SEISMIC DAMAGE MODEL FOR LOW-RISE BUILDINGS

C. SCAWTHORN*
Y. YAMADA**
H. IEMURA***

INTRODUCTION As part of seismic risk analysis, damage estimation, optimum seismic design, land-use planning, etc (a) damage predictors as a function of ground motions are needed, as well as (b) a relation between these damage predictors and structural design levels. This is especially true for low-rise building damage, since these constitute the majority of buildings and investment. In an earlier paper (Ref. 5), building damage was statistically correlated with 5% damped response spectrum accelerations at a period of 0.75 seconds. The purpose of this paper is to propose a model, using structural and non-structural elements, average building properties and non-linear material properties, from which seismic damage predictors of low-rise building (*mokuzo*) behavior can be derived, which agree with the observed statistical regressions.

MODEL In the model, resistance to lateral seismic forces is considered to be entirely due to (a) in-filled wall panels (*shinkabe* or *okabe*), (b) pierced wall panels (in-filled panels above large openings) and (c) diagonal bracing. Items (a) and (b) are considered non-structural, while (c), if any, is considered a structural element. Takeyama et al (Ref. 6) conducted static and dynamic tests of elements representative of items (a)-(c), from which force-deflection curves of the form

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

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

$$K^j = \frac{P^j}{\Delta} = \frac{1}{\Delta}\sum_i R_i P_i \qquad j=1,2 \qquad (2)$$

where j indicates first or second story, i=items (a)-(c) and R_i is the ratio of wall length per square meter of floor area. Using (2), modal frequency, shapes, etc. may be obtained using an iterative technique with story stiffness adjusted after each iteration, see Fig. 1. Natural periods calculated using this method were compared with published test results (Refs. 1,3,4), Fig. 2, with good agreement.

RESPONSE OF AVERAGE BUILDINGS Using average R_i determined from Ref. 6, shown in Table 1, as typical of present-day low-rise buildings, and response spectral shapes typical of Sendai City in the 1978 Miyagiken-oki earthquake (see Ref. 5), responses of average low-rise buildings were determined:

$$\Delta = a(SA_{.75})^b \qquad (3)$$

where a and b are given in Table 2 and Δ indicates deflection of the lower story of one or two story buildings and $SA_{.75}$ indicates response spectral accelerations at 0.75 seconds, in g. This period (ie, 0.75 sec.) was chosen because it was found to be the best correlative with damage (Ref. 5). The reason for this can be seen, since, on average

$$T_1 = .33\Delta^{.3346} \quad \text{and} \quad T_2 = .55\Delta^{.28} \qquad (4)$$

(where T_1 and T_2 are the fundamental period of one or two story buildings, respectively) and Sendai experienced average $SA_{.75} \simeq .45g$, which implies average building displacements of about 9 cm (2-sty) and 3 cm (1-sty), and thus periods of 1 sec. (2-sty) and 0.5 sec. (1-sty). Since the number of one story and two story buildings are about equal, 0.75 seconds is nicely bracketed, explaining its best correlation. Using the relation (3) and regarding the damage ratio as that portion of structures exceeding some

TABLE 1

Item	c	d	Takeyama specimen (Ref. 6)	Avg. R (m/m^2) (Ref. 2)
(a) Wall:				
shinkabe	36.9	136.	SB-6	.134
okabe	95.2	97.9	OC-6	.035
(b) Pierced wall	1.5	53.1	SA-6	.334
(c) Wall w/ bracing	143.6	663.9	OD-6	.086

TABLE 2

Building	Heavy Roof		Light Roof	
	a	b	a	b
1 story	15.6	1.56	10.6	1.68
2 story	26.7	1.28	24.2	1.32

*Monbusho Scholar,**Professor,***Assoc. Professor
School of Civil Engineering, Kyoto University

damage threshold (for given hazard level), Fig. 3, the Sendai regressions (Ref. 5) were fitted, by least squares, to determine the damage thresholds. The relations are (where $\Phi(.)$ is the cumulative distribution function of the normal distribution):

$$\text{ratio of buildings damaged} = DR_{BDMG} = 1. - \Phi\left[\frac{6.9 - \Delta}{3.4} \right] \tag{5}$$

$$\text{ratio of bldgs. destroyed} = DR_{BDST} = 1. - \Phi\left[\frac{66. - \Delta}{21.1} \right] \tag{6}$$

giving good agreement with previously obtained statistical relations, see Fig. 4. These imply a deflection threshold of damage of about 7 cm (which agrees fairly well with Takeyama's observation of 4 cm) and an ultimate deflection of about 66 cm. Since floors and roof sustain damage only at comparatively large deflections, a damage cost function (DCF) of the form:

$$DCF = f\left(\frac{\Delta}{60} \right)^2 \tag{7}$$

gives good agreement with previously determined statistical relations, in the range of observed accelerations, Fig. 4.

USE OF THE MODEL As an example, 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 calculated to be about 1/3, due to the contribution of the non-structural elements. At moderate accelerations, the number of damaged buildings would be cut almost in half, although at higher accelerations, the decrease would be negligible. The damage cost and number of buildings destroyed, however, at all acceleration levels, would be cut by about 1/3.

CONCLUSIONS A simple model of structural behavior of low-rise buildings under seismic loading has been proposed, and verified by comparison with published test results. Incorporating structural and non-structural elements, it permits the examination of damage consequences of various design levels, paving the way for optimum design.

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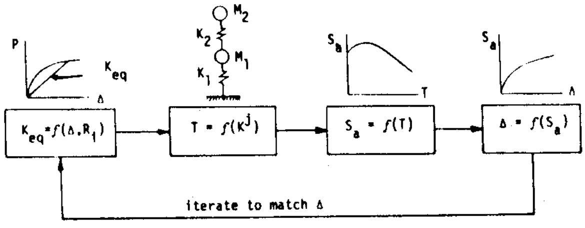

FIG. 1 Response Analysis Method

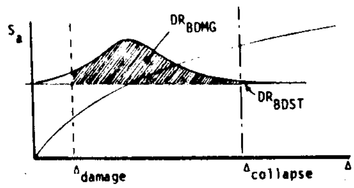

FIG. 3 Damage Ratios

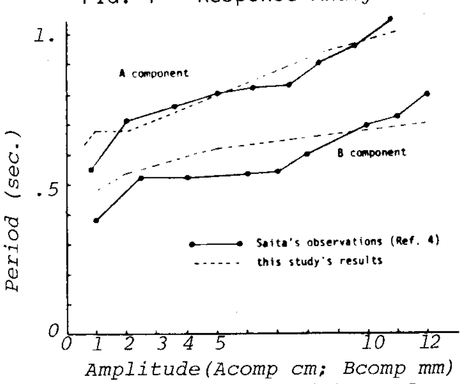

Fig. 2 Test and Model Results

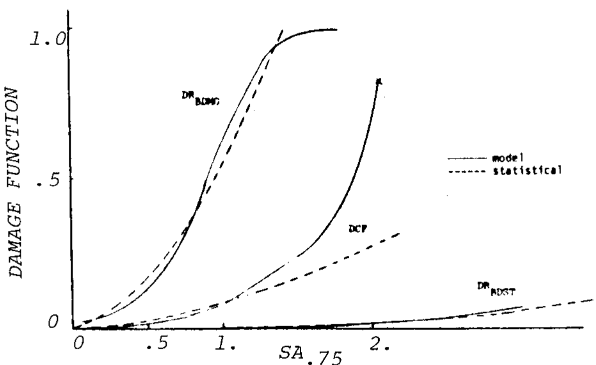

FIG. 4 Comparison of Model and Statistical Results