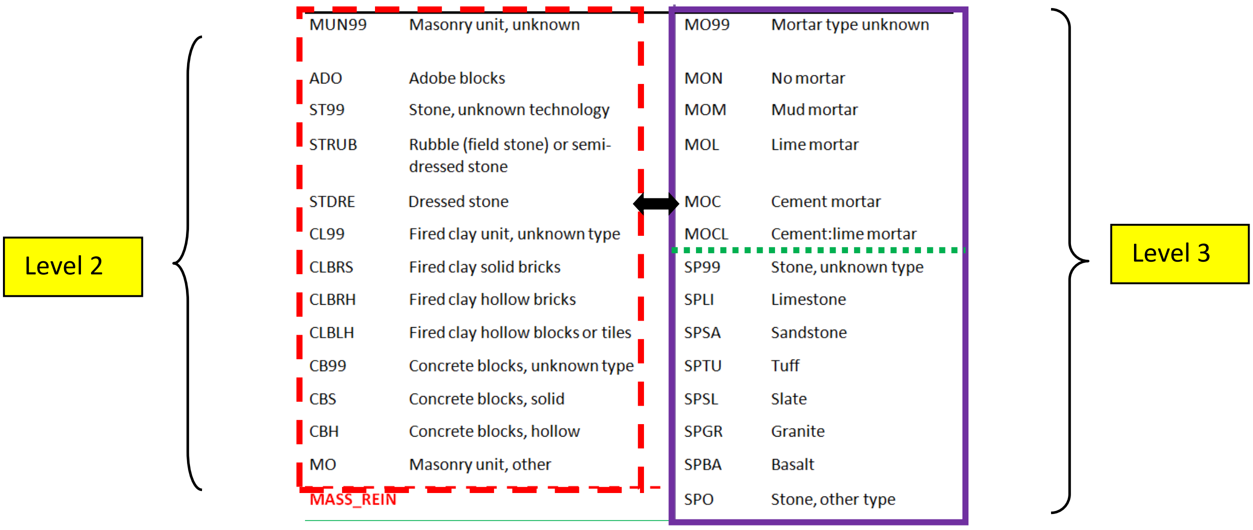

Figure B.8 Level 2 and Level 3 attribute details for masonry

Therefore, when a user wishes to describe a stone masonry building (Level 2 attribute detail), it is recommended to select a type of stone as Level 3 attribute detail, as illustrated in Figure B.9. The type of stone is expected to have a more significant influence on the seismic performance of a stone masonry building than the type of mortar, because the type of stone often determines the stone shape (or whether it can be shaped or not). For all other types of masonry units (adobe, fired solid bricks, etc.), the user needs to select only the type of mortar as Level 3 attribute detail (the type of stone obviously does not apply in those cases).

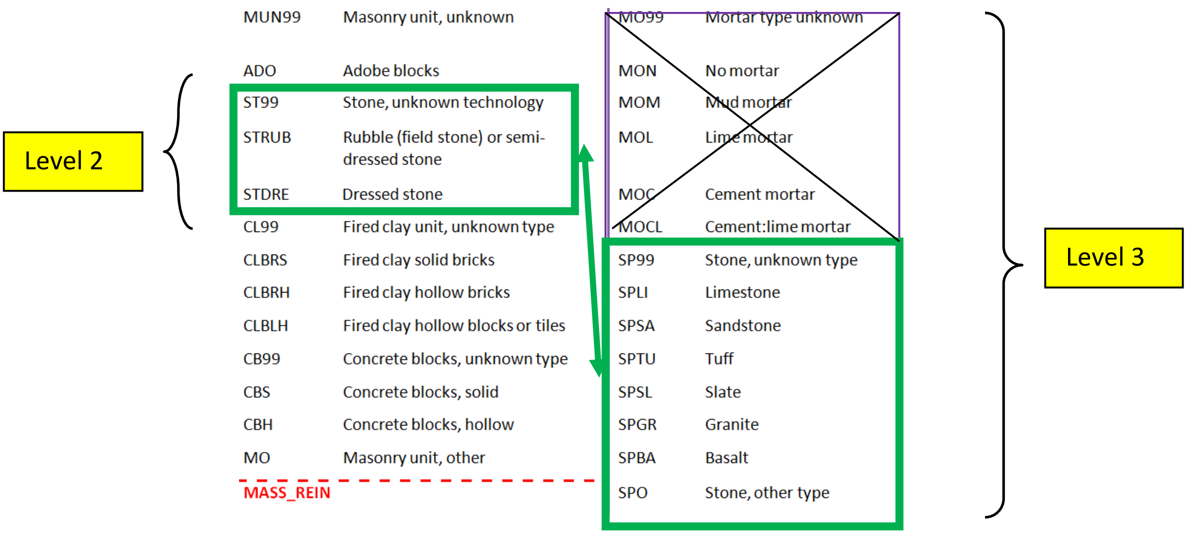

Figure B.9 Stone masonry - Level 2 and Level 3 attribute details

APPENDIX C Constraints

Concrete

Table C1: Material (Concrete) and Acceptable Lateral Load-Resisting Systems

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)
	Table 1		**Table 1**		**Table 2**
C99	Concrete, unknown reinforcement			L99	Unknown lateral load-resisting system
CU	Concrete, Unreinforced			LN	No lateral load-resisting system
CR	Concrete, Reinforced			LFM	Moment frame
		CT99	Unknown concrete technology	LFINF	Infilled frame
		CIP	Cast-in-place concrete	LFBR	Braced frame
		PC	Precast concrete	LPB	Post and beam
		CIP-PS	Cast-in-place prestressed concrete	LWAL	Wall
		PC-PS	Precast prestressed concrete	LDUAL	Dual frame-wall system
				LFLS	Flat slab/plate or waffle slab
SRC	Concrete, composite with steel section			LFLSINF	Infilled flat slab/plate or infilled waffle slab
				LO	Other lateral load-resisting system

Table C2: Material (Concrete) and Maximum Building Height

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)	Maximum Height
	Table 1		**Table 1**		**Table 2**	**Table 5**
C99	Concrete, unknown reinforcement					H:100
CU	Concrete, Unreinforced					H:10
CR	Concrete, Reinforced					H:100
		CT99	Unknown concrete technology			H:100
		CIP	Cast-in-place concrete			H:100
		PC	Precast concrete			H:100
		CIP-PS	Cast-in-place prestressed concrete			H:100
		PC-PS	Precast prestressed concrete			H:100
SRC	Concrete, composite with steel section					H:100

Steel

Unacceptable

Table S1: Material (Steel) and Acceptable Lateral Load Resisting Systems

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)		Comments
	Table 1		Table 1		Table 2		
S	Steel			L99	Unknown lateral load-resisting system		
		S99	Steel, unknown	LN	No lateral load-resisting system		
		SL	Light-weight steel members (cold-formed sections)	LFM	Moment frame		
		SR	Regular-weight steel members	LFINF	Infilled frame		
		SO	Steel, other	LFBR	Braced frame		
				LPB	Post and beam		
				LWAL	Wall		There are a few steel shear wall buildings (steel plate shear walls) in the US, Canada and NZ at least.
				LDUAL	Dual frame-wall system		
				LFLS	Flat slab/plate or waffle slab		Not common, however there are some buildings in Japan of this construction type - steel plates.
				LFLSINF	Infilled flat slab/plate or infilled waffle slab		
				LO	Other lateral load-resisting system		

Table S2: Material (Steel) and Maximum Building Height

ID	Material Type (L1)	ID	Material Technology (L2)			Maximum Height	Comments
	Table 1		**Table 1**			**Table 5**	
S	Steel					H:100	
		S99	Steel, unknown			H:100	
		SL	Light-weight steel members (cold-formed sections)			H:10	
		SR	Regular-weight steel members			H:100	
		SO	Steel, other			H:100	

Masonry

Unacceptable

Table M1: Material (Masonry) and Acceptable Lateral Load-Resisting Systems

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)
	Table 1		**Table 1**		**Table 2**
M99	Masonry, unknown reinforcement			L99	Unknown lateral load-resisting system
MUR	Masonry, Unreinforced			LN	No lateral load-resisting system
MR	Masonry, Reinforced			LFM	Moment frame
MCF	Masonry, Confined			LFINF	Infilled frame
MO	Masonry, other			LFBR	Braced frame
		MUN99	Masonry unit, unknown	LPB	Post and beam
		ADO	Adobe blocks	LWAL	Wall
		ST99	Stone, unknown type	LDUAL	Dual frame-wall system
		STRUB	Rubble (field stone) or semi-dressed stone	LFLS	Flat slab/plate or waffle slab
		STDRE	Dressed stone masonry	LFLSINF	Infilled flat slab/plate or infilled waffle slab
		CL99	Fired clay unit, unknown type	LO	Other lateral load-resisting system
		CLBRS	Fired clay solid bricks		
		CLBRH	Fired clay hollow bricks		
		CLBLH	Fired clay hollow blocks or tiles		
		CLBLH	Fired clay hollow blocks or tiles		
		CB99	Concrete blocks, unknown type		
		CBS	Concrete blocks, solid		
		CBH	Concrete blocks, hollow		

Table M2: Material (Masonry) and Maximum Building Height

ID	Material Type (L1)	ID	Material Technology (L2)	Maximum Height	Comments
	Table 1		**Table 1**	**Table 5**	
M99	Masonry, unknown reinforcement			H:30	
MUR	Masonry, Unreinforced			H:10	
MR	Masonry, Reinforced			H:30	
MCF	Masonry, Confined			H:15	
MO	Masonry, other			H:30	
		MUN99	Masonry unit, unknown	H:30	Maximum height for any type of masonry
		ADO	Adobe blocks	H:8	Evidence of a 8-storey adobe building
		ST99	Stone, unknown type	H:10	6-storey stone masonry buildings in Algeria
		STRUB	Rubble (field stone) or semi-dressed stone	H:10	
		STDRE	Dressed stone masonry	H:10	
		CL99	Fired clay unit, unknown type	H:20	17-storey brick buildings in USA, 16-storey brick masonry building in Switzerland
		CLBRS	Fired clay solid bricks	H:20	
		CLBRH	Fired clay hollow bricks	H:20	
		CLBLH	Fired clay hollow blocks or tiles	H:20	
		CLBLH	Fired clay hollow blocks or tiles	H:20	
		CB99	Concrete blocks, unknown type	H:30	24-storey reinforced block apartment building in Winnipeg, Canada
		CBS	Concrete blocks, solid	H:30	
		CBH	Concrete blocks, hollow	H:30	

Earth

Unacceptable

Table E1: Material (Earth) and Acceptable Lateral Load-Resisting Systems

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)
	Table 1		**Table 1**		**Table 2**
E99	Earth, unknown reinforcement			L99	Unknown lateral load-resisting system
EU	Earth, Unreinforced			LN	No lateral load-resisting system
ER	Earth, Reinforced			LFM	Moment frame
		ET99	Unknown earth technology	LFINF	Infilled frame
		ETR	Rammed earth	LFBR	Braced frame
		ETC	Cob or wet construction	LPB	Post and beam
		ETO	Earth technology, other	LWAL	Wall
				LDUAL	Dual frame-wall system
				LFLS	Flat slab/plate or waffle slab
				LFLSINF	Infilled flat slab/plate or infilled waffle slab
				LO	Other lateral load-resisting system

Table E2: Material (Earth) and Maximum Building Height

ID	Material Type (L1)	ID	Material Technology (L2)	Maximum Height
	Table 1		**Table 1**	**Table 5**
E99	Earth, unknown reinforcement			H:8
EU	Earth, Unreinforced			H:8
ER	Earth, Reinforced			H:8
		ET99	Unknown earth technology	H:8
		ETR	Rammed earth	H:8
		ETC	Cob or wet construction	H:8
		ETO	Earth technology, other	H:8

Wood

Unacceptable

Table W1: Material (Wood) and Acceptable Lateral Load-Resisting Systems

ID	Material Type (L1)	ID	Material Technology (L2)	ID	Type of Lateral Load-Resisting System (L1)
	Table 1		Table 1		Table 2
W	Wood			L99	Unknown lateral load-resisting system
		W99	Wood, unknown	LN	No lateral load-resisting system
		WHE	Heavy wood	LFM	Moment frame
		WLI	Light wood members	LFINF	Infilled frame
		WS	Solid wood	LFBR	Braced frame
		WWD	Wattle and daub	LPB	Post and beam
		WO	Wood, other	LWAL	Wall
				LDUAL	Dual frame-wall system
				LFLS	Flat slab/plate or waffle slab
				LFLSINF	Infilled flat slab/plate or infilled waffle slab
				LO	Other lateral load-resisting system

Table W2: Material (Wood) and Maximum Building Height

ID	Material Type (L1)	ID	Material Technology (L2)	Maximum Height
	Table 1		Table 1	Table 5
W	Wood			H:10
		W99	Wood, unknown	H:10
		WHE	Heavy wood	H:10
		WLI	Light wood members	H:10
		WS	Solid wood	H:10
		WWD	Wattle and daub	H:10
		WO	Wood, other	H:10

APPENDIX D Mapping the GEM Building Taxonomy to Other Taxonomies

Table D-1 Mapping of the GEM Building Technology to the PAGER-STR Taxonomy

No	PAGER-STR ID	PAGER-STR Description	GEM Building Taxonomy String
1	W	Wood	DX+D99/W+W99/L99/DY+D99/W+W99/L99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
2	W1	Wood stud-wall frame with plywood/gypsum board sheathing. Absence of masonry infill walls. Shear wall system consists of plywood or manufactured wood panels. Exterior is commonly cement plaster ("stucco"), wood or vinyl planks, or aluminium planks (in lower cost houses). In addition, brick masonry or stone is sometimes applied to the exterior as a non-load-bearing veneer. The roof and floor act as diaphragms to resist lateral loading. (US & Canadian single family homes).	DX+D99/W+WLI/LWAL+DU99/DY+D99/W+WLI/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO3+RWC99/F99+FWC99/FOS99
3	W2	Wood frame, heavy members (with area > 5000 sq. ft.) (US & Canadian commercial and industrial wood frame).	DX+D99/W+WHE/LPB+DU99/DY+D99/W+WHE/LPB+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO3+RWC99/F99+FWC99/FOS99
4	W3	Light post and beam wood frame. The floors and roofs do not act as diaphragms. No bracing, poor seismic load resistance path with poor connections. Wood frame may have partial infill walls with or without wood cladding.	DX+D99/W+WLI/LPB+DU99/DY+D99/W+WLI/LPB+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO99+RWC99/F99+FWC99/FOS99
	W4	Wooden panel or log construction. Walls are made of wood logs sawn horizontally in a square or circular cross section and assembled with special end joints. (Typically in central Asia, Russia).	DX+D99/W+WS/LWAL+DU99/DY+D99/W+WS/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO1+RWC99/F99+FWC99/FOS99

5	W5	Walls with bamboo/light wood log/reed mesh and post (Wattle and Daub). (Wattle and Daub- a woven lattice/sticks of wooden strips called wattle is daubed with a sticky material usually made of some combination of wet soil, clay, sand, animal dung and straw).	DX+D99/W+WWD/LWAL+DU99/DY+D99/W+WWD/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO5+RWC99/F99+FWC99/FOS99
6	W6	Unbraced heavy post and beam wood frame with mud or other infill material. Un-braced wood frame with connections meant to resist (gravity) vertical loads only. Floors or roof consists of wood purlins supporting thatched roof, wood planks or rafters supporting clay tiles.	DX+D99/W+WHE/LWAL+DU99/DY+D99/W+WHE/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO2+RWC99/F99+FWC99/FOS99
7	M	Mud walls	DX+D99/E99+ET99/LWAL+DU99/DY+D99/E99+ET99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWE/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
8	M1	Mud walls without horizontal wood elements	DX+D99/EU+ETC/LWAL+DU99/DY+D99/EU+ETC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWE/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
9	M2	Mud walls with horizontal wood elements	DX+D99/ER+ETC+RW/LWAL+DU99/DY+D99/ER+ETC+RW/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWE/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
10	RE	Rammed Earth/Pneumatically impacted stabilized earth	DX+D99/EU+ETR/LWAL+DU99/DY+D99/EU+ETR/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWE/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
11	A	Adobe blocks (unbaked sundried mud block) walls	DX+D99/MUR+ADO+MO99/LWAL+DU99/DY+D99/MUR+ADO+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
12	A1	Adobe block, mud mortar, wood roof and floors	DX+D99/MUR+ADO+MOM/LWAL+DU99/DY+D99/MUR+ADO+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWC99/FW+FW99+FWC99/FOS99
13	A2	Adobe block, mud mortar, bamboo reinforcement, straw, and thatch roof	DX+D99/MR+ADO+RB+MOM/LWAL+DU99/DY+D99/MR+ADO+RB+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO5+RWC99/F99+FWC99/FOS99

14	A3	Adobe block, straw, and thatch roof cement-sand mortar	DX+D99/MUR+ADO+MOC/LWAL+DU99/DY+D99/MUR+ADO+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO5+RWC99/F99+FWC99/FOS99
15	A4	Adobe block, mud mortar, reinforced concrete bond beam, cane and mud roof	DX+D99/MR+ADO+RCB+MOM/LWAL+DU99/DY+D99/MR+ADO+RCB+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RE+RE99+RWC99/F99+FWC99/FOS99
16	A5	Adobe block, mud mortar, with bamboo or rope reinforcement	DX+D99/MR+ADO+RB+MOM/LWAL+DU99/DY+D99/MR+ADO+RB+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
17	RS	Rubble stone (field stone) masonry	DX+D99/MUR+STRUB+MO99/LWAL+DU99/DY+D99/MUR+STRUB+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
18	RS1	Local field stones dry stacked (no mortar) with wood floors (joists), earth, or metal roof.	DX+D99/MUR+STRUB+MON/LWAL+DU99/DY+D99/MUR+STRUB+MON/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RME+RME99+RWC99/FW+FW99+FWC99/FOS99
19	RS2	Local field stones with mud mortar.	DX+D99/MUR+STRUB+MOM/LWAL+DU99/DY+D99/MUR+STRUB+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
20	RS3	Local field stones with lime mortar.	DX+D99/MUR+STRUB+MOL/LWAL+DU99/DY+D99/MUR+STRUB+MOL/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
21	RS4	Local field stones with cement mortar, vaulted brick roof and floors	DX+D99/MUR+STRUB+MOC/LWAL+DU99/DY+D99/MUR+STRUB+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RM+RM1+RWC99/FM+FM1+FWC99/FOS99
22	RS5	Local field stones with cement mortar and reinforced concrete bond beam.	DX+D99/MR+STRUB+RCB+MOC/LWAL+DU99/DY+D99/MR+STRUB+RCB+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
23	DS	Rectangular cut-stone masonry block	DX+D99/MUR+STDRE+MO99/LWAL+DU99/DY+D99/MUR+STDRE+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

24	DS1	Rectangular cut stone masonry block with mud mortar, wood roof and floors	DX+D99/MUR+STDRE+MOM/LWAL+DU99/DY+D99/MUR+STDRE+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWC99/FW+FW99+FWC99/FOS99
25	DS2	Rectangular cut stone masonry block with lime mortar	DX+D99/MUR+STDRE+MOL/LWAL+DU99/DY+D99/MUR+STDRE+MOL/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
26	DS3	Rectangular cut stone masonry block with cement mortar	DX+D99/MUR+STDRE+MOC/LWAL+DU99/DY+D99/MUR+STDRE+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
27	DS4	Rectangular cut stone masonry block with reinforced concrete floors and roof	DX+D99/MUR+STDRE+MOC/LWAL+DU99/DY+D99/MUR+STDRE+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC99+RWC99/FC+FC99+FWC99/FOS99
28	MS	Massive stone masonry in lime or cement mortar	DX+D99/MUR+STDRE+MOL/LWAL+DU99/DY+D99/MUR+STDRE+MOL/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
29	UFB	Unreinforced fired brick masonry	DX+D99/MUR+CLBRS+MO99/LWAL+DU99/DY+D99/MUR+CLBRS+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
30	UFB1	Unreinforced brick masonry in mud mortar without wood posts	DX+D99/MUR+CLBRS+MOM/LWAL+DU99/DY+D99/MUR+CLBRS+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
31	UFB2	Unreinforced brick masonry in mud mortar with wood posts	DX+D99/MUR+CLBRS+MOM/LWAL+DU99/DY+D99/MUR+CLBRS+MOM/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
32	UFB3	Unreinforced brick masonry in lime mortar	DX+D99/MUR+CLBRS+MOL/LWAL+DU99/DY+D99/MUR+CLBRS+MOL/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
33	UFB4	Unreinforced fired brick masonry, cement mortar. wood flooring, wood or steel beams and columns, tie courses (bricks aligned perpendicular to the plane of the wall)	DX+D99/MUR+CLBRS+MOC/LWAL+DU99/DY+D99/MUR+CLBRS+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/FW+FW99+FWC99/FOS99

34	UFB5	Unreinforced fired brick masonry, cement mortar, but with reinforced concrete floor and roof slabs	DX+D99/MUR+CLBRS+MOC/LWAL+DU99/DY+D99/MUR+CLBRS+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC99+RWC99/FC+FC99+FWC99/FOS99
35	UCB	Unreinforced concrete block masonry with lime or cement mortar	DX+D99/MUR+CB99+MOC/LWAL+DU99/DY+D99/MUR+CB99+MOC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
36	RM	Reinforced masonry	DX+D99/MR+MUN99+RS+MO99/LWAL+DU99/DY+D99/MR+MUN99+RS+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
37	RM1	Reinforced masonry bearing walls with wood or metal deck diaphragms	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWCP/FW+FW99+FWCP/FOS99
38	RM1L	Reinforced masonry bearing walls with wood or metal deck diaphragms low-rise	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWCP/FW+FW99+FWCP/FOS99
39	RM1M	Reinforced masonry bearing walls with wood or metal deck diaphragms mid-rise (4+ stories)	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWCP/FW+FW99+FWCP/FOS99
40	RM2	Reinforced masonry bearing walls with concrete diaphragms	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
41	RM2L	Reinforced masonry bearing walls with concrete diaphragms low-rise	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
42	RM2M	Reinforced masonry bearing walls with concrete diaphragms mid-rise	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
43	RM2H	Reinforced masonry bearing walls with concrete diaphragms high-rise	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99

44	CM	Confined masonry	DX+D99/MCF+MUN99+MO99/LWAL+DU99/DY+D99/MCF+MUN99+MO99/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
45	C	Reinforced concrete	DX+D99/CR+CT99/L99/DY+D99/CR+CT99/L99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
46	C1	Ductile reinforced concrete moment frame with or without infill	DX+D99/CR+CIP/LFM+DUC/DY+D99/CR+CIP/LFM+DUC/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
47	C1L	Ductile reinforced concrete moment frame with or without infill low-rise	DX+D99/CR+CIP/LFM+DUC/DY+D99/CR+CIP/LFM+DUC/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
48	C1M	Ductile reinforced concrete moment frame with or without infill mid-rise	DX+D99/CR+CIP/LFM+DUC/DY+D99/CR+CIP/LFM+DUC/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
49	C1H	Ductile reinforced concrete moment frame with or without infill high-rise	DX+D99/CR+CIP/LFM+DUC/DY+D99/CR+CIP/LFM+DUC/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
50	C2	Reinforced concrete shear walls	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
51	C2L	Reinforced concrete shear walls low-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
52	C2M	Reinforced concrete shear walls mid-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
53	C2H	Reinforced concrete shear walls high-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
54	C3	Nonductile reinforced concrete frame with masonry infill walls	DX+D99/CR+CIP/LFINF+DNO/DY+D99/CR+CIP/LFINF+DNO/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

55	C3L	Nonductile reinforced concrete frame with masonry infill walls low-rise	DX+D99/CR+CIP/LFINF+DNO/DY+D99/CR+CIP/LFINF+DNO/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
56	C3M	Nonductile reinforced concrete frame with masonry infill walls mid-rise	DX+D99/CR+CIP/LFINF+DNO/DY+D99/CR+CIP/LFINF+DNO/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
57	C3H	Nonductile reinforced concrete frame with masonry infill walls high-rise	DX+D99/CR+CIP/LFINF+DNO/DY+D99/CR+CIP/LFINF+DNO/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
58	C4	Nonductile reinforced concrete frame without masonry infill walls	DX+D99/CR+CIP/LFM+DNO/DY+D99/CR+CIP/LFM+DNO/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
59	C4L	Nonductile reinforced concrete frame without masonry infill walls low-rise	DX+D99/CR+CIP/LFM+DNO/DY+D99/CR+CIP/LFM+DNO/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
60	C4M	Nonductile reinforced concrete frame without masonry infill walls mid-rise	DX+D99/CR+CIP/LFM+DNO/DY+D99/CR+CIP/LFM+DNO/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
61	C4H	Nonductile reinforced concrete frame without masonry infill walls high-rise	DX+D99/CR+CIP/LFM+DNO/DY+D99/CR+CIP/LFM+DNO/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
62	C5	Steel reinforced concrete (Steel members encased in reinforced concrete)	DX+D99/SRC+CIP/L99/DY+D99/SRC+CIP/L99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
63	C5L	Steel reinforced concrete (Steel members encased in reinforced concrete) low-rise	DX+D99/SRC+CIP/L99/DY+D99/SRC+CIP/L99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
64	C5M	Steel reinforced concrete (Steel members encased in reinforced concrete) mid-rise	DX+D99/SRC+CIP/L99/DY+D99/SRC+CIP/L99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
65	C5H	Steel reinforced concrete (Steel members encased in reinforced concrete) high-rise	DX+D99/SRC+CIP/L99/DY+D99/SRC+CIP/L99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
66	C6	Concrete moment resisting frame with shear wall - dual system	DX+D99/CR+CIP/LDUAL+DU99/DY+D99/CR+CIP/LDUAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

67	C6L	Concrete moment resisting frame with shear wall - dual system low-rise	DX+D99/CR+CIP/LDUAL+DU99/DY+D99/CR+CIP/LDUAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
68	C6M	Concrete moment resisting frame with shear wall - dual system mid-rise	DX+D99/CR+CIP/LDUAL+DU99/DY+D99/CR+CIP/LDUAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
69	C6H	Concrete moment resisting frame with shear wall - dual system high-rise	DX+D99/CR+CIP/LDUAL+DU99/DY+D99/CR+CIP/LDUAL+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
70	C7	Flat slab structure	DX+D99/CR+CIP/LFLS+DU99/DY+D99/CR+CIP/LFLS+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
71	PC1	Precast concrete tilt-up walls	DX+D99/CR+PC/LWAL+DU99/DY+D99/CR+PC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
72	PC2	Precast concrete frames with concrete shear walls	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
73	PC2L	Precast concrete frames with concrete shear walls low-rise	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
74	PC2M	Precast concrete frames with concrete shear walls mid-rise	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
75	PC2H	Precast concrete frames with concrete shear walls high-rise	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
76	PC3	Precast reinforced concrete moment resisting frame with masonry infill walls	DX+D99/CR+PC/LFINF+DU99/DY+D99/CR+PC/LFINF+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
77	PC3L	Precast reinforced concrete moment resisting frame with masonry infill walls low-rise	DX+D99/CR+PC/LFINF+DU99/DY+D99/CR+PC/LFINF+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

78	PC3M	Precast reinforced concrete moment resisting frame with masonry infill walls mid-rise	DX+D99/CR+PC/LFINF+DU99/DY+D99/CR+PC/LFINF+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
79	PC3H	Precast reinforced concrete moment resisting frame with masonry infill walls high-rise	DX+D99/CR+PC/LFINF+DU99/DY+D99/CR+PC/LFINF+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
80	PC4	Precast panels (wall panel structure)	DX+D99/CR+PC/LWAL+DU99/DY+D99/CR+PC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
81	S	Steel	DX+D99/S+S99+SC99/L99/DY+D99/S+S99+SC99/L99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
82	S1	Steel moment frame	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
83	S1L	Steel moment frame low-rise	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
84	S1M	Steel moment frame mid-rise	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
85	S1H	Steel moment frame high-rise	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
86	S2	Steel braced frame	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
87	S2L	Steel braced frame low-rise	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

88	S2M	Steel braced frame mid-rise	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
89	S2H	Steel braced frame high-rise	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
90	S3	Steel light frame	DX+D99/S+SL+SC99/LFM+DU99/DY+D99/S+SL+SC99/LFM+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
91	S4	Steel frame with cast-in-place concrete shear walls	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
92	S4L	Steel frame with cast-in-place concrete shear walls low-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
93	S4M	Steel frame with cast-in-place concrete shear walls mid-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
94	S4H	Steel frame with cast-in-place concrete shear walls high-rise	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
95	S5	Steel frame with unreinforced masonry infill walls	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
96	S5L	Steel frame with unreinforced masonry infill walls low-rise	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
97	S5M	Steel frame with unreinforced masonry infill walls mid-rise	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

98	S5H	Steel frame with unreinforced masonry infill walls high-rise	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:19,8+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
99	MH	Mobile homes	DX+D99/W+WLI/LWAL+DU99/DY+D99/W+WLI/LWAL+DU99/HBET:1,2+HF99/Y99/RES+RES5/BPD/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
100	INF	Informal constructions. (Generally made of wood/plastic sheets/GI Sheets/light metal or composite etc. not confirming to engineering standards, commonly in slums, squatters).	DX+D99/MATO/L99/DY+D99/MATO/L99/H99/Y99/RES+RES6/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
101	UNK	Not specified (unknown/default)	DX+D99/MAT99/L99/DY+D99/MAT99/L99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

Table D-2 Mapping of the GEM Building Taxonomy to the HAZUS Building Taxonomy

No	HAZUS ID	Description	Height		GEM Building Taxonomy String
			Class	No. of storeys	
1	W1	Wood, Light Frame (≤ 5,000 sq. ft.)		1-2	DX+D99/W+WLI/LWAL+DU99/DY+D99/W+WLI/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO3+RWC99/F99+FWC99/FOS99
2	W2	*Wood, Commercial and Industrial (>5,000 sq. ft.)		All	DX+D99/W+WHE/LPB+DU99/DY+D99/W+WHE/LPB+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+RWO+RWO99+RWC99/F99+FWC99/FOS99
3	S1L	Steel Moment Frame	Low-Rise	1-3	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
4	S1M		Mid-Rise	4-7	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
5	S1H		High-Rise	8+	DX+D99/S+S99+SC99/LFM+DU99/DY+D99/S+S99+SC99/LFM+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
6	S2L	Steel Braced Frame	Low-Rise	1-3	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
7	S2M		Mid-Rise	4-7	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
8	S2H		High-Rise	8+	DX+D99/S+S99+SC99/LFBR+DU99/DY+D99/S+S99+SC99/LFBR+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
9	S3	Steel Light Frame		All	DX+D99/S+SL+SC99/LFM+DU99/DY+D99/S+SL+SC99/LFM+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
10	S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1-3	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
11	S4M		Mid-Rise	4-7	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

12	S4H		High-Rise	8+	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
13	S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
14	S5M		Mid-Rise	4-7	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
15	S5H		High-Rise	8+	DX+D99/S+S99+SC99/LFINF+DU99/DY+D99/S+S99+SC99/LFINF+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
16	C1L	Concrete Moment Frame	Low-Rise	1-3	DX+D99/CR+CIP/LFM+DU99/DY+D99/CR+CIP/LFM+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
17	C1M		Mid-Rise	4-7	DX+D99/CR+CIP/LFM+DU99/DY+D99/CR+CIP/LFM+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
18	C1H		High-Rise	8+	DX+D99/CR+CIP/LFM+DU99/DY+D99/CR+CIP/LFM+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
19	C2L	Concrete Shear Walls	Low-Rise	1-3	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
20	C2M		Mid-Rise	4-7	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
21	C2H		High-Rise	8+	DX+D99/CR+CIP/LWAL+DU99/DY+D99/CR+CIP/LWAL+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
22	C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	DX+D99/CR+CIP/LFINF+DU99/DY+D99/CR+CIP/LFINF+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
23	C3M		Mid-Rise	4-7	DX+D99/CR+CIP/LFINF+DU99/DY+D99/CR+CIP/LFINF+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
24	C3H		High-Rise	8+	DX+D99/CR+CIP/LFINF+DU99/DY+D99/CR+CIP/LFINF+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
25	PC1	Precast Concrete Tilt-Up Walls		All	DX+D99/CR+PC/LWAL+DU99/DY+D99/CR+PC/LWAL+DU99/H99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

26	PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1-3	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
27	PC2M		Mid-Rise	4-7	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
28	PC2H		High-Rise	8+	DX+D99/CR+PC/LDUAL+DU99/DY+D99/CR+PC/LDUAL+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWCP/FW+FW99+FWCP/FOS99
30	RM1M		Mid-Rise	4+	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:4++HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RWO+RWO99+RWCP/FW+FW99+FWCP/FOS99
31	RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1-3	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:3,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
32	RM2M		Mid-Rise	4-7	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:7,4+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
33	RM2H		High-Rise	8+	DX+D99/MR+MUN99+MR99+MO99/LWAL+DU99/DY+D99/MR+MUN99+MR99+MO99/LWAL+DU99/HBET:8++HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+RC+RC3+RWCP/FC+FC3+FWCP/FOS99
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	DX+D99/MUR+MUN99+MO99/LWAL+DU99/DY+D99/MUR+MUN99+MO99/LWAL+DU99/HBET:2,1+HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
35	URMM		Mid-Rise	3+	DX+D99/MUR+MUN99+MO99/LWAL+DU99/DY+D99/MUR+MUN99+MO99/LWAL+DU99/HBET:3++HF99/Y99/OC99/BP99/PLF99/IR99/EWMA/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99
36	MH	Mobile Homes		All	DX+D99/W+WLI/LWAL+DU99/DY+D99/W+WLI/LWAL+DU99/HBET:1,2+HF99/Y99/RES+RES5/BPD/PLF99/IR99/EW99/RSH99+RMT99+R99+RWC99/F99+FWC99/FOS99

THE GLOBAL EARTHQUAKE MODEL

The mission of the Global Earthquake Model (GEM) collaborative effort is to increase earthquake resilience worldwide.

To deliver on its mission and increase public understanding and awareness of seismic risk, the GEM Foundation, a non-profit public-private partnership, drives the GEM effort by involving and engaging with a very diverse community to:

- Share data, models, and knowledge through the OpenQuake platform
- Apply GEM tools and software to inform decision-making for risk mitigation and management
- Expand the science and understanding of earthquakes.

The GEM Foundation wishes to acknowledge the following institutions/ organizations, for their contributions to the development of this report:

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GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk