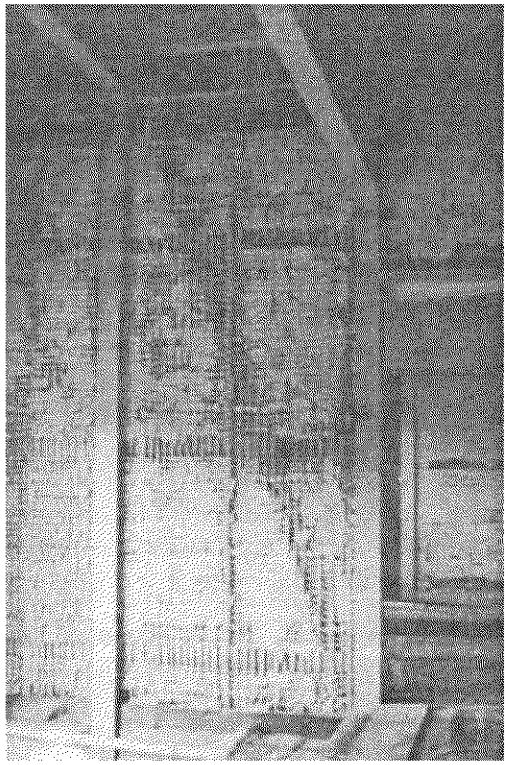

Fig. 8 Mud applied to one side of bamboo lath.

side, after troweling on one side. The final result is as shown in Fig. 2. This type of wall is termed, in Japanese, shin-kabe. There is another, somewhat less common type, termed okabe, Fig. 9, which employs a larger wooden lath over which a chicken wire-like mesh is placed and then a thin coat of stucco applied.

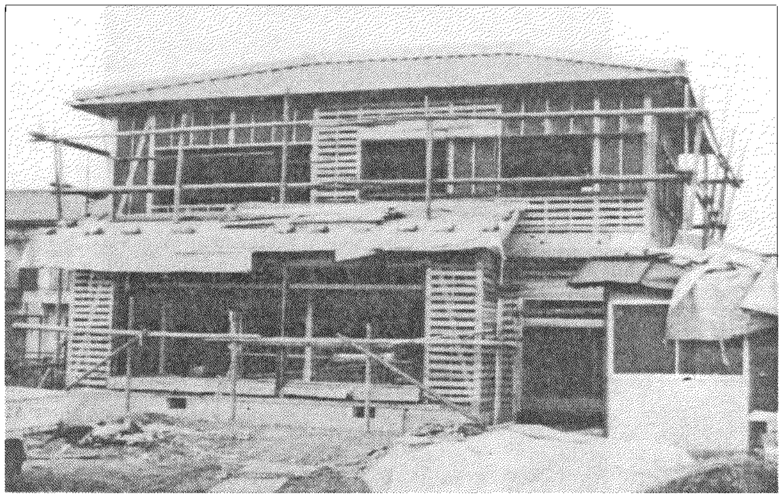

Fig. 9 Okabe type wall, prior to application of stucco.

## Seismic Damage Characteristics

In what follows, it is useful to first define several terms:

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 reported damaged 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 claimed damaged. The term Damage Ratio for Buildings Destroyed, $DR_{BDST}$, is similarly defined:

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

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 $DR_{BDST}$ (or even which earthquake, in the case of aftershocks), or 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 as defined above.

## The Miyagiken-Oki Earthquake Of 12 June 1978

Much of the following analysis is based on data from the Miyagiken-oki earthquake of June 12, 1978 which occurred at 17:14 local time, with an epicentre at 142°10' East, 38°09' North, focal depth of 40 km. and magnitude $M_l = 7.4$ (USGS $M_s = 7.5$)[7]. The earthquake and its damage have been well reported[3,4] and only certain aspects will be mentioned here. Figure 10 is a regional view showing Sendai City and its relation to the epicentre, aftershock area and regional geology. Sendai City sustained a majority of the building damage in the earthquake (e.g. 55 per cent of the destroyed buildings, 61 per cent of damaged buildings), most of which was concentrated in the softer alluvial portions of the city. Sendai is typical of most Japanese urban regions in that it is located partly on a soft alluvial plain adjacent to the sea, partly on an intermediate zone of firm uplifted older alluvium (in Japan termed diluvium), this zone continuing to hills or mountains. The distance from the epicentre to the centre 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 0.25 g. Since, for the purpose 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 5 per cent damped response spectral attenuation function[5] was made, which was modified with satisfactory results, see Figure (11). This modification has been previously reported[6] and will not be dealt with in detail here, but basically consisted of using a 'virtual epicentre' shifted towards Sendai from the epicentre of record (see Figure 10), in the attenuation function, instead of the epicentre of record.

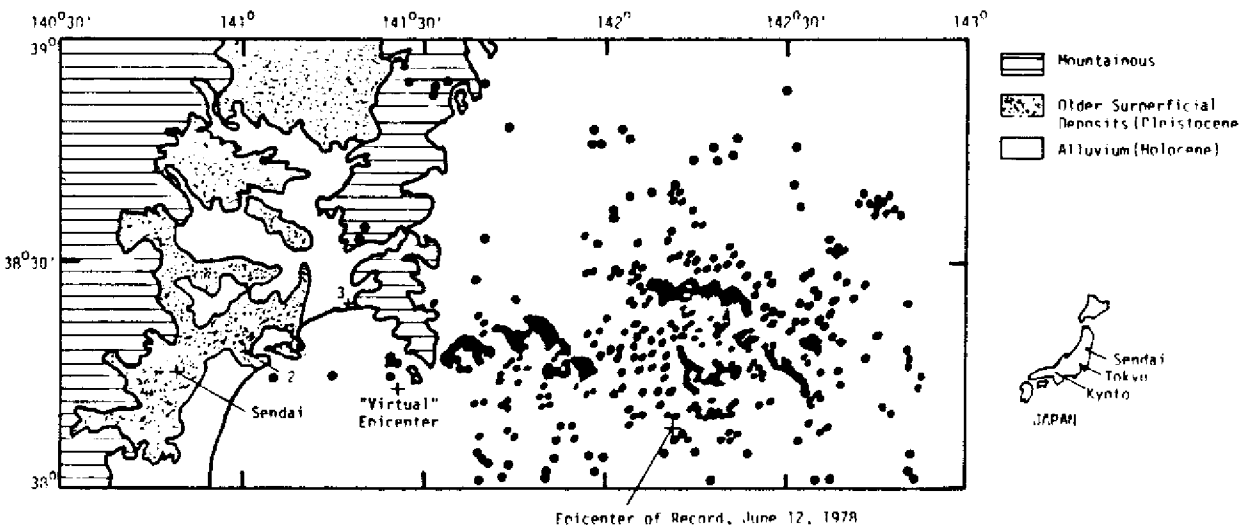


Fig 10 Regional view of Sendai, showing geology and aftershock area for period June 12 - Aug. 31, 1978.

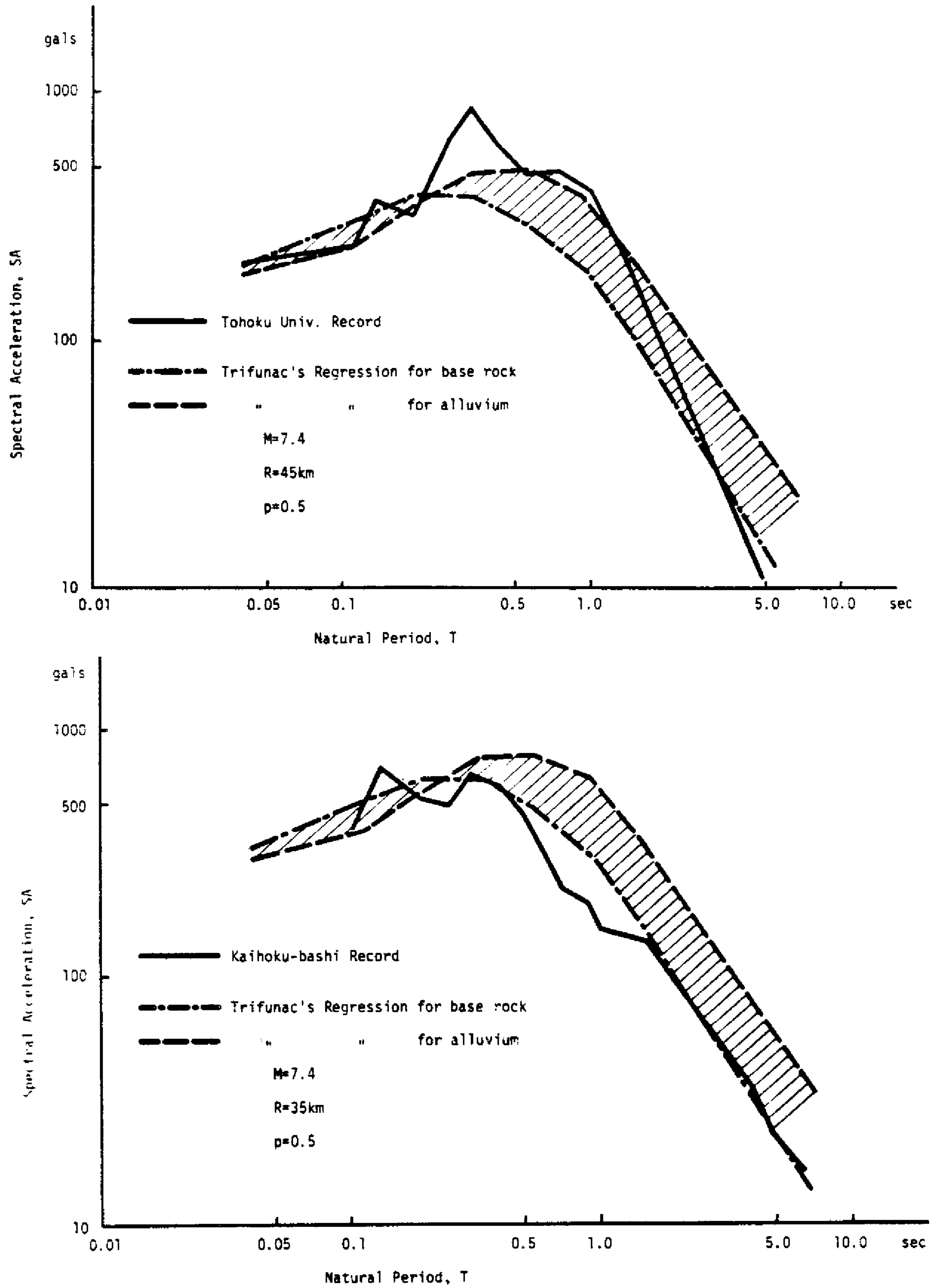


Fig 11 Response Spectra for (above) Tohoku Univ. and (below) Kaihoku bathi, compared with Trifunac's regression and 'virtual' epicentre.

This section, the statistical analysis, summarizes previous findings[6] and is included for the sake of completeness. Figure 12 is a map of Sendai showing $DR_{BDMG}$ and $DR_{BDST}$ by political subdivision experienced in the Miyagiken-oki earthquake (the political subdivisions were of sufficiently small size to be adequately categorized by a single soil type -- hard, intermediate or soft). The data in Figure 12 were regressed against the 5 percent damped spectral accelerations generated by the modified attenuation functions, described above. After examing various types of equations (linear, log-log,etc.) and different spectral acceleration periods, a correlation of log-log form for spectral accelerations 0.75 s was found to be best. These correlations are (number of observations is 17):

$$DR_{BDMG} = 1.813(SA_{0.75})^{1.744}, \quad r = 0.75, s = 0.00345 \qquad (1)$$

$$DR_{BDST} = 0.020145(SA_{0.75})^{2.525}, \quad r = 0.69, s = 0.0001 \qquad (2)$$

where $SA_{0.75}$ is the response spectral acceleration at 0.75 s (in g), r is

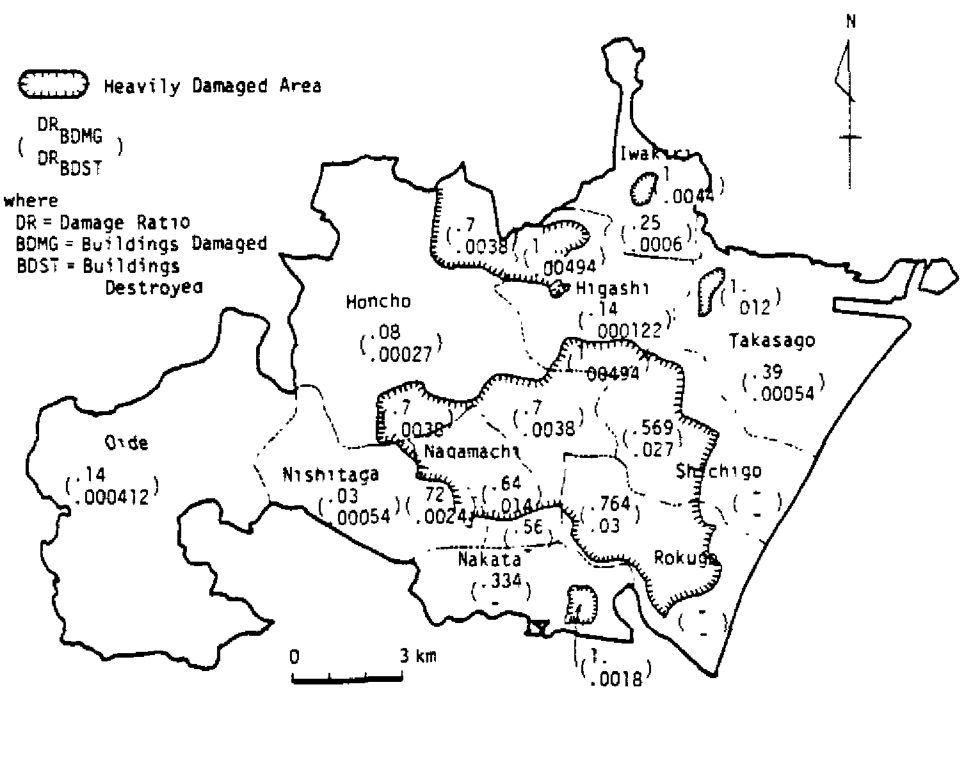


Fig 12 Sendai City political subdivisions, showing damage ratios resulting from June 12, 1978 earthquake.

the correlation coefficient and is the conditional standard deviation. Relation (1) was modified to include data from other Japanese earthquakes[7] which resulted in

$$DR_{BDMG} = 1.208(SA_{0.75})^{1.324}, \quad r = 0.69, \ s = 0.00325 \qquad (3)$$

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

$$¥ = 0.5 + 0.434 BDST + 0.0053 BDMG, \quad r = 0.998 \qquad (4)$$

where ¥ is 1978 Japanese Yen (x $10^8$). From the above relations, assuming an average value per building of $10^7$ Yen, the damage cost factor was determined[6]:

$$DCF = 0.0756(SA_{0.75})^{1.7} \qquad (5)$$

the variance of which can be approximated by

$$V_{DCF} = 0.000115 + \frac{170}{(NB)^2} \qquad (6)$$

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[6]. 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 necessary.

## Seismic Damage Model For Low-rise Buildings

Lateral resistance in the average low-rise Japanese building was discussed above and seen to derive from three elements: (1) solid walls of either shinkabe (older, bamboo lattice-mud) and/or okabe (newer, similar to stucco on lath), (2) pierced 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 the form:

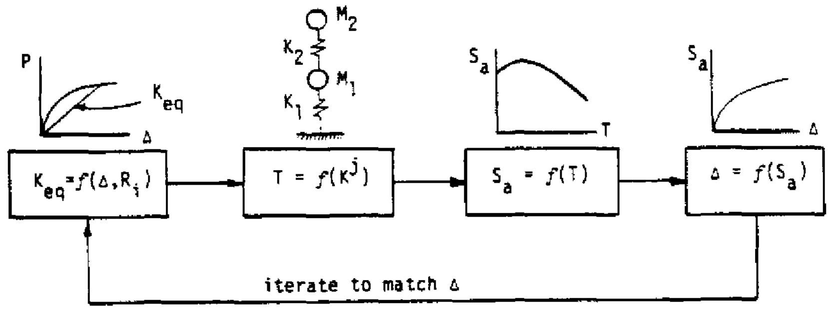


Fig. 13 Schematic representation of iterative technique used in determining natural period and displacement considering non-linear behaviour of low-rise building elements

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:

$$T_1 = 0.33\Delta^{0.335} \text{ and } T_2 = 0.55\Delta^{0.28} \qquad (10)$$

(where $T_1$ and $T_2$ are the fundamental periods of one-or two-storey buildings, respectively, determined by the iterative technique and the equivalent linear

Table II

| | Heavy Roof | | Light Roof | |
|---|---|---|---|---|
| Building | e | f | e | f |
| 1 storey | 15.6 | 1.56 | 10.6 | 1.68 |
| 2 storey | 26.7 | 1.28 | 24.2 | 1.32 |

$$P = a\Delta^b \quad \Delta \leqslant 1 \text{ cm} \tag{7a}$$

$$P = c + d\log\Delta, \Delta \geqslant 1 \text{ cm} \tag{7b}$$

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

$$K_j = \frac{1}{\Delta_j} \sum_i R_{ij} P_i \tag{8}$$

Table 1 Force-deflection characteristics for low-rise buildings
$P = a\Delta^b$, $\Delta < 1$cm
$P = c + d\log\Delta$, $\Delta \geqslant 1$cm

| | | Δ<1cm | | Δ≥1cm | | |
|---|---|---|---|---|---|---|
| Type | Specimen | a | b | c | d | $R_{ij}$ ($m/m^2$) |
| Wall: | | | | | | |
| Shinkabe | SB-6 | 37.1 | 0.70 | 36.9 | 136.0 | 0.134 |
| Okabe | OC-6 | 88.6 | 0.35 | 95.2 | 97.9 | 0.035 |
| Pierced Wall | SA-6 | 9.8 | 0.73 | 1.5 | 53.1 | 0.334 |
| Wall with bracing | OD-6 | 135.4 | 0.88 | 143.6 | 663.9 | 0.086 |

where j indicates first or second storey, i = items (1)-(3) and $R_{ij}$ is the ratio of wall length in metres per square metre of floor area. Using equation (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 storey displacement $_j$, which is then determined from the spectral acceleration and $K_j$ and thence used as the next input value in the iteration, see Figure 13. Natural periods calculated using this method were compared with published test results [10, 11] Figure 14 with good agreement. Using average $R_{ij}$ determined from standard building plans [12] shown in Table I, 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:

$$\Delta = e(SA_{0.75})^f \tag{9}$$

where e and f are given in Table II, and indicates deflections of the eave line with respect to the ground of either one- or two-storey buildings). $SA_{.075}$

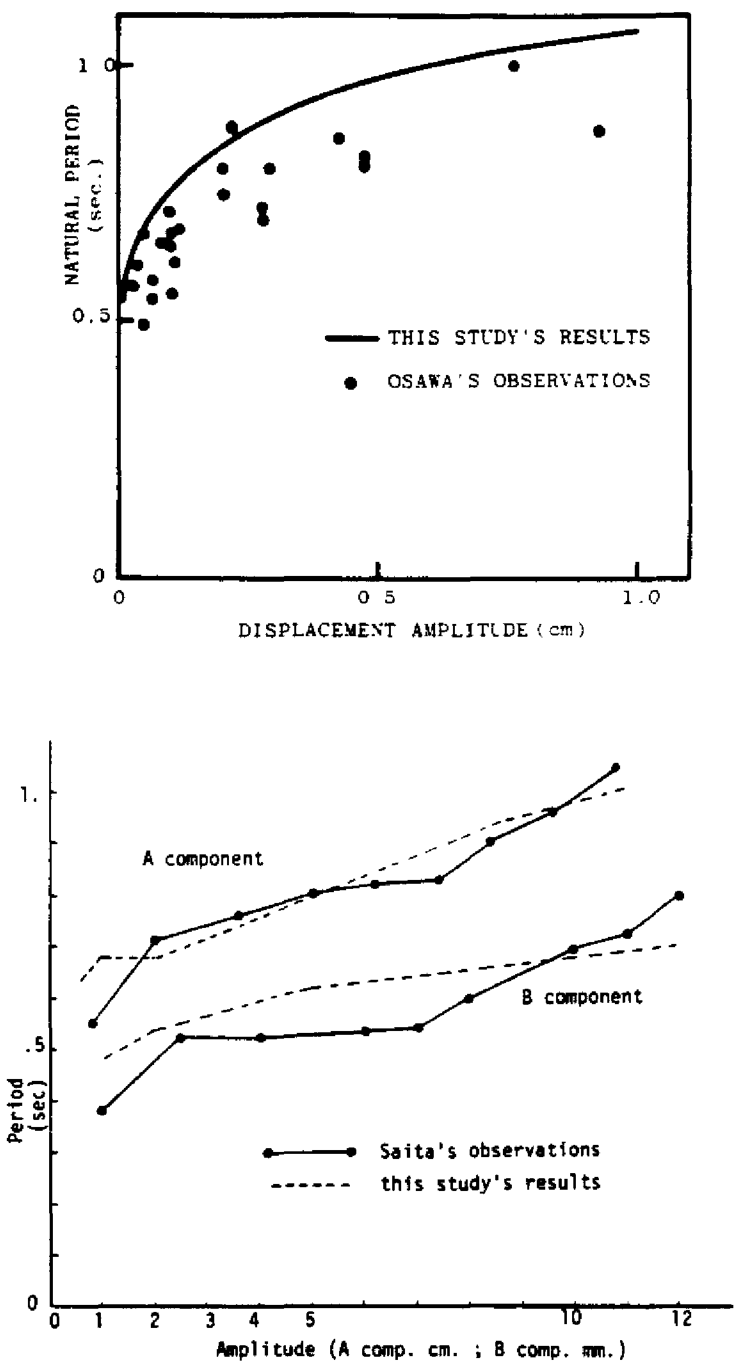


Fig. 14 Comparison of this study's results with Osawa's (above and Saita's (below) test observation of a typical low-rise buildings

stiffness, equation (8)) and Sendai experienced average $SA_{0.75} \simeq 0.45$ g, which implies average eave-line building displacements of about 9 cm (2 storey) and 3 cm (1 storey) and periods of 1.0 s (2 storey) and 0.5 s (1 storey). Since the numbers of one- and two-storey buildings in Sendai were about equal, 0.75 is nicely bracketed explaining its better correlation when compared with spectral acceleration periods of 0.32 s, 0.55 s etc. This is not to imply that 0.75 is exactly the best correlative but that response spectral accelerations around 0.75 s provide better correlations with damage than much smaller or larger periods, for Japanese low-rise buildings. Equation (10) also expresses an oft-noted fact, that the period of low-rise Japanese buildings depends on displacement, (11) which can be seen in Figure 14. By definition, the DR is that portion of the building population exceeding some damage threshold. Since the above damage model has been for an average building and equation (3) is the mean damage relation, we can say (assuming normal distribution for $\Delta$ ):

$$DR_{BDMG} = 1.208SA_{0.75}^{1.324} = 1.0 - \Phi\left[\frac{\Delta_{DMG} - \bar{\Delta}}{s_\Delta}\right] \quad (11)$$

where $\Phi$ is the cumulative distribution function of the normal distribution, $\Delta_{DMG}$ is the eave-line displacement at which damage reports commence and $\bar{\Delta}$ is the displacement as determined by equation (9). The method of least squares was used to determine $\Delta_{DMG}$ and $s_\Delta$, resulting in

$$DR_{BDMG} = 1.0 - \Phi\left[\frac{6.9 - \bar{\Delta}}{3.4}\right] \quad (12)$$

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:

$$DR_{BDST} = 1.0 - \Phi\left[\frac{66.0 - \bar{\Delta}}{21.1}\right] \quad (13)$$

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

$$DCF = 0.5\left(\frac{\Delta_1}{60}\right)^2 + 0.5\left(\frac{\Delta_2}{60}\right)^2 \quad (14)$$

(where $\Delta_1$ is the storey deflection of the first floor and $\Delta_2$ that of the second storey) gives good agreement with the previously determined statistical relation, equation (5), in the range of observed accelerations.

## Use of the Low-Rise Building Damage 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 only be about 1/3 (since doubling the bracing only doubles item (3), whereas the 'non-structural' elements, especially the walls, still contribution significantly). Scaling the Miyagiken-oki response spectra, calculations show that at moderate accelerations the number of damaged (i.e. $DR_{BDMG}$) 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 acceleration levels would be cut by about 1/3.

## Closure

The purpose of this paper has been to briefly present an overview of the situation in Japan regarding the typical construction incorporating earthen elements vis-a-vis earthquakes. After detailing the method of construction using earthen elements, the results of some researches were presented. Basically, these were the development of a building-class damage estimation, which would permit prediction of and scenario-review for damage in urban Japan, as well as providing weight into the physical behaviour of these buildings. Damage was dealt with in the form of average damage ratios, applicable to individual or groups of buildings, relating this damage to damage thresholds in terms of displacement. The correlation of low-rise building damage with response spectral acceleration in the statistical analysis section of this paper is, due to the use of average properties and natural periods for the entire low-rise building inventory, equally correlation with spectral velocity and displacement. Thus, the spectral displacement corresponding to the mean damage threshold (for $DR_{BDMG}$) can be found directly from equation (1), its value being 6.67 cm, corresponding to natural periods for one- and two-storey buildings (by equation (10)) of 0.62 and 0.94 s, respectively. The use of average properties and damage ratios for low-rise buildings is justified, we think, by the anticipated applications to urban regions where tens or hundreds of thousands of such buildings are aggregated. The data derives from the earthquake in one region, with the exception of the incorporation of other damage ratio data (for $DR_{BDMG}$) in the low-rise building section, and the results must be used with some caution due to this limitation. The analysis also relies on synthesized response spectra (based on the 'virtual epicentre' modification of Trifunac's attenuation regression) although this does not appear to be too serious drawback, based on the match obtained with the existing records. The technique of regressing damage against various structural or ground parameters has been extensively used herein. The lowest correlation coefficient determined was 0.69 for 17 observations. While this coefficients could be much higher, it satisfies at the 1 per cent confidence level the hypothesis that there exists dependence between the correlated variables.

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.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of the officials of Sendai City, who provided the damage data from the 12 June 1978 earthquake.
Mr. O Aketa's and Ms. L. Hughes' assistance with the analysis of the data and preparation of materials is also much appreciated.

## REFERENCES


1. Goto, H., and Kameda, H., "Statistical Reference of the Future EQ Ground Motion", 4th World Conf. on EQ Engineering, Santiago, Chile, pp. A-1-39 to 54 (1969).

2. H. Engel, The Japanese House, Tuttle, Tokyo (1964).

3. "Investigation of Diasters caused by the 1978 Miyagiken-oki Earthquake", Natural Hazards Special Research (1), Min. of Educ., Tokyo. 1979 (in Japanese).

4. P. Yanev, (ed), "Reconnaissance report, Miyagiken-oki earthquake, June 12, 1978", Earthquake Engg. Res. Inst., Berkeley, 1978.

5. M. D. Trifunac, et al., "Preliminary Empirical Models for Scaling Absolute Acceleration Spectra", U. Southern Calif., Dept. Civil Engg., CE 77-03, 1977.

6. C. Scawthorn, Y. Yamada and H. Iemura, "Statistical studies of low-rise Japanese building damage. The Miyagiken-oki earthquake of June 12, 1978", Proceedings of 2nd U.S. National Conference Earthquake Engineering, Earthquake Research Institute, Stanford University, 373-382, 1979.

7. - "Seismic Risk Analysis of Urban Regions", 5th Japan Earthquake Engineering Symposium, Tokyo, 1399-1406, 1978.

8. Sendai City Disaster Countermeasures Bureau, "Damage records of the Miyagiken-oki June 12, 1978", Sendai, 1978 (in Japanese). "The June 1978 Miyagiken-oki Earthquake's Building Damage Distribution and Ground Characteristics', Arch. Inst. Japan, 7th Ground and Seismic Intensity Symp., Tokyo, 1979 (in Japanese).

9. K. Takeyama, "Behaviour and design of wooden buildings subjected to earthquakes", Proc. 2nd World Conf. Earthquake Engg., 2039-2111, Tokyo, 1960.

10. Y. Osawa, et al., 'Study on the earthquake resistivity of wooden houses, Pt. I', Bull. Earthquake Research Inst., Tokyo, 45, 473-488, (1967).

11. "An Investigation of Actual Conditions of Wooden Houses in Tokyo and their Earthquake Response", Bull. Earthquake Res. Inst., Tokyo, 17, 152-167 (1939) (in Japanese).

12. Kenchiku Shiryo Kenkyusha, Plan of Two-Story Dwellings, Tokyo, 1970 (in Japanese).