STUDIES OF EARTHQUAKE DAMAGE TO JAPANESE LOW-RISE BUILDINGS

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SUMMARY

Based on data from Sendai City, Japan in the June 12, 1978 Miyagiken-oki earthquake (M_L=7.4), damage ratios for onset of damage and collapse and for damage cost for low-rise buildings are found to correlate best with response spectra at 0.75 sec. Using published test data and average building properties, a seismic damage model explains the structural behavior and permits examination of the effect of structural changes on the estimated damage. With these damage estimators, a large part of future seismic damage to urban Japan can be estimated, as well as the effects of various mitigation measures.

INTRODUCTION

One of the lesser researched topics within the earthquake risk problem has been that of regional damage estimation, although the gross damage that a region sustains in an earthquake is probably society's main concern regarding earthquakes. One of the reasons for this lack has been the lack of damage estimators (also termed damageability or vulnerability functions) for the various types and sizes of structures in today's urban regions. Although considerable research has been devoted to the response of individual structures, little effort has been devoted to the average response of classes of structures. While the value of the study of the response of individual structures is obvious, the value of building-class seismic damage estimators in such fields as land-use and city planning, microzonation, building code evolution, natural hazards insurance, disaster planning etc is also very great, when faced with the problem of estimating the damage to tens of thousands of low-rise buildings. To properly serve these fields' needs, damage estimators should not only be descriptors or predictors of damage to the structural system, given ground motion, but should also relate the response or damage to the structural system in sufficient (and yet not too much) detail such that the effects of modifications to the structural system are readily apparent, thus permitting the application of cost-benefit analysis or other decision-making methodologies.

Towards these ends, this paper presents damage estimators for low-rise buildings in Japan, which largely comprise urban Japan, based on data from Sendai City in the Miyagiken-oki earthquake of June 12, 1978. These estimators are correlations between damage measures and response spectral parameters, linked with the structural systems so that the effect of moderate changes in the structural systems, on seismic damage, can be taken into account. The link with the structural system is via a model which uses structural and non-structural wall and bracing ratios, average building properties and non-linear material properties to relate the statistical relations with typical structures.

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Definitions

The term Damage Ratio for Buildings Damaged, DR_{BDMG}, is defined:

$$DR_{BDMG} = \frac{\text{Number of Buildings reporting Damage}}{\text{Total Number of Buildings}} = \frac{BDMG}{NB}$$

Here, BDMG is number of buildings reporting damage and NB is total number of buildings for a given area. Damage is, in the above, loosely defined and includes structural or non-structural, large or small, corresponding to the number of buildings claiming damage. The term Damage Ratio for Buildings Destroyed, DR_{BDST}, is similarly defined:

$$DR_{BDST} = \frac{\text{Number of Buildings Destroyed}}{\text{Total Number of Buildings}} = \frac{BDST}{NB}$$

where Destroyed means collapse during, or razing after, the earthquake. Lastly, the Damage Cost Factor, DCF, is defined:

$$DCF = \frac{\text{Damage Repair Cost of the Building}}{\text{Replacement Value of Building}}$$

While there exist problems regarding how small the damage can be and yet be included in DR_{BDMG}, or how long after the earthquake razed buildings should be included in DR_{BDST} (or even which earthquake, in the case of aftershocks), of how accurately Damage Repair Cost is reported for DCF (and under what incentives, for example the degree of disaster relief aid), these definitions are sufficient for many aspects of damage estimation, and will be used herein.

THE MIYAGIKEN-OKI EARTHQUAKE OF JUNE 12, 1978

The earthquake of June 12, 1978 occurred at 17:14 local time, with an epicenter at 142°10' East, 38°09' North, focal depth 40 km and magnitude M_L=7.4 (USGS M_S=7.5)[2]. The earthquake and its damage have been previously reported[2,11], and only certain aspects will be mentioned here. Fig. 1 is a regional view showing Sendai City and its relation to the epicenter and aftershock area. Sendai sustained a majority of the building damage in the earthquake (eg, 55% of the destroyed buildings, 61% of damaged buildings), most of which was concentrated in the softer alluvial portions of the city. The distance from the epicenter to the center of Sendai is approximately 110 km which, given the earthquake's magnitude, resulted in surprisingly large accelerations, peak ground accelerations being on the order of 0.25g. Since, for the purposes of this study, response spectral accelerations, velocities and displacements are required for various locations and soils in Sendai, and few records were available, use of Trifunac's[10] 5% damped response spectral attenuation function was made, which was modified with satisfactory results. This modification has been previously reported[7] and won't be dealt with in detail here, but basically consisted of using a "virtual epicenter" shifted towards Sendai from the epicenter of record (see Fig. 1), in the attenuation function, instead of the epicenter of record.

Low-rise buildings, especially of wooden construction, constitute the great majority of urban Japan (eg, in Osaka 80% of all buildings are wood and 90% are one or two story). The structure of the typical wooden low-rise building (see Engel[1] for a detailed description), Fig. 2, basically consists of a post and lintel vertical load carrying system with lateral resistance deriving from mud-infilled two-way bamboo latticed walls and, more recently, some bracing. Especially characteristic is the wide-spread use of heavy tile roofs and very large wall openings. Foundations in the past consisted of stone or concrete weats and usually now are low perimeter concrete walls. Due to these features, these structures are sensitive to ground movement, which is not treated explicitly in this paper. Thus, although there was some damage in Sendai due to ground failure, this has been implicitly included in the analysis, so that the relationships derived herein are for damage due to shaking and a moderate (ie, typical) degree of ground failure. In Sendai, about 550 low-rise buildings were destroyed and 60,000 reported damage, of a total of about 145,000.

STATISTICAL ANALYSIS OF LOW-RISE BUILDING DAMAGE IN SENDAI

This section, the statistical analysis, summarizes previous findings[7] and is included for the sake of completeness. Fig. 3 is a map of Sendai showing DR_{BDMG} and DR_{BDST} by political subdivision experienced in the Miyaigiken-oki earthquake (the political sub-divisions were of sufficiently small size to be adequately categorized by a single soil type- hard, intermediate or soft). The data in Fig. 3 were regressed against the 5% damped spectral accelerations generated by the modified attenuation functions, described above. After examining various types of equations and different spectral acceleration periods, a correlation of log-log form for spectral accelerations of 0.75 sec. was found to be best. These correlations were:

$$DR_{BDMG} = 1.813(SA_{.75})^{1.744} \quad , r=.75, s=.00345 \qquad (1)$$

$$DR_{BDST} = .020145(SA_{.75})^{2.525} \quad , r=.69, s=.0001 \qquad (2)$$

where $SA_{.75}$ is the response spectral acceleration at 0.75 sec. (in g), r is the correlation coefficient and s is the conditional standard deviation. Relation (1) was modified to include data from other Japanese earthquakes[7], which resulted in:

$$DR_{BDMG} = 1.208(SA_{.75})^{1.324} \quad , r=.69, s=.00325 \qquad (3)$$

Damage costs were reported in Sendai[8], from which the following relation was determined:

$$¥ = 0.5 + .434\ BDST + .0053\ BDMG \ , \quad r=.998 \qquad (4)$$

where ¥ is 1978 Japanese Yen ($x10^8$). From the above relations, assuming an average value per building of 10^7 Yen, the damage cost factor was determined:

$$DCF = 0.0756(SA_{.75})^{1.7} \qquad (6a)$$

the variance of which can be approximated by :

$$V_{DCF} = .000115 + \frac{170}{(NB)^2} \qquad (6b)$$

The above relations permit damage estimates for low-rise buildings in Japanese regions to be made, when use is made of various response spectral acceleration attenuation regressions, which was illustrated in Scawthorn et al[7]. However, they do not in themselves explain the damage or permit any estimation of the effects of changes in the buildings' structures on the damage (for example, what would be the effect of an increase in the required bracing ratio?). For this, a physical model is needed.

SEISMIC DAMAGE MODEL FOR LOW-RISE BUILDINGS

Lateral resistance in the average low-rise Japanese building is assumed to be due to combinations of three elements: (1) solid walls of either *shinkabe* (older, bamboo lattice-mud) and/or *okabe* (newer, similar to stucco on lath), (2) partial walls of the same materials, and (3) walls of the above materials with diagonal wood bracing. Items (1)-(2) are usually considered non-structural, while (3), if existing, is considered structural. Takeyama et al[9] conducted static and dynamic tests of elements representative of items (1)-(3) from which force-deflection curves of the form:

$$P = a\Delta^{b} \qquad \Delta < 1 \text{ cm} \qquad (7a)$$

$$P = c + d \log \Delta \qquad \Delta \geq 1 \text{ cm} \qquad (7b)$$

may be determined, where P is the horizontal load acting at the top of a one-story wall panel (kg/cm), Δ is the deflection of the top of the panel (cm) and a-d are constants, Table 1. Building story equivalent linear stiffness per unit building horizontal projected area, K_j, may then be expressed:

$$K_j = \frac{1}{\Delta} \sum_i R_{ij} P_i \qquad (8)$$

where j indicates first or second story, i=items (1)-(3) and R_{ij} is the ratio of wall length per square meter of floor area. Using eqn. (8) modal frequency, modal shapes, response to spectral acceleration, etc. were obtained using a step-wise linear iterative technique in which the K_j are based on a value of the story displacement Δ_j, which is then determined from the spectral acceleration and K_j and thence used as the next input value in the iteration, see Fig. 4. Natural periods calculated using this method were compared with published test results[4,5], Fig. 5, with good agreement. Using average R_{ij} determined from standard building plans[3], shown in Table 1, as typical of present-day low-rise buildings, and response spectral shapes typical of Sendai in the Miyagiken-oki earthquake (described above), responses of average low-rise buildings were determined:

$$\Delta = e(SA_{.75})^{f} \qquad (9)$$

where e and f are given in Table 2, and Δ indicates deflections of the eave line with respect to the ground (of either one or two-story buildings). $SA_{.75}$ was used here because it had previously been found to be the best correlative with damage, in the above statistical analysis. The reason for this can now be seen since, on average:

$$T_1 = .33\Delta^{.335} \qquad \text{and} \qquad T_2 = .55\Delta^{.28} \qquad (10)$$

(where T_1 and T_2 are the fundamental period of one or two story buildings, respectively, determined by the iterative technique and the equivalent linear stiffness, eqn. (8)) and Sendai experienced average $SA_{.75}$=.45g which implies average eave-line building displacements of about 9 cm. (2-sty) and 3 cm (1-sty) and periods of 1.0 sec. (2-sty) and 0.5 sec. (1-sty). Since the number of one and two story buildings in Sendai were about equal, 0.75 sec. is well bracketed, explaining its better correlation when compared with spectral acceleration periods of 0.32, 0.55 etc. seconds. This is not to imply that 0.75 sec. is exactly the best correlative but that response spectral accelerations around 0.75 sec. provide better correlations with damage than much smaller or larger periods, for Japanese low-rise buildings. Eqn. (10) also expresses an oft-noted fact, that the period of low-rise Japanese buildings depends on displacement[5], which can also be seen in Fig. 5.

By definition, the DR_{BDMG} is that portion of the building population exceeding some damage threshold, Since the above damage model has been for an average building and eqn. (3) is the mean damage relation, we can say (assuming a normal distribution for $\overline{\Delta}$):

$$DR_{BDMG} = 1.208(SA_{.75})^{1.324} = 1.-\Phi[\frac{\Delta_{DMG} - \overline{\Delta}}{\sigma_{\Delta}}] \qquad (11)$$

where Φ is the cumulative distribution function of the normal distribution, Δ_{DMG} is the eave-line displacement at which damage reports commence and $\overline{\Delta}$ is the displacement as determined by eqn. (9). The method of least squares was used to determine Δ_{DMG} and σ_{Δ}, resulting in:

$$DR_{BDMG} = 1. - \Phi[\frac{6.9 - \overline{\Delta}}{3.4}] \qquad (12)$$

The damage threshold determined herein is 6.9 cm. which is somewhat larger than Takeyama's[9] observation of cracking at about 4 cm. This difference is not great, however, when it is considered that Takeyama's observation was for the beginning of cracking and was based on static tests whereas this study's 6.9 cm. is based on the observed damage claims of Sendai in an actual earthquake. It should also be noted that these values are for deflections at the top of a 3 m. wall. Similarly, a destruction threshold can be determined:

$$DR_{BDST} = 1. - \Phi[\frac{66. - \overline{\Delta}}{21.1}] \qquad (13)$$

Lastly, due to floors and roof sustaining damage only at comparatively large deflections, a damage cost function of the form:

$$DCF = .5(\frac{\Delta 1}{60})^2 + .5(\frac{\Delta 2}{60})^2 \qquad (14)$$

(where Δ_1 is the story deflections of the first floor and Δ_2 that of the second story) gives good agreement with the previously determined statistical relation, eqn. (5), in the range of observed accelerations.

Use of the Low-rise Building Damage Model

Damage estimators, such as eqn. (6a), permit regional damage projections, Fig. 6. Alternatively, suppose it is proposed to double the amount of bracing presently used, in the first floor only. Using the model, the resulting increase of stiffness is calsulated to only be about 1/3 (since doubling the bracing only doubles item (3), whereas the "non-structural" elements, especially the walls, still contribute significantly). Scaling the Miyagiken-oki earthquake response spectra, calculations show that at moderate accelerations the number of damaged (ie, DR_{BDMG}) buildings would be cut almost in half, while at higher accelerations the decrease in DR_{BDMG} would be very small or negligible. The damage cost and number of buildings destroyed, however, at all accleration levels would be decreased by about 1/3.

DISCUSSION AND CONCLUSIONS

Damage estimators for an important class of Japanese buildings have been presented, which permit prediction of and scenario-review for damage in urban Japan, as well as providing insight into the physical behavior of these buildings. The data derives from one earthquake in one region, with the exception of the incorportation of other damage ratio data (for DR_{BDMG}) and the results must thus be used with some caution due to this limitation. The analysis also relies on synthesized response spectra (based on the "virtual epicenter" modification of Trifunac's attenuation regression) although this does not appear to be too serious a drawback[7]. The accuracy of estimation based on the results herein is of course an important question. The damage estimation technique has already been illustrated[7] and it will simply be noted here that, while the individual estimates may have fairly large variances, the total damage estimate for an urban region will have a smaller coefficient of variation, by the central limit theorem. The applicability of the results to regions outside of Japan is unclear. While the architecture of the Japanese house is unique, the basic techniques and perhaps some of the results could find application in parts of China, India, Central America etc where mud-on-wood-lattice walls are used.

The purpose of this paper has been to present a methodology and results for building seismic damage stimators in urban Japan, of use in disaster planning, land-use planning, code-writing, etc. Based on statistical analysis of observed damage from the June 12, 1978 Miyagiken-oki earthquake, damage ratios were found to correlate best with 5% damped response spectra at a period of 0.75 sec. Damage costs were correlated with numbers of buildings damaged and destroyed, from which damage cost as a function of response spectra were determined. Based on published test results and average building properties, a seismic damage model was formulated which exhibited nonlinear behavior and from which damage thresholds in terms of displacements were determined. The model is useful in examining damage consequences of structural changes.

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NB: (J) indicates Japanese language

TABLE 1:

FORCE-DEFLECTION CHARACTERISTICS FOR LOW-RISE BUILDING ELEMENTS

$P = a\Delta^b \quad \Delta \le 1$ cm ; $P = c + d \log \Delta \quad \Delta \ge 1$ cm

TYPE	SPECIMEN	Δ ≤ 1 cm		Δ ≥ 1 cm	
		a	b	c	d
WALL: Shinkabe	SB-6	37.1	0.70	36.9	136.0
Okabe	OC-6	88.6	0.35	95.2	97.9
PIERCED WALL	SA-6	9.8	0.73	1.5	53.1
WALL WITH BRACING	OD-6	135.4	0.88	143.6	663.9

TABLE 2:

RESPONSE PROPERTIES FOR AVERAGE LOW-RISE JAPANESE BUILDINGS

$\Delta = e(SA_{.75})^f$

BUILDING	HEAVY ROOF		LIGHT ROOF	
	e	f	e	f
1 Story	15.6	1.56	10.6	1.68
2 Story	26.7	1.28	24.2	1.32

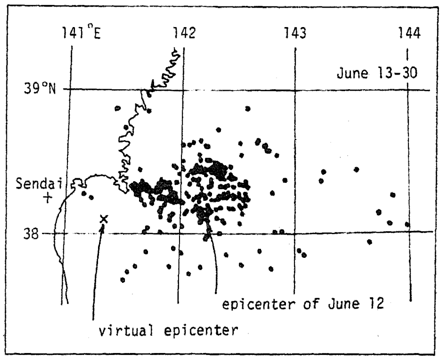

Fig. 1: Aftershock Distribution, 1978 Miyagiken-oki Earthquake

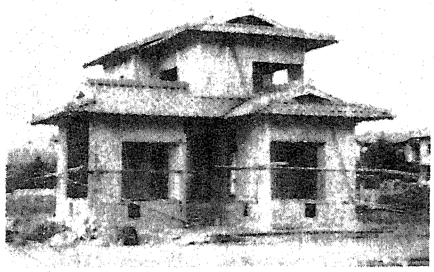

Fig. 2: Typical Japanese house under construction, note heavy roof, etc.

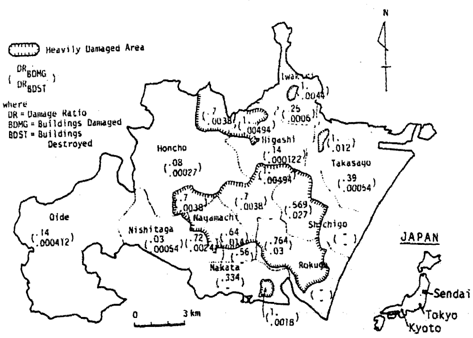

Fig. 3: Damage Distribution, Sendai City, Japan

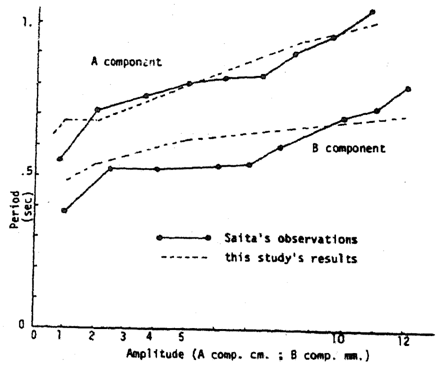

Fig. 5: This Study's results compared with Saita's test results (Ref. 5)

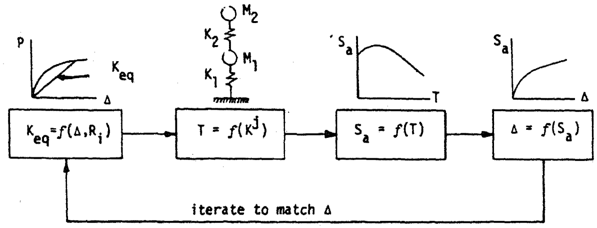

Fig. 4: Schematic representation of iterative technique used in determining natural period and displacement considering non-linear behavior.

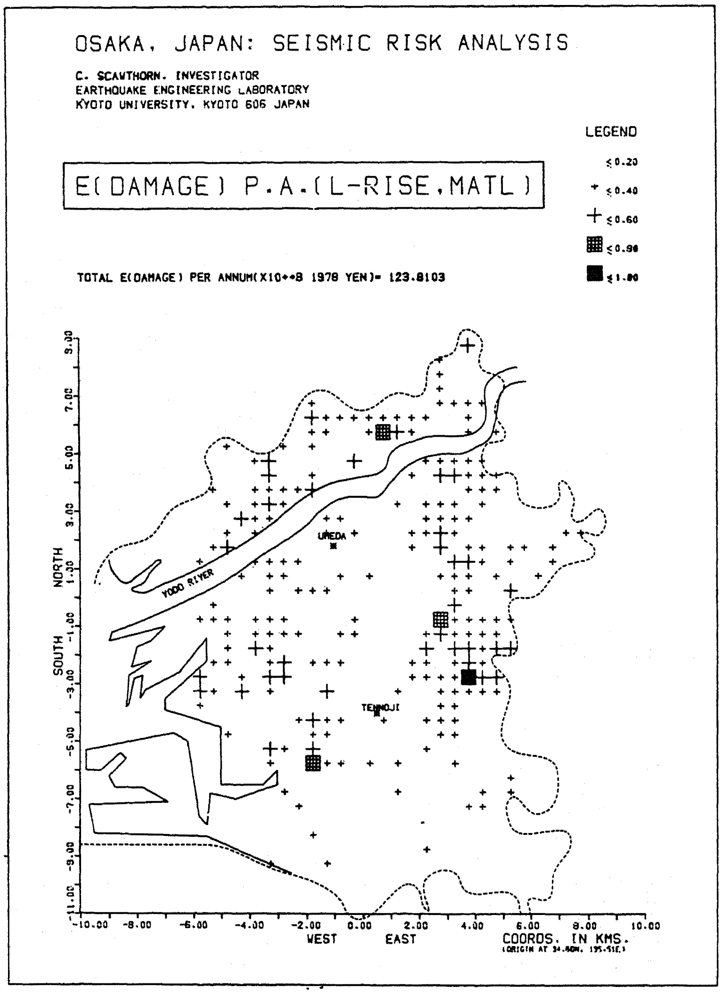

Fig. 6: Example of application of damage estimators: Annual expected damage of Osaka City low-rise building structures (material only)