Capturing Uncertainty in the Design of Prescriptive Guidelines for Confined Masonry Housing for Haiti

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ABSTRACT

A prescriptive set of design and construction guidelines for confined masonry housing reconstruction in Haiti were developed following the January 2010 earthquake. The guidelines were based upon structural engineering calculations that considered the major sources of uncertainty in both the engineering and architectural design conditions in which they would be employed. The challenge of the assignment was to limit the design variables so that a balance of seismic safety and economy could be achieved while keeping the guidelines straightforward and simple to replicate. At the same time, it was critical to ensure that the design assumptions and limitations were culturally appropriate and consistent with local construction practices.

Introduction

The 12 January 2010 Magnitude 7.0 earthquake in Haiti caused over 233,000 deaths [1], most of which resulted from the collapse of poorly-designed and constructed buildings. Post-earthquake damage assessments indicated that more than 50% of the buildings in the densely-populated capital of Port-au-Prince were damaged or collapsed as a result of the earthquake [1], including many informally-constructed concrete block houses. Numerous multi-story buildings built according to highly variable standards due to Haiti’s lack of a building code were also destroyed.

Following the earthquake, Guy Nordenson and Associates (GNA) was hired by Build Change, an international non-profit social enterprise focused on earthquake-resistant permanent housing design and construction in post-earthquake situations, to develop permanent housing resources for Haiti’s reconstruction phase. The first task was to develop a set of engineering design criteria for Haiti through both literature and field research. These criteria included loading requirements that met both site-specific needs and international standards as well as material guidelines consistent with existing local materials and construction skills. The second task was to use these criteria to develop through structural engineering calculations a set of prescriptive design guidelines for confined masonry housing, the most prevalent construction system in Haiti. This work built upon Build Change’s previous work developing similar resources for confined masonry houses in Indonesia and China; however, the guidelines were tailored to Haiti’s local conditions.

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architectural preferences and construction practices.

The need for a set of prescriptive design guidelines for confined masonry housing as opposed to standardized house designs arose from the fundamental mission of Build Change to assist homeowners in rebuilding safe, permanent housing after an earthquake with locally-available, culturally-appropriate materials and construction techniques. This homeowner-driven design and construction process requires a high degree of flexibility in the technical guidelines because each homeowner faces different budget and site constraints and has unique preferences and priorities which influence the design. At the same time, the process requires high technical precision to ensure the reliability and safety of the housing designs when exposed to local natural hazards.

The challenge of the project was to comply with these two competing objectives, particularly for multi-story housing which requires greater engineering expertise and is a critical need in the urban environment of Port-au-Prince. The assignment required an understanding of the major sources of uncertainty in Haiti’s design conditions and the reduction of these uncertainties to a minimum number of variables that could be simply applied in prescriptive design guidelines.

Capturing Uncertainties in Engineering Design Criteria

The uncertainties in the design criteria for the project included not only the design wind and seismic loads but also the selection of appropriate material quality standards that were low enough to be achievable in the field yet high enough to allow for realistic and economical housing designs, including multi-story construction. The criteria were also subject to the approval of Haiti’s Ministere des Travaux Publics, Transports, et Communications (MTPTC), a requirement which added a layer of complexity as the agency desired consistency between Build Change’s guidelines and those that they were developing in parallel.

Because no building code existed in Haiti at the time of the earthquake, the first step was to select an existing code to determine loading requirements for the design. The International Building Code (IBC) was selected because its methodology permitted the incorporation of the Pan American Health Organization’s (PAHO) 2008 wind maps and the US Geological Survey’s (USGS) 2010 seismic maps issued after the earthquake. According to the PAHO maps, wind conditions were fairly consistent across the country so a single criterion corresponding to a wind speed of 119 mph and Exposure Category C was selected. For seismic loading, the 2010 USGS maps corresponding to a 2% probability of exceedance in 50 years were condensed into two peak ground accelerations in the reconstruction zone: 0.6g (Orange Zone) and 1.0g (Red Zone).

Material design criteria were determined through the collection of field data, including surveys based on visits to local manufacturers and retailers and discussions with the MTPTC’s testing laboratory and other NGOs working in Haiti. The primary focus of the field research was the selection of design strength values for cast-in-place concrete and concrete block masonry, the main components of confined masonry housing in Haiti. The criteria for other materials such as steel rebar and lumber were easier to determine and subject to less variability. Cast-in-place concrete minimum design compressive strength at 28 days (f’c) was set at 17.2 MPa (2500 psi) based on the assumption of specific mix proportions and the use of quality cement and aggregate which were determined to be locally available. This value included a reduction of approximately
15% to account for strength loss due to improper mixing and/or curing. The field survey uncovered significant variation in the strength of concrete block masonry. Variability in block strength resulted from improper curing conditions, inconsistent cement content, excess water, and poor sand quality. Concrete blocks fabricated by reputable manufacturers according to strict proportions and material quality standards were found to have strength greater than 13.8 MPa (2000 psi). Those fabricated in highly uncontrolled circumstances were determined to have strengths as low as several hundred psi.

To reduce the number of variables considered in the development of the guidelines, a strategy was developed to minimize the range of variation in concrete block strength. Through calculations, a value of 4.8 MPa (700 psi) was selected as the minimum permitted compressive strength that could reasonably be used to build an earthquake-resistant house. This value also corresponded to blocks which would pass a simple field test of remaining intact when dropped from a 6 foot height. A value of 11.7 MPa (1700 psi) was chosen as a reasonable upper limit on strength that could be achieved in favorable conditions including those fabricated by reputable manufacturers. This reduced range was converted into three discrete values for the guidelines.

The variation in both seismic ground motion (i.e. 2 zones) and block strength (i.e. 3 values) coupled with the need to develop both one and two-story housing options could have resulted in a multitude of design conditions and associated calculations as well as a highly complex and confusing set of guidelines. To reduce the number of variables and the complexity of the design guidelines, each concrete block strength was coupled with an anticipated seismic performance [Table 1]. The primary benefit of this approach is that it permitted the use of one set of guidelines for one-story buildings and one set for two-story buildings. Having limited versions of the guidelines simplifies their implementation and reduces misunderstanding, thereby allowing the information to be better understood and, ideally, replicated. This approach also allows for an understanding of the improvement in the seismic performance that could be achieved if the concrete block manufacturing industry in Haiti is more tightly controlled. The poor quality of most blocks in Haiti at the time that the guidelines were developed made it near-impossible to design for the highest anticipated ground motions in Haiti; however, as the quality control standards for block production improves, it will enable an increased seismic performance for an identical house built with better blocks because the design is governed by the in-plane shear failure of the block walls under seismic loading rather than by the failure of the reinforced concrete confining elements.

**Capturing Uncertainties in Architectural Design Criteria**

After establishing a methodology to reduce the number of variables considered in the engineering design criteria, uncertainties in the architectural design criteria were identified and addressed. First, an extensive field survey was conducted to understand local architectural and construction practices such as typical house layouts, room dimensions, story heights, window and door configurations, roof types and structural dimensions. This information was used to set reasonable limits on the ranges of dimensions for these variables considered in the structural calculations that formed the basis of the guidelines. Three house layout typologies – Kay, Creole and Open Corner – were identified as the most common, and maximum and minimum dimensions were established for wall, floor and roof locations to bound the calculations.
The most significant variable to affect the structural calculations was the likelihood of a second story being added to a house. In Haiti it is a common practice to incrementally expand housing both vertically and horizontally over time as families grow and acquire more financial resources. Multi-story buildings are also a necessity in many parts of the densely populated capital city. The addition of a second story significantly changes the gravity and seismic demands on the ground floor of the building, thereby increasing the cost to build the first story. Therefore, it was important to find a balance between the need for safety in the event of a second story being added and the need for economy in the design of single-story buildings. To satisfy this balance, it was decided that single-story houses with timber-frame roofs could be designed for the seismic loads of the single story only. Single-story houses with flat concrete roofs, however, were much more likely to be vertically expanded so their guidelines were developed assuming two stories. Table 1, therefore, is divided into two cases, and the required block strength is more stringent for single-story concrete roof houses than for single-story timber-frame roof houses.

The guidelines also established rules meant to counter unsafe construction practices so that these conditions could be disregarded in the calculations because they would result in overly complex and expensive construction. These included limits on the asymmetry of wall configurations in a house to reduce torsional effects during a seismic event; restrictions on wall discontinuities between levels; and detailing requirements for stairs which can act as compression struts in a seismic event and change the anticipated behavior of a building.

Conclusion

The challenge of developing a set of prescriptive guidelines for homeowner-driven post-earthquake reconstruction in Haiti was that it required the consideration of a large number of uncertainties in engineering and architectural variables that are in traditional situations provided to the engineer through building codes and specific requirements of the client. The methodology that was used to limit these variables could be considered as a framework in developing similar flexible guidelines for other post-earthquake reconstruction projects.

Table 1. Correlation between seismic design criteria and concrete block strength.

<table>
<thead>
<tr>
<th>Concrete Block Strength</th>
<th>Seismic Design Criteria</th>
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<tbody>
<tr>
<td><strong>Case 1: Single Story with Lightweight Roof</strong></td>
<td></td>
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<tr>
<td>4.8 MPa (700 psi) min</td>
<td>Permitted in all zones (Orange and Red)</td>
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<tr>
<td><strong>Case 2: Single Story with Concrete Roof / Two Story</strong></td>
<td></td>
</tr>
<tr>
<td>4.8 MPa (700 psi) min</td>
<td>Not Permitted</td>
</tr>
<tr>
<td>6.9 MPa (1,000 psi) min</td>
<td>Permitted in orange zones only</td>
</tr>
<tr>
<td>11.7 MPa (1,700 psi) min</td>
<td>Permitted in all zones</td>
</tr>
</tbody>
</table>

References

1. Earthquake Engineering Research Institute, Learning from Earthquakes: The Mw 7.0 Haiti Earthquake of January 12, 2010: Report #1, EERI Special Earthquake Report, April 2010