ABSTRACT

Cost premiums were developed by comparing building design requirements found in national model codes and current local codes, both with and without seismic requirements, and then developing structural designs and construction cost estimates for selected representative building types. Six building types were selected for study and three designs were developed for each of the six building types: (1) a design developed without consideration of any specified seismic hazard, but with a lateral force-resisting system in conformance with requirements for wind load based on current requirements; (2) a design based on local building code provisions current at the time of this study; and (3) a design based on the current national standard for seismic design.

Costs assume competitively procured prices in the Memphis-area market in the fourth quarter of 2012. Quantities and materials were selected to represent building practices typical of the region, at an overall mid-level of quality. Cost premiums were in line with estimates in other cities with significant seismic hazards, in contrast to a 1983 study that found a higher premium in Memphis. Additional findings assessing the benefits expected from building in conformance with the current national standards for seismic safety are also included.
Cost Analysis and Benefit Studies of Codes and Standards for Earthquake-Resistant Construction in Memphis, Tennessee

A. Hortacsu\textsuperscript{1} and J. R. Harris\textsuperscript{2}

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\textbf{Introduction}

This paper summarizes the findings of the ATC-89 project, which investigated cost premiums associated with earthquake-resistant building construction in the middle Mississippi River Valley region. This project was conducted by the NEHRP Consultants Joint Venture, a partnership of the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering (CUREE) with funding provided by National Institute of Standards and Technology, a bureau of the United States Department of Commerce and lead agency of the National Earthquake Hazards Reduction Program (NEHRP).

The cost premium for earthquake-resistant construction is of great interest in regions that

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have significant seismic hazard, but have not suffered serious damage from earthquakes in the memories of people now living. The middle Mississippi River Valley was struck by very large earthquakes in 1811 and 1812, and scientific study has found evidence of multiple large earthquakes prior to that. This past earthquake history indicates that the earthquake hazard, thus risk for loss of human life due to earthquakes in the region is high. This inference is confirmed by hazard assessment information based on expert consensus studies conducted by leading seismologists who are engaged with the U.S. Geological Survey. Based on risk to life-safety, the hazard is very similar to coastal California, but there have been essentially no damaging earthquakes to remind the populace of the hazard. This understandably leads to questions about the value (cost) of including earthquake-resistant construction requirements in the local building codes.

Similar studies were conducted in 1982 and 1998 through the Building Seismic Safety Council (BSSC) under sponsorship of the Federal Emergency Management Agency (FEMA). In this current project, cost premiums were developed by comparing building design requirements found in national model codes and current local codes, both with and without seismic requirements, and then developing structural designs and construction cost estimates for selected representative building types. The team also analyzed the benefits of earthquake-resistant construction. The team performing the work on this project consisted of structural engineers, a cost estimator, a geotechnical engineer, an architect, a contractor/developer, and a building official.

Building Types and Designs Studied

Selection of building types for this study was initiated by an analysis of construction data for Shelby County, Tennessee, provided by the NIST Applied Economics Office. These data covered building information from several decades, ranging from the 1940s to 2007. The project team, with the assistance of Memphis-area professionals, analyzed this data set and then projected to future expectations based on observations of current construction practice in the region. Six building types were selected for study: a three-story apartment, a four-story office, a one-story retail, a one-story warehouse, a 6-story hospital, and a two-story elementary school. Each design was configured to be a realistic building in terms of size, structural system, and location within the metropolitan area.

Three designs were developed for each of the six building types:

1. A design developed without consideration of any specified seismic hazard, but with a lateral force-resisting system in conformance with requirements for wind load based on ASCE/SEI 7-05, *Minimum Design Loads for Buildings and Other Structures* [1]. This wind load is consistent with recent and projected future building codes in Memphis.

2. A design developed based on current local building code provisions. At the time this study was performed, Memphis and Shelby County were in the process of adopting a new model building code, but the implementation of the structural provisions of that code was delayed pending resolution of local application of seismic design provisions. Thus for structural design purposes, the current Memphis and Shelby County Building Code is based upon the 2003 edition of *International Building Code* [2] with a local amendment permitting seismic
design based on the 1999 *Standard Building Code* [3], except for hospitals and other essential facilities. In the case of hospitals and other essential facilities, this code requires compliance with the seismic provisions of the 2003 *International Building Code*, which essentially results in hospital designs consistent with current national seismic requirements.

3. A design was developed based on ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* [4], which is the current national standard for earthquake-resistant design and is also the basis of the structural provisions of the 2012 edition of *International Building Code* [5].

In a few cases, the lateral strength required for seismic design was less than that required for code-specified wind design. In such cases, the design strength was not reduced (i.e., wind load cases governed the minimum design strength for these buildings).

**Design Development and Cost Estimation**

Because experience in seismic design was judged to be critical in developing efficient designs, teams performing the structural design work included firms from California and Colorado. The resulting designs and cost estimates were extensively reviewed by Memphis-area professionals who were consulted at length about local codes and design practices for each building type.

Cost estimates were developed by a cost consulting firm using a national database of construction costs. Costs assume competitively procured prices in the Memphis-area market in the fourth quarter of 2012. Quantities and materials were selected to represent building practices typical of the region, at an overall mid-level of quality. The quantities and materials assumed in the estimates were reviewed by local design and construction professionals and found to be consistent with local practices.

Estimates include costs for structural systems and nonstructural systems, including equipment and architectural finishes that would be provided as part of the core and shell. Estimates consider costs for building construction only, excluding costs related to site development and utilities. These excluded costs are considered relatively constant for different structural designs. In the case of commercial buildings, estimates exclude costs for items that would normally be associated with tenant improvements. The estimates include an allowance for contingencies that might be missed in the preliminary design of nonstructural aspects of the buildings. Costs associated with design, testing, and inspection services are also excluded, except for special inspections associated with seismic design requirements.

**Summary of Cost Analyses**

Table 1 and Table 2 summarize construction cost ratios among the three different design levels. Table 1 compares cost estimates for the seismic designs to these for the wind design, whereas Table 2 compares the cost estimates for the two seismic designs. In Table 1, the column labeled “Wind” is taken as the base, and is populated with the value 1.0. Similarly, “Current Local Seismic Code” is taken as the base in Table 2. The columns labeled “Cost Ratio” are
populated with ratios of construction costs, and the “Cost Premium” column indicates the cost premium as a percentage of the base. The results in the tables can be interpreted as follows: the design according to the current local seismic code design for the three-story apartment building is shown to have a cost ratio of 1.003 when compared to the wind design, indicating a cost differential of 0.3% more than the design for wind only. Thus, it is shown that construction cost premiums associated with meeting current national standards for earthquake resistance are small, generally 3% or less over design for wind only, and 1% or less over what is currently required for seismic design in the Memphis area.

Table 1. Summary of construction cost ratios and cost premiums at three design levels.

<table>
<thead>
<tr>
<th>Building</th>
<th>Wind (1)</th>
<th>Cost Ratio (4)</th>
<th>Cost Premium</th>
<th>Cost Ratio (4)</th>
<th>Cost Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment</td>
<td>1.0</td>
<td>1.003</td>
<td>0.3%</td>
<td>1.012</td>
<td>1.2%</td>
</tr>
<tr>
<td>Office</td>
<td>1.0</td>
<td>1.021</td>
<td>0.21%</td>
<td>1.028</td>
<td>2.8%</td>
</tr>
<tr>
<td>Retail</td>
<td>1.0</td>
<td>1.003</td>
<td>0.3%</td>
<td>1.005</td>
<td>0.5%</td>
</tr>
<tr>
<td>Warehouse</td>
<td>1.0</td>
<td>1.004</td>
<td>0.4%</td>
<td>1.014</td>
<td>1.4%</td>
</tr>
<tr>
<td>Hospital</td>
<td>1.0</td>
<td>1.025</td>
<td>2.5%</td>
<td>1.025</td>
<td>2.5%</td>
</tr>
<tr>
<td>School</td>
<td>1.0</td>
<td>1.010</td>
<td>1.0%</td>
<td>1.014</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

Notes: (1) Wind-only lateral design for all buildings is conducted according to ASCE/SEI 7-05.
(2) The current local seismic code is the 2003 International Building Code. For most buildings, the local code allows structural design to conform to the 1999 Standard Building Code, which is less demanding and was used for all buildings except the hospital. The local code does not permit the exception for design of hospitals. ASCE/SEI 7-02 was used as the basis for the hospital design.
(3) The current national seismic code design for all buildings is conducted according to 2012 International Building Code with ASCE/SEI 7-10 used as the basis.
(4) Ratios are total construction costs for seismic design relative to wind design.

Summary of Benefit Studies

Benefit studies were also undertaken, highlighting the changes in the required strength and the key requirements for toughness in vulnerable portions of the lateral force-resisting systems (LFRS) among the three designs. The lateral strength required depends upon changes in the best estimate of the seismic ground motion hazard and upon changes in the seismic design parameters that allow for differing abilities of structural systems to accept damage without collapse. For the six buildings studied, the lateral strength required by the current national seismic code ranges from less than that required for wind alone to as much as ten times more. It should be noted that the designs with increased strength due to higher seismic demands will also provide improved performance under extreme winds that exceed code requirements but are not
uncommon in the region. In particular, the connections of the tilt-up buildings, when detailed for seismic requirements, will show improved wind resistance.

Table 2. Summary of construction cost ratios and cost premiums for seismic designs.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment</td>
<td>1.0</td>
<td>1.009</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>Office</td>
<td>1.0</td>
<td>1.007</td>
<td>0.7%</td>
<td></td>
</tr>
<tr>
<td>Retail</td>
<td>1.0</td>
<td>1.002</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>Warehouse</td>
<td>1.0</td>
<td>1.010</td>
<td>1.0%</td>
<td></td>
</tr>
<tr>
<td>Hospital</td>
<td>1.0</td>
<td>1.000</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>School</td>
<td>1.0</td>
<td>1.004</td>
<td>0.4%</td>
<td></td>
</tr>
</tbody>
</table>

Notes: See Notes for Table 1.

When comparing the current national seismic code to the current local seismic code (for all buildings except for the hospital), the lateral strengths required by the national code are 1.1 to 1.9 times more than the strengths required by the current local seismic code. Since the current local seismic code for hospital design requires compliance with the seismic provisions of the 2003 IBC, the required strengths in the hospital designs are consistent with current national seismic requirements.

Given the now prevalent styles of construction in Memphis, the most significant changes in the details to accommodate increased strength requirements in the lateral force-resisting system include:

- Stronger and tougher connections to tie heavy walls, such as tilt-up concrete panels or masonry walls, to floor and roof diaphragms that provide lateral support for the walls,
- Stronger and tougher connections of diagonal braces in steel frames, and
- Use of structural wood panels, such as plywood or oriented strand board, as sheathing in wood frame construction, unless a significant strength penalty is taken for other types of sheathing, such as gypsum wallboard.

In general, benefits were assessed on a qualitative basis for each building. The publication of FEMA P-58-1, Seismic Performance Assessment of Buildings, Volume 1 – Methodology [6], however, provided a new opportunity to assess the performance of individual buildings on a quantitative, probabilistic basis. As a result, buildings in this study that fit within the range of applicability of the FEMA P-58-1 methodology were also assessed on a quantitative basis. Table 3 presents the rates for all these performance indicators expressed as a ratio of the loss expected from the design based upon wind load only. The hospital designed for the current national
seismic standard has a probability of collapse of about 5% of that expected for the same building designed for wind only.

Table 3. Summary of estimated annualized loss rates.

<table>
<thead>
<tr>
<th></th>
<th>Wind</th>
<th>Current Local Seismic Code(^{(1)})</th>
<th>Current National Seismic Code(^{(1)})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loss</td>
<td>Prob. of Collapse</td>
<td>Fatalities</td>
</tr>
<tr>
<td>Apt. (^{(2)})</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Office</td>
<td>1.0</td>
<td>0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>Hospital</td>
<td>1.0</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Notes: 

\(^{(1)}\) Ratios of losses relative to wind design.

\(^{(2)}\) Losses for the wind design were taken as equivalent to current local seismic code design.

The benefits analysis results in Table 3 show that the apartment and office buildings (both common building types in Memphis), when in conformance with the current national seismic code, will have improved resistance to collapse and proven weaknesses. The analysis also shows that the probabilistically estimated rate of collapse due to seismic ground shaking is in line with the stated target for the national seismic code, which is a 1% chance in 50 years (or 0.02% per year) for ordinary buildings. That target is not met for buildings designed according to the seismic provisions of the current Memphis and Shelby County Building Code.

Conclusions

The major conclusion of this study is that construction cost premiums associated with meeting current national standards for earthquake resistance are small, generally three percent or less over design for wind only, and one percent or less over what is currently required for seismic design in the Memphis area. Benefits associated with improved seismic design, whether measured quantitatively or qualitatively, were shown to be significant.

Acknowledgments

The NEHRP Consultants Joint Venture is indebted to the members of the ATC-89 Project Team for their efforts in performing this work. In particular, NEHRP Consultants Joint Venture would like to acknowledge the Project Technical Committee, consisting of David Bonneville, Ryan Kersting, John Lawson, and Peter Morris; the Working Groups, including Kevin Cissna, Evan Hammel, Erica Hays, Guy Mazotta, Albert Misajon, Fred Rutz, and Gene Stevens; and the Project Review Panel, consisting of Ashraf Alsayed, Michael Corrin, Julie Furr, Richard Howe, Richard Meena, Luke Newman, Robert Norcross, Robert Paulus, and John Walpole. The NEHRP Consultants Joint Venture also gratefully acknowledges the input and guidance provided by Jack Hayes (NEHRP Director), Steve McCabe (NEHRP Deputy Director), and Matthew
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