

Assessment of earthquake vulnerability of buildings

S.W.Cochrane & W.H.Schaad

Swiss Reinsurance Company, Zurich, Switzerland

ABSTRACT: A method for assessing the vulnerability of buildings to earthquake damage is presented. The method was derived by considering which characteristics of buildings affect their vulnerability, by how much, and how the influence of these characteristics can best be combined to produce realistic vulnerability values. The data relating the various characteristics to vulnerability were obtained from damage analyses and from reports in the literature. The optimal approach was found to be determining vulnerability on the basis of construction material type and modifying the values as necessary to account for building age, regularity and the subsoil in the vicinity of the building.

1 INTRODUCTION

Structural and building engineers are interested in the performance of buildings during earthquakes to help verify design assumptions and the adequacy of building codes. Members of the insurance profession have a similar interest in the behaviour of buildings during earthquakes but for them, the monetary aspects of the resulting damage are more important. In parallel with the opportunity to improve engineering design methods, damage investigations can provide valuable information to insurers on the vulnerability of different classes of buildings and therefore help refine earthquake tariffs.

A significant amount of information relating vulnerability (in terms of building damage cost ratios) to different building classes exists in the literature and in the files of insurance companies. This information is based either on statistical analyses of damage in past earthquakes or, quite often, on the opinions of experts in the field. In either case, it is not damage to individual buildings but instead the statistical mean damage of many buildings of similar construction type, age, height or other characteristics which is considered and related to earthquake intensity (usually Modified Mercalli). A major problem for those wishing to avail themselves of this vulnerability information is that each study has tended to produce results which show the relationship between vulnerability and specific building parameters or combinations of parameters and which are not easily applied in other cases where the parameters, for example, the age or construction type have changed. It was, therefore, decided to collect and summarize

the available information and synthesize from it a clear, concise, and from an insurer's perspective, applicable, vulnerability assessment tool. The procedure followed and the results obtained are reported herein.

2 PROCEDURE

The synthesis of the vulnerability assessment comprised the following two major tasks:

1. determine building parameters which have most influence on vulnerability and quantify their influence;
2. develop tool with which vulnerability can be assessed by taking account of the building characteristics of a particular insured portfolio.

2.1 Task 1

Vulnerability information was obtained from an extensive search of the literature and from four analyses of earthquake losses carried out internally by Swiss Re. These were Albstadt, Germany, 1978, Swiss Re (1990); Popayán, Columbia, 1983, Swiss Re (1984); Chile, 1985, Swiss Re (1988) and Mexico City, 1985, Swiss Re (1989). On the basis of that review, the building parameters most commonly used to describe differences in the vulnerability of building samples or insured portfolios were found to be:

age	building height
insured value	regularity and symmetry
building use	building quality (base shear)
subsoil	construction material type.

These various parameters are used to different extents by different investigators. Thus,

for example, insurance company studies concentrate on insured values and building use as this information is readily available and comprehensible whereas engineering studies tend to concentrate on base shear from design codes, construction material type, subsoil and building height. Insurance companies do, however, have access to repair costs for calculation of damage ratios whereas engineering companies obtain such information in less detail or simply estimate it. There was also a significant number of the information sources from which no quantitative data could be extracted because vulnerability was expressed not as a monetary damage ratio but as a percentage of buildings affected or the like. Such a ratio could still be used to qualitatively assess vulnerability. Direct comparison of vulnerability values was also made difficult by the fact that several forms of monetary damage ratio exist. Ideally, to permit direct application to insured values, the vulnerability had to be expressed as the ratio of the sum of the repair costs of buildings of a particular age, type or height etc., in a given Modified Mercalli Intensity (MMI) zone, to the total replacement value of all buildings with the same characteristics in that MMI zone. This quantity is denoted as the "mean damage ratio" or MDR at a given MMI. The most commonly encountered variation from the true MDR is the mean damage ratio of affected buildings which takes no account of undamaged buildings within a particular MMI zone. The MMI parameter is far from ideal as a measurement of ground shaking. It is a subjective value and highly dependent on the experience of the investigator. It is, nevertheless, a very useful parameter for statistical damage analyses and many risk maps show seismicity in terms of MMI return periods.

For ease of application it was decided that the influence of each parameter on vulnerability should be represented on a multiplicative scale, that is, as a multiple or factor of the vulnerability at a selected starting point. Task 1 also considered the important aspect of interdependence between the parameters.

2.2 Task 2

Having determined the important building parameters and the manner in which they can be combined to influence vulnerability, a particular combination of parameters was chosen as the basis for vulnerability estimation. As shown in the results, several combinations were theoretically feasible; the deciding factors were global application and the availability of data. This task also comprised determination of the absolute MDR's to which the calculated influence factors would be applied.

3 RESULTS - TASK 1

A graphical representation between masonry building AGE and relative vulnerability is shown in Figure 1.

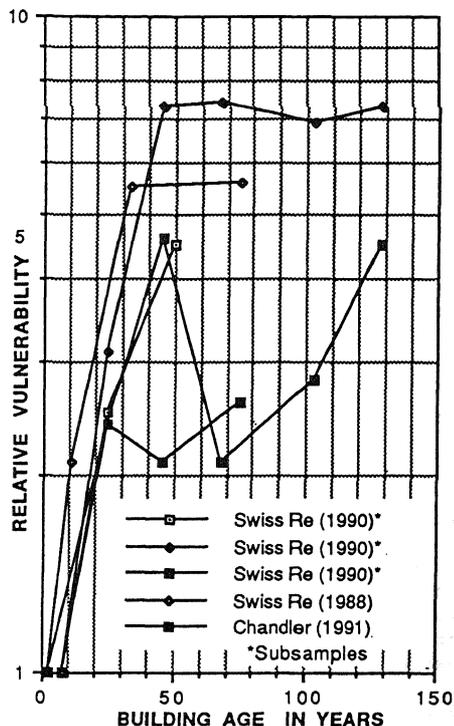


Figure 1. Influence of age on vulnerability of masonry.

Age represents the time elapsed between the construction of the building and the occurrence of the earthquake and relative vulnerability is the ratio of MDR at a particular age to MDR at age five years. The resulting trend is that the MDR increases more or less linearly (on the semi-logarithmic plot) up to about fifty years old at which age masonry buildings are four to five times more vulnerable. Age can influence vulnerability in two ways:

- (i) the obvious deterioration of material strength and performance particularly for brick and mortar construction,
 - (ii) improved seismic design methods in newer buildings particularly in high-rise steel and concrete frame buildings.
- The results of these two influences are equal - newer buildings are generally less vulnerable.

Figure 2 shows the relationship between SUM INSURED as a multiple of the local average building value in each affected portfolio and the ratio of vulnerability of a particular sum insured class to the vulnerability of the smallest sum insured class. According to Figure 2, the smallest sum insured class is

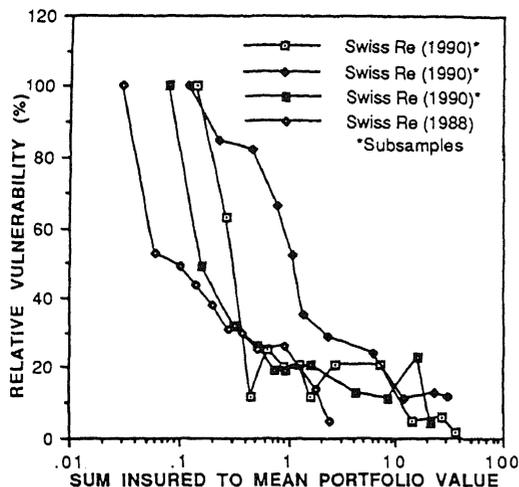


Figure 2. Influence of sum insured on vulnerability.

about 6 times more vulnerable than the average valued class. The individual curves therefore show the decrease in vulnerability with increasing sum insured values within (and not between) the respective case studies. That the curves can not be used to estimate vulnerability of portfolios in other regions or countries where only the average building value is known is a disadvantage. Further, this parameter is not a physical feature of a building or portfolio of buildings but simply a monetary value which reflects the quality of the construction materials, the age of the building and the general quality of design, construction and execution.

Buildings categorized by USE fall into three groups: residential, commercial or industrial. Swiss Re (1985) report residential building vulnerability up to five times larger than either commercial or industrial building vulnerabilities. This fact is usually ascribed to the less stringent design requirements and more vulnerable construction materials used in residential construction. Using this direct relation between building use categories and vulnerability could, however, lead to erroneous vulnerability assessments. Inner city residential buildings may, for example, be redeveloped for commercial purposes without any changes to structural strength and vulnerability.

SUBSOIL and BUILDING HEIGHT are usually treated separately with increasing vulnerability ascribed to "poorer" subsoil conditions or increasing height. Nevertheless, the spectacular increase in vulnerability as a result of resonance effects (Mexico City, 1985; Romania, 1977 and others) suggests a more complex interrelationship between the subsoil under a building and building height. Thus the influence of the subsoil should be dealt with in two modes of behaviour: damage

caused by instability of the subsoil (local failure) and resonance effects (where the earthquake ground motions are influenced by the subsoils which nevertheless remain stable).

Within the first of these groups we recognize 3 distinct types of subsoil instability; compaction, liquefaction and landslides.

In the second group, the effect of the subsoil is less obvious because the ground surface remains intact and the mass of soil remains more or less stable.

Discussions of the influence of subsoil on vulnerability have tended to consider the soil mass instability and resonance effects as one problem. This is usually dealt with using the so-called MICROZONATION technique in which the MMI of the different microzones are increased or decreased by increments of intensity relative to some assumed average ground condition. NZNSEE (1984) summarises subsoil microzone effects from several such studies and presents the following assessment:

Table 1. Subsoil Influence on MMI.

Deep alluvium	+ 2
High porosity sediment	+ 1
Compact sediment (assumed average ground)	0
Basement rock	- 1

This procedure has the advantage of being easy to use but the validity of the MMI changes can only be assessed after the relationship between absolute MDR's and MMI has been established. This is dealt with later in this paper.

The influence of REGULARITY and SYMMETRY is one of the least well documented probably because of the difficulty in quantifying these factors. Nevertheless, past earthquakes have consistently exposed the greater vulnerability of irregular buildings and the influence can be significant. In one of the few detailed studies reported, Tiedemann (1990) quotes vulnerabilities four times larger for "moderately irregular and asymmetrical buildings" compared to "regular and symmetrical". The meaning of these descriptive terms is rather unclear. Kyriakides (1987) suggests that for a building to be considered regular, it must have symmetry, a simple and sound structural system and no weak points. Thus we can exclude buildings with soft storeys, T, L and H-shaped plan buildings, buildings on sloping ground etc..

The influence of improved BUILDING DESIGN CODES on vulnerability are indeed significant but little quantitative data is available to permit comparisons. Of the few available, Hopkins (1989), suggests MDR's decreased by a factor of almost ten at MMI VIII as a result

of code improvements in New Zealand.

Categorization of buildings and assignment of vulnerabilities on the basis of their CONSTRUCTION MATERIAL TYPE is more common. One of the most frequently used sources is the graphical relationship proposed by Sauter & Shah (1978) in which damage ratios are given for ten common construction material types. Swiss Re (1985) report the vulnerability of unreinforced masonry, for example, six times greater than that of reinforced concrete framed buildings in the same MMI zone.

Consideration of the interdependence of these various influence factors will not be discussed in detail in this paper. It is obvious from the group of influence parameters discussed above, that some, for example sum insured, are highly dependent on several of the others - age, construction material type, building quality and regularity and symmetry. It follows therefore that a vulnerability value assessed on the basis of sum insured should not need to be modified to take account of changes in those parameters but should be modified to account for changes in subsoil and height effects. Similarly, it can be reasoned that base shear (as defined in most building codes) takes account of age, material type, usually subsoil but not regularity and symmetry. Finally, using the same reasoning, it can be concluded that vulnerabilities derived on the basis of construction material type should be modified by age, subsoil and, regularity and symmetry factors to give a realistic vulnerability value when one or more of those characteristics change.

4 RESULTS - TASK 2

The object of this project was to develop a vulnerability assessment tool with general, that is, worldwide applicability. Of the three possible combinations discussed above, the first - using the sum insured to estimate vulnerability - is rejected because it can only be applied locally. The second - using base shear - is probably the most desirable but presently impractical because of lack of data. The third combination using construction material type as the primary influencing factor is proposed as the most feasible vulnerability assessment tool. This would be in the form of MDR versus MMI curves for different material types corresponding to specific age, regularity and subsoil conditions, complemented by tables of influence factors for these three parameters.

The proposed material classification system is shown in Table 2 below. The proposed classification system, in addition to considering the basic material types, also considers in general terms the load carrying system (ie. whether flexible [frame] or rigid [wall]) and modern forms of construction (precast frame, lift-slab buildings and tilt-up walls).

With this classification system in place, the next step is to compile the available MDR data. This proved to be a major problem because of the limited amount and reliability

Table 2. Construction Material Classification System.

Construction Material Type	Description
1A	Wood frame with light exterior wall finish (eg. plaster, stucco, weather-board).
1B	Wood frame with brick veneer finish.
2A	Steel frame with steel bracing or reinforced concrete shear walls or with lightweight cladding systems.
2B	Steel frame without bracing or shear walls and with non-load bearing walls of reinforced concrete, brick, glass etc.
3A	Reinforced concrete frame with reinforced concrete or brick shear walls.
3B	Reinforced concrete frame without shear walls and with load or non-load bearing walls of precast concrete, brick, glass etc.
3C	Precast concrete frame and lift-slab buildings with or without shear walls.
4A	Reinforced concrete, precast tilt-up, reinforced masonry or reinforced hollow block bearing (or non-bearing with pilasters) walls.
4B	Unreinforced brick or solid block bearing walls.
4C	Unreinforced hollow block bearing walls.

of usable data. Much of the existing data on vulnerability is poorly documented and vaguely defined and data does not exist for all construction types and/or at high intensity shaking (MMI X to XII). Thus while there are many papers written on the subject of vulnerability, there is relatively little, original, empirical data. Most of the vulnerability curves produced are best estimates of the various authors (based on the little factual data) which are in turn often reused to produce other estimates. We therefore must accept that with the exception of the Swiss Re damage analyses Swiss Re (1984, 1988, 1989, 1990) the information available had already been filtered, hopefully on the basis of experienced judgment. In addition to the four Swiss Re studies, major sources of data were

Table 3. Age Influence Factors.

		Modified Mercalli Intensity														
Construction Material		VI			VII			VIII			IX			X		
Type	Age Group	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3	Y1	Y2	Y3
1A		0.9	1.0	1.1	0.9	1.0	1.1	0.7	1.0	1.3	0.9	1.0	1.3	0.9	1.0	1.3
1B		0.5	1.0	1.5	0.5	1.0	1.5	0.7	1.0	1.1	0.9	1.0	1.1	0.9	1.0	1.1
2A		0.4	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.4	1.0	2.2	0.6	1.0	1.5
2B		0.4	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.4	1.0	2.2	0.6	1.0	1.5
3A		0.4	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.4	1.0	2.2	0.6	1.0	1.5
3B		0.4	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.4	1.0	2.2	0.6	1.0	1.5
3C		0.4	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.4	1.0	2.2	0.6	1.0	1.5
4A		0.4	1.0	2.0	0.6	1.0	1.5	0.8	1.0	1.5	0.9	1.0	1.4	0.9	1.0	1.1
4B		0.4	1.0	2.0	0.6	1.0	1.5	0.8	1.0	1.5	0.9	1.0	1.4	0.9	1.0	1.1
4C		0.4	1.0	2.0	0.6	1.0	1.5	0.8	1.0	1.5	0.9	1.0	1.4	0.9	1.0	1.1

Age Group Y1 < 15 years
 Y2 15-40 years
 Y3 > 40 years

Influence factors for steel and concrete frame buildings (Types 2 and 3) are for building code changes only.

ATC 13 (1985), Dowrick (1989), NZNSEE (1984), Chandler (1991) and Whitman (1973).

To standardize the MDR data in terms of age, regularity and subsoil, it was first necessary to determine the full range of influence factors. The influence of age on masonry structures is shown in Figure 1. Less detailed information relating to wood and, steel and concrete frame buildings was also reviewed. On the basis of that review, the matrix of age influence factors (multiplicative) shown on Table 3 is proposed. Much interpolation and extrapolation of values was required because the available data correspond to only one or two age groups. The factors have been weighted such that factor 1.0 corresponds to an average age of 30 years, consistent with the MDR curves presented in this report. Age 30 years was taken as the pivot point for the age influence factor because in the absence of specific age information it would be a reasonable average age to assume.

The extrapolation and interpolation of values have also been based on the following:

- ° age is most significant for masonry construction
- ° for brittle structures, age influence is more significant at lower intensities
- ° steel and reinforced concrete frame structures show little true aging change but instead, design code differences which are related to age, prevail.

The influence of regularity is still in much doubt. However it is our opinion that the curves shown in this report represent a regularity condition somewhere between "regular" and "moderately irregular". The curves are, therefore, slightly conservative but we lack the data to justify any reduction in vulnerabilities.

The influence of subsoil type in terms of changes MMI was presented in Table 1 as a possible solution. Comparing the effects of these MMI increments with the available data gives a reasonable correlation and they are

therefore proposed as a suitable series of subsoil influence factors. The average condition is that described in Table 1 as "compact sediment". It is stressed that while age data and some subsoil data were available in the Swiss Re studies, in the other cases it had to be assumed that the data corresponded to the defined average conditions.

With the standardized MDR data available, new summary curves were drawn up for the ten previously described construction material types. These are shown on Figure 3.

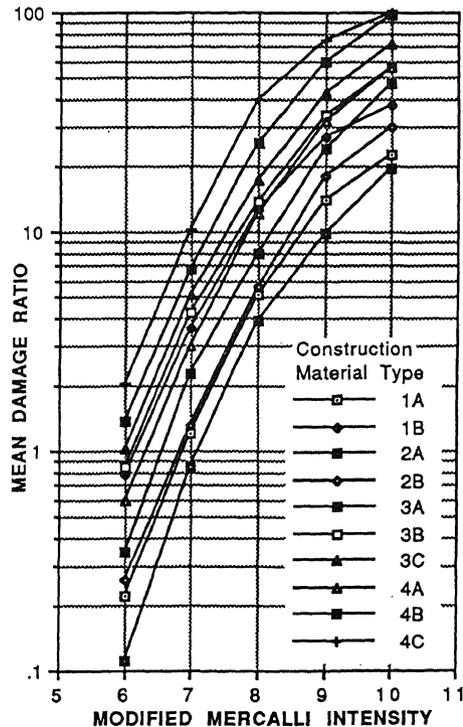


Figure 3. Vulnerability curves per construction material type.

5 APPLICATION OF RESULTS AND CONCLUSIONS

The vulnerability curves presented in this report may be used to estimate building damage caused directly by earthquakes as a result of ground shaking and movement. They do not reflect damage from fire following earthquake, damage to building contents or business interruption. The curves as derived may be modified to assess vulnerability for other conditions of age, subsoil conditions and perhaps eventually regularity. For portfolios in which details of material type, age, etc., are not known, the average values should be assumed. A further modification - a "country factor" - is probably necessary to take account of differing execution and workmanship skills in different countries. This factor would tend to increase the MDR values as the curves are in general based on data from countries with superior execution and workmanship (California, New Zealand, Germany, Chile).

Two additional economic factors which would tend to increase the MDR values are worthy of consideration. These relate to large event inflation and monopolistic insurers. Experience shows that in major catastrophic events producing large numbers of losses, repair costs and therefore MDRs are inflated. This results on one hand from poor loss adjustment by the insurance companies as a result of time constraints and on the other hand from demand for services and building materials, etc. exceeding the supply. To the best of our knowledge (at least for the Swiss Re loss analyses) the vulnerability data used in this study was based on damage from relatively small events suggesting that the large event inflation effect is absent. With monopolistic insurance companies, there is a tendency towards slightly lower settlements resulting in smaller MDRs. In this study, the insurance companies involved in the Albstadt and New Zealand events were monopolies. Exactly how much influence these economic factors should have on the vulnerability values is not yet known but the influence should be noted.

Despite the sometimes questionable quality of the raw data, it is felt that this empirical approach to vulnerability assessment for insurance purposes offers many advantages over other, theoretical approaches, not the least of which is its simplicity and adaptability. The proposed vulnerability assessment tool provides a framework in which new data may be added as it becomes available to improve its validity and usefulness.

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