A STATISTICAL EVALUATION OF THE IMPORTANCE OF NON-STRUCTURAL DAMAGE TO BUILDINGS

H. TIEDEMANN (I)

SUMMARY

The M 7.5 earthquake on February 4, 1976 in Guatemala was utilized to analyse statistically 2,280 cases of damage in the area of Guatemala City and 42 buildings in other regions. Among modern buildings, cases involving only non-structural damage account for more than 84% of the sample and 72% of the values involved. Considering non-structural elements contained in the sample which incorporates structural damage, more than 90% of damaged values are non-structural parts. In view of the importance of non-structural damage, some suggestions concerning risk optimization are made.

INTRODUCTION

It has been known for some time that non-structural damage to buildings (damage to fill-in and partition walls, plaster, paintwork, suspended ceilings, windows, doors, electric and sanitary fittings, etc.) contributes considerably to earthquake damage. In view of this, damage to a large number of buildings caused by the M 7.5 earthquake which hit Guatemala on February 4, 1976 was analysed to provide statistical information regarding the importance of non-structural damage. This data could be welcome as quantitative basis for decisions to be made by engineers, architects and those confronted with the potential social or economic impact of earthquakes.

Of the total sample, the vast majority represents buildings in Guatemala City and its immediate surroundings. This is a particular advantage as epicentral distance is practically uniform for all buildings, viz. abt. 160 to 175 km. As also building standards do not show much scatter in this area, the data is far more consistent than it would have been if collected over a large range of epicentral distances.

A further factor which should be mentioned is the rather homogeneous subsoil of Guatemala City. Nearly all formations are quarternary. One finds tephra with intercalated layers of pumice diamictons and fluvio-lacustrine sediments over most of the town area. These diamictons are massive unsorted valley filling deposits with locally stratified tops. In general, their maximum thickness is about 50 m. Over about 5% of the town area, one finds airfall pumice and cinders over volcanic rocks and mudflow, and only about 1 to 2% is light gray biotite tuff, i.e. tertiary material which is rather soft as well.

All this tends to reduce the generally multi-dimensional damage aspect permitting more direct deductions for this large sample which was exposed to MM VI if we follow Espinosa (1). The author would consider a MM-intensity of half but definitely not more than one degree more as equally defendable.

(I) Advisory member of the management of Swiss Reinsurance Co., Zürich, Switzerland; Engineering Consultant for Swiss Re Group.

OBSERVATIONS

The statistical material has been grouped in 3 tables, the first one showing buildings involving collapse or total constructive loss. If we disregard adobe buildings cases of collapse represent a minority. This is of interest in connection with potential danger to life.

Table 2 shows all buildings where structural damage was involved even if it was very small. This means that most of the losses (all of which are shown in US $) stem from non-structural parts which generallv contribute about 70% of the building cost.

Table 3 contains all buildings where no structural damage was noted during inspections. As these inspections were done for insurance purposes, i.e. also for assessing pre-earthquake values and actual repair/replacement losses to permit calculating indemnities, inspections were rather thorough.

The first section in each table shows the findings for buildings in Guatemala City and its immediate neighbourhood. The second section is for other regions in Guatemala. This second section does not only represent a comparativelv small sample but epicentral distance ranges from about 15 to 260 km.

In each table the findings are entered separately for single storey buildings, 2 - 4 storey buildings, 5 - 8 storey buildings, for 9 and more storeys, for factory sheds, as well as for adobe buildings which are predominantly one-storey structures.

If we disregard adobe buildings, the rest may be considered representative for modern building populations as found in many earthquake countries. Building quality generally increases with height as the taller structures are usuallv more modern and better engineered. Very tentatively, one may assume that on the average earthquake resistance is about as if designed for 4% g for 5 storey buildings reaching 6% g for many of the higher buildings in the sample. The data for factory buildings stems from a rather mixed population (diverse construction materials, design, span, height of columns) and should be viewed with reservation. Factory buildings listed under other regions contain some items which were at least partially of adobe.

The first column in each table gives the number of cases and the percentage this number represents of all buildings of this type in the region, e.g. Guatemala City. This tells us most about disruptiveness of the damage. Disruptiveness, e.g. indirect losses, loss of life and personal injury potential, social and commercial consequences may be severe if damage is only non-structural (Table 3).

In the following columns the total pre-earthquake value of the buildings is shown and the percentage of the total per building category this represents per section, followed bv similar figures for the total loss. In connection with values, a discriminating reader not familiar with building cost in this or comparable countries may be surprised by the low average values which he may calculate from the data given. As we are dealing with a homogeneous situation as regards construction and repair costs, this is of no direct importance.

For interest sake, the Mean Damage Ratio (MDR) as used extensively in several papers of the MIT on Seismic Design Decision Analysis (2 - 5) has been stated in the last column of the tables. As most buildings of 5 floors and more incorporate concrete moment resisting frames corresponding to about UBC 2 or better (1970 edition), the figures of MDR's shown and those one may calculate from the tables for complete samples, may serve as warning.

TABLE 1

BUILDINGS INVOLVING COLLAPSE OR TOTAL CONSTRUCTIVE LOSS

	n	%	VALUE	%	LOSS	%	MDR
GUATEMALA CITY & SURROUNDINGS							
1 STOREY	73	3.63	993,600	4.79	837,600	16.62	84.3
2-4 STOR.	2	1.61	133,900	1.20	129,900	9.28	97.01
5-8 STOR.	0						
9 & ABOVE	0						
FACT. BLDGS.	8	9.2	485,400	2.22	449,400	15.78	92.58
ADOBE	13	44.83	293,900	36.96	230,200	67.31	95.96
OTHER REGIONS							
1 STOREY	7	25.93	175,500	27.21	91,500	55.25	52.14
2-4 STOR.	0						
FACT. BLDGS.	2	15.38	242,700	16.76	228,500	63.42	94.15

Table 1 shows all those cases which represent collapse or total constructive loss, i.e. buildings where reconstruction was cheaper than repair. If we consider that a shattered but still standing building cannot be repaired economically and that this represents about two thirds of the cases, we obtain about 25 cases of collapse, i.e. slightly more than 1% of the residential, commercial or administrative buildings in Guatemala City. This is in line with the author's findings after other comparable events and with data published (6).

As engineering is more sophisticated if taller or more valuable buildings are involved, it is not surprising that these classes fare better. It should, however, be noted that it is the total constructive loss component which produces the relative weight of the single-storey category and not the occurrence of collapse.

The high incidence of collapse and total constructive loss in adobe buildings is not surprising in general but it supplies food for thought that about 45% of the cases, 37% of the value and more than two thirds of the loss are concentrated in this damage category although the intensity was only MM VI or slightly more. Incidentally, the heavy loss of life experienced in Guatemala (abt. 23,000 casualties) is practically exclusively attributable to this class of buildings. The risk to life is underlined by the MDR of about 95%. (In the province of Chimaltenango, about 200 km from the epicenter, where 13,754 lives were lost, the overall MDR exceeded

80% although the intensity was not above the one noted in Guatemala City.)

If we collect the data for modern buildings for residential, commercial, or administrative use, i.e. for buildings of one storey and more but excluding adobe and factory buildings, we note that only about 3.5% of the cases, 2.3% of their value and about 10.5% of the loss belong to this gravest class of damage.

TABLE 2

BUILDINGS INVOLVING SOME STRUCTURAL DAMAGE

	n	%	VALUE	%	LOSS	%	MDR
GUATEMALA CITY & SURROUNDINGS							
1 STOREY	237	11.78	2,661,900	12.83	1,186,350	23.54	44.57
2-4 STOR.	14	11.29	3,680,900	32.93	468,200	33.45	12.72
5-8 STOR.	12	50	3,988,900	45.94	1,259,000	66.86	31.56
9 & ABOVE	1	25	2,355,000	26.66	601,400	66.21	25.54
FACT.BLDGS.	22	25.29	5,071,200	23.17	614,300	21.57	12.11
ADOBE	8	27.59	195,100	30.06	82,800	24.21	42.44
OTHER REGIONS							
1 STOREY	5	18.52	136,100	21.10	34,300	20.71	25.20
2-4 STOR.	1	50	111,200	77.65	49.300	93.90	44.33
FACT. BLDGS.	5	38.46	564,000	38.95	83,000	23.04	14.72

Table 2 comprises those cases where structural damage was involved, however slight, but not collapse.

It is not surprising that the percentage of structural damage is similar for single and 2 - 4 storey buildings as both have similar resistance and building characteristics. It is, however, surprising that the 5 - 8 storey buildings, which are in general better engineered and have otherwise received more attention during construction than the lower class of buildings, are nearly five times more afflicted by structural damage than the preceding groups. In buildings of 9 storeys and more, the percentage drops to 25% but it is seen that not only the uncertainties from a meagre sample are to be considered but that grouping according to storey numbers is rather coarse. From a different set of statistical data compiled by the author, which will be published shortly, it may be seen that damage tends to accumulate in what one may call resonance bands. This supports the statement that the pronounced structural damage seen in the 5 - 8 storey group is probably due to unfavourable site effects.

As the figures in the table are self-explanatory (the interested reader may calculate confidence limits or other combinations of data), the combination of Tables 1 and 2 shall be discussed briefly.

If Tables 1 and 2 are combined, we find that 15.67% of the 1 to 9^+ storey buildings (excluding adobe and factories) in Guatemala City and surroundings involve structural damage. For values this percentage is 27.94% and for losses 48.56%. The MDR for this class of damage is 32.45%.

As regards values and losses, we should, however, remember that roughly 70% of the investments in buildings like those in Guatemala City go into non-structural elements and that it would be absolutely wrong to assume that it was failure of structural members of cases shown in Table 2 which led to non-structural damage. In fact, excessive shaking of buildings caused shattered or fractured fill-in or partition walls, damage to palster and paintwork, damage to ceilings, etc., and parallel to this cracks in structural elements like columns, girders, beams and in one case even floor slabs. In view of this, one could seriously consider transferring about 60 or 70% of the values and losses to Table 3.

TABLE 3

BUILDINGS INVOLVING ONLY NON-STRUCTURAL DAMAGE

	n	%	VALUE	%	LOSS	%	MDR
GUATEMALA CITY & SURROUNDINGS							
1 STOREY	1,702	84.59	17,095,400	82.38	3,015,965	59.84	17.64
2-4 STOR.	108	87.10	7,364,700	65.88	801,600	57.27	10.88
5-8 STOR.	12	50	4,694,700	54.06	624,000	33.14	13.29
9 & ABOVE	3	75	6,477,700	73.34	306,900	33.79	4.74
FACT.BLDGS.	57	65.52	16,333,900	74.62	1,784,400	62.65	10.92
ADOBE	7	24.14	214,100	32.98	29,000	8.48	13.55
OTHER REGIONS							
1 STOREY	15	55.56	333,500	51.70	39,800	24.03	11.93
2-4 STOR.	1	50	32,000	22.35	3,200	6.1	10
FACT.BLDGS.	6	46.15	641,300	44.29	48,800	13.54	7.61

Table 3 shows data for all those buildings where only non-structural damage was observed. If we consider that the distribution of buildings per storey category is similar for most earthquake regions and large isoseismal areas, i.e. if we do not consider exclusively damage to metropolitan areas, we see that most of the disruptiveness of an earthquake including the loss to a nation or to a society arises from non-structural damage, and, as the MDR's shown in the last column of Table 3 indicate, this non-structural damage is considerable.

Translating abstract figures in such a way that their impact is easier to comprehend frequently helps to understand a problem. Following this method here, we could visualize that a MDR of 17.64% for single storey buildings could mean that on the average 25% of all non-structural parts of our own houses are lost. As it is highly improbable that only one wall out of four is shattered beyond repair leaving the other 3 unscratched, this damage percentage means that we may find damage in every corner of our homes. It will probably not need explanation that repair of this damage will be even more disruptive than the actual damage.

From a second set of statistical data (not included here) which does not only comprise insured losses but all cases, it was possible to calculate that the MDR is reduced only slightly if no-loss buildings are included. This is obvious if one considers that cases listed here include also those where the loss amounted to few dollars only.

What does this mean? For the most interesting types of buildings discussed already earlier (1 to 9 storeys and more), we find that 84.33% of all cases relate to non-structural damage which represents disruptiveness better than percentage of values or losses. Considering values, we get 72.06%, and if we transfer about 70% from the earlier tables this percentage rises to beyond 90%! In terms of loss, we calculate 51.44% non-structural damage of the total damage to 1 - 9+ storey buildings in the area of Guatemala City as per Table 3. Adding the approximate non-structural element from the earlier tables, we reach more than 85%.

In passing it may be added that if (insured) earthquake losses to contents of buildings and factories, to machinery and indirect losses like loss of profit and on standing expenses are added, the amount of structural loss shrinks to less than 8% of the total loss. If we consider further that total indirect losses are much graver than those represented by the insured ones (where frequently only high-value risks are covered selectively), the importance of non-structural losses rises even more. Ambraseys (personal communication) found that non-structural losses caused by the Thessaloniki earthquake of June 20, 1978 amounted to about 99.5% of all damage.

RISK OPTIMIZATION

Efforts of earthquake engineers have so far concentrated predominantly on structural elements. This holds for earthquake building codes as well. The figures show that damage and misery caused by earthquakes could be reduced substantially if an equal amount of attention would be paid to non-structural parts of buildings. If we further consider that earthquakes have occured which caused losses amounting to about 50% of the GNP of the country although their magnitude was not impressive, we may take this as an additional incentive to improve those parts which cause most losses.

In conclusion, some suggestions are made which concern optimization of performance of non-structural parts. Much may appear obvious to the expert but more than two decades of experience with a large number of insured and un-insured loss cases demonstrates that it is generally the neglect of the obvious which causes most of the damage.

1. Compatibility of Structural and Non-Structural Parts: Most of the damage to non-structural parts concerns walls. If such walls are built of bricks or similar brittle material, it is evident that a flexible load supporting structure like a steel or soft RC-frame will produce deflections in such walls which lead to substantial damage. Flexible columns and plate glass are, for instance, far more compatible and such glass plates are far cheaper to replace, but prohibitive heating and air-conditioning cost may require stecial care in design. It is therefore suggested to look into the question of wall elements which are less vulnerable than brick walls.

2. Reduction of Amplitudes: One should try to avoid designs which would bring the building into the probable range of natural periods of the subsoil. Not much research has been done in this field, although it is obvious that

the immediate force shaking the buildings is not the distant earthquake but the vibrational energy in and the performance of the material on which the buildings are founded. There are good reasons to believe that, e.g. physical configurations including depth of soft subsoils (on which today the absolute majority of buildings in earthquake zones are founded), favours the development of predominant subsoil periods. The best-known example in this respect is the fondo del lago region of Mexico City.

Resonance avoidance is one of the most important tenets in mechanical engineering and it is difficult to convince someone why this should not be so for civil engineers and architects if they have to deal with dynamic forces. Already Richter (7) wrote: Rigid construction seems the only logical procedure when the foundation is really soft. - This appears to be unknown to most architects and engineers particularly in tropical earthquake regions!

Amplitudes may also be greatly reduced by providing adequate damping. It seems worth while to invest more thought in damping of buildings than so far, in particular as this would also reflect beneficially on the performance of the structure.

3. Avoidance of Complex Vibrational Behaviour: It is probably a very strong biological urge which drives architects to try to outrun competitors by producing ever more showy designs. Such buildings tend to be highly asymmetrical and the consequences are complex vibrational patterns and - as the author has found in a study of different statistical data which will be published shortly - mean damage ratios which are about 500% above those of regular buildings.

As nothing is probably more difficult than combatting a strong biological urge, the only feasible escape from this dilemma appears to be that designers should try to counteract the adverse features of such designs by investing particular care and additional safety. (Cf. (7), 648, 649 in this respect.)

If such unsafe monstrosities would be penalized adequately by insurers, this could provide a further incentive to invest more care.

4. Proper Attachment of Fixtures: If one has seen innumerable instances of inadequate fastening of, e.g. facading, suspended ceilings, fixtures, etc. in Managua, Fruili, Guatemala, Mexico, etc., one wonders why so little care is spent on items which could be improved at very little additional cost.

5. Ease of Repair: In certain parts of the world, pressure from consumers and automobile associations as well as from special research facilities has prompted several manufacturers of motor cars to consider ease of repairs in their designs. Why is this not adopted in the design and construction of buildings as well? Loss data shows that, e.g. the use of easily replaceable partition walls instead of standard brickwork found in many countries would reduce repair expenses noticeably.

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