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LOSSES ASSOCIATED WITH BUILDING DAMAGE IN MEMPHIS

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ABSTRACT

The NCEER Loss Assessment of Memphis Buildings (LAMB) Project is a coordinated research program that combines talents from structural engineering, seismology, risk/reliability and socioeconomic researchers. The effort provides a demonstration of how these various disciplines can be integrated to estimate economic losses for a scenario earthquake in the Memphis area. This paper summarizes the methodological approach developed to estimate direct economic loss. Input from other LAMB tasks, including ground motion estimates, fragility curves and building inventories, are used to estimate physical damage. Relationships between building damage, repair costs, and direct business losses are developed and calibrated using actual loss data from the Northridge earthquake. This information was provided by the ATC-38 study of Northridge building damage and a follow-up mail survey sent to the building owners and occupants. Losses are estimated and reported in a GIS-based software tool developed for LAMB. Attention is focused on two classes of buildings, concrete and masonry, and on the expected reduction in potential losses that could be realized by applying structural mitigation measures.

KEYWORDS

loss, assessment, buildings, Memphis, urban, economic, damage state, Northridge earthquake

INTRODUCTION

The Loss Assessment of Memphis Buildings (LAMB) Project is a coordinated research program sponsored by the National Center for Earthquake Engineering Research (NCEER) and involving researchers in the structural engineering, seismology, risk and reliability, and socioeconomic fields. The LAMB effort develops and implements a methodological framework for estimating expected losses from seismic events at the urban level. It provides a demonstration of how the various disciplines can be integrated in an application focusing on a scenario M 7.5 earthquake with epicenter at Marked Tree, Arkansas. A methodology is developed to estimate the expected losses that would be experienced in Memphis, Tennessee some 50 km to the southeast, and in the remainder of Shelby County. This paper focuses on the estimation of expected damage to the building stock and the associated direct economic loss. Direct loss is defined here to include structural and nonstructural repair costs, contents loss, and business interruption to occupants of the damaged buildings. Particular attention is paid to the concrete and masonry classes of buildings and to the potential loss reduction that could be realized by applying structural mitigation measures.

LOSS ESTIMATION FRAMEWORK AND TOOL

The objective of this study is to develop and implement a loss estimation methodology for the LAMB Project. The approach consists of two main tasks -- damage assessment and economic impact analysis. Damage for the building stock at risk is estimated by combining results from LAMB ground motion, inventory, and risk and reliability studies, as described in companion papers in this proceedings. Ground motion information consists of a series of peak ground acceleration (PGA) values associated with simulated acceleration time series produced at Lamont-Doherty Earth Observatory (Horton et al., 1996). These time series correspond to the ground motion at varying distances from the epicenter for numerous simulations of the M=7.5 Marked Tree seismic event. Distances from locations within Shelby County to the epicenter range from roughly 35 to 80 km. Building inventory information consists of the number and square footage of buildings by structural type in each of the County's 133 census tracts, as estimated at Cornell University (Jones and Malik, 1996). This inventory data is based upon records of individual buildings in the Shelby County Tax Assessor's database. Concrete and masonry buildings are located individually and characterized according to structural subtypes consistent with the fragility curve analysis development. Building usage information is also available. Risk and reliability information is input in the form of fragility curves for concrete and masonry buildings (Huo and Hwang, 1996; Kunnath et al., 1996; Costley and Abrams, 1996). Fragility curves are based on PGA and calibrated for four descriptive damage states. Two sets of fragility curves are provided -- one for the original, unmitigated condition and the other for the retrofitted or mitigated condition. For other structural types, standard damage algorithms based on expert opinion from ATC-13 (1985) are applied.

Synthesis of all of these inputs for damage assessment is performed within a geographic information system (GIS) setting to facilitate mapping and display of the information. Figure 1 below shows an example screen from the LAMB loss assessment tool for Shelby County with census tract boundaries indicated. Estimated ground shaking is shown for a simulated earthquake together with a partial building inventory of unreinforced masonry and concrete frame structures. Fragility curve information can then be applied to estimate expected building damage on a census tract level for the county.

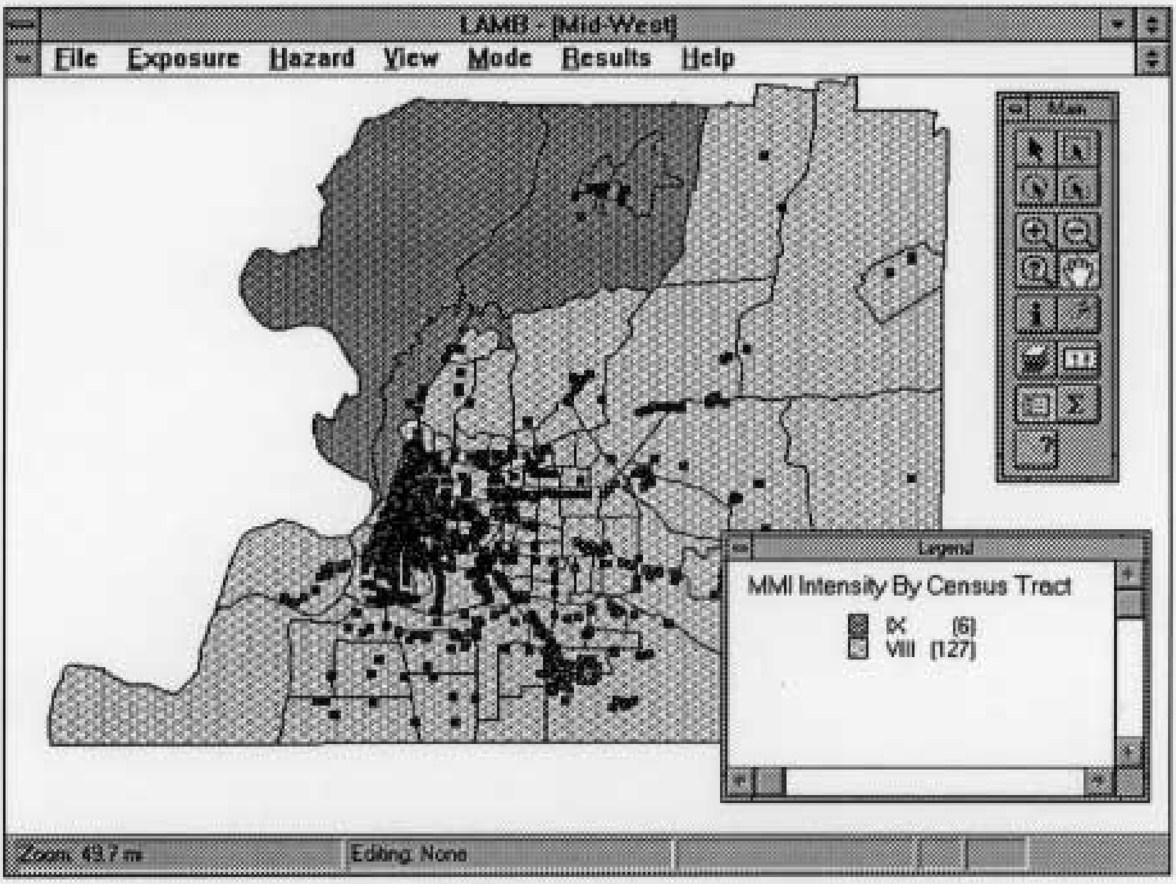

Figure 1. LAMB Loss Assessment Tool, Ground Shaking and Building Inventory Screen

After damage estimation, the direct economic loss associated with the damage is assessed. Estimates of economic loss are made in association with both the "unmitigated" and the "mitigated" sets of damage results. For this purpose, economic models are developed that associate repair cost and business interruption loss with the physical damage states. Traditionally, the correlation between physical damage and dollar loss represents a significant gap in knowledge. There have been few empirical studies published on actual repair costs in past earthquakes, in part because of the paucity of available data. This study makes use of a survey of building damage in the Northridge earthquake conducted by the Applied Technology Council as ATC-38, "Development of a Database on the Performance of Structures Near Strong-Motion Recording Sites," and a follow-up mail survey conducted one year later that focused on actual repair costs and business disruption.

In addition to the methodological framework described above, a baseline loss estimation model is also implemented using existing methodologies. These include ground motion attenuation relationships and ATC-13 (1985) damage models adjusted for Midwest construction practices. The results using this default baseline model will provide a point of comparison for loss estimates using the more sophisticated LAMB methodology. The remainder of this paper describes progress in implementing the methodology described above and will focus on the development of the economic loss models. Because the LAMB Project is scheduled to be completed in late 1996, results described here are partial and represent work in progress.

ECONOMIC LOSS MODEL CALIBRATION

This section focuses on the development of models for assessing the direct economic losses associated with building damage. Existing methodologies such as ATC-13 directly relate ground shaking parameters to repair cost as a percentage of structural replacement value, and are based upon expert opinion. The Northridge earthquake provided an important opportunity for collecting actual data for calibrating economic loss models to observed structural damage.

ATC-38 Northridge survey

Immediately following the Northridge earthquake, the Applied Technology Council conducted a survey in which licensed engineers collected detailed information on building damage through field observation. This study, referred to as ATC-38, was intended to develop a database on the performance of structures near strong-motion recording sites. (ATC-38, forthcoming) The database includes completed inspection forms and photographs for 484 buildings within approximately 1000 feet of a strong-motion station at 24 different sites. This database would enable structural performance to be analyzed with reference to reliable information on the seismic input. Data collected included structural type, square footage, and other physical description of the buildings, as well as descriptions of damage. A summary assessment of overall damage was provided according to the classification scheme shown in table 1. At the time of the field survey, much of the damage had yet to be repaired. Thus while the database includes estimated repair cost information, these represent the survey engineers' assessments rather than actual data.

Table 1. ATC-38 Damage State Classification[a]

Damage State	Description
N	None. No damage is visible, either cosmetic or structural.
I	Insignificant. Damage requires no more than cosmetic repair. No structural repairs are necessary.
M	Moderate. Repairable structural damage has occurred. The existing elements can be repaired essentially in place, without substantil demolition or replacement of elements.
H	Heavy. Damage is so extensive that repair of elements is either not feasible or requires major demolition or replacement.

Note: (a) Abstracted from ATC-38

EQE conducted a follow-on mail survey one year after the earthquake to collect information on actual repair costs and operational disruption and recovery associated with the building damage. This data is presented in an appendix of the ATC-38 report. Only non-residential buildings were included because the study was designed to investigate the impact on businesses. The questionnaire was sent to a total of 326 buildings, of which 61 were completed and returned and 62 could not be delivered by the post office, generally because of invalid or insufficient address. This amounts to a 23 percent response rate for those questionnaires that were delivered, a rate similar to other business surveys on the Northridge earthquake. As expected, the response rate varied inversely with the degree of building damage. No completed surveys were returned from buildings in the "heavy" damage category, which are likely to have been either demolished or condemned.

The intent of the mail survey was to develop a database that would enable two types of analysis: (1) identification of trends and issues relating building damage to economic impact, and (2) analysis of individual building cases. It is acknowledged from the outset that the results do not represent an unbiased sample of businesses impacted by the Northridge earthquake and that the original and final sample sizes also restrict the degree to which results can be generalized.

The questionnaire consisted of three parts. Part I requested general building information such as the use of the building. Part II pertained to structural and nonstructural repairs and was directed toward the building owner. Questions pertained to building damage and the costs, types, and timeframes related to actual repairs. Part III pertained to contents loss and business impact and was directed toward the building occupant. Questions included the pre-earthquake value of building contents, extent of loss to contents, and associated replacement expenditures and timeframes. Information was also sought on non-building earthquake-related disruption (e.g., lifeline outage) and on business interruption and recovery.

Repair costs

Repair cost models were developed based on information in the ATC-38 Northridge field survey database. Results from the mail survey were used to validate and calibrate these results as far as possible. This approach was adopted because while the mail surveys provided information on the actual costs of repair, the limited sample size did not enable the development of generalized models. On the other hand, repair cost information from the field survey, while available for over 300 buildings, is based on the inspectors' judgment. Checking the inspection results against the survey data wherever feasible provided a sense of the accuracy of the repair cost models developed from the ATC-38 data. Note that the "heavy" damage category is not validated, however, because no surveys were returned in this category. Also, results presented below are based upon a preliminary database provided by ATC prior to publication that is subject to revision.

In the ATC-38 database, each building is evaluated in terms of both the general damage state as described in table 1 and quantitative repair costs for structural, nonstructural, equipment and contents damage or loss, respectively. Repair cost is defined in terms of damage factors or percentages of replacement value and is assessed according to the ATC-13 damage classification shown in table 2. While all of the buildings had general damage state information, not all had complete records of repair cost assessment.

Table 2. ATC-13 Damage Classification

Damage Category	Damage Factor Range (% of Replacement Cost)	Central Damage Factor
1	0 %	0 %
2	0 - 1 %	0.5 %
3	1 - 10 %	5 %
4	10 - 30 %	20 %
5	30 - 60 %	45 %
6	60 - 100 %	80 %
7	100 %	100 %

The distribution of estimated repair costs for buildings in each general damage state was examined in terms of structural, nonstructural, and contents damage. The average damage factor for each general damage state was estimated by applying the central damage factors shown in table 2 above. Results are reported in table 3, together with the total number of building cases on which these distributions are based.

Table 3. Structural, Non-structural, and Contents Damage Factor Distributions by Damage State [(a)]

Damage	None (N)			Insignificant (I)			Moderate (M)			Heavy (H)		
Range	Str.	N-str.	Cont.	Str.	N-str.	Cont.	Str.	N-str.	Cont.	Str.	N-str.	Cont.
0%	86%	82%	64%	34%	9%	22%						
0-1%	14%	16%	29%	63%	71%	55%	22%	24%	64%			
1-10%		2%	7%	4%	18%	16%	51%	46%	15%	14%	80%	50%
10-30%					3%	6%	22%	20%	15%	14%		25%
30-60%						1%	4%	7%	6%	29%		25%
60-100%								2%		43%	20%	
Total [(b)]	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Ave.d.f.[(c)]	0%	0%	1%	0%	2%	3%	9%	12%	7%	51%	20%	19%
Cases	49	45	42	195	183	153	45	41	33	7	5	4

Notes: (a) Source: preliminary ATC-38 database.
(b) Columns may not add due to rounding errors.
(c) Average damage factor based on applying central damage factors.

Table 3 demonstrates the increase in repair cost associated with higher general damage states. Several observations can be made regarding these distributions. First, within each general damage state, the distribution of building damage covers a considerable spread. Structural damage for buildings in the "moderate" damage category varies from the 0-1 percent range to the 30-60 percent range. Furthermore, there is substantial overlap between the general damage states. While 63 percent of buildings in the "insignificant" damage category suffered 0-1 percent structural damage, 14 percent of buildings in the "no" damage and 22 percent in the "moderate" damage categories also had estimated repair costs in this range. These observations indicate that in developing repair cost models corresponding to the general damage states, it would be important to account for the distribution of damage rather than simplying applying a mean damage factor.

In addition, differences between structural, nonstructural and contents loss are noteworthy. Table 3 shows that in the "no" and "insignificant" damage states, contents loss is generally greater than nonstructural damage, which in turn is slightly larger than structural damage. On the other hand, average estimated repair cost in the "moderate" damage state is highest for nonstructural damage and in the "heavy" damage state is greatest for structural damage.

To validate and establish the accuracy of these results, actual repair cost data collected from the mail survey were used to make comparisons on an individual building basis. Comparisons were made for structural damage and contents loss based on information for 15 and 8 buildings, respectively.

To validate the structural repair cost information, damage factors were calculated based on the reported actual repair costs and an estimate of structural replacement value. Replacement value was estimated from standard square footage costs based on *Means Construction Costs*, combined with the ATC-38 records on structural type, height, and floor area of the buildings. Repair costs were estimated from responses to two survey questions: the actual amount spent on building repairs, and the share of this amount applied to structural (as opposed to nonstructural) repairs. Because repair costs were often reported in dollar ranges rather than exact figures, damage factor ranges were estimated. The most closely associated ATC-13 damage category was then determined and compared with the inspectors' assessments. Results are shown in table 4.

As shown in the diagonal cells in the table, in 7 of the 15 building cases, the actual damage factor range is consistent with the inspectors' assignments in the ATC-38 database. In all but one of the remaining 8 cases, however, the inspectors underestimated the structural repair costs. This indicates that the structural repair cost distributions shown in table 3 above may be skewed toward smaller repair costs than actually were incurred. In applying the results for urban seismic loss estimation, one reasonable option may be to use the structural damage distributions in table 3 to produce a lower bound estimate of damage and shift the distributions upward to produce a "best" estimate. This adjustment could be based upon a combination of findings shown in table 4 and expert judgment.

Table 4. Validation of Inspection Estimates of Structural Repair Cost

Actual Damage		Inspection Estimate of Repair Cost (No. Bldgs.)		
Range	ATC-13 Class	0 %	0 - 1 %	1 - 10 %
0 %	1	3	1	
0 - 1 %	2	3	3	
1 - 10 %	3		4	1

It is interesting to compare these results with current concensus information based on expert opinion such as, in particular, the national standardized earthquake loss estimation methodology being developed by the National Institute of Building Sciences (NIBS). The NIBS methodology defines five damage states (none, slight, moderate, extensive, complete) based upon descriptions of physical damage for different structural types. (RMS, 1995) Based on these descriptions, it is reasonable to infer that the classification approximates the ATC-38 scheme in table 1, except that "extensive" and "complete" damage both correspond to the "heavy" damage state. The NIBS methodology provides single damage factors rather than ranges associated with each damage state. The damage factors, which are consistent with expert opinion in ATC-13, are specifically 0 percent (none), 5 percent (slight), 15 percent (moderate), 50 percent (extensive), and 100 percent (complete). In comparison with the average damage factors reported in table 3 and the upward shift implied in table 4 (at least for the "no" and "insignificant" damage categories), the ATC-38 Northridge results appear to be consistent with expert opinion as embodied in the NIBS damage factors.

Although a similar validation exercise was not undertaken for nonstructural damage, the mail survey did provide information on the structural/non-structural breakdown of building repair costs. Results, shown in table 5, demonstrate that the percent of building repairs associated with structural as opposed to nonstructural damage increases with the general damage state. This observation is consistent with the damage distributions reported in table 3.

Table 5. Actual Structural/Non-structural Breakdown of Building Repair Costs

Damage State	No. of Cases	Mean Percent Structural	Mean Percent Non-structural
None	2	33 %	67 %
Insignificant	10	42 %	58 %
Moderate	5	73 %	27 %

To validate the inspector assessments on contents loss, contents damage factors were estimated for 8 buildings for which sufficient information was available. Damage factors were estimated from responses in the mail survey on pre-earthquake contents value and post-earthquake contents loss. This validation exercise confirmed the ATC-38 contents loss estimates in all of the cases, indicating that the ATC-38 assessments are probably very reliable for this category of losses.

Taking into consideration these validation results, the distributions shown in table 3 provide a reasonable basis for developing repair cost models to be used in LAMB. Further investigation showed, however, that it is possible and useful to develop more detailed models. In the case of structural damage, the ATC-38 results can be used to develop separate damage models according to structural type; specifically, for concrete, masonry, wood, and other structural building types. The database shows, for instance, that damage factor distributions for masonry buildings are generally higher than those for concrete buildings at each of the four general damage states. Further investigation also showed that the loss distributions for building contents differed according to the usage of the facility. In particular, residential buildings had less contents loss at the lower damage states and more loss at the higher damage states in comparison with commercial and industrial buildings, with public/non-profit buildings having an intermediate distribution. For the LAMB economic loss model, therefore, structural repair cost is evaluated according to structural type and contents damage according to general usage category.

Business losses

In addition to repair and replacement cost for physical damage to buildings and their contents, direct economic losses are also incurred due to business disruption. The mail survey included questions on the extent to which the business was functional immediately after the earthquake (i.e., within one week) and one month, six months, and one year afterwards. Results on initial business disruption are shown in table 6. Because business disruption could have been due to lifeline disruption as well as building damage, the functionality results were reviewed in light of survey responses regarding disruption to water, electric power, and gas service. In one case, it was judged that business disruption was probably due primarily to lifeline disruption rather than building damage. Table 6 reflects this adjustment. Although information was not available on businesses located in heavily damaged buildings, it would be reasonable to assume 0 percent functionality immediately after the earthquake.

Table 6. Building Damage and Business Functionality

	General Damage State of Building		
Business Functionality[a]	None	Insignificant	Moderate
Full (100%)	100 %	91 %	50 %
Most (over 60%)		9 %	25 %
Partial (20-60%)			25 %
Minimal (under 20%)			
Not at all (0%)			
Total	100 %	100 %	100 %
Number of Cases	8	23	8

note: (a) functionality class adjusted to reflect lifeline disruption

Table 6 shows that for the survey sample, all of the businesses located in buildings with no damage were fully functional. However, in buildings with "insignificant" damage, roughly 1 out of 10 suffered minor business disruption. This impact was probably due primarily to nonstructural or contents damage and related clean-up activities. In buildings with "moderate" damage, only half of the businesses reported complete functionality.

While these results provide some useful information on business disruption, their limitations should be recognized. Because few respondents reported any significant degree of business disruption, it was not possible to estimate recovery functions based on the survey data. Furthermore, it should be kept in mind that distributions in table 6 are based upon a small sample and could be biased because businesses which suffered substantial disruption may have permanently closed or relocated. To develop business interruption models for the LAMB study, the information presented above will be supplemented by results from other independent surveys of business disruption in the Northridge earthquake.

CONCLUSIONS

As part of the NCEER LAMB coordinated research project, a methodology is currently being developed for estimating direct economic losses due to building damage in earthquakes. As with other recent efforts such as the NIBS standardized loss estimation methodology (RMS, 1995) and the Early Post-Earthquake Damage Assessment Tool (Eguchi et al., 1994), this study demonstrates the importance of multi-disciplinary coordination in achieving this objective. Results are anticipated to provide several benefits. Because the LAMB economic loss estimation methodology is calibrated with survey data on building damage and associated economic impact from the 1994 Northridge earthquake, the resulting models are empirically based. They therefore complement existing loss estimation methodologies where the correlation between structural damage and losses (i.e., repair costs and direct business disruption), generally derive from expert opinion. It is therefore possible to compare and potentially to integrate the existing expert-based methodologies with the new empirical models. In addition, the LAMB loss estimation approach evaluates not only expected losses but also the expected reductions in loss attributable to seismic strengthening of masonry and concrete building classes. This information can provide valuable input into decision-making for earthquake hazard mitigation.

Several areas should be explored in further research. It will be important to extend the analysis to evaluate indirect economic impact, to consider the seismic hazard in a probabilistic rather than single-event framework, and to refine the economic loss models with information from other earthquake disasters. Furthermore, although demonstrated for the Memphis region, the methodology is general and can be applied to urban seismic risk assessment in other urban areas.

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