STRONG MOTION CHARACTERISTICS NEAR THE SOURCE REGION OF THE HYOGOKEN-NANBU EARTHQUAKE FROM ANALYSES OF THE DIRECTIONS OF STRUCTURAL FAILURES

Kentaro MOTOKI[1] And Kazuoh SEO[2]

SUMMARY

More than 20,000 structures were damaged during the 1995 Hyogoken-Nanbu Earthquake. The causes of fatal damages have been already carefully studied and reported. However, quantitative analysis of the structural failure is still difficult. Our purpose is to observe directions of structural failure in Kobe City, to understand how strong motion affected damaged structures.

First, we found the following phenomenon: In the western part of Kobe City, structures collapsed toward the southeast direction, but in the eastern part of the city, they collapsed toward the opposite one.

Second, to explain the regularity of the structural failures, nonlinear response analyses with SDOF models were performed with strong ground motion obtained around the source region. The response was characterized by an impulsive large displacement. As a result, the response amplitude in the normal component to the fault strike is much larger than that in the parallel component, and such tendency was consistent with failure direction of structures. It was concluded that structural damage were typically caused by the implusive motion.

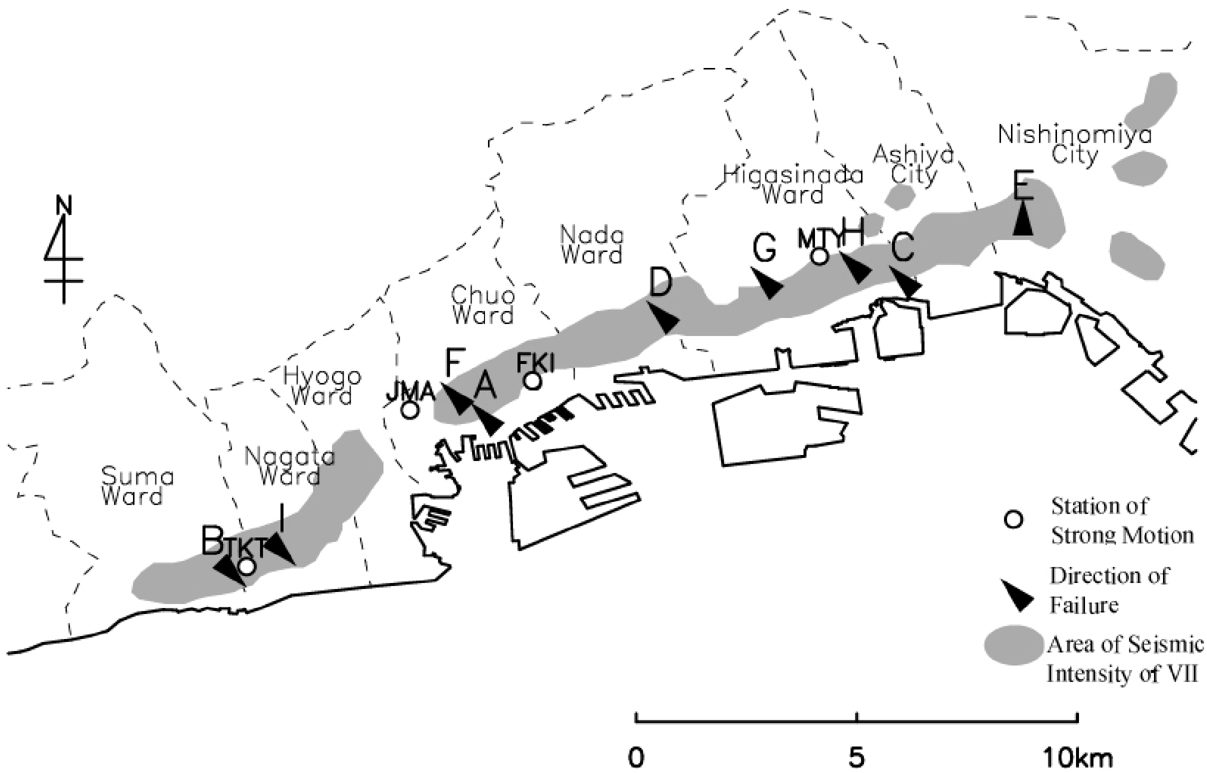
INTRODUCTION

The 1995 Hyogoken-Nanbu Earthquake caused heavy damages near the source region. Especially, the areas called as “earthquake damage belt” were suffered the greatest damage by the strong shaking. It is important to understand the reason why structures were damaged so heavily and why structural damage was concentrated in a specific zone in Kobe City. It seems very essential to prepare for such earthquake disasters in the future. In this paper, focussing the direction of structural failure, which component of strong motion was the most destructive against structures is discussed based on response analyses.

THE DIRECTIONS OF STRUCTURAL FAILURE

As it is well known, the municipality office No. 2 of Kobe City was collapsed in intermediate story (6th story). The upper stories displaced toward the northwest without the displacement toward the opposite direction. It is quite clear because the bridge at 8th story just fell down without crashing by compress or share force. The Hanshin Highway fell down toward the northwest direction along 600 meters in width. Such that, the direction of structural failure is determined by the behavior of the upper stories. The direction of systematic failures shown in Fig.1 reveals remarkable regularity on respective damaged areas: structures collapsed toward the southeast direction in the western part and toward the northwest in the eastern part of Kobe City. We investigated these feature patterns for 113 wooden structures and 66 non-wooden structures and about half number of structures were collapsed toward the same direction as stated. Since school buildings are uniform in floor design, in

[1] *Dept. of Built Environment, Tokyo Institute of Technology, Japan, fax: +81-45-924-5502*
[2] *Dept. of Built Environment, Tokyo Institute of Technology, Japan, fax: +81-45-924-5502*



A: Kobe City Office
B: Trains at Takatori Station
C: Hanshin Highway
D: Utility pole at Rokkomichi Station
E: Shukugawa Apartment
F: NHK (Japan Broadcasting Corporation)
G: Coffee shop
H: Kobe Commercial High School
I: The 3rd Motoyama Primary School

Figure 1 The Distribution of Observed Strong Motions and the Directions of Systematic Structural Failure

Photograph 1 Kobe City Office (from northwest, left), The Bridge of KobeCity Office (middle), Hanshin Highway (from north east, right)

in floor design, in location around playground like L or U character in shape and away from next building enough not to hit each other during earthquake, we surveyed such school buildings so as to discuss the directions of failures in detail. Although some of school buildings were failed without regularity, subsidence and remaining walls were found in such cases [AIJ 1997]. However, we identified that buildings in the 3rd Motoyama Primary School and in Kobe Commercial High School were failed toward the same direction to regularity without ground failure. Furthermore, it was reported that wooden houses collapsed toward the same direction [Matsuda, T. *et al.* 1995]. The regularity among the direction of failure implies that these structures suffered not from cyclic motions, but from some impulsive motions during the earthquake. Because the cyclic motion will provide possibility of structural failures for the both direction as same.

DIRECTIONAL CHARACTERISTICS OF STRONG MOTION BASED ON RESPONSE ANALYSES

Strong motion records were obtained in the source region (see Fig.1) and 2 stations are located in the area of seismic intensity of VII in the JMA scale. We performed response analysis of SDOF model with the records to explain the direction of structural failures. We assumed that damage level can be explained by maximum ductility factor. We applied Takeda model [Takeda, T. *et al.* 1970] to analyze response deformation assuming viscous damping ratio and exponential index of slope of unloading curve as 0.05 and 0.5, respectively. Base shear coefficient can be justified accordingly to provide a maximum ductility that was assumed as 5, as illustrated for the fault normal component and the fault parallel component in Fig. 2. In all of stations, base shear coefficients for the fault normal direction were larger than these for fault parallel direction in the period range between 0.2 and 1.0 second. Therefore, it is found that the strong motion in the fault normal component is more destructive against structures than that in the fault parallel direction. These characteristics correspond to the regularity of failured direction. Then, the further discussions will be focussed on the component of the fault normal component.

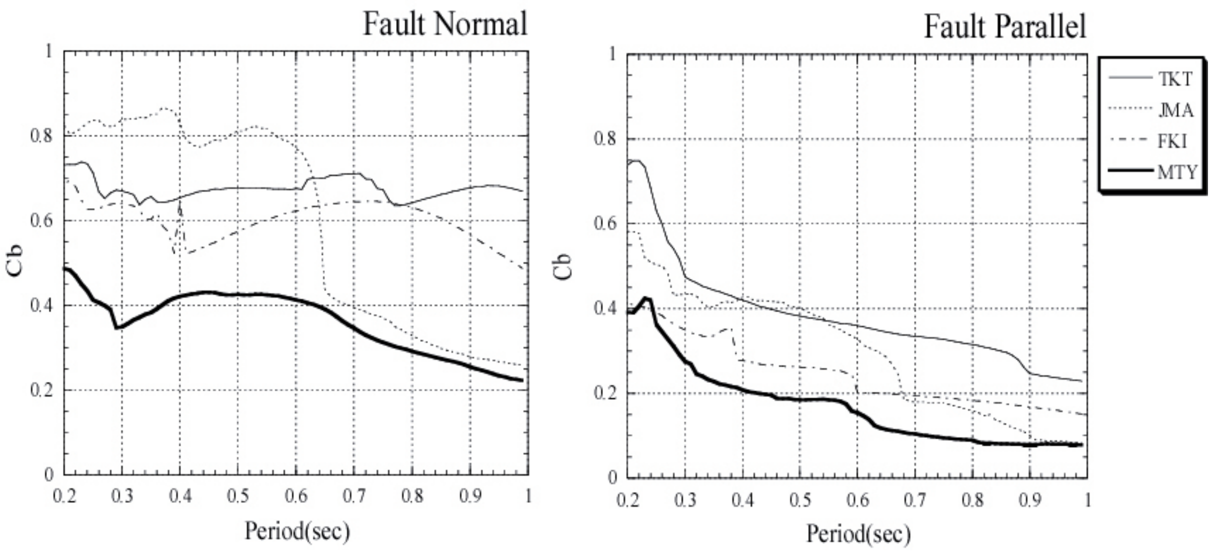


Figure 2 The Base Share Coefficient Justified to Provide a Maximum Ductility that is assumed as 5 of TKT, JMA, FKI and MTY Stations.

In the case that the ductility factor is assumed as 1, 2, 3, 5 and 10, the base share coefficients for TKT and FKI are illustrated in Fig.3. At that time, the ratio of maximum deformation in the northwest direction to the maximum one in the southwest direction is represented in Fig. 4. Namely, when it is larger than 1, the structure system is deformed toward the northwest direction. On the contrary, when the ratio is smaller than 1, the system is deformed toward the opposite direction. With a smaller ductility factor such as 1 (thin solid line in Fig.4), directional characteristics of strong motions are not recognized so clearly because plastic deformation drift is not developed and the response behavior is similar to a response of elastic system. With a larger ductility factor such as value is 5 or 10 (thick solid and dashed lines in Fig.4, respectively), the deformations of JMA, FKI and MTY stations are developed toward northwest direction and the deformation of TKT station is developed toward the southeast direction.

Such procedure is under the assumption that the structure is able to resist to strong shaking without failure and is evaluated only by the maximum response without taking into account the behavior in time domain. The response in displacement as illustrated in Fig. 5 in time domain shows rapid increase. The process of growing plastic drift is checked in Fig.5 in order to make clear which component of the strong motion is the most effective one.

According to time duration in Fig. 5, the specific motions marked by arrows quickly develop the deformation in most of the period range.

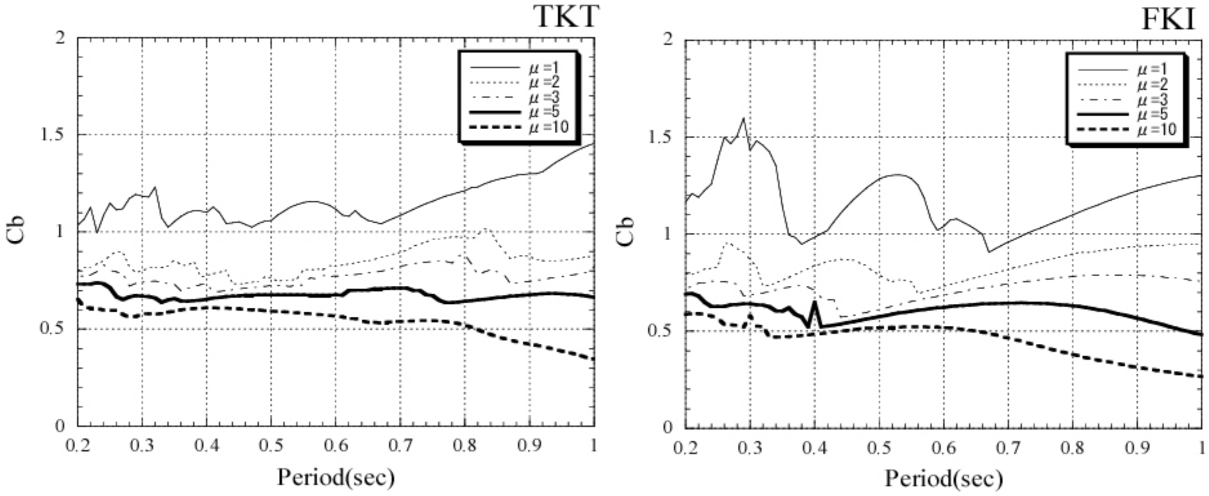


Figure 3 The Base Share Coefficient Jusified to Provide a Maximum Ductility that is assumed as 1, 2, 3, 5 and 10 of TKT and FKI Stations.

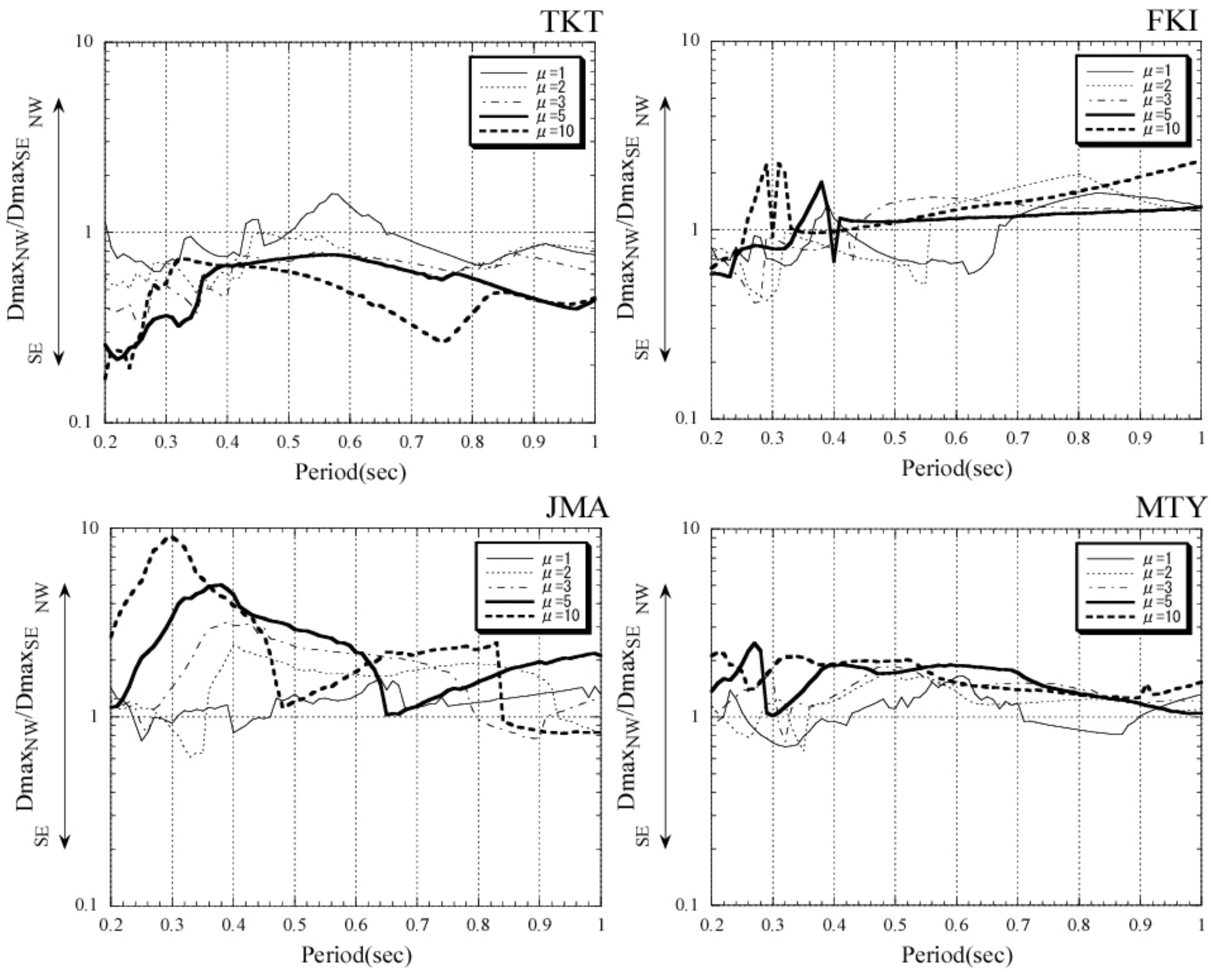


Figure 4 The Ratio of Maximum Deformation toward the Northwest Direction by the Maximum one toward the Southeast Direction

DISCUSSIONS

The directional characteristics of observed strong motion based on the response analysis are coincident with the directions of actual structural failures during the earthquake. But real structural systems may have characteristics

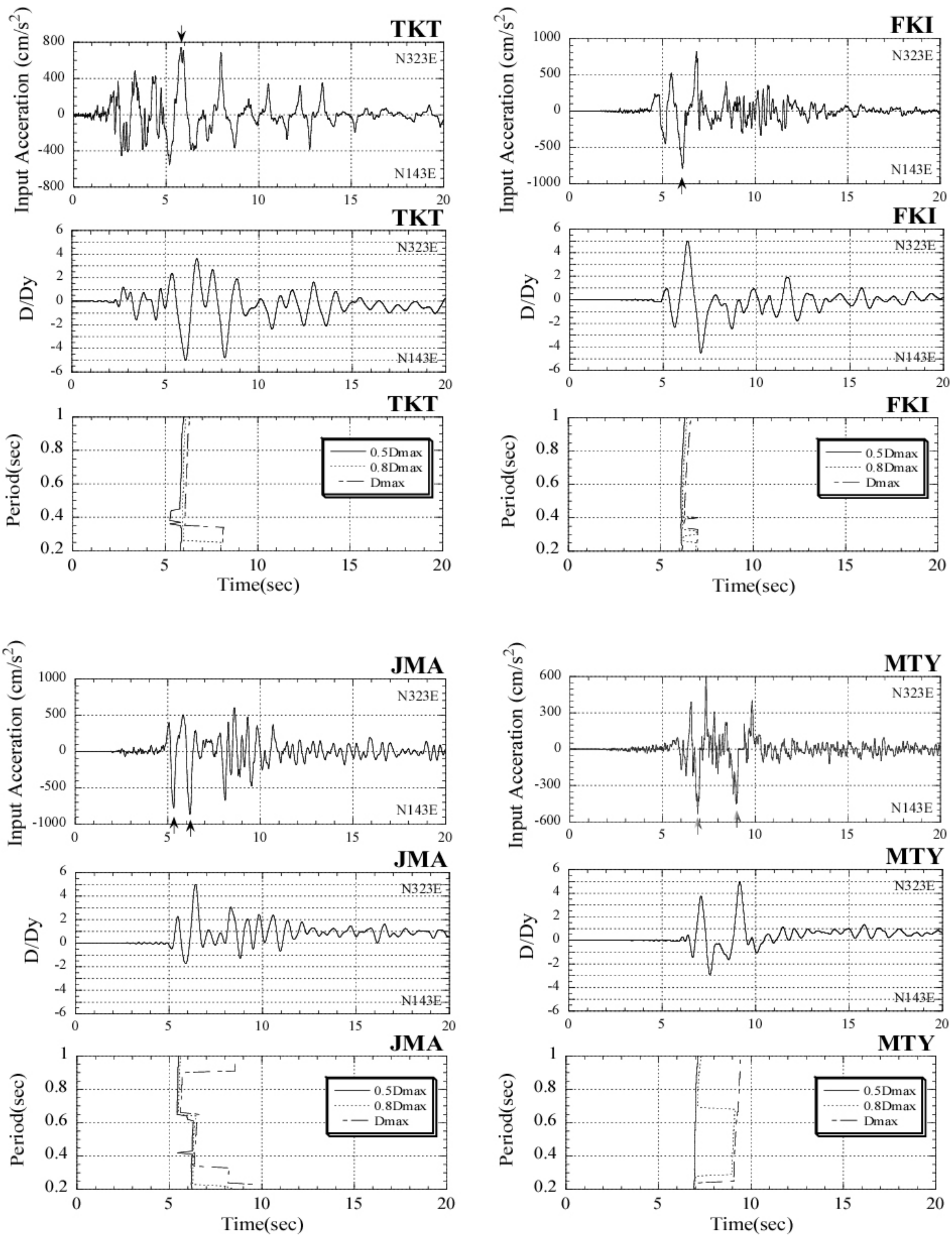


Figure 5 The Response in Displacement of SDOF with the Natural Period of 0.5 Second and the Occurrence Execeeding the Displacement of 0.5 Dmax, 0.8 Dmax and Dmax, Respectively, with assumed ductility as 5

to reduce restoring force before being collapsed because of P-Δ effect, brittle fractures and so on. In the situation to reduce restoring force, the structural system tends to be damaged more inclined toward one direction than the system without reduction. In this point, the real system will be affected by ground motion by directional characteristics of ground motions. Extensible structures that do not have enough strength to resist for earthquake, wooden houses for example, might be collapsed toward the specific direction, while stiff and brittle structures were not failed so much but having no directional response by strong motion during the Hyogoken-Nanbu earhtquake. Especially, most of typical school buildings were strong enough to resist with slight damage even in severe damaged zone [Committee of Education 1998]. Damaged buildings in school were caused by bad soil condition and foundation or fragile because of additional construction to upper stories without strengthening columns and beams. In the latter case, the buildings were brittle and insufficient to sustain. The damaged buildings must have possessed lower assumed base shear coefficient in Fig. 3. Therefore, the damaged buildings tend to be suffer toward the specific direction. It is reasonable that structural damages were caused not by cyclic motions, but by impulsive motions.

CONCLUSIONS

We classified structural failures by its direction from photographs and made response analysis using SDOF model for observed strong motions. The followings were concluded.

1 We found a very systematic feature concerning structural failures during the Hyogoken-Nanbu earthquake. Structures were collapsed toward the southeast direction in the western part of Kobe City and structures were collapsed toward the opposite direction in eastern part of Kobe City.

2 According to the results of response analyses, the directional regularity structural failure could be explained very well. Structural system has lower resistance, the directional characteristics of strong motion appeared more clearly. We pointed out that impulsive component caused structural failures.

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REFERENCES

Architectural Institute of Japan (1997): Report of survey damage of reinforced concrete buildings by the 1995 Hyogoken-Nanbu Earthquake public building division (in Japanese)

Committee of Education of Kobe City (1998): Memorials of restoration and reconstruction of damaged schools and kindergartens on the Great Hanshin-Awaji Earthquake (in Japanese)

Inoue, R. *et al*. (1996): A Detailed Survey on the Damage of Buildings during the Hyogoken Nanbu Earthquake (Kobe) Earthquake with References to Aftershock Data and Geology, 11th WCEE

Kitamura, H. *et al*. (1998): Research of Structural Damage in the Hyogoken-Nanbu Earthquake Estimation of Seismic Energy Input Based on Damage of Structures, Journal of Structural and Construction Engineering Vol.503 (in Japanese)

Matsuda, T. *et al*. (1995): Collapsed directions of wooden houses by the Hyogo Nanbu Earthquake, The Proceedings of Symposium on the Great Hanshin-Awaji Earthquake and its Geo-Environments (in Japanese)

Motosaka, M. *et al*. (1996): Analysis on Amplification Characteristics of Ground Motions in Kobe City Taking Account of Deep Irregular Underground Structure –Interpretation of Heavily Damaged Belt Zone During the 1995 Hyogoken-Nanbu Earthquake-, Journal of Structural and Construction Engineering Vol.488 (in Japanese)

Takeda, T. *et al*. (1970): Reinforced concrete response estimates of earthquakes, Journal, Structural Division, ASCE, Vol. 96