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Damage to Buildings Caused by the 1999 Chi-Chi, Taiwan Earthquake and Earthquake Response Analyses Using Recorded Strong Ground Motions

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Abstract

The Chi-Chi, Taiwan earthquake, which occurred on 21 September, 1999, brought about severe damage. In this earthquake, many free field strong ground motion records were obtained in a wide range of areas. Most of the strong ground motions were recorded beside reinforced concrete school buildings with simple shapes. Very useful and valuable data were provided for investigating the relationship between strong ground motions and damage to structures.

Damage to buildings caused by the 1999 Chi-Chi earthquake was investigated and earthquake response analyses were made for recorded strong ground motions. The relation between actual damage to buildings and results of earthquake response analyses was examined.

The results of the damage investigation show that severe damage was found at Chungliao, 5 km north-west of the epicenter, and Tongshi, Puli, and Kuoshing, 10-20 km east of the Chelongpu fault. We found moderate damage in Shikang and Wufong, but around the Chelongpu fault, we did not find severe damage except at locations very near the fault. These were explained by the results of the earthquake response analyses using single-degree-of-freedom (SDOF) systems.

The results of the earthquake response analyses show that from the distributed records, strong ground motion with the most destructive power was recorded at Puli, 20 km east of the Chelongpu fault, except one due to local conditions. These findings corresponded to actual damage. However, the destructive power of the record at Puli was smaller than that of the 1995 Hyogoken-Nanbu earthquake. Moreover, it was shown that the elastic response at 1.0 sec is the best index of the destructive power of strong ground motions and that the results of analyses of investigated school buildings approximately correspond to actual damage if the strength of brick walls is considered.

Key words: the 1999 Chi-Chi earthquake, earthquake response analysis, Takeda model, maximum ductility factor, required strength

1. Introduction

The Chi-Chi, Taiwan earthquake which occurred on 21 September, 1999, with local and surface-wave maginitudes of 7.3 and 7.7, respectively, at a depth of 7 km, brought about severe damage. More than 2,000 people were killed and approximately 10,000 buildings collapsed. In this earthquake, many free field strong ground motion records were obtained in a wide range of areas. Most of the strong ground motions were recorded beside reinforced concrete school buildings with simple shapes. Very useful and valuable data were provided for investigating the relationship between strong ground motions and damage to structures.

Damage to buildings caused by the 1999 Chi-Chi earthquake was investigated and earthquake response analyses were made using recorded strong ground motions. The relation between actual damage to buildings and results of earthquake response analyses was examined.

2. Outline of investigation on damage to buildings

During the 1999 Chi-Chi earthquake, many buildings were severely damaged in a wide range of areas. The number of collapsed buidlings was about 10,000.

Damage investigation was made mainly on reinforced concrete school buildings, because:

· school buildings are located in inhabited areas and equally distributed in a wide range of areas,

· the shapes of school buildings are simple, regular, and similar to each other, therefore, they are easy to analyse (typical plans of school building are shown in Figure 1),

· most strong motion observation sites were beside school buidlings and

· most buildings in Taiwan are reinforced concrete structures.

Damage investigation was made in Taichung and Nantou county where damage was severe (Figure 2). Building data for earthquake response analyses, such as member dimensions, span lengths, story heights, and reinforcements were collected, in addition to carrying out building damage inspections. The locations of investigated buildings (strong motion observation points) are shown in Figure 3. An outline of investigated buildings (strong motion observation points), the results of the investigation and level of damage in the surrounding areas (area damage level) are shown in Table 1. The area damage level was judged as quantitatively as possible according to Table 2. Area of 500 m by 500 m square around the buildings and school buildings were investigated. The target of the investigation was damage caused by strong ground motions, excluding soil failures such as fault, landslide and liquiefaction. The number of sites and buildings investigated were 14 and 23,

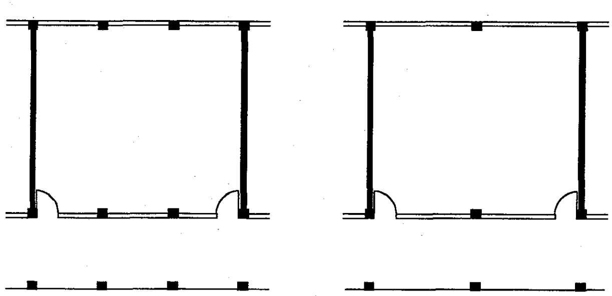


Fig. 1. Typical plans of school buildings

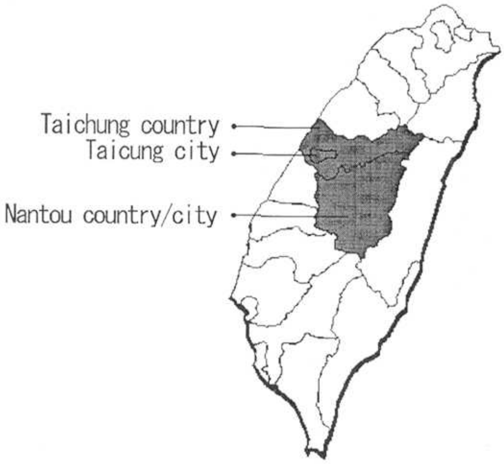


Fig. 2. Location of Taichung and Nantou county

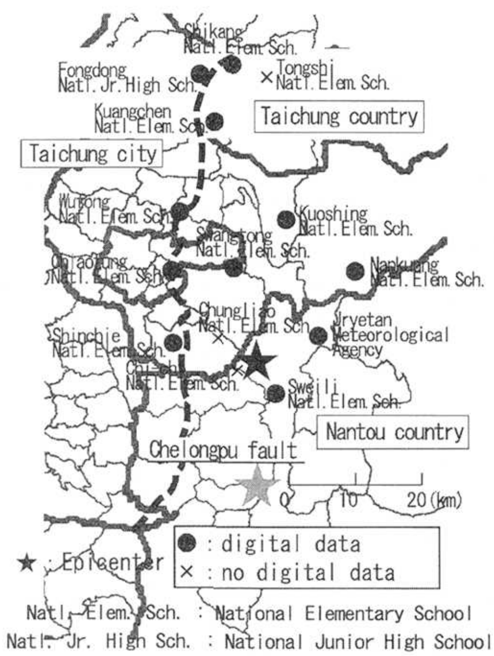


Fig. 3. Location of investigated buildings (strong ground motion observation points)

Table 1. Investigated buildings (strong ground motion observation points) and results of investigation

No.	Name	Location	No. of station	Building data (symbol) and building damage level	Area damage level
1	Shikang National Elementary School	Shikang, Taichung county	068	◎major○moderate○moderate○moderate	3
2	Tongshi National Elementary School	Tongshi, Taichung county	—	×(demolished)×no damage	4
3	Fongdong National Elementary School	Fengyuan, Taichung county	102	×no damage×major(complicated shape)	2
4	Kuangcheng National Elementary School	Taichung, Taichung county	052	○minor	2
5	Wufong National Elementary School	Wufong, Taichung county	065	○minor×(demolished)	3
6	Chiaotung National Elementary School	Chiaotung, Nantou county	075	○slight	2
7	Swangtong National Elementary School	Swangtong, Nantou county	071	○moderate○no damage	2
8	Nankuang National Elementary School	Puli, Nantou county	074	×(demolished)○no damage	4
9	Kuoshing National Elementary School	Kuoshing, Nantou county	072	○moderate×(demolished)	4
10	Sweili National Elementary School	Sweili, Nantou county	078	×(demolished)	2
11	Jryetan Meteorological Agency	Urchi, Nantou county	084	◎major	-
12	Chi-chi National Elementary School	Chi-chi, Nantou county	—	×(demolished)○no damage	2
13	Chungliao National Elementary School	Chungliao, Nantou county	—	◎collapsed	5
14	Shinchie National Elementary School	Minjien, Nantou county	129	○slight	1

— at No. of station: no accelerogram
Building data : ◎ : data in detail , ○ : simple data, × : no data (reason)

Table 2. Definition of area damage level

Area damage level	Situation	Approximate collapse ratio (%)
5	Annihilation. Many buildings collapsed.	
	Most buildings were damaged.	30
4	A large number of buildings collapsed.	
	Most of buildings collapsed or were severely damaged in some part	10
3	There are some collapsed or severely damaged buildings.	
	Between 2 and 4.	3
2	There are a few severely damaged buildings.	1
	There are many slightly damaged buildings.	
1	There is no severely damaged building.	0
	There are some slightly damaged buildings.	
0	There is no damaged buildings.	0

respectively. Building damage level (no, slight, minor, moderate, and major damage and collapse) was judged according to the reference (Architectural Institute of Japan, 1980).

Simple data for many points and detailed data for some points were obtained, although some buildings had already been demolished or were being demolished.

Some of the damaged reinforced concrete buildings and their surrounding areas are shown in Photos 1 to 21.

Severe damage was found at Chungliao, 5 km north-west of the epicenter, and Tongshi , Puli, and Kuoshing, 10–20 km east of the Chelongpu fault. We found moderate damage in Shikang and Wufong, but around Chelongpu fault, we did not find severe damage except at locations very near to the fault.

Photo 1. Building C of Shikang National Elementary School, which was severely damaged

Photo 2. Severely damaged tops of columns at building C of Shikang National Elementary School

Photo 3. Surrounding area of Shikang National Elementary School

Photo 4. Surrounding area of Tongshi National Elementary School

Photo 5. Surrounding area of Wufong National Elementary School

Photo 6. Building A of Nankuang National Elementary School in Puli, which was severely damaged and was being demolished

Photo 7. Surrounding area of Nankuang National Elementary School

Photo 8. Building B of Kuoshingi National Elementary School

Photo 9. Shear failure of non-structural wall at building B of Kuoshing National Elementary School

Photo 10. Surrounding area of Kuoshing National Elementary School

Photo 11. A building of Jryetan Meteorological Agency

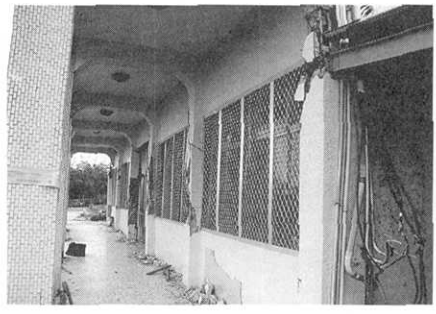


Photo 12. The front of first story of Jryetan Meteorological Agency

Photo 13. A damaged column by the first story front entrance at Jryetan Meteorological Agency

Photo 14. The front of building A at Chungliao National Elementary School which was originally a two-story but looked like one-story building

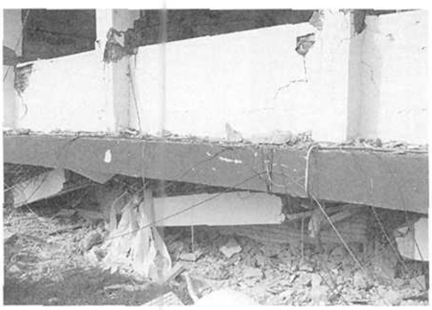


Photo 15. Collapsed first story of building A at *Chungliao National* Elementary School

Photo 16. Close-up of Photo 15 (Longitudinal bars buckled although there were many longitudinal bars.)

Photo 17. Severely damaged first story of building B at Chungliao National Elementary School

Photo 18. Close-up of Photo 17 (Longitudinal bars buckled. Pipes were found.)

Photo 19. Surrounding area of Chung-liao National Elementary School

Photo 20. Building A of Shinchie National Elementary School in Minjien

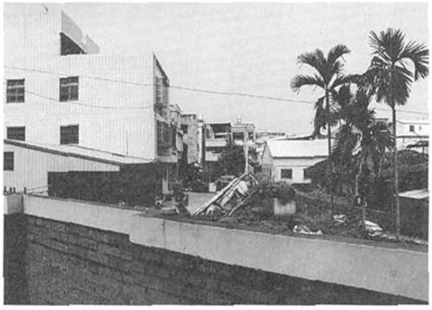


Photo 21. Surrounding area of Shinchie National Elementary School

3. Characteristics of strong ground motions

During the earthquake, many free field strong ground motion records were obtained in a wide range of areas. Reinforced concrete school buildings with simple shapes were located near strong motion observation points. Very useful and valuable data were provided for investigating the relationship between strong ground motions and damage to structures. The locations of seismographs installed throughout Taiwan are shown in Photo 22, with 637 on free field sites and 56 in buildings, totalling 693.

Earthquake response analyses were conducted with single-degree-of-freedom (SDOF) systems using strong ground motion records as inputs at the damage investigation site. Characteristics of strong ground motions were examined first and compared with strong motions from other damaging earthquakes.

Strong ground motion records for damage investigation sites are shown in Table 3, together with reference records. The peak ground velocity (PGV) was calculated using elastic response analyses for a period of 15 sec and a damping factor of 0.707, instead of integrating accelerogram data, in order to avoid velocity remaining after strong ground motions. (WATABE, 1985) Some accelerograms and elastic response

Photo 22. Locations of seismographs in Taiwan (a display in Taiwan Meteorological Agency photographed by permission)

Table 3. Strong ground motions

ID	Station(Station No.)	Direction	Earthquake	PGA	PGV	SI
068NS	Shikang National Elementary School (068)	NS	1999 Chi-Chi, Taiwan	371.1	217.8	161.2
068EW	〃	EW	〃	507.6	180.0	185.3
052NS	Kuangcheng National Elementary School Building(052)	NS	〃	438.6	117.4	261.6
052EW	〃	EW	〃	353.4	155.2	206.1
102NS	Fongdong National Jr. High School(102)	NS	〃	169.8	74.0	118.1
102EW	〃	EW	〃	298.3	112.0	143.7
065NS	Wufong National Elementary School(065)	NS	〃	538.0	74.3	194.0
065EW	〃	EW	〃	778.7	120.2	186.7
075NS	Chiaotung National Elementary School(075)	NS	〃	264.4	33.3	61.1
075EW	〃	EW	〃	313.2	84.0	104.6
071NS	Swangtong National Elementary School(071)	NS	〃	622.1	62.8	139.3
071EW	〃	EW	〃	516.0	54.9	136.3
074NS	Nankuang National Elementary School(074)	NS	〃	380.3	46.0	133.6
074EW	〃	EW	〃	604.0	68.6	204.6
072NS	Kuoshing National Elementary School(072)	NS	〃	358.3	54.3	135.2
072EW	〃	EW	〃	465.5	78.7	154.1
078NS	Sweili National Elementary School(078)	NS	〃	310.4	31.9	81.9
078EW	〃	EW	〃	444.7	38.8	111.5
084NS	Jryetan Meteorological Agency (084)	NS	〃	428.5	52.5	134.2
084EW	〃	EW	〃	999.0	113.2	392.3
129NS	Shinchie National Elementary School(129)	NS	〃	616.8	37.3	111.3
129EW	〃	EW	〃	971.2	58.5	153.7
FKI	Osaka Gas Fukiai Station	NS	1995 Hyogoken-nanbu	802.0	130.4	359.0
SLM	Sylmar	EW	1994 Northridge	826.7	125.7	277.5
KSR	Kushiro Meteorological Agency	EW	1993 Kushiro-oki	711.4	33.1	115.4
ELC	El-Centro	NS	1940 Imperial Valley	341.7	34.8	93.1

PGA: peak ground acceleration($cm/sec.^2$), PGV: peak ground velocity(cm/sec.) SI: spectrum intensity(cm)

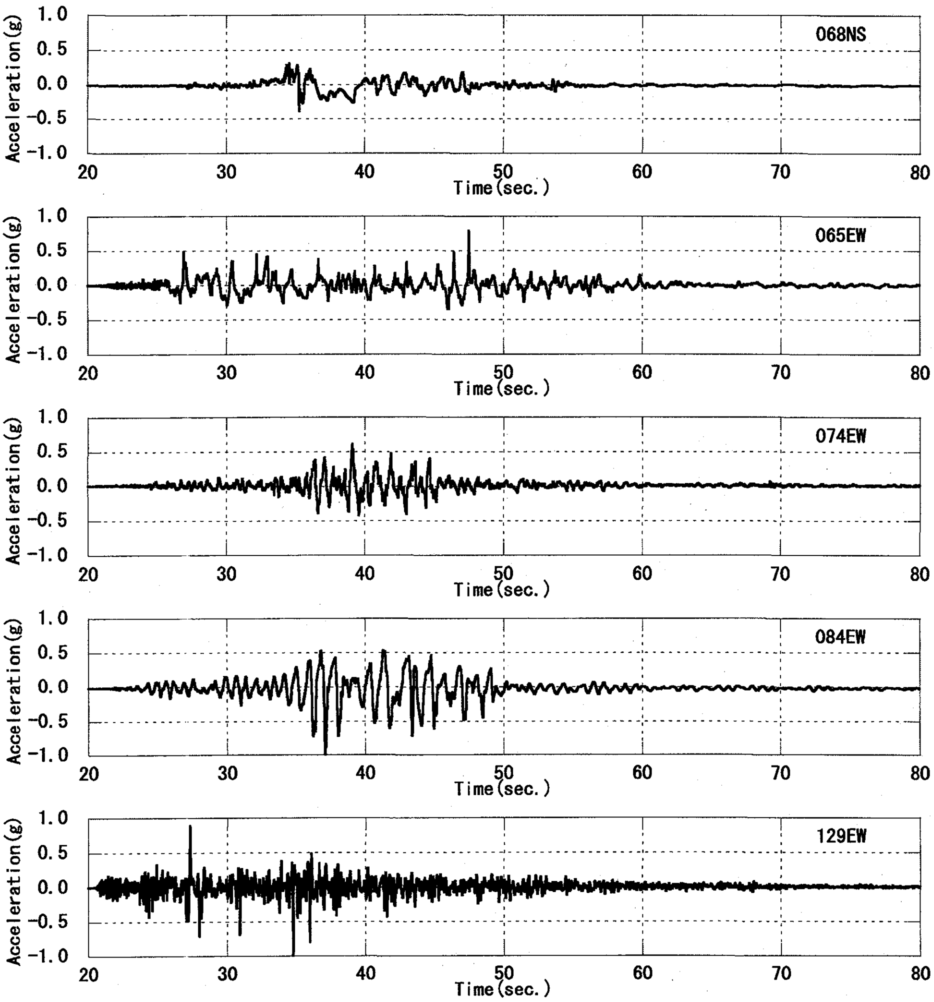


Fig. 4. Time histories of ground acceleration

acceleration spectra with a damping factor of 5% are shown in Figures 4 and 5, respectively. Three strong ground motions points, Chungliao National Elemantary School at Chungliao where damage was severest among the investigation points, Tongshi National Elementary School at Tongshi, the site of the next severest damage, as well as Puli and Kuoshing and Chi-Chi National Elementary School, which was the nearest to the epicenter, were not included in the distributed CD-ROM (LEE, 1999).

In Table 3, peak ground acceleration (PGA) was greater than 500 cm/sec^2 at six points: 068, 065, 071, 074, 129, and 084. In particular, very large PGAs of greater than 1 g were recorded in EW components at points 129 and 084.

Large peak ground velocities (PGV) were recorded at 068 and 052. In particular,

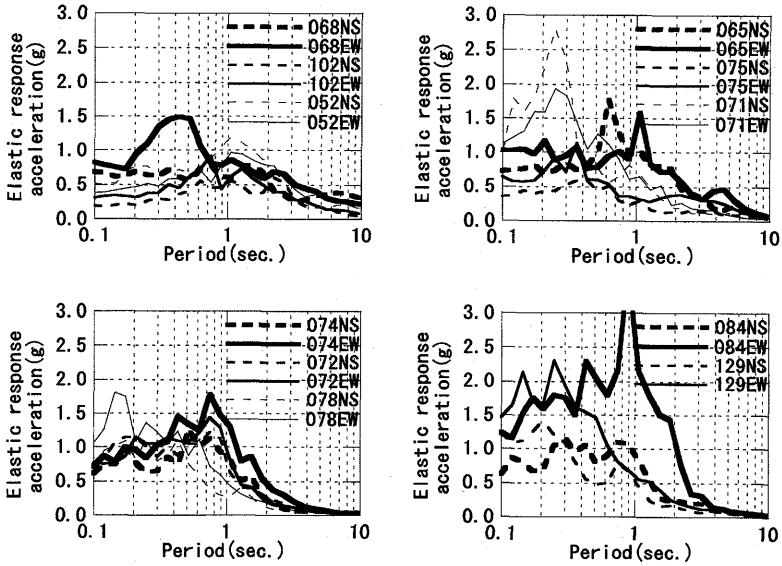


Fig. 5. Elastic response acceleration spectra (damping factor 0.05)

a very large PGV of over 200 cm/sec was recorded at 068 NS, which is far larger than that of FKI from the 1995 Hyogoken-Nanbu earthquake.

On the other hand, spectrum intensities, which represent the destructive power of strong ground motions more adequately than PGA and PGV (Sakai, 1998), at points 129 and 068 are 153.7 cm and 185.3 cm, respectively. Both values are far smaller than that of FKI, which is 359.0 cm. Spectrum intensity of 084 EW is, however, larger than that of FKI.

For accelerograms (Figure 4) in 129 EW, short periods dominate and the PGA pulse is spike shaped, although long periods dominate in 084 EW. Rather long periods dominate in the records at Puli (074) and Wufong (065) where severe damage was found. The accelerogram of Shikang (068 NS) with very large PGV is distinctive because the acceleration shifts to one side for a long duration of about 4 sec.

For elastic response acceleration spectra (Figure 5) in Shinchie (129 EW), the short period dominates and responses of around 1 sec, which bring about damage to buildings (Sakai, 1999), are small. In contrast, responses of around 1 sec are large in Puli (074), Kuoshing (072), Wufong (065) and Jryetan (084) where severe damage was found. The values are very large in Jryetan (084). However, the Jryetan Meteorological Agency is located at the summit of a 1,000 m high mountain and is 300 m higher than Jryetan lake at its foot. We think that very destructive ground motions at 084 occurred due to local conditions. The responses around 1 sec are largest at 074 EW except for 084 EW. The responses of around 1 sec of 068 NS with very large PGV are smaller than those of 065 EW and 074 EW.

Elastic response acceleration spectra with a 5% damping factor from 068 NS with

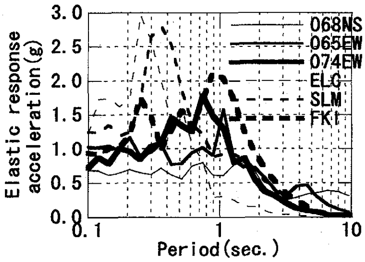


Fig. 6. Comparison of elastic response acceleration spectra (damping factor 0.05) from records by the 1999 Chi-Chi, Taiwan earthquake and other earthquakes

a very large PGV, 074 EW and 065 EW, where severe damage was found are shown in Figure 6 for comparison with the reference earthquake records FKI, SLM and ELC. The values of 068 NS for around 1 sec, which bring about severe damage to buildings, are smaller than those of SLM. The values of 074 EW and 065 EW are larger than those of SLM, but are smaller than those of FKI.

4. Inelastic earthquake response analyses using single-degree-of-freedom systems

Inelastic earthquake response analyses using SDOF systems with the Takeda hysteresis model (TAKEDA, 1970), assuming reinforced concrete buildings, were carried out in order to assess the destructive power of recorded strong ground motions more accurately. The primary curve of the Takeda model is shown in Figure 7. The ratio of cracking to yielding force, the ratio of post-yielding to initial stiffness and the ratio of yielding to initial stiffness are assumed to be 0.3, 0.01, and 0.25, respectively. The damping coefficient is proportional to instantaneous stiffness with an initial elastic damping factor of 0.05. The bases of systems were assumed to be fixed. The equation of motion was solved numerically using the Newmark-β method (NEWMARK, 1959) with $\beta=1/6$, and the time increment of the numerical integration was taken as one-twentieth of the initial elastic period.

The required base shear coefficient, which produces constant maximum response ductility factors (called 'allowable ductility factors μ_a'), were adopted as the inelastic seismic response, which represents damage to buildings. Required base shear coefficients (called 'required strength spectra') were calculated for allowable

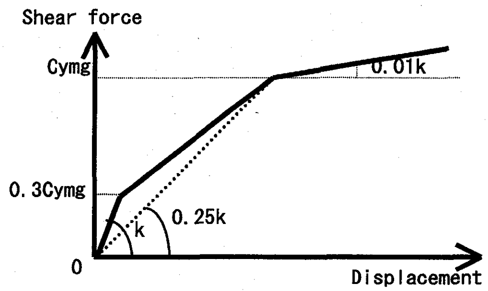


Fig. 7. Primary curve of Takeda model

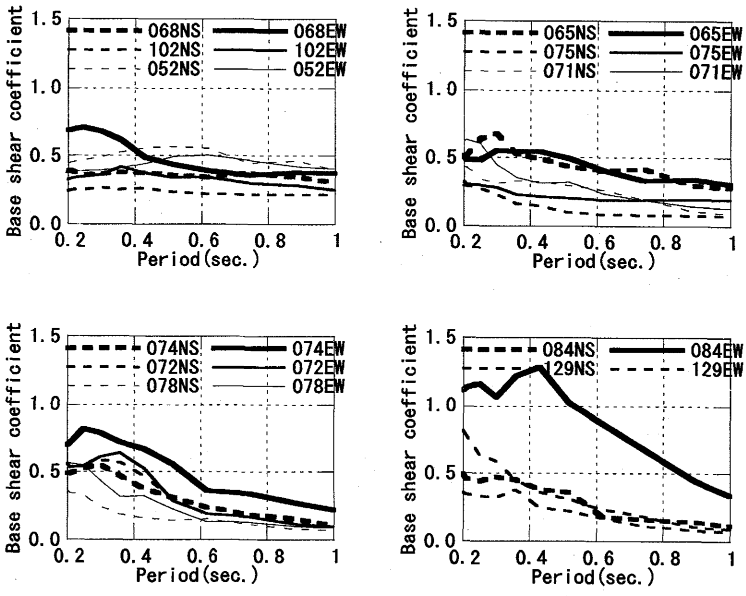


Fig. 8. Required strength spectra

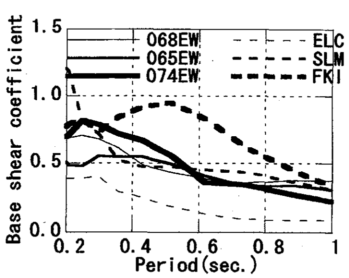


Fig. 9. Comparison of required strength spectra from records by the 1999 Chi-Chi, Taiwan earthquake and other earthquakes

ductility factors $\mu_a=2$.

The required strength spectra in the period range from 0.2 to 1.0 sec, to which most buildings belong, are shown in Figure 8. The results are as expected from the elastic response acceleration around 1.0 sec, i.e., the required strength spectra from 084 EW are very large but those from 129 EW are far smaller. The spectra from 074 EW are largest except for 084 EW occurred due to local conditions, hence 074 EW has the most destructive power. Comparing the reference earthquake records in Figure 9, the spectra from 074 EW with the most destructive power were, however, smaller than FKI.

5. Correlation between the results of earthquake response analyses and structural damage

The relationship between PGA, PGV, SI and elastic response acceleration with a

Table 4. Analyzed buildings and results of damage investigation and earthquake response analyses

ID	Name of a building	Story	Dir	Period (sec.)	τu	C_1	C_2	D	record ID	μ_1	μ_2
IAT	Shikang National Elementary School Building A	3	T	0.35	0.756	0.45	0.85	3	068NS	2.74	1.20
IAL			L	0.35			0.65		068EW		
IBT	Shikang National Elementary School Building B	2	T	0.35	0.605	0.62	1.35	3	068NS	2.48	0.92
IBL			L	0.35			0.98		068EW		
ICT	Shikang National Elementary School Building C	2	T	0.35	0.605	0.28	0.73	4	068EW	7.15	1.27
ICL			L	0.35			0.51		068NS		
IDT	Shikang National Elementary School Building D	1	T	0.35	0.605	0.47	1.79	2	068EW	6.67	0.32
IDL			L	0.35			1.13		068NS		
SAT	Kuangcheng National Elementary School Building A	2	T	0.35	0.756	0.50	1.57	2	052EW	3.75	0.74
SAL			L	0.35			0.85		052NS		
UAT	Wufong National Elementary School Building A	2	T	0.35	0.756	0.32	1.22	2	065NS	7.09	1.55
UAL			L	0.35			0.77		065EW		
NAT	Chiaotung National Elementary School Building A	2	T	0.35	0.756	0.27	0.88	1	075NS	1.36	0.61
NAL			L	0.35			0.47		075EW		
OAT	Swangtong National Elementary School Building A	1	T	0.35	0.756	1.25	2.88	2	071NS	1.29	0.59
OAL			L	0.35			2.06		071EW		
OBT	Swangtong National Elementary School Building B	2	T	0.35	0.907	0.78	2.36	0	071EW	1.46	0.45
OBL			L	0.35			1.57		071NS		
PAT	Nankuang National Elementary School Building A	2	T	0.35	0.907	0.67	2.41	0	074NS	2.47	0.77
PAL			L	0.35			1.25		074EW		
KAT	Kuoshing National Elementary School Building A	3	T	0.35	0.907	0.63	0.70	3	072NS	2.51	0.77
KAL			L	0.35			0.76		072EW		
TAT	Jryetan Meteorological Agency	2	T	0.35	0.756	0.39	0.99	4	084NS	4.03	2.48
TAL			L	0.35			0.72		084EW		
GAT	Shinchie National Elementary School Building A	2	T	0.35	0.756	0.44	2.85	1	129NS	1.64	0.22
GAL			L	0.35			1.64		129EW		

Dir: building direction of analysis (T: transverse, L: longitudinal)
τu: ultimate shear stress of columns (N/mm^2)
C_1: base shear coefficient calculated not considering brick walls
C_2: base shear coefficient calculated considering brick walls
D: building damage level (0: no damage, 1:slight damage, 2:minor, 3: moderate, 4: major damage)
μ_1: root sum square of maximum response ductility factor in two directions not considering brick walls
μ_2: root sum square of maximum response ductility factor in two directions considering brick walls

5% damping factor at 1.0 sec and area damage level is shown in Figure 10. Almost no correlation was found for PGA and a weak correlation for PGV and SI, whereas, there is good correlation for elastic response acceleration with a 5% damping factor at 1.0 sec with area damage level.

Next, inelastic earthquake response analyses using SDOF systems were performed for 13 buildings where we could collect data such as member dimensions. The analysed buildings are shown in Table 4. The weight of the buildings was calculated assuming a unit weight of 1.2 ton/m^2. The period of the building is calculated from member, story height, and span dimensions assuming a concrete stiffness of 21,000 N/mm^2.

Strength (base shear coefficient) is calculated assuming that the ultimate shear stress of columns τ_u shown in Table 4, i.e., τ_u is 0.756 N/mm^2, which is one-twentieth of the average compressive strength (Architectural Institute of Japan, 1988) calculated from data using the Schmit hammer test of buildings constructed three to ten years ago (Architectural Institute of Japan, 1999). The ultimate shear stress τ_u was assumed to be $0.8 \times 0.756 = 0.605$ N/mm^2 and $1.2 \times 0.756 = 0.907$ N/mm^2 for buildings constructed before 1981 and after 1997, respectively, considering the deterioration over time of concrete and the major revisions of earthquake resistant design regulation in

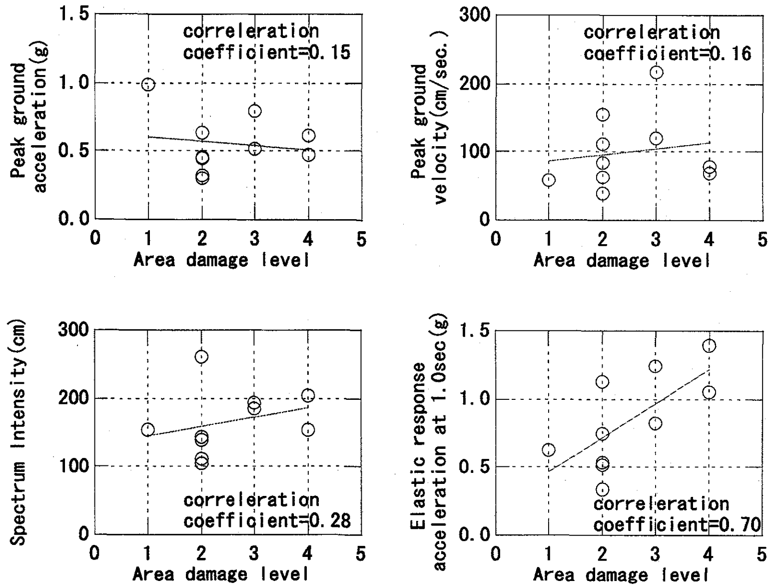
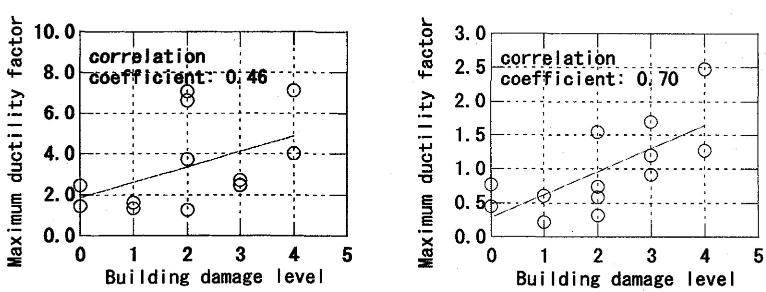


Fig. 10. Relation between index of representing the destructive power of strong ground motions and area damage levels



(1) not considering brick wall **(2) considering brick wall**

Fig. 11. Relation between building damage levels and maximum response ductility factors

Taiwan in 1981 and 1997.

All walls were made of brick without reinforcing. Two cases, i.e., considering and not considering brick walls, were analysed. The brick walls were considered in the case of walls without openings. In the case considering brick walls, the ultimate shear stress of the brick wall τ_u is assumed to be one-sixth of that of reinforced concrete walls, i.e., $2.5/6=0.42\,N/mm^2$ and $0.756/6=0.12\,N/mm^2$ in the longitudinal and transverse directions, respectively. The analytical model of the system was the same as that described in Chapter 4.

The relationship between building damage (0: no, 1: slight, 2: minor, 3: moderate, and 4: major damage) and the square root of the sum of squares (SRSS) in the two directions of maximum response ductility factors is shown in Figure 11. A good correleration is found for the case considering brick walls, whereas, a good correleration is not found for the case not considering brick walls. The values of response ducility factors for building damage are also more appoximate for the case considering brick walls.

6. Conclusions

Damage to buildings during the 1999 Chi-Chi earthquake was investigated and earthquake response analyses were made using recorded strong ground motions. The relation between actual damage to buildings and results of earthquake response analyses was examined.

It was found from the damage investigation that:

· severe damage was found at Chungliao, 5 km north-west from the epicenter, and Tongshi, Puli, and Kuoshing, 10–20 km east from Chelongpu fault,

· moderate damage was found in Shikang and Wufong, but around Chelongpu fault, severe damage was not found except for places very near to the fault, and

· these were explained by the results of the earthquake response analyses using single-degree-of-freedom (SDOF) systems.

It was found from the earthquake response analyses that

· strong ground motion with the most destructive power was recorded at Puli, 20 km east of Chelongpu fault, among the distributed records except for one record at site 084 due to local conditions,

· this finding corresponded to the actual damage,

· the destructive power of the record at Puli was considerably smaller than the one at Fukiai from the 1995 Hyogoken-Nanbu earthquake,

· the elastic response at 1.0 sec is a better index for representing the destructive power of strong ground motions than PGA, PGV, and S.I. and

· the results of the earthquake response analyses for investigated school buildings approximately correspond to the actual damage if the strength of brick walls is considered.

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References

Architectural Institute of Japan, 1980, Reports on the damage investigation of the 1978 Miyagiken-oki earthquake, 145 (in Japanese).

Architectural Institute of Japan, 1988, Standard for structural calculation of reinforced concrete structures, (in Japanese)

Architectural Institute of Japan, 1999, Preliminary report on the 1999 Chi-Chi, Taiwan earthquake, 72–73 (in Japanese).

LEE, W.H.K, SHIN T.C. KUO K.W. and CHEN K.C., 1999, CWB Free-Field Strong-Motion Data from the 921 Chi-Chi Earthquake, Vol. 1, Digital Acceleration Files on CD-ROM.

NEWMARK, N.M., 1959, A method of computation for structural dynamics, *Proc. ASCE,* **95**, No. ST 3, 67–94.

SAKAI, Y., MINAMI, T. and KABEYASAWA T., 1998, Simplified method to express characteristics of strong ground motions, *Proceedings of the third symposium on the disaster by near-field earthquake*, 265–268 (in Japanese).

SAKAI, Y., 1999, Destructive power of strong ground motions: What kind of strong ground motions bring about great damage? Interdisciplinary study on the generations of strong ground motions of high acceleration and velocity and their influences to earthquake damage, 7–18 (in Japanese).

TAKEDA, T., SOZEN, M.A. and NIELSEN, N.N., 1970, Reinforced concrete response to simulated earthquakes, *Journal, Structural Division, ASCE,* **96**, No. ST 5, 2557–73.

WATABE M., OHASHI Y. and HASEBE H., 1985, Research on design earthquake ground motions for high-rise buildings (part 1), *Summaries of technical papers of annual meeting, Architectural Institute of Japan*, B *Structures* 1, 135–136 (in Japanese).

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1999年台湾集集地震による建物被害と強震記録を用いた地震応答解析

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1999年台湾集集地震は，甚大な人的および構造物被害をもたらしたが，同時に，広範囲に渡り，非常に多くの強震記録が観測された．記録の多くは，鉄筋コンクリート造学校建物のすぐ脇で観測されており，地震動と構造物の被害の関係を検討するための非常に貴重かつ有用な資料が提供された．

本報では，鉄筋コンクリート造学校建物を中心に行った被害調査の概要を述べ，1999年台湾集集地震で観測された強震記録を用いた，鉄筋コンクリート造建物の地震応答解析を行い，今回記録された地震動の性質，破壊力，既往の強震記録との比較，実際の被害と応答解析結果の対応性について検討した．

その結果，被害が大きかったのは，震源から5kmほど北西の中寮，車籠埔断層から東に10〜20kmほど離れた東勢，埔里，國姓で，車籠埔断層近傍は，石岡，霧峰でやや大きな被害があったが，それ以外は，断層直上を除いては，さほど大きな被害はなかったこと，この結果は，一自由度系を用いた弾塑性地震応答解析から説明できること，特殊な要因で発生したと考えられる記録を除けば，公開された記録の中では車籠埔断層から東に20km以上離れた，埔里における記録が最も大きな破壊力をもち，実際の被害とも対応するが，1995年兵庫県南部地震の破壊力よりは，かなり小さいこと，地震動の破壊力の指標として，既往のものより，周期1秒の弾性応答が適していること，調査した鉄筋コンクリート造学校建物の被害と地震応答解析結果は，非構造煉瓦壁を考慮すれば，ほぼ対応することがわかった．

キーワード：1999年台湾集集地震，地震応答解析，Takedaモデル，最大応答塑性率，必要耐力