Mismatches in Climatically and Seismically Responsive Global Dominant Building Forms

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SUMMARY

This paper presents a cross-disciplinary analysis of the relative seismic resistance and climatic appropriateness of global building forms. The first part compares climatically and seismically responsive forms in 20 different climate zones across the world's most seismically hazardous regions. The second part analyzes the climatic and seismic appropriateness of the global building stock against the seismic hazard map and historical meteorological records. Preliminary analysis shows that seismic performance varies significantly among building forms that are suitable for their respective climates, with general poor expected performance from those typically found in arid and high altitude climates. Furthermore, the more seismically vulnerable heavyweight constructions are found to dominate in the seismically hazardous regions of Central Asia, the Middle East, and South America where such construction is generally suitable for their climates. With the exception of a few poorer countries, lightweight constructions are found mostly in richer nations in the seismically active regions.

Keywords: thermal performance, seismic performance, building stock; lightweight/heavyweight construction

1. INTRODUCTION

Dominant building forms where the majority of the people inhabit are derived from and influenced by many different and interdependent physical and socio-cultural factors. Often it is not clear which factor is the ruling determining force. As Amos Rapoport points out in his seminal work *House Form and Culture* (1969:48), "even with the most severe physical constraints and limited technology man has built in ways so diverse that they can be attributed only to *choice*, which involves cultural values." But regardless of how a building form is determined, it must be responsive to the demands, constant or occasional, exerted by the physical environment.

Despite the advances in our understanding of earthquake risks, research in construction methods to reduce those risks, and improvements in building codes, events in the recent past have demonstrated that loss due to earthquakes remains unabated (Coburn & Spence, 2002:9-11). It has become apparent that cross-disciplinary approaches are needed to provide additional insights to the understanding of global earthquake risks and the identification of vulnerable building types.

One such approach is to explore not only the seismic resistance but also the climatic appropriateness of global dominant building forms. Because the provision of protection from external weather conditions is the fundamental function of buildings, responsiveness to the climate should and does markedly influence the forms, particularly in the rural and smaller urban areas of developing countries where vernacular forms still dominate the building stock. Buildings that are climatically responsive, however, can perform quite differently in earthquakes and the relationship between the seismic and climatic responsiveness is not well understood.

Unfortunately, there are many places in the world facing both challenging climatic conditions and seismic hazards, such as western South America, the Middle East, and Central Asia. For these regions, both appropriate seismic and thermal performance of the dominant building forms are critical for safety as well as for comfort.

Building forms with respect to seismic and climatic appropriateness have been researched and investigated extensively, but to date mostly separately. As a result, there is a gap in our understanding of the relationship *between* climatically and seismically responsive building forms. Could characteristics that make a building climatically appropriate compromise its seismic resistance, or vice versa? Are there mismatches between the seismically responsive and climatically responsive building forms? By assessing the *relative* climatic and seismic responsiveness of building forms based on first principles, the present study makes the first attempt to examine this cross-disciplinary issue.

2. METHODS

For the first part of the present study, the appropriate building forms for different climates were generated and their relative seismic responsiveness ranked. In the second part of the study the distribution of dominant building forms are cross-mapped against the global distribution of earthquake hazards and different meteorological variables to assess the relative seismic and climatic appropriateness of the existing global building stock based on construction materials.

2.1. Identifying Regions of Interest

Regions exposed to both seismic hazards and challenging climatic conditions were visually identified (Fig. 2.1) by mapping earthquake occurrences of magnitude 5 or greater between 1973-2011 from the USGS/NEIC (PDE) Catalog against the world map of the Köppen-Geiger Climate Classification. This system, updated by Markus Kottek et al. (2006), categorizes the world's climates into 31 different classes or zones (not all climatologically important) based on five main climate types, six different precipitation/humidity considerations, and eight air temperature considerations. For clarity, only the five main climate types are shown in Fig. 2.1.



Figure 2.1. Cross-map of earthquakes ≥M5 between 1973-2011 (USGS/NEIC) and Köppen-Geiger main climate types as updated by Kottek et al. (2006)

Six specific countries then were selected for analysis (in alphabetical order): China, Japan, Pakistan, Peru, Taiwan, and Turkey. These locations are by no means exhaustive but they do represent some of the most climatically diverse and challenging places in the world that are also very prone to earthquakes. Subsequent studies will include more countries.

2.2. Generating Climatically Responsive Building Forms

Climate data from between 13 to 22 cities/towns for each of the selected countries were obtained from www.weatherbase.com, a climate information database that sources from the National Climatic Data Center in the U.S. The data, in the form of historical weather records (e.g. monthly mean minimum and maximum temperatures, relative humidity, and rainfall) were then fed through the Mahoney

Tables (discussed below) to generate the appropriate building forms for each climate zone in each country.

Not all of the climate zones found in a particular country were included in the analysis because climate information for the cities/towns in each zone were not always available (usually due to small geographic coverage). However, care has been taken to include as many different climate zones as possible. Altogether 20 of the 31 climate classes were included in the analysis. In addition, because some variability among data within the same climatic zone was expected, for each climate class in each country, data from between two to ten cities/towns were used.

The Mahoney Tables, developed by Koenigsberger, Ingersoll, and Mayhew (1973: 239-262), is a weighting system that specifies building form elements, such as window sizes and construction materials, based on meteorological variable inputs. Table 2.1 lists the possible form specifications (column B) in five main categories (column A) as selected and reorganized by the authors based on potential seismic ramifications. It should be noted that climatically responsive elements are not limited to those recommended by the Mahoney Tables, but they do suffice for the purpose of this study.

2.3. Ranking Seismically Responsive Building Forms

Although a building form's seismic and thermal performances are each complex in its own right, there are nevertheless elements – such as the five categories from the Mahoney Tables – that bear both thermal and structural implications (Table 2.2) and can be used to assesse the relative climatic and seismic responsiveness. However, unlike for climatically responsive building forms, there exists no generative tool similar to the Mahoney Tables for seismically responsive building forms. In fact, the general principles for seismic responsiveness by themselves are not so much sufficient to *create* the appropriate building forms from scratch as to *shape* the building forms in the right directions.

Even though the climatically responsive forms generated from the Mahoney Tables are only schematic, distinct elements are nonetheless specifiable *solely* based on the duration and severity of the climatic factors. A seismically responsive form is, on the other hand, contingent not only on the level of the seismic hazard, but also on the site condition, sub-soil properties, connection details, construction quality, and other factors that are not so easily defined as meteorological variables. Therefore, instead of generating climatically and seismically appropriate forms independently and then comparing the two, first principles were used to evaluate the seismic responsiveness of the forms generated from the Mahoney Tables. Column C of Table 2.1 shows the preliminary assessment of the relative seismic responsiveness for each specification option; column D lists the reasoning behind these ratings. It should be noted that although heavyweight constructions are considered as less seismically responsive both here and in the global building stock analysis later, not all such constructions are seismically inappropriate. With adequate building codes and engineering inputs, heavyweight constructions can be made earthquake resistant; it is the weak masonry and un-engineered reinforced concrete (RC) buildings that are the most dangerous. Yet it is this kind of heavyweight constructions that still constitute most of the building stock in the rural and developing regions.

The different levels of relative seismic responsiveness then were translated into numerical values (very low to low = 0, low to medium = 1, medium to high = 2) and summed across all five categories to produce a relative seismic responsiveness score for each climatically appropriate built forms generated via the Mahoney Tables. The scores then were averaged across all cities/towns in the same climate zones and compared across the 20 different climate classes.

2.4. Assessing the Relative Climatic and Seismic Responsiveness of the Global Building Stock

In 2008 the U.S. Geological Survey (USGS) released the database for their unprecedented global building inventory project that detail the proportions of different building types, subdivided into urban/rural and residential/non-residential, for each country in the world. It consists of data collected directly and data inferred from neighboring regions for places where information was not accessible

A. Built Form Elements			C. Relative Seismic	D. Rationale
Main Category	Sub Category	B. Possible Specification Options	Responsiveness	
1. Layout		 Orientation north and south (long axis east-west) 	Low to Medium	 Potentially long and thin buildings that can suffer torsional effect
		 Compact courtyard planning 	Very low to low	 Potentially irregular and/or unsymmetrical built forms with reentrant corner concerns
2. Spacing		 Open spacing for breeze penetration 	Medium to high	 Less likely to cause pounding or battering
		 As above, but protection from cold and hot wind 	Medium to high	between buildings during earthquakes
		 Compact layout of estates 	Low to Medium	 Potential pounding or battering between buildings during earthquakes
3. Internal Planning		 Rooms single banked; permanent provision for air movement 	Low to Medium	 Less mutually supportive intersecting walls
(Air Movement)		 Rooms double banked; temporary provision for air movement 	Medium to high	 More mutually supportive intersecting walls
		 No air movement required 	Medium to high	
4. Openings	a. Size	• Large (40-80% of wall area)	Very low to low	 Greatest interruptions of transfer of forces and weakening to lateral support; overall most detrimental to wall structural integrity
		 Medium (25-40% of wall area) 	Low to Medium	 Considerable interruptions of transfer of forces and weakening to lateral support; potentially compromising to the wall structural integrity
		• Small (15-25% of wall area)	Medium to high	 Moderate interruptions of transfer of forces and weakening to lateral support
		• Very small (10-20% of wall area)	Medium to high	 Least interruptions of transfer of forces and weakening to lateral support
	b. Position	 In north and south walls at body height on windward side 	No effect	 Cardinal directions do not affect seismic responsiveness
		• As above, but with openings also in internal walls	Low to Medium	 Potentially compromising the internal mutually supportive intersecting walls
5. Materials	a. Walls and Floors	 Light, low thermal capacity 	Medium to high	 Higher strength-to-weight ratio; less damaging when collapsed
		 Heavy, over 8 hour time-lag 	Very low to low	 Tend to have low strength-to-weight ratio; fatal when collapsed
	b. Roofs	 Light, reflective surface, cavity 	Medium to high	 Same as for walls and floors
		 Light, well insulated 	Medium to high	
		 Heavy, over 8 hour time-lag 	Very low to low	 Same as for walls and floors

Table 2.1. Mahoney Tables specifications (Koenigsberger et al., 1973) for built form elements and their relative seismic responsiveness

(Jaiswal & Wald, 2008). Although the data quality varies widely from country to country, its availability made it possible to cross-map the distribution of global building stock against both climates and earthquake hazards for the second part of the present study.

A. Built Form Elements	B. Potential Thermal Implications	C. Potential Structural Implications
1. Layout	Thermal buffer, air movement/ventilation, solar access	Reentrant corner concerns, unwanted torsional effect, structural discontinuity/ sudden change in lateral stiffness
2. Spacing	Welcome/unwanted solar access (solar heat gain/overshadowing), air movement/ventilation	Pounding/battering of adjacent components during quake
3. Internal Planning (Air Movement)	Thermal buffers, air movement/ventilation	Resistance/susceptibility to lateral force, distribution of forces, sudden change in lateral stiffness
4. Openings	Air movement/ventilation, useful/unwanted solar heat gain/loss	Weakening of shear wall (lateral bracing) system, overturning risk
5. Materials	Insulation, thermal mass, infiltration	Relative rigidity (ability to resist stress)

Table 2.2. Built form elements and their potential thermal and structural implications

Because construction material is the single thermally consequential information that can be gleaned from the database, it became the only building form element that was used to assess the relative climatic and seismic responsiveness of the global building stock. To make the analysis more manageable, the data for each country were aggregated into lightweight and heavyweight constructions from more than 80 different building types. Lightweight constructions are characterized by their low thermal capacities; they include wooden structures (but exclusive of those with adobe infills), mobile homes, and informal structures that are often constructed with sheet metals. Heavyweight constructions have substantial thermal mass; they include reinforced concrete (RC), adobe, and masonry type structures.

The lightweight versus heavyweight construction breakdown for the global building stock was then mapped in GIS (Geographic Information System) against the global seismic hazard map produced by GSHAP (1999) and three climatic factors: air temperatures, diurnal temperature range (DTR), and humidity. The reason for using specific climate components instead of the Köppen-Geiger Climate Classification was so that the relative climatic appropriateness of lightweight and heavyweight constructions can be better assessed. For example, the advantage of thermal mass lies in its ability to dampen indoor day-to-night temperature swings, thereby reducing chances of overheating and overcooling as the outdoor temperature fluctuates. This quality is especially critical for "free-running" buildings that do not rely on mechanical systems for heating or cooling. It follows that heavyweight construction would be the more appropriate choice where the DTR is large. On the other hand, regions with high humidity can benefit from more permeable structures often found in lightweight constructions to better provide thermal comfort for the occupants.

Global climate data were obtained from the Climatic Research Unit (CRU) TS3.1 time series datasets covering the month-by-month climate variation over the period 1901-2009 at high-resolution (0.5x0.5 degree) grids. Specifically, the following variables were used: daily mean temperature, monthly average daily minimum and maximum temperatures, and diurnal temperature range. These were processed by the authors to obtain seasonal average values across the years, taking June to August as summer and December to February as winter for the north hemisphere. Because relative humidity is not available as one of the variables included in the dataset, the six different humidity classes from the Köppen-Geiger Climate Classification were used instead.

3. RESULTS AND DISCUSSIONS

3.1. The Relative Seismic Responsiveness of Climatically Responsive Building Forms

After the climatically responsive building forms were generated via the Mahoney Tables for each climate class, it became clear that the diversity of different forms does not necessarily follow the overall climate class diversity or the diversity found in each country. A total of 16 distinct building forms were generated across 20 different climate classes. However, in six instances the same form is actually found to be suitable for a different climate zone in each of the countries where it is found. The number of distinct building forms could also be less or more than the number of distinct climate classes within individual countries.

The estimated seismic responsiveness of the climatically appropriate building forms are equally diverse, ranging from relatively low responsiveness (score = 3) to relatively high responsiveness (score = 9), with 11 being the best possible score and 2 the worst. While score variation across the 20 climate classes was expected, a few markedly different climatically responsive building forms were actually found to have the same seismic responsiveness scores.

For example, both in Taiwan and Peru, an east-west axis, open-spaced lightweight building with insulated roof, single banked rooms with permanent provision for air movement, and large openings has the same score (8) as an east-west axis, compact-spaced lightweight building with insulated roof, double banked rooms with temporary provision for air movement, medium-size and internal wall openings. This is not entirely surprising because theoretically (at least in terms of scores), a built form with a less seismic responsive element in one category (e.g. heavyweight walls) can be compensated by one or more elements that are more seismic responsive element in another category (e.g. small-size opening and double banked internal partitions with more mutually supporting intersecting walls).

Obviously in reality the various elemental contributions to a building's seismic performance are much more complex and cannot be so readily swapped, especially as noted earlier, it is really the unengineered and/or non-code compliant heavyweight constructions that are the most dangerous. Nevertheless, a comparison of the seismic responsiveness scores across the 20 different climate classes as calculated using this simplified ranking system (Fig. 3.1) suggests some interesting relationships between a building form's seismic and climatic responsiveness.



Figure 3.1. Estimated seismic responsiveness scores for climatically appropriate building forms in 20 different climate classes, organized by main climate types (A=equatorial, B=arid, C=warm temperate, D=snow, E=polar; score 0-3= very low to low seismic responsiveness, 4-7=low to medium, 8-10=medium to high)

Because multiple building forms can be suitable for the same climate classes, it follows that the seismic responsiveness scores also vary quite markedly within the same main climate types. However, building forms suitable for the different climate classes under the main climate type B (arid) appear to have an overall lower seismic responsiveness with the exception of one climate class (Fig. 3.1). The

low seismic responsiveness for these building forms are primarily attributed to heavyweight construction materials, internal partition openings, compact spacing, and courtyard layout.

Comparing at the level of main climate types, building forms suitable for type A (equatorial) appear to be the most seismically responsive with lightweight construction, open spacing, and symmetrical layout despite the fact that they also have large openings. A few climate classes within the main climate type C (warm temperate) fare slightly better precisely because their building forms have medium-size openings instead, while sharing the same specifications in other categories. Similarly, building forms suitable for main climate type D (snow) are generally more seismically responsive than the forms for type B (arid) because they tend to have symmetrical layout, open spacing, and smaller windows despite also having the less responsive elements of heavyweight construction materials and internal partition openings.

Altitude also seems to negatively influence building form's seismic responsiveness as the scores for high altitude climate classes (dashed bordered in Fig. 3.1) are consistently lower than their normal altitude counterparts for main climate type A, B, and C

3.2. The Relative Seismic Responsiveness of the Global Building Stock

Although the USGS global building stock inventory is divided into four categories – urban residential, rural residential, urban non-residential, and rural nonresidential, the actual data shows very little variations between the four. In fact, the proportions of heavyweight to lightweight constructions make no distinctions among the four categories in most countries, with the exception of Turkey, Lithuania, Chile, Mexico, Colombia, and Germany (the latter three largely due to lack of data). But the most prominent differences among the four categories of building stock data are found in East and Southeast Asia, particularly in Japan where the urban/rural, and residential/non-residential dichotomy has a significant effect on the building typology. Almost all urban non-residential buildings in Japan are heavyweight while almost all rural residential buildings are lightweight. Furthermore, proportion of lightweight constructions make up almost the entire building stock for Myanmar and Laos, the data for these two countries, as well as for Malaysia, Bangladesh, and Papua New Guinea, have been rated as low quality by the USGS.



Figure 3.2. Construction breakdown of global rural residential building stock (USGS, 2008) versus global seismic hazard map (GSHAP, 1999)

As shown in Fig. 3.2, most of the world's residential building stock, both urban and rural, is heavyweight. While several Central and Eastern European countries such as Hungary, Slovakia, Lithuania, Croatia, Bosnia, and Serbia have around 15% of their building stocks in lightweight, most countries with large proportions (\geq 50%) of lightweight construction are among the highly developed nations – specifically USA, Canada, Australia, New Zealand, Japan, and Malaysia. Several such countries also belong to the lower spectrum of the Human Development Index (HDI), in particular

Mozambique, Gabon, and Equatorial Guinea in Africa; Guyana in South America; and Myanmar, Papua New Guinea, Laos, the Philippines, and rural Indonesia in the seismically active Southeast Asia. Additionally, most Small Island Developing States (SIDS) with low to medium HDI such as the Bahamas (but with the exception of Cuba, Haiti, and Dominican Republic) also have a significant proportion or almost all of their building stock in lightweight construction, which is appropriate as the majority of SIDS are located along the Ring of Fire.

However, for many low to medium HDI countries situated in the highly seismically hazardous regions of Central Asia, the Middle East, Central and South America, their building stock consists almost entirely of heavyweight constructions, mostly in the form of weak masonry or un-engineered RC structures (with the exception of El Salvador, Costa Rica, Guatemala, Nicaragua, and Honduras that have around 15% lightweight). As most heavyweight constructions are sensitive to the construction and material quality and are more lethal when they fail, such construction is likely to be unsuitable for these regions. This is in light of Coburn and Spence's observation (2002:8) that the majority of the fatalities in earthquakes are attributed to the collapse of weak or unreinforced masonry buildings.

3.3. The Relative Climatic Responsiveness of the Global Building Stock

Most low to medium HDI countries with substantial proportions of lightweight constructions are situated around the equator, where the mean temperature hovers around 25-35°C throughout the year (Fig. 3.3) and the diurnal temperature range (DTR) is small (Fig. 3.4). For these countries, especially the ones in Southeast Asia where it is also fully humid or monsoonal, lightweight construction is most likely to provide thermal comfort for the occupants. Together with the cross-map against global seismic hazards (Fig. 3.2) the comparisons against temperature, DTR, and humidity seem to suggest that a good proportion of the building stock in Southeast Asia is reasonably responsive to both the seismic and climatic demands. However, for countries around the Himalayas such as Nepal, Bhutan, and southern China, their heavyweight dominant building stock is more suitable for its cold climate with large DTR than for its seismically hazardous locale.



Figure 3.3. Construction breakdown of global rural residential building stock (USGS, 2008) versus summer seasonal average of daily maximum temperatures (CRU, 2009)

While also unsuitable for its seismically active location particularly in the north, the almost entirely heavyweight building stock of Pakistan is generally appropriate for both its cold northern mountain climate and desert climate for the rest of the country where the average daily maximum temperature can easily reach 45°C in the summer (Fig. 3.3) and the large DTR is especially pronounced in the winter. Similarly, the heavyweight dominated building stock of India is climatically appropriate but seismically unsuitable for the western part of the country. However, the rest of India is much more humid and monsoonal with low DTR and therefore can benefit from lightweight constructions. Central America is another region where lightweight construction would be more responsive both seismically and climatically as its mean temperature remains around 20-30°C throughout the year with low DTR.

The building stock with the greatest mismatch between seismic and climatic responsiveness belong to the Middle East and Central Asia, where it is especially seismically hazardous. While countries in the Middle East face average daily maximum temperature as high as 40-45°C in the summer (Fig. 3.3) perennial large DTR such as the 20-25°C day-to-night difference in western Iran (Fig. 3.4), those in Central Asia suffer from extreme cold with the average daily minimum temperature in the winter easily dipping below -30°C and a substantial summer DTR between 15-20°C. The heavyweight dominant building stocks in these regions are therefore very suitable for these harsh conditions and especially useful to modulate the large DTR.

The cases of Japan and New Zealand, two highly seismic countries with high quality data, are more complicated as not only does the building stock for both consists of a mixture of heavyweight and lightweight constructions, but their mostly temperate climate also experiences hot summers and cold winters, a combination that can call for either lightweight or heavyweight constructions as long as they are designed and used correctly. Nevertheless, the lightweight dominated building stock (rural only for Japan) may still prove to be the more climatically suitable choice for both countries given both are fully humid with relatively small DTR throughout the year.



Figure 3.4. Construction breakdown of global rural residential building stock (USGS, 2008) versus summer seasonal average of diurnal temperature range (CRU, 2009)

The US is another country where both lightweight and heavyweight constructions may be suitable due to the sheer size of the country and the climate diversity that comes with it. However, as the most seismic part of the country is the west coast (Fig. 3.2), specifically California where the temperature is mild with reasonable DTR and little humidity, the lightweight dominated building stock is therefore deemed both seismically and climatically responsive.

The heavyweight dominated South American west coast presents perhaps the most complicated scenario. While thermal mass is climatically inappropriate for most of Colombia and Ecuador where the mean temperature is perennially high and the DTR is small, building with high heat capacity may be beneficial or even necessary in parts of Peru and Chile. In fact, Peru has one of the most varied climates in the world with an average daily mean temperature spanning from 0 to 30°C throughout the year, a substantial DTR in the winter, and a humidity range from fully humid to monsoonal to desert. As a result, its mostly heavyweight building stock, although largely unsuitable for its highly seismic landscape, can have varied responsiveness to its climate.

4. CONCLUSIONS

The preliminary analysis presented in this paper has demonstrated that seismic responsiveness varies significantly among building forms that are suitable for their respective climates, with general poor expected performance from those typically found in arid and high altitude climates. This is in line with the global building stock analysis that shows that heavyweight constructions, especially in the form of

un-engineered structures, dominate most of the world's most seismically hazardous regions of Central Asia, the Middle East, Pakistan, western India and parts of western South America. Although the use of such construction can increase the seismic vulnerability of buildings, heavyweight constructions with thermal mass are generally considered climatically suitable for these countries. For other regions of high seismic activities such as Central America and the rest of India, their heavyweight dominant building stock is neither seismically nor climatically appropriate. The few seismically hazardous regions with a significant proportion of the building stock in lightweight constructions are among both the most developed nations – such as the US, Japan, and New Zealand – and the poorest countries – such as Papua New Guinea, the Philippines, and many Small Island Developing States (SIDS). In these cases the use of lightweight construction is considered to be both seismically and climatically responsive.

Overall this study has showed that for most of the world, the dominant building forms are likely to perform poorly in earthquakes even in highly hazardous areas. Although it is not surprising that seismic hazards do not strongly affect the way people build due to social, cultural, and economic influences, this analysis suggests that climate may also play an important role in both perpetuating and mitigating the building vulnerability. Much in-depth research is needed to develop a better understanding of how the physical demands of climate and seismic hazards interact and combine, and how engineering expertise can help mitigate either or both of these demands, especially with respect to heavyweight constructions. Furthermore, the influence of important socioeconomic and culture factors that are not discussed in this paper, such as urbanization and the use of mechanical systems for cooling and heating, would also need to be considered. By taking this cross-disciplinary approach towards risk and vulnerable building stock identification, it may be possible to produce better retrofitting strategies and construction guidelines that can transform the very act of risk reduction into a catalyst for safer and more comfortable living and working places.

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