Improving earthquake casualty and loss estimation

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ABSTRACT: This paper describes our research, in progress, in developing a regional, earthquake casualty estimation model. Previous US casualty estimation attempts lacked a sufficient empirical data base and were not tested in accordance with recent casualty data. Recent earthquake casualty and health service response research shows that structural failure is the primary cause of serious earthquake, built environment casualties, and that structural damage potential should be the foundation of casualty estimation. Other factors should also be integrated. For example, geologic performance such as landslides are especially lethal. Also, the performance of nonstructural elements and building contents and the response and personal characteristics of building occupants are predominately associated with less severe injuries. The training of local responders and the capacity of the local health care system are additional important process elements. Finally, effective casualty estimation is an iterative process that requires continuing refinement and integration of research methods to meet the changing needs of disparate user groups.

1 EARTHQUAKE CASUALTY ESTIMATION

1.1 *Development plan for US regional process*

The major purpose of our overall project is to develop a comprehensive earthquake casualty estimation process that is usable at the regional level by organizations and individuals involved in earthquake hazard reduction. In Phase One, we analyzed existing casualty estimation methods and assessed their utility given our extensive yet still emerging data bases; further, we assessed these models' ability to be integrated into existing loss estimation models. In the current phase, we are developing a prototypical, regional casualty estimation model and testing this model in three regional areas - the central US, the Pacific Northwest, and the San Francisco Bay Area. We are presently collecting initial background data, developing criteria for site selection, determining candidate sub regions, and designing an evaluation procedure to test these applications.

1.2 *Previous US casualty estimates*

Earthquake casualty estimates have been made for over

specific needs, usually preparedness, and focused on specific scenario earthquakes. They generally were gross estimates for use in policy determination, not for specific medical planning. The estimates were usually for large areas, e.g. the FEMA studies (FEMA 1980, 1985, 1990), or for large numbers of buildings, e.g., the Berkeley campus of the University of California. These estimates often suffered from the following problems:

1. They lack a significant data base on which to base estimation procedure;
2. They have not been tested in accordance with what data has been available;
3. They are based on overly simplistic assumptions about casualties and health services.

Unfortunately, there had been very little research or systematic data collection directed at developing more accurate and useful estimation procedures at the time when many of these estimations were completed (NAS 1988).

1.3 *General casualty estimation approaches*

The major casualty estimation approaches are: 1) the non-building specific approach, 2) the building specific approach, and 3) the composite approach. The non-building specific approach is a "top-down approach" that develops casualty estimates for a geographic area. These estimates are based on gross mortality and morbidity ratios. The building specific

approach is a "bottom-up" approach that relates casualties to the performance of specific building types (ATC 1985, 1987). The composite approach combines specific building type loss estimates with gross mortality and morbidity casualty ratios. The more sophisticated casualty estimation processes rely on fragility curves or probability matrices to express casualty rates as a function of shaking intensity and building damage level (Ohta et al 1986; Shinobu et al 1990).

2 EARTHQUAKE CASUALTY RESEARCH FINDINGS

Our prototypical casualty estimation modeling is based, in part, on our findings from selective studies of injury, health care utilization, and health care response patterns in recent international earthquakes including Chile, Mexico City, San Salvador and the US. Since last year, we have added valuable results from our historical cohort and case control studies of injuries, survival and search and rescue in collapsed buildings, and emergency medical services in the 1989 Loma Prieta and 1990 Philippine earthquakes to this data base. These findings, summarized below, illustrate several specific demand and supply factors useful in developing earthquake casualty estimation models and in designing more effective emergency preparedness and response programs.

2.1 Factors related to demand

The injury pattern analysis found:
1. The performance of the natural and built environments was associated with earthquake related mortality and morbidity. For example, geologic performance, especially landslides, was responsible for numerous fatalities in the 1989 Philippine earthquake (Durkin 1991d).
2. Almost all fatalities and most serious injuries in and around the built environment were associated with structural failure,
3. The majority of fatalities and serious casualties came from a small number of damaged structures, consistent with statistical experience in other fields. For example, the Cypress Viaduct and Veteran's Hospital collapses accounted for most fatalities in the Loma Prieta and San Fernando earthquakes, respectively,
4. Well designed, modern earthquake resistant structures pose relatively little serious casualty threat to their occupants,
5. High occupant, non-ductile, collapsing reinforced concrete structures were extremely lethal. However, falling sections of URM buildings, striking passersby and falling on top of other buildings, caused deaths and serious injuries,
6. Occupant contact with non structural elements and building contents was a major source of minor injuries but were associated with few serious injuries,

7. While interior non structural elements and building contents posed a relatively low risk of serious injury, certain elements and settings were particularly hazardous,
8. Occupant actions contributed to injuries--with many victims injured while attempting to take protective actions.
9. Personal characteristics contributed to injury type and severity.

2.2 Factors related to supply

The injury and health service pattern analyses found:
1. Many earthquake injuries are sufficiently minor to be treatable outside of the hospital setting,
2. Health service utilization requires better management.
3. In most cases, the regional health care system is resilient enough to handle casualty demand.

2.3 Supply and demand results from the Loma Prieta earthquake

A discussion of injury patterns in the 1989 Loma Prieta earthquake will illustrate the previous findings. So far, our Loma Prieta assessment has included fatalities and work-related injuries from the entire affected region, as well as serious injuries in Santa Cruz County . We also performed a case study of emergency medical response in heavily damaged Santa Cruz County.

2.4 Loma Prieta fatalities

Structural failure was the underlying cause of most fatal injuries. For example, Table 1 shows that fifty-seven of the sixty-five fatalities (.88) were associated with some type of structural failure. All, but one of the eighteen work-related fatalities was the direct result of structural failure or its complications (e.g., fire). Fatalities occurred in the collapse of a non-ductile, reinforced concrete structure (the Cypress Street Viaduct), the failure of two fifty-foot spans of the San Francisco-Oakland Bay Bridge, the partial or complete failure of unreinforced masonry buildings, the collapse of a four story, wood frame, apartment building, the collapse of an agricultural water tower and the collapse of a transmission tower.

In another "bridge-related" incident, which occurred thirty minutes after the earthquake, a twenty-three year old, female drove into the gap created by the collapse of the upper deck closure span of the Bay Bridge suffering fatal injuries (CDC 1989).

The failure of unreinforced masonry buildings contributed to nine fatalities overall including six work-related deaths. In San Francisco, five motorists, in three separate vehicles, were killed when portions of the

Table 1. Breakdown of Loma Prieta earthquake fatalities by structural type, frequency, and proportion.

	N	P
Structural Failure		
Bridges		
Reinforced Concrete		
Cypress Viaduct	42	.646
Steel Truss		
Bay Bridge	1	.015
Buildings		
Unreinforced Masonry		
Exterior Wall Falls On Cars	5	.077
Exterior Wall Pieces Strike Victim: Outside	1	.015
Roof Collapse Due To Adjacent Bldg. Collapse	3	.046
Wood Frame	3	.046
Apartment Bldg. Collapse		
Other Structures		
Transmission Tower Collapse	1	.015
Water Tower Collapse	1	.015
Total Related To Structural Failure	57	.876
Other Causes		
Landslide	1	.015
Falls/Stairway	2	.031
Employee Evacuation/Heart Attack	1	.015
Smoke Inhalation/Fire	1	.015
Carbon Monoxide Inhalation/Generator	1	.015
Gunshot Wound/ Directing Traffic	1	.015
Vehicle Collusion With Horses	1	.015
Total Related To Other Causes	8	.123
Total Fatalities	65	1.00

exterior wall of a multi-story, unreinforced masonry building collapsed on top of their vehicles. All of these fatalities were work related. In downtown Santa Cruz, two victims were inside a single story, unreinforced masonry commercial building when its roof collapse was triggered by a wall failure in the adjacent, multi-story URM. Just down the street, a similar collapse pattern killed a person inside a two-story department store. Finally, in Watsonville, falling exterior wall and parapet material critically injured a woman outside of a bakery housed in a URM structure..

Three were killed when the top two stories of a four story, wood frame, San Francisco Marina District,

apartment building collapsed onto the first residential floor. Two were killed in one of the apartments while an infant, being evacuated by its mother, died in a collapsed stairwell. Two additional fatalities are related to the failure of other structures. A communications technician was killed by a falling transmission tower in Los Altos. A second victim died in the collapse of an agricultural water tower.

Eight Loma Prieta deaths (.12) are related to causes other than structural failure. One of these was due to slope failure. The victim, discovered five days after the earthquake, was found buried under earth from a Santa Cruz cliff that apparently gave way during the earthquake.

Two, San Francisco deaths were attributed to stairway falls either during or immediately after the earthquake. In the first case, a fifty-nine year old man was observed to fall down a ten foot flight of stairs. In the second instance, a sixty-eight year old, female tourist was found lying on the floor of a darkened basement garage at the foot of the stairway leading to a hotel lobby.

Other fatalities include a public agency supervisor who suffered a fatal heart attack after evacuating his agency, a third San Francisco death was apparently caused by smoke inhalation during a residential fire caused by an earthquake induced gas leak, and a thirty-four year old male who died from carbon monoxide inhalation from an emergency generator in Alameda County. Finally, the death of a civilian, shot while directing traffic in San Francisco after the earthquake was considered indirectly, earthquake-related by the San Francisco Coroner's Office (S.F. Coroner 1992).

Perhaps the most bizarre death attributed, indirectly, by a coroner's office to the Loma Prieta earthquake, happened approximately seven hours after the event when a pickup truck, traveling a darkened Santa Cruz freeway, crashed into three horses killing the driver and all of the animals.

2.5 Hospital admissions in Santa Cruz County

The proportion of emergency room cases that are actually admitted to a hospital, as opposed to being treated and released, is one way to gauge the relative severity of earthquake-related injuries. In the seventy-two hours after the earthquake, the three Santa Cruz County hospitals admitted only twenty-three patients with serious earthquake-related injuries. This number stems from a medical record review, as part of County and local hospital's, post-earthquake, medical assessment of the 981 cases seen in hospital ER's during the seventy-two hour interval.

Unlike the overall fatality distribution, falls were responsible for over half of the Santa Cruz County

hospitalizations. Only one fifth of the serious injuries were due to structural failure. Closer scrutiny reveals that the elderly were the most frequent fall victims. Whereas a younger individual might escape a fall with minor bruises, the elderly victims in this group were more likely to suffer a fractured hip and several days of hospitalization. In several cases, it appeared that the earthquake injury provided a convenient opportunity for the physician to treat a pre-earthquake condition.

Heavy building contents, such as packing crates, were responsible for the serious, building content injuries.

2.6 *Loma Prieta work-related injuries*

Table 4 provides a breakdown of occupational injuries in the Loma Prieta earthquake. Like fatalities, occupational injuries related to structural collapse were concentrated at the Cypress Viaduct collapse, the Bay Bridge, and scattered among a small number of unreinforced masonry buildings.

Being hit by a falling or overturning object was most frequently associated with injury during the period of shaking - accounting for over thirty percent of the injuries. .Falls were the second most common injury both during and after the shaking. One quarter of the injuries during the earthquake and one third of the post-earthquake ones were attributed to falls. Bumping into or being thrown into an object such as a wall or counter ranked third, and accounted for one-fifth of the shaking related injuries

Surprisingly, sixty-percent of the Loma Prieta, occupational injuries are associated with taking protective action such as attempting to evacuate a building or take shelter under a desk (Durkin et al 1991c).

2.7 *Loma Prieta Injury Severity*

The overall severity of injuries in past US earthquakes has tended to be relatively light. For example, the 1983 Coalinga, California earthquake had no fatalities, even though most of the downtown, unreinforced masonry buildings suffered a complete or partial collapse. The Loma Prieta earthquake was no exception. The Loma Prieta earthquake fatality rate was less than one per one hundred thousand population. Only about seven percent of work-related injuries required hospitalization. In the case of Santa Cruz County, the hospitalization rate for earthquake-related injuries was about the same. On the supply side, the health care utilization analysis found that eighty-three percent of the casualties were treated on an outpatient basis and sixty percent of the victims were treated in non-hospital settings.

Table 2. Disabling, work-related injuries in Loma Prieta earthquake.

Injury Mechanism	EQ N 277	Post N 48	Both N 325
Due to structural collapse			
Bridge	.036		.031
URM-related	.014	.020	.015
Not due to structural collapse			
Hit by falling object	.155		.132
Hit by overturning object	.137		.111
Thrown or bumped into object	.205		.175
Fall related injuries	.260	.333	.271
Other stairway related		.125	.018
Sprains due to shaking	.125		.018
Strained taking evasive action	.083		.071
Holding on	.025		.022
Other	.029		.076
Unknown	.040		.034

2.8 *Loma Prieta Health Service Response*

The health service response case study found that: 1) the Santa Cruz 9-1-1 emergency response system was severely taxed, but remained functional and responsive, 2) advanced life support transports were fewer than normal, 3) the Santa Cruz County medical system was able to accommodate the injury load because the health care system was extensive. Although initially disrupted, the three community hospitals did not suffer severe structural damage, and the demand for major medical care was light. A revised 9-1-1 EMS disaster procedure based on this experience is expected to substantially improve disaster management of limited ambulance resources, while maintaining rapid call processing (Thiel et al, forthcoming).

3 PROBLEMS WITH CURRENT METHODS

Our suitability analysis documented the following problems with research methods for characterizing earthquake injuries and building damage (Durkin & Thiel 1991a).

3.1 *Research problems related to earthquake injury*

1. Early earthquake injury studies did not adequately categorize injury type and severity.
2. Few previous studies considered the physical setting role in earthquake injuries.
3. Previous studies did not link earthquake injuries to physical setting elements.

4. Research has largely ignored the role of occupant behavior and personal characteristics in earthquake injury susceptibility.

5. Historical data collection has tended to record only specific injury data and not focused on what happened to others at risk in the same place or similar situations. Recent studies address this problem (Noji et al 1990; Roces et al, forthcoming).

6. Traditional, institutionalized methods for injury data collection (e.g. medical records procedures) don't systematically collect information, such as injury location, contributing physical element, and circumstances surrounding the injury, that is potentially useful to earthquake casualty estimations.

3.2 *Research problems related to building damage*

1. Current methods for describing physical setting performance (e.g. building damage classification schemes) are inadequate for explaining or predicting many earthquake injuries.

2. Methods for collecting post-earthquake damage data lack sufficient detail to be very useful in casualty studies.

3. Pre-earthquake hazard assessment methods (e.g. ATC-14) need refinement to usefully predict earthquake casualties.

4. Pre-earthquake physical setting documentation is highly perishable following an earthquake.

4 CONCLUSIONS

These findings have major implications for earthquake casualty modeling: 1) structural damage potential remains a major predictor of serious earthquake casualties, but non-structural performance remains a key source of minor injuries remains a key source of minor injuries and a potential risk for major ones; 2) casualty estimates based exclusively on hospitalization data may greatly underestimate the true earthquake sourced medical demand; and, 3) future casualty models should estimate the resiliency of the entire local health care system.

Casualty estimates geared to the failure and especially the collapse potential of structures are critical. Our findings suggest that there are two principal earthquake casualty sources. The first is from the normal injury mix from low to moderate building damage, that is non building collapse. These injuries seem to be distributed proportional to the population and do not create excessive demands on the local health care system, since there are not likely to be massive numbers of severe casualties concentrated in a given local area from these damage categories. The second is from collapse of buildings that yield large numbers of serious, life threatening injuries.

This suggests that casualty estimation processes should first identify those areas where there are large populations of high hazard structures, and second where there are collapse hazard structures, often distributed within the community.

The identification of where there will be concentrations of collapse hazard structures within the community is not overly difficult. The major contributors to building damageability include site location and characteristics; structural system; and configuration. However, merely classifying a structure and its site is not the end of the hazard determination process. The identification of damageability is a problem of statistics, not deterministic statements.

We must also integrate additional factors such as geologic, non structural, and occupant performance into our evolving models. Furthermore, to successfully integrate casualty estimation with loss estimation we need better ways of describing the relationship between physical setting performance and building occupant performance (Durkin 1991b).

Finally, the injury and response patterns that we have observed, suggest that primary, secondary, and tertiary prevention measures like building retrofit aimed at reducing structural failure, selective securing of dangerous non structural elements, and appropriate response training of building occupants, community members and health service providers could substantially reduce the number and severity of future US earthquake casualties - even in a catastrophic earthquake (Durkin & Thiel 1992). Therefore, evolving earthquake casualty estimation methodologies need to include the effect of alternative hazard reduction measures.

5 ACKNOWLEDGMENTS

6 REFERENCES

Applied Technology Council 1985. *Earthquake damage evaluation data for California, ATC-13*. Redwood City, California: ATC.

Centers for Disease Control, 1989. Earthquake associated deaths -- California, *MMWR*; 38:45, 767-770.

Durkin, M. E., & C. C. Thiel, Jr, 1991a. Integrating earthquake casualties and loss estimation. *Proceedings of the workshop on modeling earthquake casualties for planning and response.* Sacramento, California: VSP Associates and California Medical Services Authority.

Durkin, M. E., 1991b. Estimating casualties in earthquakes: an assessment. *Proceedings of the fourth international conference on seismic zonation.* Oakland, California: EERI.

Durkin, M. E., C. C. Thiel Jr., J. E. Schneider, & T. DeVried, 1991c. Injuries and emergency medical response in the Loma Prieta Earthquake. *Bulletin of the seismological society of America.* 81, 5: 2143-2166.

Durkin, M. E., 1991d. Social impacts and emergency response. in A.J. Schiff (ed), Philippine earthquake reconnaissance report. *Earthquake spectra.* Supplement A to Volume 7: 115-130.

Durkin, M.E., & C. C. Thiel, Jr, 1992. Improving public policy aimed at earthquake casualty reduction. *Earthquake spectra: public policy theme issue.* 8, 1: 95-113.

Federal Emergency Management Agency, 1980. *An assessment of the consequences and preparedness for a catastrophic California earthquake: findings and actions taken.* Washington, D.C.: FEMA

Federal Emergency Management Agency, 1985. *An assessment of damage and casualties for six cities in the central United States resulting from earthquakes in the New Madrid seismic zone.* Washington, D.C.: FEMA, CUSEPP.

Federal Emergency Management Agency, 1990. *Estimated future earthquake losses for St. Louis City and County Missouri.* Washington, D.C.: FEMA, CUSEC.

National Academy of Sciences, 1988. *Estimating losses from future earthquakes: panel report and technical background.* Washington, D.C.: NAS.

Noji, E.K., H.K. Armenian, A.P. Oganessian, 1990. Case-control study of injuries due to earthquake in Soviet Armenia. *Annals of emergency medicine.* 19: 449.

Ohta, Y., H. Ohashi, H. Kagami, 1986. A semi empirical equation for estimating occupant casualty in an earthquake. *Proceedings of the 8th European conference on earthquake engineering.* Lisbon. 2.3: 81-88.

Roces, C.R., M.M. Dayrit, M.E. White, M.E. Durkin, forthcoming. Risk factors for injuries due to the 1990 earthquake in Luzon, Philippines. *Bulletin of the world health organization.*

San Francisco County Coroner's Office, 1992. Personal communication.

Shinobu, S., A. Coburn, and R. Spence, 1990. *Human casualties in building collapse: literature review.* Cambridge, England: University of Cambridge.

Thiel, C.C., D. Hiatt, J. Schneider, and M. Durkin, forthcoming. 9-1-1 emergency response in Santa Cruz County in the Loma Prieta Earthquake. *Journal of pre-hospital care and disaster medicine*