SPECTRAL STORY DRIFT DEMAND ANALYSIS FOR BUILDING STRUCTURES DURING THE 1999 CHI-CHI TAIWAN EARTHQUAKE

Keh-Chyuan Tsai*, Yuan-Tao Weng, and Liu-Chyuan Chang
Department of Civil Engineering
National Taiwan University
Taipei, Taiwan 106, R.O.C.

Key Words: strength factor, drift spectra, generalized shape function, model participation factor

ABSTRACT

The 921 Chi-Chi earthquake caused a very significant number of building collapses and damage of various degrees. Many collapsed buildings had pedestrian corridors and open fronts on the ground floors. Using a modified modal participation factor and the generalized shape function computed from the nonlinear push over analysis, story drift demands imposed on soft first story building systems are studied in this paper. Generalized shape functions are constructed from the nonlinear static push over analysis of shear buildings having specific distributions of story stiffness and strength. Nonlinear response spectrum analyses were performed on the ground acceleration recorded from 51 sites located in the Taipei Basin and 62 sites in the Taichung Region. Analytical results indicate that soft first story buildings are likely to have story drift demands significantly greater than regular buildings of short fundamental period. Results of the nonlinear dynamic analysis of a 6-story structure indicate that the maximum story drift demand can be satisfactorily predicted by the story spectral drift constructed from the generalized shape functions.

I. INTRODUCTION

At 1:47a.m. of September 21, 1999, a magnitude $M_L = 7.3$ earthquake struck the central region of Taiwan. Survey data indicates that approximately 3,000 buildings totally collapsed as a result of the earthquake, with more than 10,000 others partially collapsed and countless others damaged to various degrees (ARBI, 1999). Many collapsed buildings had pedestrian corridors and open fronts on the ground floor as shown in Figs. 1 and 2, and only one wall at the back of the building along the street direction. Due to the long rainy season in Taiwan, Taiwanese developers commonly construct buildings with pedestrian corridors, and this popular style has become a local practice and is prescribed in the building codes. Thus, the pedestrian corridor buildings represent a large portion of the failed structures, and experienced different levels of damage. Fig. 1 indicates that approximately 84% of the damaged RC structures are pedestrian corridor buildings, and roughly 45% of the pedestrian corridor buildings are classified as severely damaged or worse. This type of building damage accounts for the majority of the complete building

*Correspondence addressee

Fig. 1 Collapse of a typical building having a pedestrian corridor

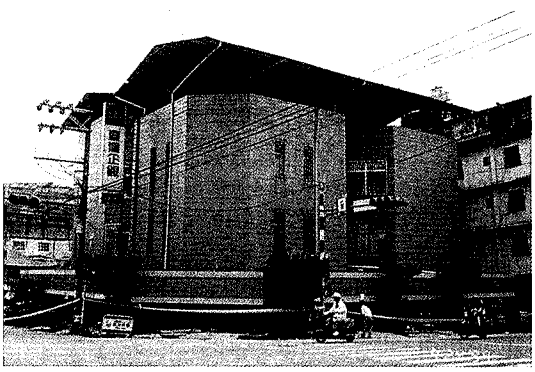

Fig. 2 Collapse of a typical building having open front

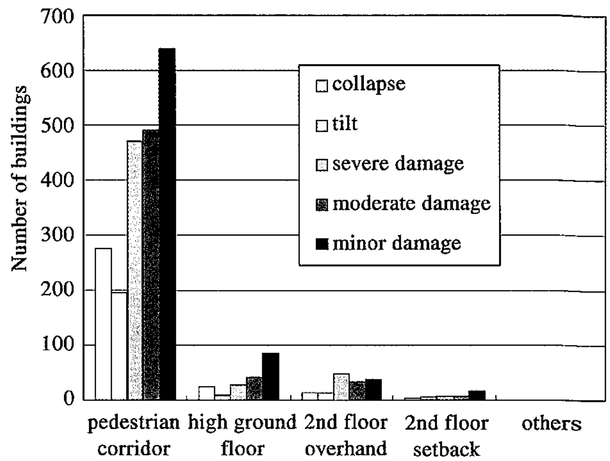

Fig. 3 Number of damaged RC structures with respect to vertical configuration

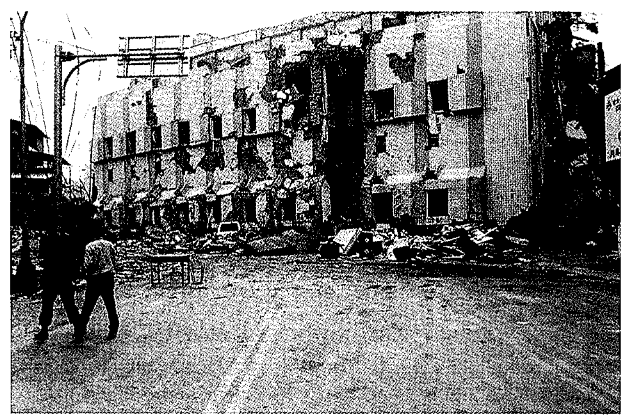

Fig. 4 Collapse of an apartment building at Fengyuan

collapses near the epicenter due to severe ground shaking (Tsai *et al.*, 2000). In the affected area, more than two dozen modern 10 to 20-story apartment buildings overturned or collapsed (Fig. 4). These were buildings with reinforced concrete moment resisting frames. Most of them were constructed with cast-in-place 15cm thick exterior walls and 12cm thick partition walls. The observed damage to reinforced concrete structures suggested a large effect in masonry and lightly reinforced concrete nonstructural components. These building were typically designed following requirements for moment resisting frames identical to the Uniform Building Code (ICBO, 1997) used in the United States, albeit generally one edition behind the latest published. Seismic force requirements of building designs in Taiwan for the past 25 years are given in Table 1. In Nantou County, where most of the damage occurred, the specified (Ministry of the Interior, R.O.C., 1974~1997) peak-ground-acceleration to consider for design was 0.23g (for a 475 years return-period earthquake), which translates into a design coefficient of approximately 0.11g for short period structures. Incidentally, that coefficient was 0.05g from 1974 to 1982, and 0.08g from 1982 to 1996, before the higher aforementioned value was adopted in 1997. Alternatively, the code permits the use of a slightly larger seismic force to size members with some relaxation on the ductile detailing of the reinforcements, following what is prescribed in the *UBC*. Many of these high-rise residential buildings that collapsed were engineered and constructed in the last decade. Many of them appear to have had tall floors and open plaza features at the ground level. In this research, the story drift demands imposed on the building systems having various strength and stiffness distributions are studied by analyzing the drift spectra constructed from the generalized shape functions.

II. RESPONSE SPECTRA ANALYSIS FOR SOFT FIRST STORY BUILDING SYSTEMS

As noted above, the extensive vulnerability of the existing building inventory, as revealed by this earthquake, must be addressed before other equally

Table 1 Seismic Force Requirements in Taiwan

Year	Seismic Base Shear	Remarks
1974	$Vw = Z\,K\,C\,W$	Z=1.25, 1.0, 0.75 K=0.67, 0.8, 1.0, 1.33 $C=0.1/0.3\sqrt{T}, C_{\max}=0.10$; $W=D+0.25L$
1982	$Vw = Z\,K\,C\,I\,W$	Z=1.0, 0.8, 0.6 K=0.67, 0.8, 1.0, 1.33 I=1.0, 1.25, 1.5; $C=1/8\sqrt{T}$, $C_{\max}=0.15$; $W=D$
1989	$Vw = Z\,K\,C\,I\,W$	Same as 1982, except $C=0.248/T$ for Taipei Basin; $C=1/8\sqrt{T}$ elsewhere
1997	$V = \dfrac{Z\,I\,C\,W}{1.4\,\alpha_y F_u}$	Z=0.33, 0.28, 0.23, 0.18 I=1.0, 1.25, 1.5; $C_{\max}=2.5$; $W=D$ $\alpha_y=1.2$ (WSD), $\alpha_y=1.5$ (USD); $F_u \approx 2.9, 2.5, 2.1$

destructive earthquakes strike again in the country. Particular attention is paid to buildings having soft stories and open fronts. In order to gain insights into the seismic demands imposed on the building structures during the main shocks of the Chi-Chi earthquake, elastic and inelastic response spectra are constructed and studied extensively for various regions island wide (Tsai *et al.*, 2001). In particular, this paper discusses the spectral responses for soft first story building systems using the free-field ground motion records obtained in the *EW* direction from 51 and 62 sites in the Taipei Basin and the Taichung Region.

III. RECORDED GROUND MOTIONS IN THE TAIPEI BASIN AND THE TAICHUNG REGION

Figure 5 shows the shake contour map for the Chi-Chi earthquake using the geometric mean of two horizontal PGA values. Taipei Basin is about 180km north of the epicenter, the recorded peak ground accelerations (PGAs) in the east west direction (greater than the ones in NS direction) range between 50 and 140 gal. The corresponding averages and the COVs of elastic acceleration spectra S_a for 2, 5 and 10 percent damped SDOF systems are given in Fig. 6. Original un-scaled ground motion records have been used in finding various response spectra. In order to show the effects of the variation of these ground accelerations on the spectral accelerations of the SDOF system having a specific period, the coefficients of variation (COV) spectra of the S_a were computed. This COV is defined as the standard deviation of S_a divided by the mean of S_a for specific SDOF system considering the given ground motion samples. It is evident that the effects of the variations of these ground accelerations, even within the same geographical region, on the structural responses are rather significant. It is important to keep this in mind in interpreting the analytical results and casting the predicted mean values onto the actual responses of the damage structures. It is found that the average of 51 PGAs is about 72gal but the variations of the S_a are rather significant, especially for the intermediate and long period systems. It should be noted that the

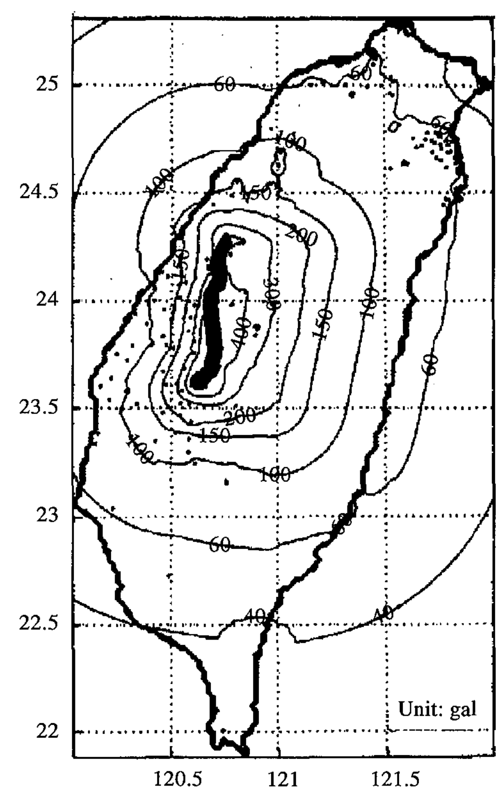

Fig. 5 Shake contour map for the Chi-Chi earthquake (using geometric mean of both two horizontal components, adopted by Central Weather Bureau in 1999)

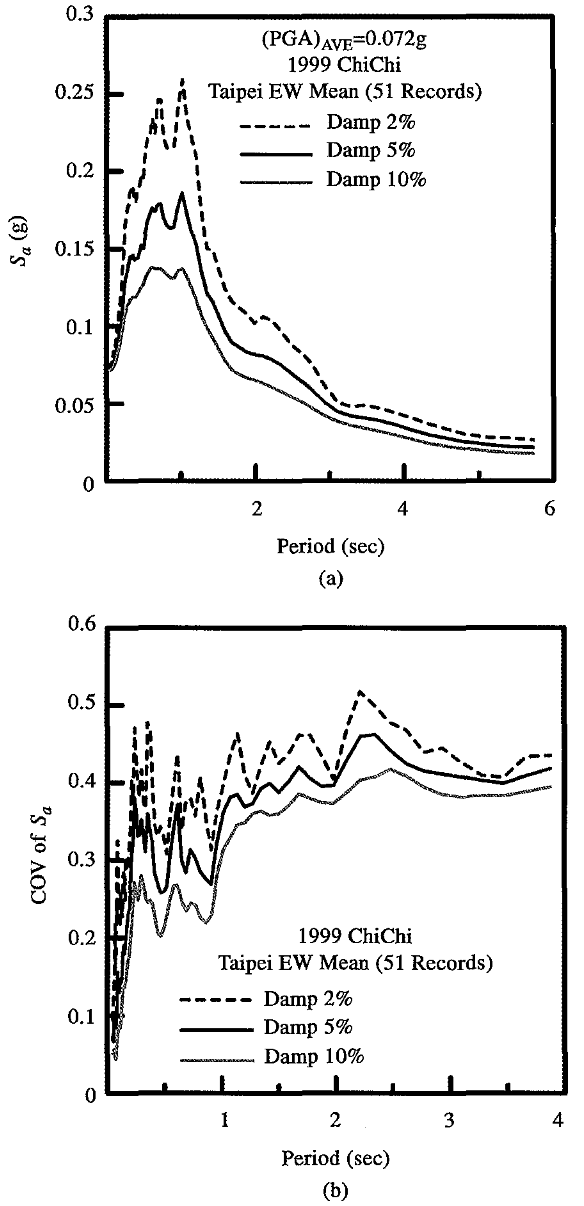

Fig. 6 Averaged elastic acceleration response spectra and COVs computed for 51 stations in the Taipei Region

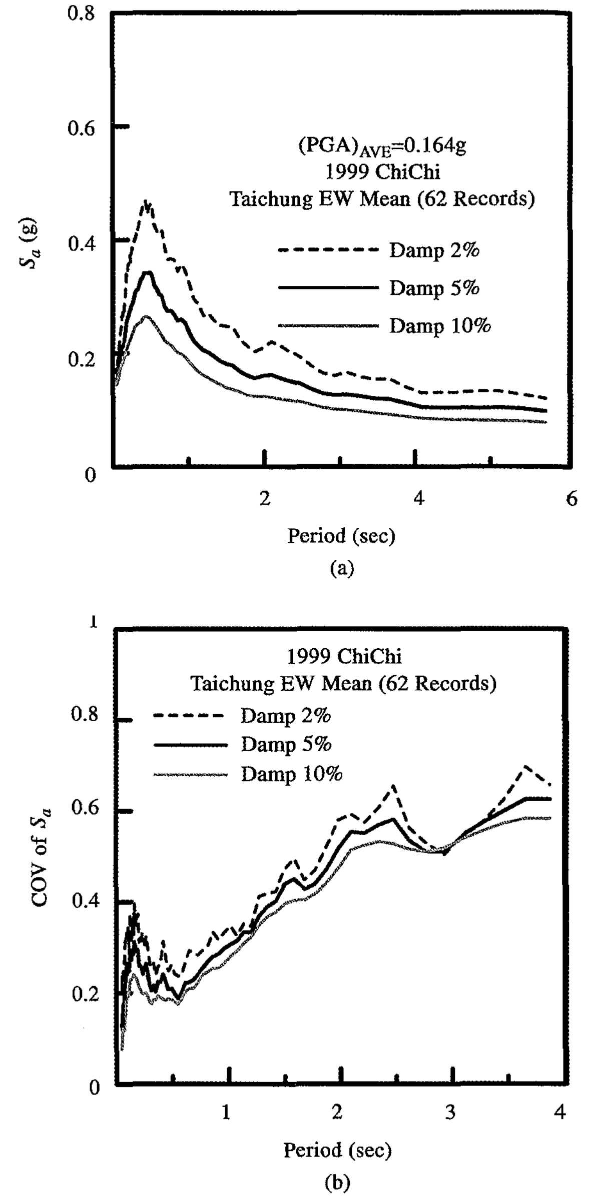

Fig. 7 Averaged elastic acceleration response spectra and COVs computed for 62 stations in the Taichung Region

duration of the strong shaking due to the September 21, 1999 Chi-Chi earthquake experienced in the Taipei region was over 40 seconds due to both seismological and geological reasons (Tsai and Huang, 2000; Lee and Loh, 1999). For the Taichung region, 62 free field ground motion records were chosen for this study. The epicentral distances of these 62 sites range from about 20km to 50km. The average of the 62 PGAs in EW direction is about 164gal. Their averaged acceleration response spectra and the COVs are shown in Fig. 7. Some reinforced concrete buildings located in Taipei and many in the Taichung region suffered damage of various degrees, ranging from cracks in in-fill partitions or external window walls, to collapse of ground floor or overturn of entire multi-story buildings. The effects of near field ground motions recorded at another eighteen sites are presented in a separate study (Weng and Tsai, 2000).

IV. SEISMIC FORCE REQUIREMENTS AND INELASTIC RESPONSE SPECTRA

As shown in Table 1, there have been four major editions of seismic building codes adopted during the past 25 years. In general, seismic design forces increased as newer versions of the building code were

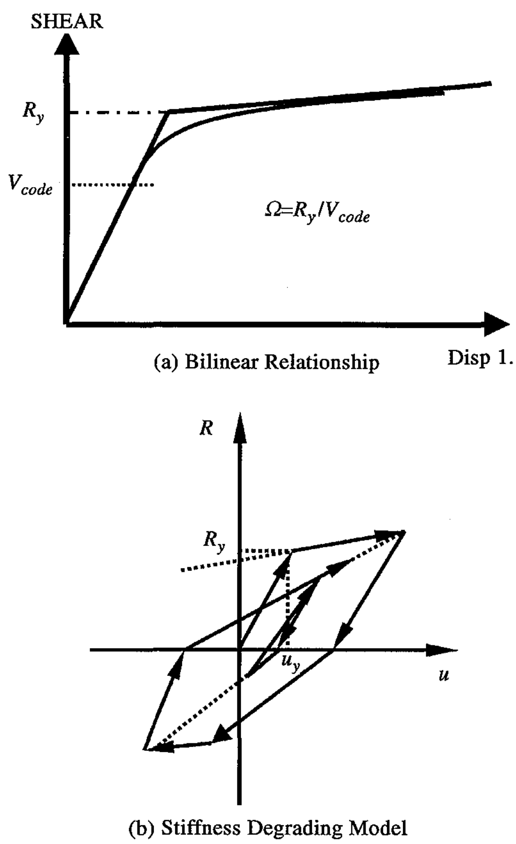

Fig. 8 Lateral force versus displacement relationship

adopted. Due to a large number of buildings constructed during the 80s and the early 90s, it is believed that a significant number of buildings were designed based on the 1982 and 1989 seismic building codes. Therefore, elastic and inelastic response spectra were critically assessed for regular and soft first story building systems designed and constructed using the 1982 and 1989 seismic force requirements. Using Z=0.8, I=1.0 and K=1.0, the design base shear is V_{code}=0.8CW, where C varies as given in Table 1. As the ultimate strength method has been widely adopted, the governing load combination involving the seismic force is Q=0.75(1.4D+1.7L+1.87EQ). When the strength factor is governed by flexural yielding of the beam members (i.e. $\Phi M_n=0.9M_n$), as in the case of strong column weak beam design, then the yield strength of the system, $R_y=\Omega\ V_{code}$, can be characterized with a strength factor Ω=0.75×1.87/0.9=1.55. Thus, a properly designed reinforced concrete structure generally possesses a lateral yield strength of at least about 1.50 times the code prescribed seismic base shear. An idealized bilinear base shear versus roof displacement relationship showing the Ω ratio of yielding strength R_y and V_{code} is schematically given in Fig. 5a. Figs. 9a and 10a show the spectral yield strength of building systems constructed in the Taipei and Taichung Regions, respectively, in terms of system weight based on the 1982 seismic force requirements for five different Ω values. An Ω value of 3.0 or 4.5 represents a conservative or very strong system, while an Ω value of 0.75 or 0.5 can be viewed as a substandard structure, due to poor workmanship or low concrete strength. Using Ω as the key parameter, the displacement spectra for 5% damped systems with elasto-plastic and cyclically degrading force-deformation characteristics (Mahin and Lin,1983) given in Fig. 5b are shown in Figs. 9b and 10b for the Taipei and Taichung Regions, respectively. These averaged spectra were constructed using the responses computed for the main shocks recorded in the EW direction from 51 and 62

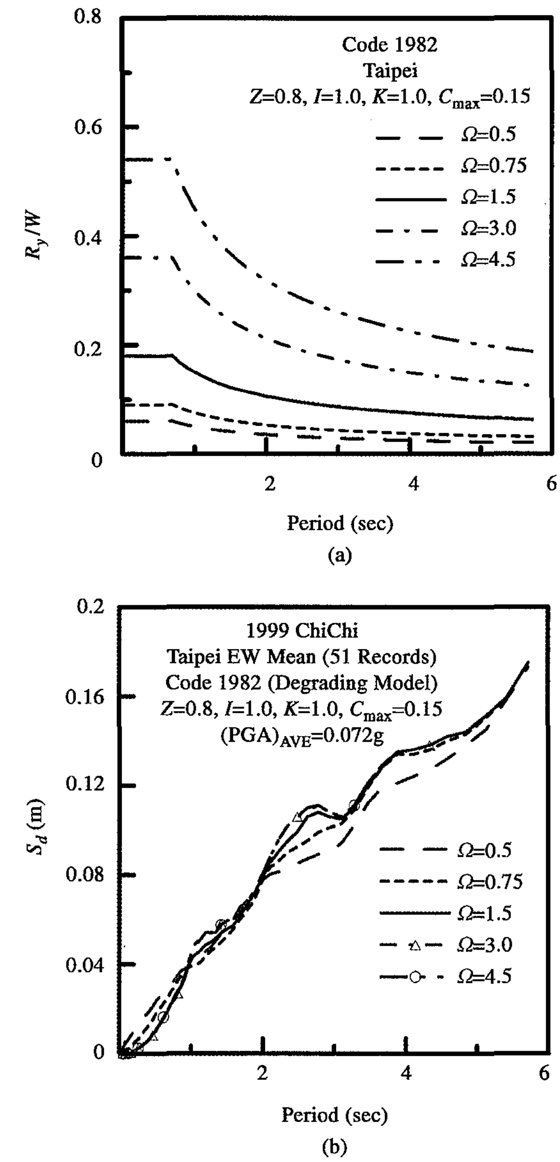

Fig. 9 Spectral Yield capacities and the corresponding inelastic displacement spectra for the Taipei Region

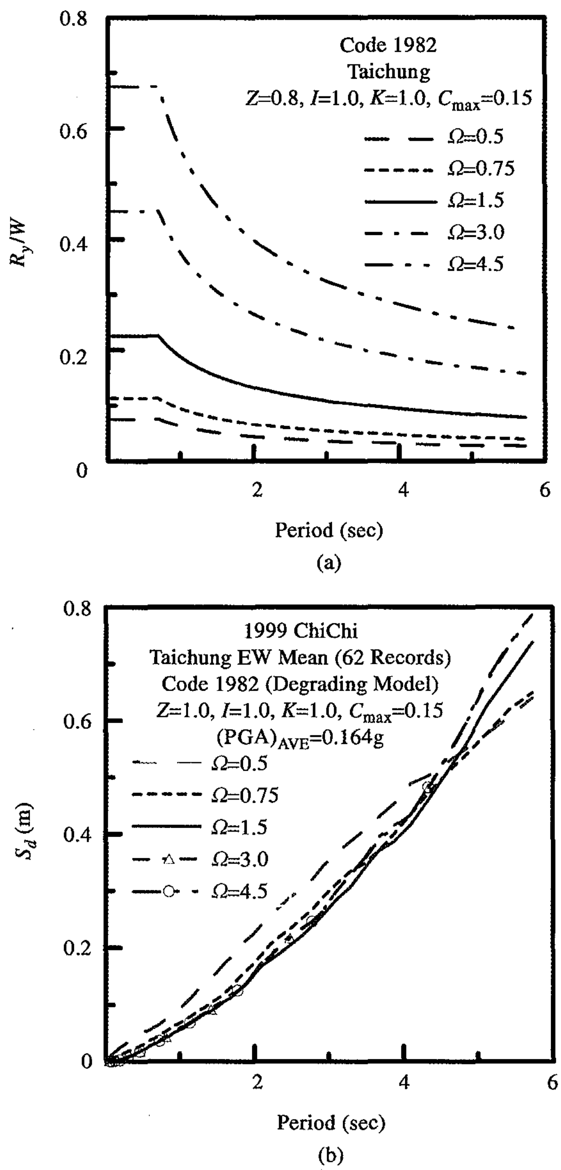

Fig. 10 Spectral yield capacities and the corresponding inelastic displacement spectra for the Taichung Region

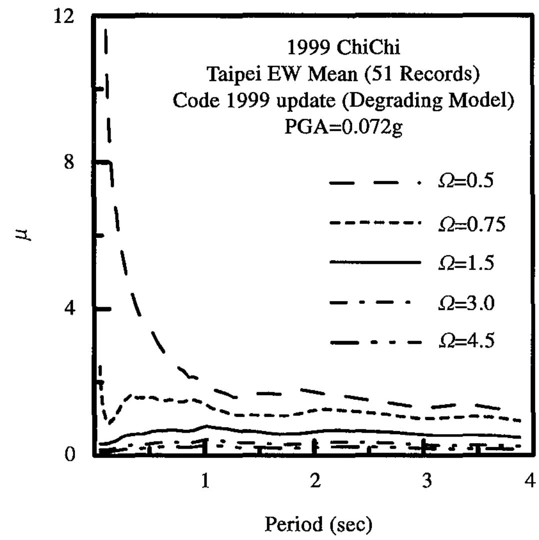

Fig. 11 Ductility demand spectra for the Taipei Region

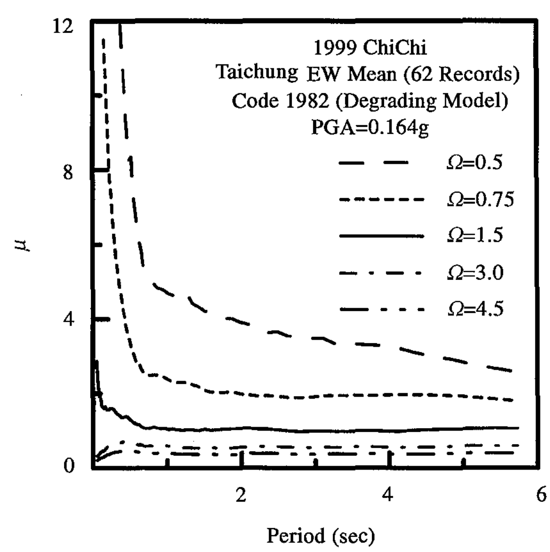

Fig. 12 Ductility demand spectra for the Taichung Region

sites for the Taipei and Taichung Regions, respectively. For substandard structures (Ω values smaller than 1.5) designed by using the 1982 seismic force requirements, the ductility demands imposed by the Chi-Chi earthquakes can be significantly greater than 4.0 as shown in Figs. 11 and 12 for short period structures in Taipei and Taichung Regions. As shown in Table 2, the Fu factor is a function of the prescribed structural ductility capacities ranging from 1.6 to 4.8 for various structural systems. Fig. 13 compares the force reduction factors derived from the spectral force response ratios and that prescribed in the Taiwan building code. In Fig. 13, the curves of R_μ are constructed by dividing the elastic shear demand (μ=1.0) of each SDOF system by the inelastic shear demand of the SDOF having the same vibration period and a specific ductility demand (μ=2.0 or 4.0). The shaded margins in Fig. 13 indicate that Fu values in the Taipei and Taichung regions are larger than R_μ for certain short period ranges. This somewhat suggests that some of the code prescribed force reduction factors, Fu, may be too large to control the ductility demand in these ranges of buildings.

V. STORY DRIFT DEMANDS IMPOSED ON MDOF BUILDING SYSTEMS

In order to compute inelastic deformation

Table 2 List of the normalized spectra acceleration coefficient C and structural seismic force reduction factor Fu for hard rock site (1999)

T	Shortest	Shorte	Short	Medium	Long
C	$T \leq 0.03$ sec $C=1.0$	$0.03 \leq T \leq 0.15$ sec $C=12.5T+0.625$	$0.15\text{sec} \leq T \leq$ 0.333 sec $C=12.5T+0.625$	$0.333\text{sec} \leq T \leq 1.315$ sec $C=1.2T^{2/3}$	$1.315\text{sec} \leq T$ $C=1.0$
Fu	$T \leq 0.03$ sec $Fu=1.0$	0.03 sec$\leq T \leq 0.15$ sec $Fu=\sqrt{2R_a-1}$ $+(\sqrt{2R_a-1}-1)(T-0.15)/0.12$	$0.15\text{sec} \leq T \leq$ 0.242 sec $Fu=\sqrt{2R_a-1}$	0.242 sec$\leq T \leq 0.333$ sec $Fu=\sqrt{2R_a-1}$ $+(Ra-\sqrt{2R_a-1})(T-0.242)/0.091$	$0.333\text{sec} \leq T$ $Fu=R_a$

$R_a=1+(\mu-1)/2$, $\mu=1.6$ to 4.8

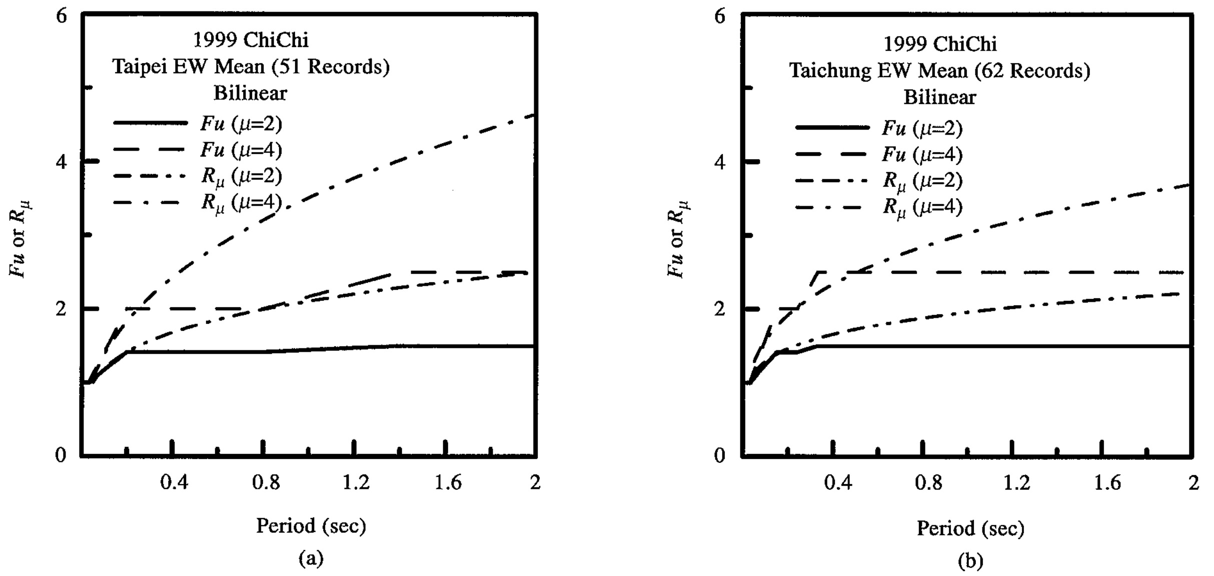

Fig. 13 Comparing Fu with R_μ for the Taipei Basin and the Taichung Region

demands imposed on the building structures, simplified analytical procedures have been proposed by many researchers (Krawinkler and Seneviratna, 1996; Fajfar, 1999) and given in model seismic design specifications (ATC, 1996; BSSC, 1997). The "capacity spectrum method" assumes an MDOF system responds essentially in the first mode. It incorporates results of the push over analysis into the nonlinear spectral acceleration versus spectral displacement curve in order to find the peak lateral floor displacements of an MDOF building system. Following the same logic (Fajfar and Fischinger, 1987), in this research it is assumed that the building maximum lateral displacement demands imposed by the earthquake can be estimated by multiplying the inelastic spectral displacement S_d of a specific elasto-plastic SDOF, a modified first mode participation factor Γ_1 and a participation factor-consistent deformed shape function $\phi_1(y)$. That is, the peak lateral displacement $u_1(y)$ along the height of the MDOF system, and its spectral first story drift angle θ_1 can be computed from:

$$u_1(y)=S_d \cdot \Gamma_1 \cdot \phi_1(y) \tag{1}$$

$$\theta_1=S_d \cdot \Gamma_1 \cdot \phi_1(h_1)/h_1 \tag{2}$$

where the modified first modal participation factor is computed from the same shape function $\phi_1(y)$:

$$\Gamma_1=\frac{\Sigma m_i \phi_{i1}}{\Sigma m_i \phi_{i1}^2} \tag{3}$$

For a shape similar to the first mode of an MDOF system having uniform mass distribution along the height, it is evident in Eq. (3) that the value of Γ_1 is always greater than 1.0. The computation of the shape functions and the accuracy of the proposed method in estimating the nonlinear story drift demands for soft or weak story building systems are presented in the following sections.

VI. GENERALIZED VERTICALLY REGULAR AND IRREGULAR BUILDING SYSTEMS

It is noted that many of the severely damaged buildings appear to have tall floors and open plaza features at the ground level. It is found from the modal analyses that the fundamental mode shapes, for the regular buildings can be approximated by an inverted triangle having a linear shape function while for the soft first story building, it can be characterized by a bi-linear shape function (Tsai *et al.*, 2000b). In this paper, using an iterative procedure, the shape functions computed from nonlinear push over analysis of inelastic frame models are adopted. The effects of the vertical irregularity on the first mode shapes were investigated by constructing 2- to 20-story inelastic building models. It is assumed that:

1. the mass distribution over the building height is uniform and the vertical distribution of the design lateral forces is an inverted triangle;
2. the ground floor height is 4 meters and typical floor height is 3 meters;
3. the lateral stiffness distribution for a regular building is approximately uniform over the full height;
4. the definition of soft story and weak story follows those given for the irregular buildings in the model building codes (ICBO, 1997; Ministry of Interior, R.O.C., 1982~1997). A soft first story building is a building where the lateral stiffness ratio, R_{soft} between the first and the second story is smaller than 0.8. Likewise, a weak first story building is one where the ratio of the yield strength to the design shear ratio between the first and the second floor, R_{weak} is smaller than 0.8.
5. if H_n is the building height (in meters), the fundamental period, T (in seconds) of the building follows (Ministry of Interior, R.O.C., 1982~1997):

$$T=0.07(H_n)^{3/4} \tag{4}$$

VII. DRIFT SPECTRA INCORPORATING THE GENERALIZED SHAPE FUNCTIONS

The story drift spectra for regular or irregular building systems were constructed using the following procedures:

1. assume the buildings range from 2- to 20-story with the floor-to-floor height noted above
2. compute the fundamental period from Eq. (4) for a given building height, find the corresponding spectral displacement S_d for a specific Ω value from results like those shown Figs. 9b or 10b
3. predict a modal participation factor Γ', a value of about 1.3 is a good starting point
4. construct an inelastic structural model having the same fundamental period, story and building heights as that given in step 2, but with a specific set of R_{soft} and R_{weak} values
5. perform a nonlinear pushover analysis until the roof displacement of the structure reaches $\Gamma' \times S_d$, obtain the maximum structural lateral displacement pattern, set the normalized structural lateral deformation shape as the fundamental deformed shape function,
6. compute the corrected participation factor from Eq. (3) using the shape function obtained in step 5
7. repeat steps 3 through 6 until the corrected participation factor converges to a specified tolerance, set the final deformed shape as the participation factor-consistent shape function
8. repeat steps 2 through 7 for the range of building heights interested

It is found that the story drift spectra can then be conveniently and satisfactorily constructed from Eq. (2), if the regression analysis is performed on the shape functions for the whole range of building heights having a specific set of R_{soft} and R_{weak} values. The specification of the story mass in step 4 is required only when a dynamic analysis of the MDOF system is desired. The modified participation factor spectra computed for regular and irregular buildings are shown in Fig. 14. These are computed from the participation factor-consistent deformations given in Table 3. It is noted that the modal participation factors for regular and soft story buildings are quite different. For regular buildings, it is about 1.5 regardless of the height of the building. The modified first mode participation factor of the soft first story cases is generally smaller than that of regular buildings of the same height or period, but approaching 1. 5 as building height increases. However, the proposed method failed to differentiate regular systems from irregular systems having the strength irregularity of R_{weak}=0.8 alone (no soft story) on the participation factor. This is because both systems yield at the same level of lateral loads for a given system Ω value, and reach essentially the same lateral displacement. It is found in Fig. 14 that the effects of irregularity indices, R_{soft} and R_{weak}, in reducing the value of the participation factors are more pronounced in the systems having a lower strength factor Ω. Using the ground motion records noted previously, the mean and the corresponding mean plus one standard deviation (1.0σ) of the first story drift spectra are computed and shown in Figs. 15 and 16 for the Taipei and Taichung Regions, respectively. Similarly, Fig. 17 shows the averaged first story drift spectra for the R_{soft} and R_{weak} values equal to 0.7 or 0.9. The flow chart for constructing the generalized shaped functions is given in Fig. 18.

Table 3 Generalized first and top story drift angles, θ_1 and θ_{TOP} for various Ω, R_{soft} and R_{weak} values (Taipei Region)

$K_1/K_2=R_{soft}$	$R_1/R_2=R_{weak}$	Ω	generalized ground floor drift angle θ_1	generalized top floor drift angle θ_{TOP}
1.0	1.0	0.5	$\theta_1=2.31T^{0.401}$	$\theta_{TOP}=0.180T^{-1.01}$
0.7	0.7	0.5	$\theta_1=4.69T^{0.748}$	$\theta_{TOP}=0.112T^{-0.530}$
0.7	1.0	0.5	$\theta_1=3.14T^{0.609}$	$\theta_{TOP}=0.157T^{-0.898}$
1.0	0.7	0.5	$\theta_1=4.03T^{0.667}$	$\theta_{TOP}=0.134T^{-0.725}$
0.8	0.8	0.5	$\theta_1=4.25T^{0.798}$	$\theta_{TOP}=0.131T^{-0.840}$
0.8	1.0	0.5	$\theta_1=2.82T^{0.534}$	$\theta_{TOP}=0.166T^{-0.946}$
1.0	0.8	0.5	$\theta_1=3.77T^{0.754}$	$\theta_{TOP}=0.146T^{-0.919}$
0.9	0.9	0.5	$\theta_1=3.50T^{0.781}$	$\theta_{TOP}=0.153T^{-0.997}$
0.9	1.0	0.5	$\theta_1=2.54T^{0.463}$	$\theta_{TOP}=0.174T^{-0.978}$
1.0	0.9	0.5	$\theta_1=3.24T^{0.739}$	$\theta_{TOP}=0.160T^{-1.018}$
1.0	1.0	1.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.930}$
0.7	0.7	1.5	$\theta_1=2.65T^{0.419}$	$\theta_{TOP}=0.181T^{-0.797}$
0.7	1.0	1.5	$\theta_1=2.65T^{0.419}$	$\theta_{TOP}=0.181T^{-0.797}$
1.0	0.7	1.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.930}$
0.8	0.8	1.5	$\theta_1=2.42T^{0.366}$	$\theta_{TOP}=0.189T^{-0.846}$
0.8	1.0	1.5	$\theta_1=2.42T^{0.366}$	$\theta_{TOP}=0.189T^{-0.846}$
1.0	0.8	1.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.930}$
0.9	0.9	1.5	$\theta_1=2.22T^{0.320}$	$\theta_{TOP}=0.196T^{-0.887}$
0.9	1.0	1.5	$\theta_1=2.22T^{0.320}$	$\theta_{TOP}=0.196T^{-0.887}$
1.0	0.9	1.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.930}$
1.0	1.0	4.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.928}$
0.7	0.7	4.5	$\theta_1=2.65T^{0.419}$	$\theta_{TOP}=0.181T^{-0.798}$
0.7	1.0	4.5	$\theta_1=2.65T^{0.419}$	$\theta_{TOP}=0.181T^{-0.798}$
1.0	0.7	4.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.928}$
0.8	0.8	4.5	$\theta_1=2.42T^{0.366}$	$\theta_{TOP}=0.189T^{-0.849}$
0.8	1.0	4.5	$\theta_1=2.42T^{0.366}$	$\theta_{TOP}=0.189T^{-0.849}$
1.0	0.8	4.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.928}$
0.9	0.9	4.5	$\theta_1=2.22T^{0.320}$	$\theta_{TOP}=0.196T^{-0.888}$
0.9	1.0	4.5	$\theta_1=2.22T^{0.320}$	$\theta_{TOP}=0.196T^{-0.888}$
1.0	0.9	4.5	$\theta_1=2.05T^{0.280}$	$\theta_{TOP}=0.201T^{-0.928}$

VIII. ACCURACY ASSESSMENTS

In order to examine the accuracy of the proposed method in predicting the maximum seismic responses of the MDOF building systems, dynamic analyses were performed on a 6-story structure. The overall height of the structure is 19m and the corresponding first mode period is 0.637 sec. The story mass, the typical story and the first story stiffnesses for the 6-story structure of various irregularities are given in Table 4. Using the TAP017 *EW* direction ground accelerations (PGA=0.11g), the maximum roof and ground floor displacements and the first story drift angle computed from nonlinear dynamic analyses using the *DRAIN2D+* (Tsai and Li, 1994) computer program, with bilinear but non-degrading elements, are given in Table 5. The modified modal participation factors, the shape functions and the lateral displacements computed from the proposed method are given in Table 6. In the table, the discrepancies of the first story drifts computed from these two methods are also shown. It is found that the error is less than 10% for the regular model and the case of R_{weak}=0.8 studied, but the error for the case of R_{weak}=0.8 is 36.55% and that for R_{soft}=0.8, R_{weak}=0.8 is 35.09%. In Fig. 19, the maximum first story drifts obtained from the nonlinear dynamic frame analysis using just the *TAP*017(*EW* direction) record are compared with the spectral responses incorporating the generalized shape functions. In Fig. 20, the averaged maximum first story drifts computed from frame analyses are compared with the averaged spectral responses for 51 sites in Taipei region. It can be seen in Fig. 20 that the first story drift spectra computed from the generalized shape functions give conservative and satisfactory results for the 6-story structure

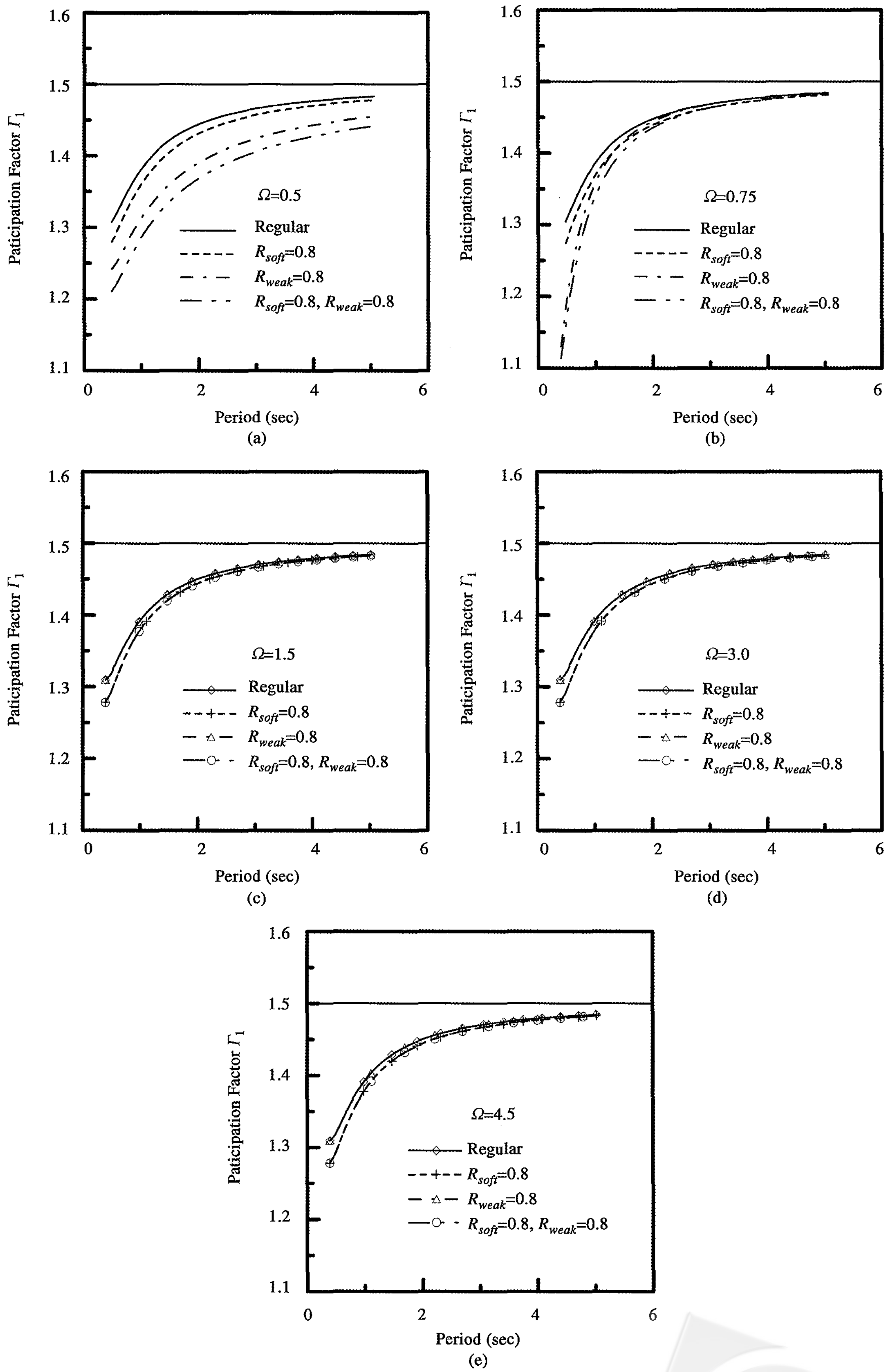

Fig. 14 Modified modal participation factors for systems having various vertical irregularities and spectral yield capacities in the Taipei Region

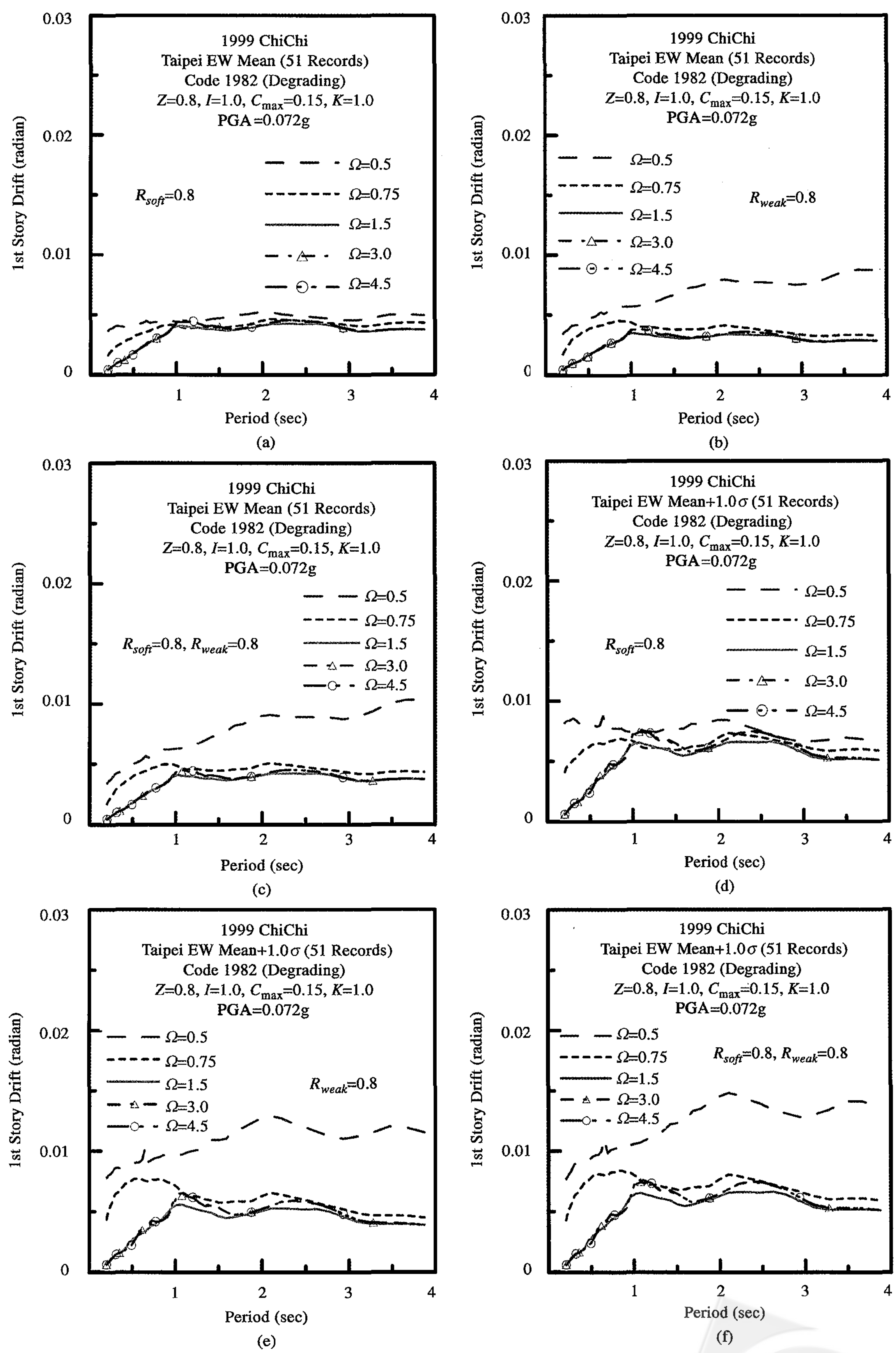

Fig. 15 The mean and mean plus one standard deviation (1.0σ) of the first story drift spectra for irregular buildings with the R_{soft} and R_{weak} values equal to 0.8 in the Taipei Region

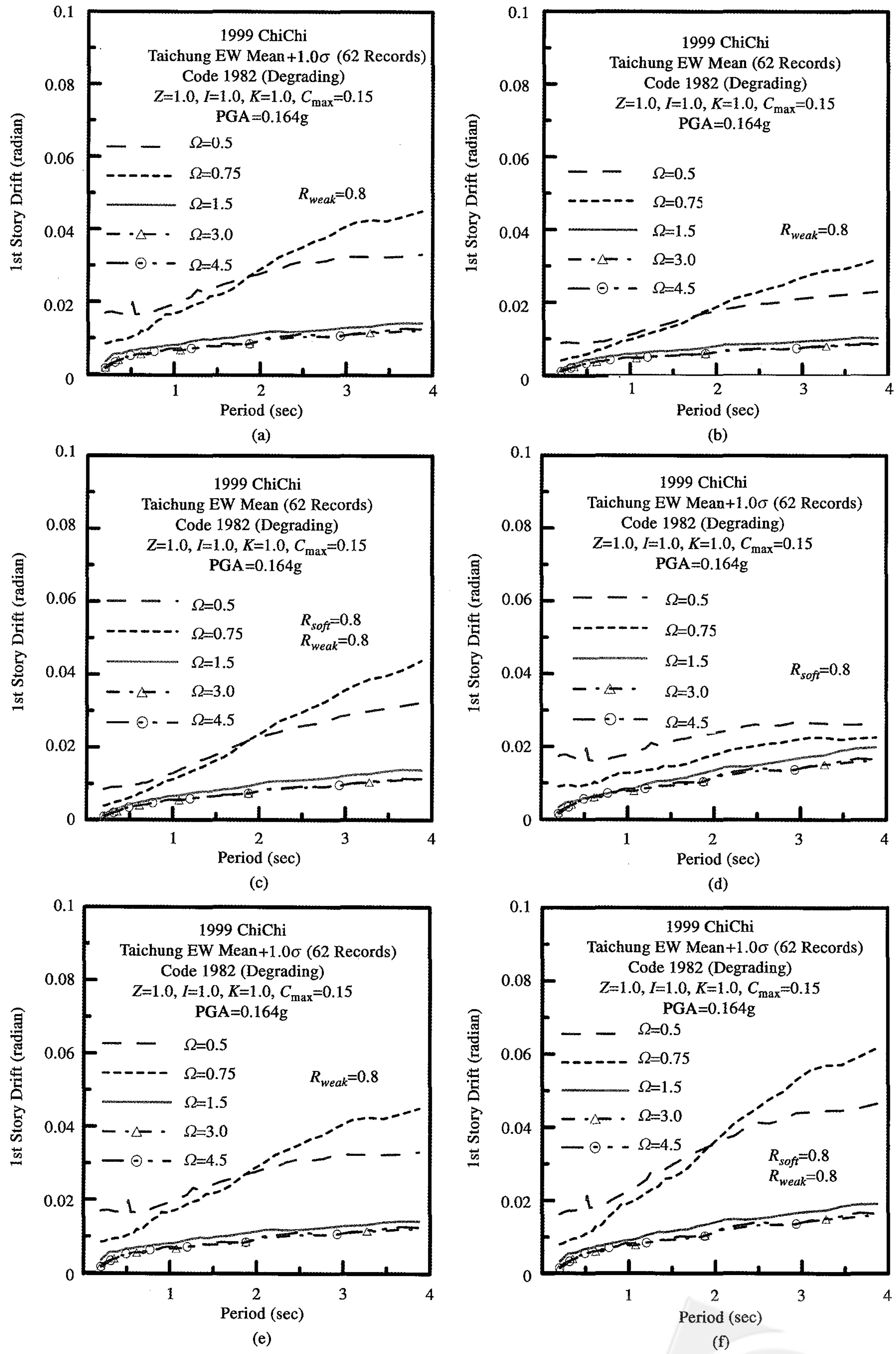

Fig. 16 The mean and mean plus one standard deviation (1.0σ) of the first story drift spectra for irregular buildings with the R_{soft} and R_{weak} values equal to 0.8 in the Taichung Region

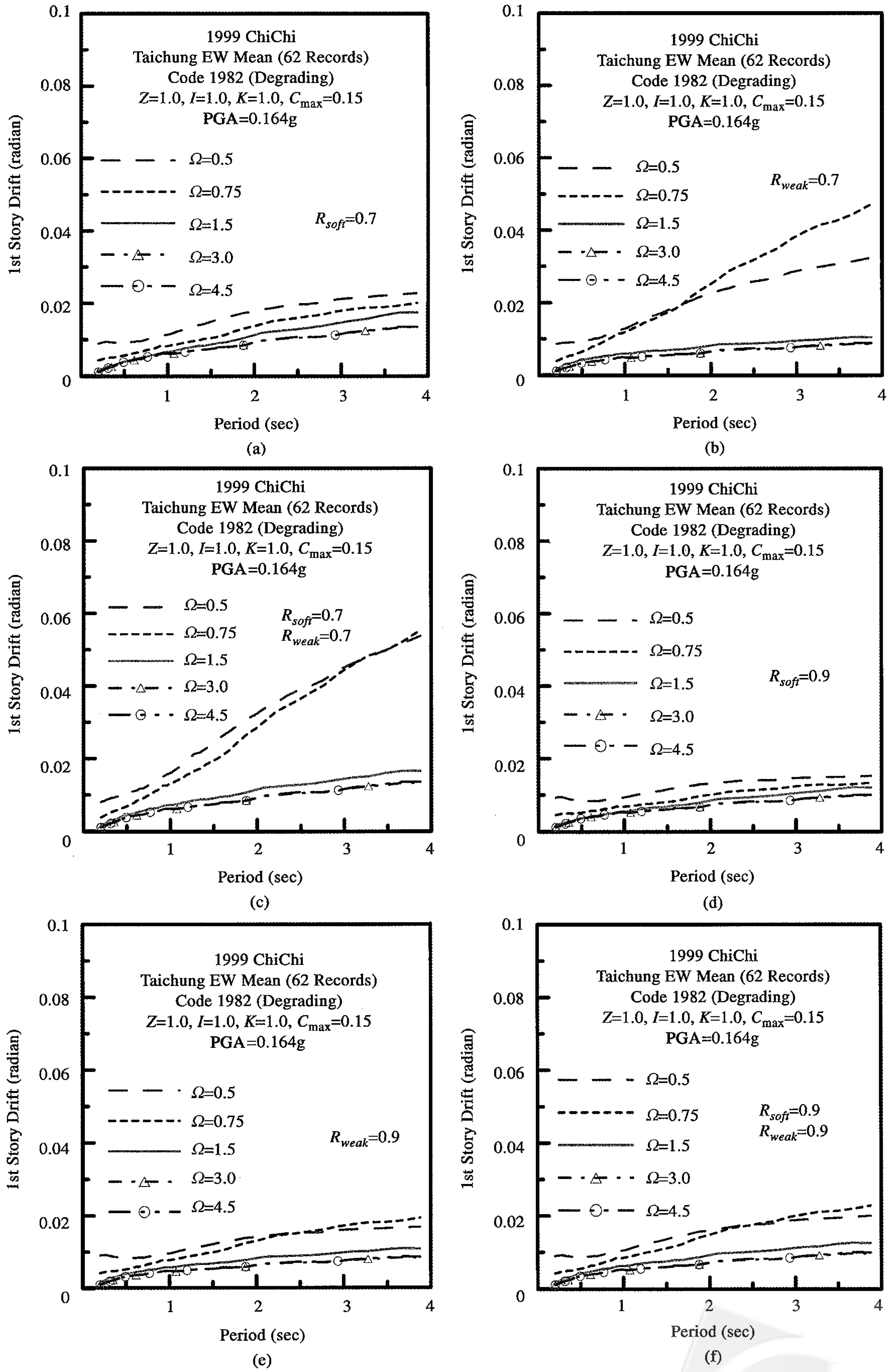

Fig. 17 Averaged first story drift spectra for irregular buildings with the R_{soft} and R_{weak} value is equal to 0.7 or 0.9 in the Taichung Region

Table 4 Story mass, lateral stiffness for typical and ground floors for a 6-story frame in Taipei

	Regular	R_{soft}=0.8	R_{weak}=0.8	R_{soft}=0.8, R_{weak}=0.8
(ton)	17.68	15.67	17.68	15.67
EI(kN-m^2)	121275	121275	121275	121275
$(EI)_1$(kN-m^2)	121275	97020	121275	97020

Table 5 Maximum roof and ground floor displacements, and first story drifts for a 6-story frame having various weak or soft story indices (TAP017)

	Regular	R_{soft}=0.8	R_{weak}=0.8	R_{soft}=0.8, R_{weak}=0.8
u_{roof}(cm)	2.813	2.777	2.813	2.777
u_1(cm)	2.226	2.237	2.222	2.235
θ_1 (rad.)	0.00335	0.00375	0.00342	0.00379

Table 6. Generalized shape function, modified participation factor, spectral first story drift and error for a system having a fundamental period of 0.637 second and with various R_{soft} values (TAP017)

Γ_1	Regular 1.345		R_{soft}=0.8 1.323		R_{weak}=0.8 1.345		R_{soft}=0.8, R_{weak} =0.8 1.323	
	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)
6F	1.000	3.128	1.000	3.075	1.000	3.128	1.000	3.075
5F	0.953	2.981	0.957	2.943	0.967	3.025	0.973	2.992
4F	0.863	2.699	0.878	2.700	0.907	2.837	0.922	2.835
3F	0.739	2.312	0.768	2.362	0.821	2.568	0.851	2.617
2F	0.587	1.836	0.631	1.940	0.717	2.243	0.765	2.352
1F	0.415	1.298	0.477	1.467	0.597	1.867	0.666	2.048
θ_1(rad.)		0.00325		0.00367		0.00467		0.00512
Error of θ_1		2.99%		2.13%		36.55%		35.09%

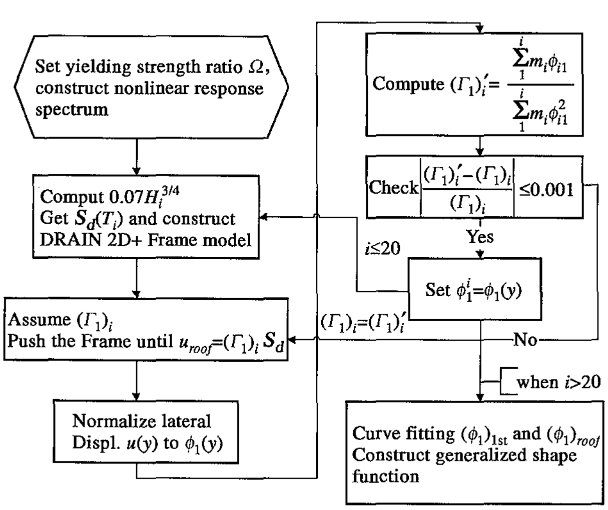

Fig. 18 Flow chart for constructing the modified modal participation factor and the generalized shape function spectra

studied.

Similarly, but under stronger earthquake shaking (*TCU*095, *EW* direction, *PGA*=0.367g), the maximum roof and ground floor displacements and the first story drift angle computed from the *DRAIN2D+* are given in Table 7. The modified modal participation factors, the shape functions and the lateral displacements computed from the proposed method are given in Table 8. It is found that the error is less than 26% for the four models studied.

IX. DISCUSSION OF ANALYTICAL RESULTS

Based on the analyses noted above, it appears that the maximum seismic story drift spectra for building systems vibrating essentially in the first mode can be satisfactorily predicted using the proposed

Table 7 Maximum roof and ground floor displacements, and first story drifts for a 6-story frame having various weak or soft story indices (TCU095)

	Regular	R_{soft}=0.8	R_{weak}=0.8	R_{soft}=0.8, R_{weak}=0.8
u_{roof}(cm)	24.551	24.871	22.831	23.235
u_1(cm)	20.627	21.122	19.776	20.368
θ_1(rad.)	0.0331	0.0372	0.0361	0.0397

Table 8. Generalized shape function, modified participation factor, spectral first story drift and error for a system having a fundamental period of 0.637 second and with various weak or soft story indices (TCU095)

Γ_1	Regular 1.226		R_{soft}=0.8 1.208		R_{weak}=0.8 1.212		R_{soft}=0.8, R_{weak} =0.8 1.192	
	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)	ϕ_{i1}	$\Gamma_1 S_d \phi_{i1}$ (cm)
6F	1.000	39.135	1.000	38.563	1.000	38.698	1.000	38.062
5F	0.953	37.277	0.957	36.905	0.956	37.007	0.961	36.566
4F	0.864	33.809	0.877	33.823	0.874	33.830	0.888	33.799
3F	0.740	28.956	0.766	29.551	0.760	29.426	0.787	29.951
2F	0.588	23.004	0.630	24.306	0.620	23.993	0.663	25.239
1F	0.415	16.237	0.476	18.340	0.461	17.847	0.523	19.902
θ_1(rad.)		0.041		0.046		0.045		0.050
Error of θ_1		22.66%		23.25%		23.71%		25.33%

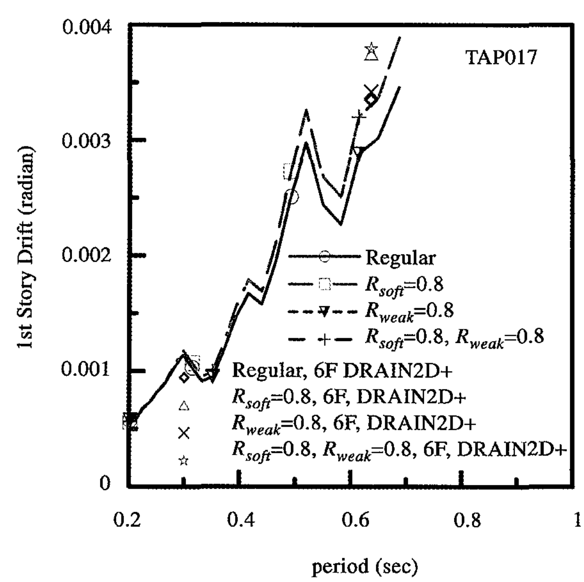

Fig. 19 Comparisons of the maximum first story drifts computed from nonlinear dynamic frame analyses and the spectral displacements obtained from the generalized shape functions using the TAP017 records

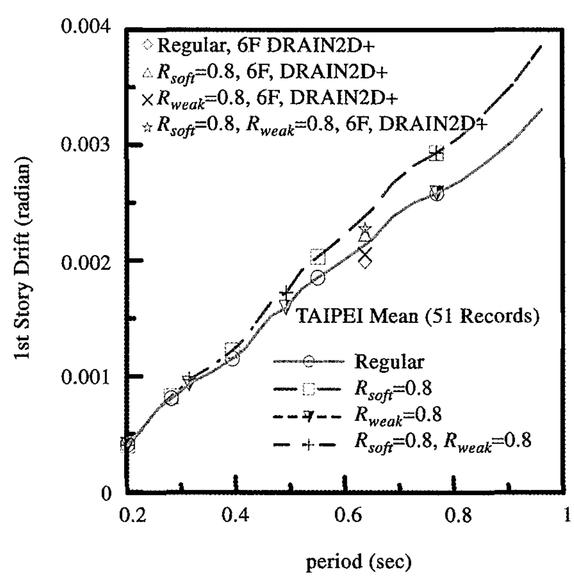

Fig. 20 Comparisons of the averaged maximum first story drifts computed from nonlinear dynamic frame analyses and the averaged spectral displacements obtained from the generalized shape functions using 51 acceleration records obtained from the Taipei Region

procedures. It is found that the shapes of the first story drift spectra for regular (not shown here) and irregular (Figs. 15 and 16) buildings are about the same, but the magnitudes of the spectral first story drift demands on the irregular buildings are significantly greater than those in regular ones. It is evident from Figs. 15 and 16 that the equal displacement theory can be extended to story drift analysis for structures having normal or strong lateral strength ($\Omega > 1.5$). However, for substandard structures, ($\Omega < 1.5$) having a weak story (R_{weak} = 0.8), the story drift demand is significantly greater than that of the normal or strong structures across the full range of periods. Comparing Figs. 15b with 15a (or 16b with 16a), it is apparent that the effects of the first-story weakness on the story drift demand is much more pronounced than the effects of softness of the first floor. Given the variations of the ground acceleration intensity as suggested in Figs. 6 and 7, the mean and the mean plus one standard deviation (1.0σ) of the first story drift demand being greater than 0.005 radian, shown in Fig. 15, for intermediate to long period substandard structures has been damaging. This is confirmed by a significant number of cracks of various degrees observed in in-fill masonry and reinforced concrete partition walls of many multi-story *RC* buildings in the Taipei region. For story drift demands imposed on the buildings in the Taichung region during the Chi-Chi main shocks (averaged *PGA*=0.164g), Fig. 16 indicates that the mean and the mean plus one standard deviation (1.0σ) of the first story drift demand for irregular buildings are greater than 0.01 radian for substandard structures. These large story drift demands could be fatal if non-ductile details of reinforcing steel ties or bar splices exist in the ground floor columns.

X. DESIGN IMPLICATIONS

For long period structures having a normal or strong lateral strength in Taichung, Figs. 17(a)~(c) indicate that the averaged first story drift demand for irregular buildings with R_{soft} and R_{weak} values equal to 0.7 are significantly greater than those of R_{soft} and R_{weak} values equal to 0.8. And in many cases their first story drifts exceed 0.01 radian. But if the R_{soft} and R_{weak} value is raised up to 0.9, as shown in Figs. 17(d)~(f), the averaged first story drift demands can be significantly reduced for intermediate and long period structures. Thus, before further data becomes available, it appears that the lower limit of the R_{soft} and R_{weak} ratios for the soft or weak story prescribed in the Taiwan seismic building code could be raised from 0.8 to 0.9 for damage control, especially for structural rehabilitation design of existing old buildings.

XI. SUMMARY AND CONCLUSIONS

Using the ground accelerations recorded during the 1999 Chi-Chi Taiwan Earthquake, the story drift response spectra were constructed by using the displacement response spectra, the lateral floor displacements obtained from the nonlinear frame push over analysis, and a deformation-consistent modal participation factor. It is confirmed that the dynamic peak story drift angle can be satisfactorily predicted using the proposed procedures. Analytical results indicate that the effects of first story weakness on the story drift demand are much more pronounced than the effects of softness of the first story for substandard structures. This suggests that the extensive vulnerability of the existing substandard building inventory, as revealed by this earthquake, must be addressed before other equally destructive earthquakes strike again in Taiwan. Particular attention must be paid to buildings having weak or soft story features.

ACKNOWLEDGEMENTS

The financial support provided by the National Center for Research on Earthquake Engineering (NCREE) is very much appreciated. The assistance provided by research assistants Messrs. J.W. Lai, J. G. Liu and Y.H. Lin during the study is very much appreciated. The ground motion records prepared by the Central Weather Bureau and further processed by the NCREE are acknowledged.

NOMENCLATURE

F_u, R_μ	seismic force reduction factor
H_n	building height (m)
R_y	structural yielding strength
S_a	spectral acceleration (g)
S_d	spectral displacement (m or cm)
T	the fundamental period (second)
R_{soft}	soft story ratio
R_{weak}	weak story ratio
V_{code}	design base shear (kN)
u_1	first story lateral displacement (m or cm)
Ω	strength factor
Γ_1	modified first modal participation factor
μ	ductility ratio
θ_1	first story drift angle (radian)
ϕ_1	deformed shape function

REFERENCES

1. ABRI, 1999, “Preliminary Reconnaissance Report for the 921 Chi-Chi Earthquake,” Architecture and Building Research Institute, Ministry of Interior, R.O.C. (in Chinese)
2. Applied Technology Council (ATC), 1996, “Seismic Evaluation and Retrofit of Concrete Buildings,” Vols. 1 and 2, ATC-40, Applied Technology Council, Redwood City.
3. BSSC, 1997, NEHRP Guidelines for the Seismic

Rehabilitation of Buildings, FEMA-273, Developed by ATC for FEMA, Washington D.C.
4. Building Technology Standards, 1974, 1982, 1989, 1997, Ministry of Interior, R.O.C.
5. Fajfar, P. and Fischinger, H., 1987, "Nonlinear Seismic Analysis of RC Buildings: Implications of a Case Study," *European Earthquake Engineering*, Vol. 1, pp.31-43.
6. Fajfar, P., 1999, "Capacity Spectrum Method Based On Inelastic Demand Spectra.," *Earthquake Engineering and Structural Dynamics*, Vol. 28, pp. 937-979.
7. Krawinkler, H., and Seneviratna, G. D. P. K., 1996, "Pros and Cons of a Pushover Analysis for Seismic Performance Evaluation," *Engineering Structure* 20, pp. 452-464.
8. Lee, G. C., and Loh, C. H., 1999, "Preliminary Report From MCEER-NCREE Workshop on the 921 Taiwan Earthquake," Multidisciplinary Center for Earthquake Engineering Research.
9. Mahin, S. A., and Lin, J., 1983, "Construction of Inelastic Response Spectra for Single Degree of Freedom System," Report No.UCB/EERC-83/17, University of California, Berkeley.
10. Tsai, K. C., and Li, J. W., 1994, "DRAIN2D+, A General Purpose Computer Program for Static and Dynamic Analysis of Inelastic 2D Structures, Supplemented with a Graphic Processor VIEW2D, User's Guide," *CEER/R83-03,* Center for Earthquake Engineering Research, National Taiwan University.
11. Tsai, K. C., Hsiao, C. P., and Bruneau, M., 2000a, "Overview of Building Damages in Chi-Chi Earthquake," *Earthquake Engineering and Engineering Seismology*, Vol. 2, No. 1, pp. 93-108.
12. Tsai, K. C., Weng, Y. T., Jang, L. C., and Lai, J. W., 2000b, "Spectral Responses and Building Damages in 1999 Chi-Chi Taiwan Earthquake," *Proceedings of the International Conference on Advances in Structural Dynamics*, Hong Kong.
13. Tsai, K. C., Weng, Y. T., Jang, L. C., Lai, J. W., Liu, J. G., and Lin, Y. H., 2001, "Response Spectrum Analyses Using Chi-Chi Earthquake Ground Accelerations," Center for Research on Earthquake Engineering, College of Engineering, National Taiwan University, CEER Report. (in Chinese)
14. Tsai, Y. B., and Huang, M. W., 2000, "Strong Ground Motion Characteristics of the Chi-Chi, Taiwan Earthquake of September 21, 1999," *Earthquake Engineering and Engineering Seismology*, Vol. 2, No. 1, pp. 1-22.
15. UBC, 1997, Uniform Building Codes, International Conference on Building Officials, Whittier CA.
16. Weng, Y. T., and Tsai, K. C., 2000, "Inelastic Soft Story Drift Spectra due to Near Fault Earthquakes," *Proceedings of the International Conference on Stability and Structural Dynamics*, Taipei, Taiwan.

Manuscript Received: Aug. 15, 2001
Revision Received: Feb. 19, 2002
and Accepted: Mar. 01, 2002

台灣九二一集集大地震中建築結構之層間位移角反應譜需求分析

蔡克銓 翁元滔 張劉權

國立台灣大學土木工程學系

摘 要

本研究以九二一集集大地震在台北及台中非近斷層區域的測站資料製作單自由度非線性反應譜，及進行一系列的多自由度非線性靜力側推分析，以模擬各種不同軟化或弱化狀態下建築結構的側向變位特性。並利用迴歸分析求出不同強度、不同底層軟化或弱化的狀態下其所對應的廣義位移函數後，配合單自由度非線性反應譜動力分析的結果，計算出結構物層間位移角反應譜。本文亦探討台北、台中兩遠域地區內建築物在集集大地震中的反應特性，最後以一個六層樓之建築結構爲例，進行非線性歷時動力分析，並與本研究利用廣義位移函數所推算之結果加以比較及驗證。

關鍵詞：強度因子，樓層層間變位角反應譜，廣義位移函數，振態參與因子。