CYCLIC RESPONSES GENERATING A CRITICAL DAMAGE OF REINFORCED CONCRETE STRUCTURE DURING AN INTENSE EARTHQUAKE GROUND MOTION

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SUMMARY

In the recent damaging earthquakes such as the 1994 Northridge, California and the 1995 Hyogo-ken Nanbu, Japan earthquakes, intense earthquake ground motions have been obtained. Cyclic inelastic responses that produce a critical damage for a reinforced concrete structure are examined and discussed. Analytical models are established representing either flexural yielding or shear failure. In analysis, employed are real earthquake strong ground motions and synthetic earthquake motions as well. Establishing that a structure suffer a critical damage or collapse when the cyclic inelastic responses will be greater than specified, evaluated are both the number of occurrence of inelastic response flow and development of inelastic responses produced when the structure remains beyond the stiffness deteriorated point. One can find the evidence indicating that during intense earthquake ground motion, the structure leads to critical damage following a certain times of occurrence of yielding, showing the cyclic inelastic response increased greater than the specified critical response. Utilizing the results obtained herein, the mechanisms of a critical damage and/or collapse of a reinforced concrete structure during a damaging earthquake ground motions are discussed, focusing on both the number of occurrence of inelastic response flow and development of inelastic responses obtained when subjected to intense ground motions.

INTRODUCTION

In recent damaging earthquakes such as the Kushiro-oki, Japan earthquake (M=7.8) of January 15, 1993, the Northridge, California earthquake (M=6.7) of January 17, 1994 and the Hyogo-ken Nanbu, Japan earthquake (M=7.2) of January 17, 1995, ground motion records are obtained of which peak acceleration amplitudes is great. Some records show the peak acceleration nearly equal to or greater than the acceleration of gravity: i.e., greater than 980cm/s^2. The peak velocity of motion is great as well. During these earthquakes, a large number of both building and civil structures have suffered from critical and serious damages. Some of those structural systems have been heavily damaged, and some completely collapsed down.

In this study presented herein, evaluated and discussed are cyclic inelastic responses of a reinforced concrete structure obtained when subjected to intense strong earthquake ground motions. A structure can be critically damaged or collapsed against a seismic action when a large amount of inelastic response is generated producing large deformation and/or deflection within the structure. Within the discussion, cyclic inelastic responses are examined from a point of view that in what manner a structure will increase the response generating an excessively large inelastic response yielding a structure a critical damage. Employing real strong earthquake motions and a set of synthetic earthquake motions as well, numerical analysis has been conducted. Within the analysis, (1) the number of occurrence of inelastic response flow beyond the stiffness deteriorated point, and

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(2) the development of inelastic response within the corresponding response flow is evaluated. Utilizing the results obtained herein, the mechanisms of a critical damage and/or collapse of structure are examined and discussed, focusing on both the number of occurrence of inelastic response flow and development of inelastic responses within the corresponding flow of a reinforced concrete structure. [Kubo et al., 1998]

ANALYTICAL PROCEDURE

Analytical Steps

A structure is considered heavily damaged and/or collapsed down when the amount of inelastic response of structure to be greater than the prescribed quantity. A structure suffers from a critical damage when the total amount of cyclic inelastic response becomes greater than specified.

A structure will be represented by a single-degree-of-freedom (SDOF) oscillating system. Within the analysis, emphasis is placed upon the following two responses of structure. The one is the number of occurrence of inelastic displacement response flow beyond the yielding point: i.e., the number of occurrence of yielding of the structure. And the other is the magnitude of inelastic displacement response flow beyond the yielding point: i.e., the amount of development of inelastic response within the corresponding flow. The responses of the number of occurrence and magnitude of inelastic response are examined from the following viewpoints. How many times of cyclic inelastic responses are essentially generated when a structure suffers from a critical damage? In what manner will a structure suffer critically damaged and/or collapsed producing a large inelastic response?

Analytical Modelling of Structure

A reinforced concrete structure is employed. The primary curve of the system is described by the tri-linear model, reflecting both cracking and flexural yielding or shear failure mode of structure. Two types of hysteresis model are prescribed. The one is the so-named Takeda hysteresis rule that represents well the flexural yielding mode, and the other the Origin-Oriented hysteresis rule that represents the shear failure mode of a structure.

For discussion herein, the following two system parameters are prescribed. The one is the stiffness of structure, determined from the fundamental period of the system. The other is the stiffness beyond the flexural yielding or shear failure point of the structure. In this study, the fundamental periods are taken for 0.2, 0.4 and 0.8 seconds, representing a low-rise stiff, an intermediate-rise intermediately rigid, and a high-rise flexible structure, respectively. The stiffness beyond the flexural yielding or shear failure point is determined as for the ratio of the stiffness beyond the point (k_3) compared to the initial stiffness (k_1) to equal 1/1000 and 1/50. The stiffness ratio of 1/1000 indicates the tendency that the structure deteriorates completely its stiffness when the response falls beyond the point, while that of 1/50 indicates the fact that the stiffness deteriorates gradually beyond the point. As a result, a set of twelve analytical models are established: i.e., two cases for hysteresis models, three cases for stiffness of structure, and two cases for stiffness beyond the flexural yielding or shear failure mode point.

Conditions for Critical Damage

A structure will suffer from damage with increase of inelastic responses. Herein the study, the structure is judged critically damaged when it produces an inelastic response, the ductility factor of which falls in the range greater than prescribed. The critical ductility factor prescribed herein is 10 for a stiff structure, 5 for an intermediately stiff structure, and 3 for a flexible structure, respectively. The conditions prescribed herein indicate the tendency that inelastic deformation critical to the damage of structure is determined from the response expressed in the term of ductility factor and, simultaneously, the magnitude of inelastic response as well.

Structural Model for Analysis

To evaluate responses subjected to an intense earthquake ground motion, a SDOF oscillating system is employed. The mass m of the system is taken unity as $1.0kg$, the spring constant k will be determined from the prescribed fundamental periods of 0.2, 0.4 and 0.8 seconds. The property of dashpot c is determined for the fraction of critical damping to be equal to 0.05.

The primary curve of the system is uniquely determined from the following three system parameters: (1) the flexural yielding or shear failure strength of the structure is specified as 3.0N; (2) the cracking strength of the structure is taken as one-third of the flexural yielding or shear failure strength, i.e., 1.0N; and (3) the ratio of the secant stiffness obtained for the flexural yielding or shear failure point to the initial stiffness is prescribed as 1/4. Both initial stiffness and stiffness beyond the flexural yielding or shear failure point are prescribed as analytical parameters.

RESPONSES OBTAINED WHEN SUBJECTED TO REAL STRONG EARTHQUAKE MOTIONS

Earthquake Strong Ground Motions Utilized in Analysis

The following seven real earthquake strong ground motions are utilized in analysis: the El Centro S00E component (ELC NS) during the 1940 Imperial Valley earthquake; the Taft S69E component (TFT EW) during the 1952 Kern County earthquake; the Hachinohe Harbour EW component (HCH EW) during the 1968 Tokachi-oki earthquake; the Tohoku University NS component (THU NS) during the 1978 Miyagi-ken Oki earthquake; the Kobe JMA NS component (JMA NS) during the 1995 Hyogo-ken Nanbu earthquake; and the Izumi NS component (IZM NS) and the Miyanojyo NS component (MYJ NS) during the 1997 Kagoshima-ken North-West earthquake. The acceleration response spectrum diagrams for these motions are illustrated in Figs. 1(a) and (b).

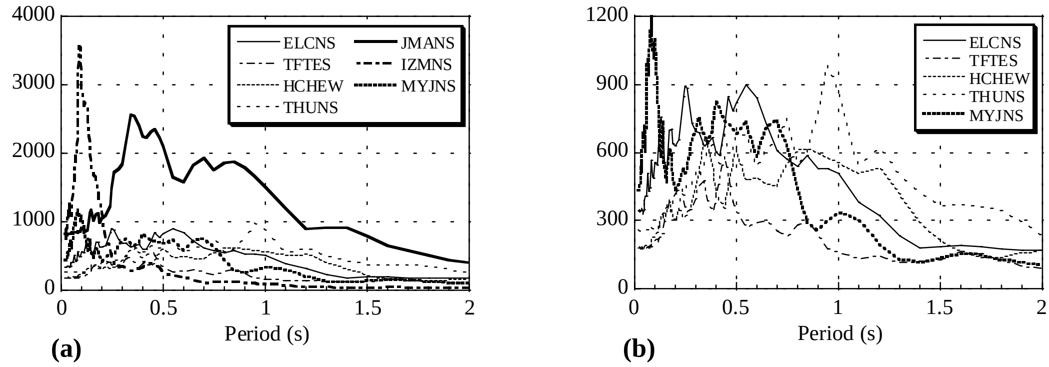


Figure 1: Acceleration response spectrum diagrams of the real earthquake strong ground motions: (a) spectrum diagrams for the seven real strong ground motions; and (b) spectrum diagrams for the five real strong ground motions excluding the JMA NS and IZM NS components.

Evaluation of Cyclic Inelastic Responses

The responses are evaluated subjected to the real strong ground motions. The amplitudes of acceleration are normalized in each ground motion record for the inelastic response to yield the critical response: i.e., inelastic response expressed in terms of ductility factor of 10, 5 and 3 for the structure whose fundamental period equals 0.2s, 0.4s and 0.8s, respectively. Note that the amplitudes of peak ground acceleration are not identical with one another among the cases discussed herein. Table 1 tabulates the magnification coefficients determined for analysis upon structures whose fundamental period is specified to be 0.4 seconds.

TABLE 1: Magnification Coefficients for Acceleration Amplitude: Fundamental Period of Structure = 0.4 seconds

Hysteresis Model	Takeda Model (Flexural Yielding Structure)		Origin-Oriented Model (Shear Failure Structure)	
Stiffness Ratio (k_3/k_1)	1/1000	1/50	1/1000	1/50
ELC NS	2.56	2.80	1.51	1.97
TFT EW	5.67	5.59	2.38	2.77
HCH EW	1.90	2.02	1.01	0.98
THU NS	1.67	1.81	0.84	0.77
JMA NS	1.07	1.01	0.37	0.41
IZM NS	14.81	16.06	8.51	8.46
MYJ NS	2.55	2.68	2.78	3.58

Magnification coefficients in the columns of the Takeda model are generally greater than those in the columns of the Origin-Oriented model. The coefficients in the columns for stiffness ratio 1/50 are greater than those for the ratio 1/1000. For the response in which a greater magnification coefficient is evaluated, a higher level of excitation shall be needed for the structure to produce cyclic inelastic responses generating critical damages.

Results for Flexural Yielding Mode Structures

The results obtained for the flexural yielding mode structures are summarized in Figs. 2 through 7. Figures 2, 4 and 6 show the number of occurrence of inelastic response flow beyond the yielding point for the structures of which fundamental periods are 0.4s, 0.2s and 0.8s, respectively. The axis x designates the number of occurrence of response flow generating a large amount of inelastic responses. The dark-shaded and thin-shaded lines represent the results in the case that the stiffness ratio k_3/k_1 are taken to be 1/1000 and 1/50, respectively.

In Fig. 2, the result shown by the dark-shaded line obtained for the JMA NS is 3. The structure experiences three times of inelastic displacement flow, reaching the specified critical damaging response. When the structure whose mode is flexural yielding and stiffness ratio k_3/k_1 equals 1/1000 suffers from critical damage, it experiences three times of new development in inelastic response, when subjected to the JMA NS component.

Results for Structures of Which Fundamental Period Equal 0.4s.

Figures 3 (a) and (b) show the development of inelastic displacement within each flow, obtained when subjected to the JMA NS and IZM NS components, respectively. Note that the resultant response in terms of ductility factor falls in the value of 5 specified for a structure of which fundamental period equals 0.4s. In Fig. 3 (a), one can find the evidence that when the structure whose stiffness ratio k_3/k_1 equals 1/1000 is critically damaged subjected to the JAM NS component, it experiences an inelastic response of 4.0 in ductility factor in the positive direction, and experiences that of 4.2 in ductility factor in the negative direction, and experiences that of 5.0 in ductility factor in the negative direction, reaching the critical inelastic response. The structure suffers from three times of inelastic response flow, and it is critically damaged in the negative direction experiencing three times of inelastic response flow.

Results for Structures of Which Fundamental Periods Equal 0.2 and 0.8s.

Figures 5 and 7 illustrate the development of inelastic displacement response within each cyclic response flow for the structures whose fundamental periods equal 0.2s and 0.8s, respectively. The results shown in figures (a) and (b) are obtained when subjected to the JMA NS and IZM NS components, respectively.

Results for Shear Failure Mode Structures

A set of Figs. 8 through 13 show the results obtained for the shear failure mode structures. The legends of the figures are identical to those in Figs. 2 through 7.

RESPONSES OBTAINED WHEN SUBJECTED TO SYNTHETIC EARTHQUAKE MOTIONS

Generation of Synthetic Earthquake Ground Motions Utilized in Analysis

From the study using real earthquake strong ground motions, it has been revealed that the properties of ground motion are of significance to the cyclic responses generating critical damage for a reinforced concrete structure. Hereinafter the responses subjected to synthetic ground motions are examined of which both spectral properties and duration of motion are prescribed. It can be examined from discussion on the results how significant either the spectral content of motion or the duration of motion to the cyclic inelastic responses producing a critical damage to a reinforced concrete structure.

The following three types of synthetic motion are generated as tabulated in Table 2. Ten waveforms in each type are produced. Since the possible type of synthetic motion is considered not realistic whose dominant period of motion is long, while duration of motion is short, the three types, Type-A through C in Table 2, are examined. The spectral contents of motion are specified as shown in Fig. 14, and the duration of motion is prescribed by using the Type B and Type C envelope functions introduced by Jennings and others [Jennings et al., 1968] for Types-A and C and Type-B motions, respectively.

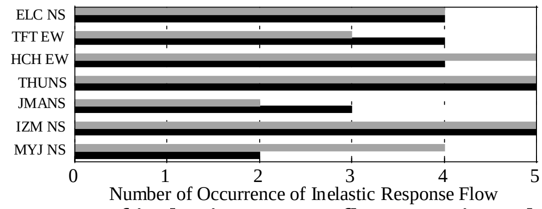
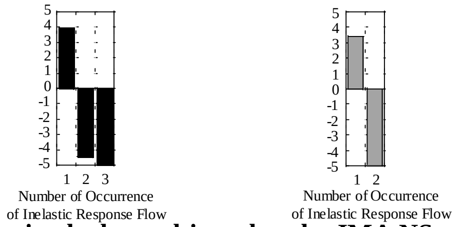
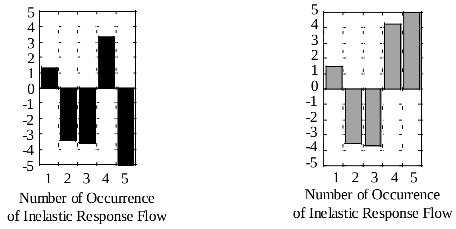


Figure 2: Number of occurrence of inelastic response flow experienced to be critically damaged: a flexural yielding mode structure; and fundamental period = 0.4 seconds.



(a) Results obtained when subjected to the JMA NS component.



(b) Results obtained when subjected to the IZM NS component.

Figure 3: Development of inelastic response experienced to be critically damaged: a flexural yielding mode structure; and fundamental period = 0.4 seconds.

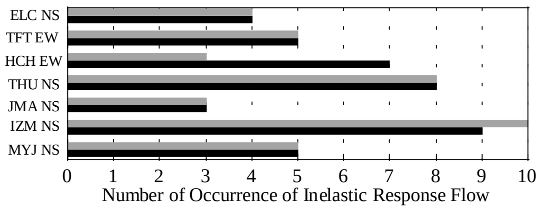


Figure 4: Number of occurrence of inelastic response flow: flexural yielding mode; and fundamental period = 0.2 seconds.

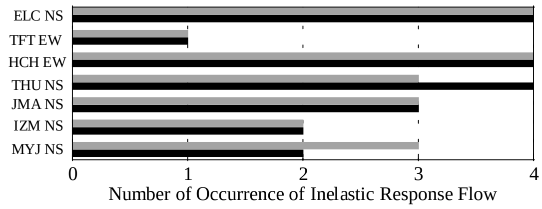
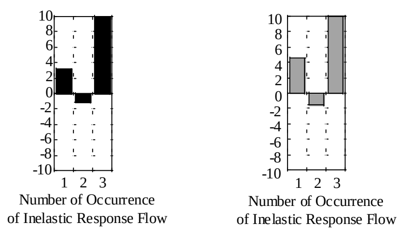
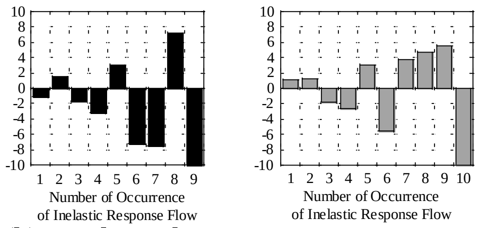


Figure 6: Number of occurrence of inelastic response flow: flexural yielding mode; and fundamental period = 0.8 seconds.

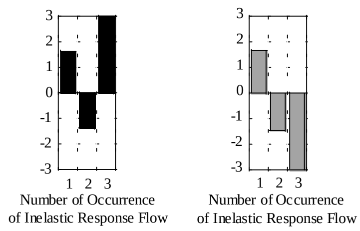


(a) Results to the JMA NS component.

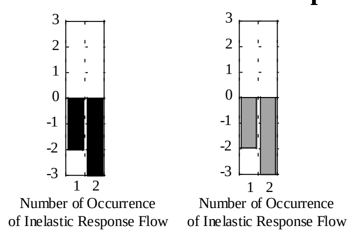


(b) Results to the IZM NS component.

Figure 5: Development of inelastic response experienced to be critically damaged: flexural yielding mode; and fundamental period = 0.2 seconds.



(a) Results to the JMA NS component.



(b) Results to the IZM NS component.

Figure 7: Development of inelastic response experienced to be critically damaged: flexural yielding mode; and fundamental period = 0.8 seconds.

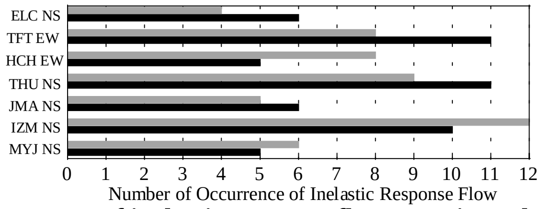
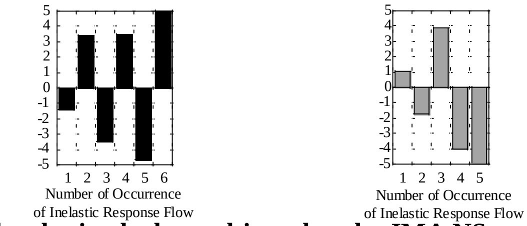
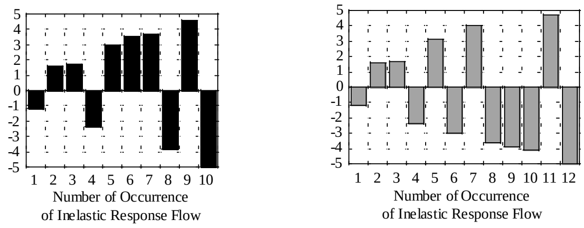


Figure 8: Number of occurrence of inelastic response flow experienced to be critically damaged: a shear failure mode structure; and fundamental period = 0.4 seconds.



(a) Results obtained when subjected to the JMA NS component.



(b) Results obtained when subjected to the IZM NS component.

Figure 9: Development of inelastic response experienced to be critically damaged: a shear failure mode structure; and fundamental period = 0.4 seconds.

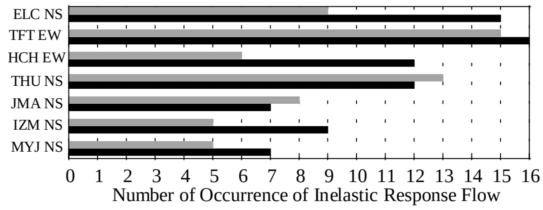
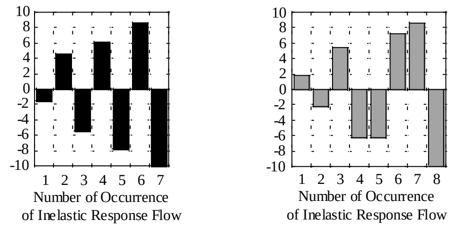
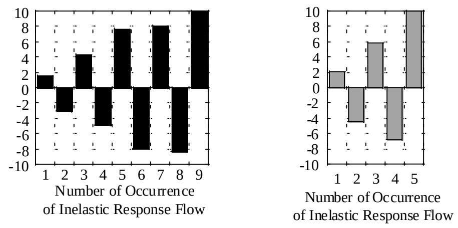


Figure 10: Number of occurrence of inelastic response flow: shear failure mode; and fundamental period = 0.2 seconds.



(a) Results to the JMA NS component.



(b) Results to the IZM NS component.

Figure 11: Development of inelastic response experienced to be critically damaged: shear failure mode; and fundamental period = 0.2 seconds.

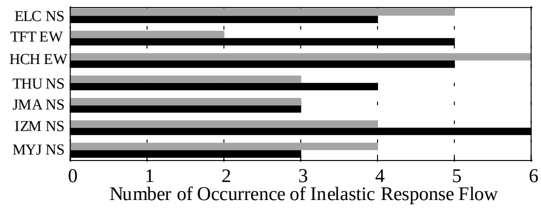
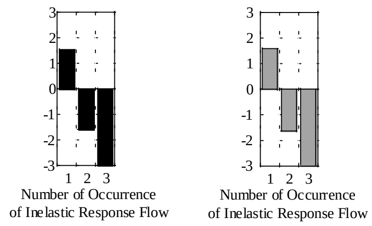
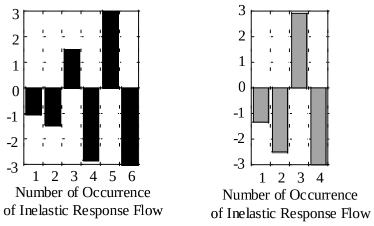


Figure 12: Number of occurrence of inelastic response flow: shear failure mode; and fundamental period = 0.8 seconds.



(a) Results to the JMA NS component.



(b) Results to the IZM NS component.

Figure 13: Development of inelastic response experienced to be critically damaged: shear failure mode; and fundamental period = 0.8 seconds.

The duration of strong motion portion of the Jennings' Type B and C envelope functions are 11 and 2 seconds, respectively. The number of cyclic excitation included in the Type-A synthetic motion is expected 5.5 times as large as that in the Type-B motion from the relation 11s/2s=5.5, and that in the Type-C motion 2.75 times as large as that in the Type-B motion. Spectral contents of the synthesized motions are illustrated in Fig. 15.

TABLE 2: Types of Synthetic Earthquake Motions

		Duration of Strong Motion Portion	
		11 seconds	Two seconds
Dominant Periods of Motion	0.2-0.4 seconds	Type-A	Type-B
	0.4-0.8 seconds	Type-C	-

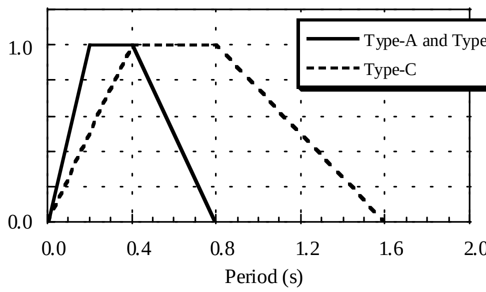


Figure 14: Prescribed Spectral Contents for Synthetic Motions.

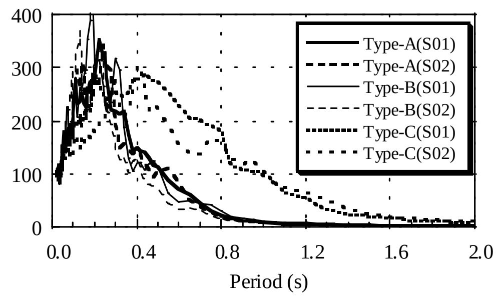


Figure 15: Evaluated Spectral Contents of the Synthetic Motions (Two in Each Case)

Results for Flexural Yielding Mode Structures

In the analysis employing synthetic motions, response are obtained exclusively for the structure whose (1) ultimate mode is flexural yielding, (2) fundamental period equals 0.4seconds, and (3) stiffness ratio k_3/k_1 equals 1/1000. The results obtained herein are illustrated in Figs. 16 through 21. The legends of the figures are identical to those in the previous sessions. The average of the number of occurrence of response flow beyond the flexural yielding point taken across the synthetic motions Type-A, B and C is shown in Fig. 22.

CONCLUDING REMARKS

Inelastic cyclic responses of a reinforced concrete structure obtained when subjected to an intense strong ground motion are evaluated. Prescribing that a structure will be critically damaged or collapsed when the inelastic response is increased, falling in the value of the specified response. Within the process of a structure damaged critically, the number of occurrence of inelastic response flow and development of inelastic responses during the corresponding flow are examined. The concluding remarks itemized in the following have been found.

(1) When subjected to real earthquake ground motions, a structure whose fundamental period equals 0.4s experiences twice to 12 times of the inelastic response flow beyond the flexural yielding or shear failure point, depending the earthquake ground motion component employed in the analysis.
(2) The number of occurrence of inelastic response flow evaluated for a stiff structure is larger than that for a flexible structure, which required for the cyclic inelastic responses of structure to be yielded the critical damaging response.
(3) The number of occurrence of flow for a shear failure structure is larger than that for a flexural yielding structure. Note that, however, a flexural yielding structure is not vulnerable compared with a shear failure structure. The intensity of ground motion required for the flexural structure to gain the specified response is almost twice as great as that for the shear structure as listed in Table l.
(4) The stiffness ratio k_3/k_1 is of less significance for cyclic inelastic responses discussed herein.
(5) When subjected to synthetic motions, the number of occurrence of inelastic response flow is found dependent upon characteristics of ground motion process. The number of occurrence evaluated when subjected to the motions with long duration of motion is greater than that with short duration of motion. The ratio of numbers, however, is not essentially equal to that of duration of intense motion portion.
(6) The rearrangement of the synthetic motions in accordance with the number of occurrence of response flow in decreasing order is Type-A, Type-C and Type-B. The rearranged order corresponds to the number of cycles of ground motion included in the synthetic motion. The ratios, however, do not correspond to the number of cycles of ground motion in a quantitative discussion.

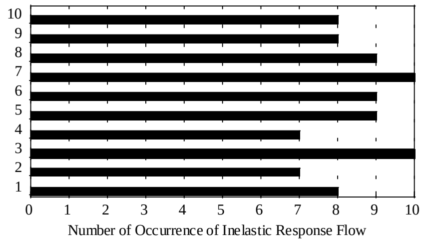


Figure 16: Number of occurrence of inelastic response flow experienced to be critically damaged obtained when subjected to the Type-A synthetic motions.

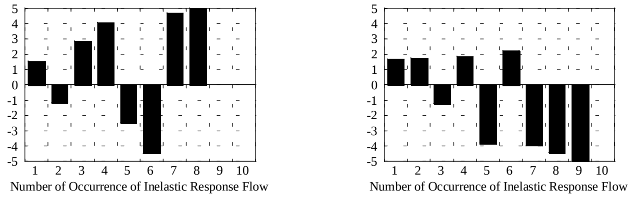


Figure 17: Development of inelastic response experienced to be critically damaged obtained when subjected to the Type-A synthetic motions.

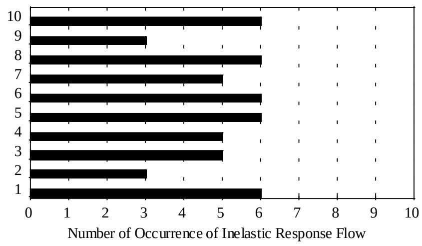


Figure 18: Number of occurrence of inelastic response flow subjected to the Type-B motions.

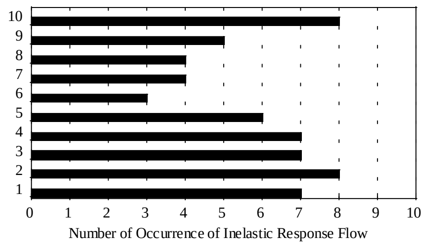


Figure 20: Number of occurrence of inelastic response flow subjected to the Type-C motions

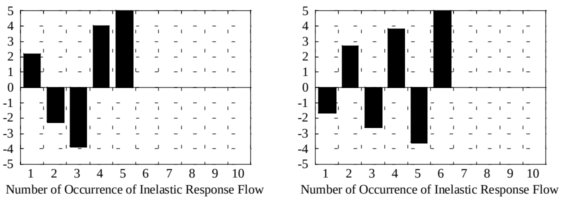


Figure 19: Development of inelastic response subjected to the Type-B motions.

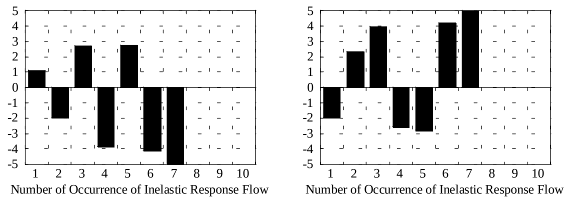


Figure 21: Development of inelastic response subjected to the Type-C motions

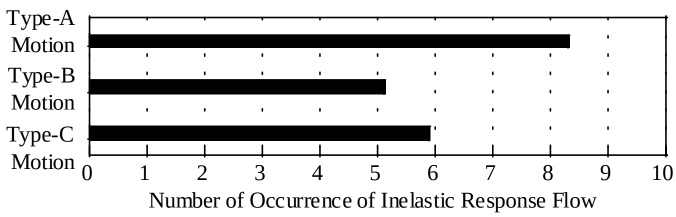


Figure 22: Average of occurrence of inelastic response flow taken across the 10 components of synthetic Type-A, Type-B and Type-C motion.

REFERENCE

Jennings, P.C., Housner, G.W. and Tsai, N.C. (1968), "Simulated Earthquake Motions", *Report of Earthq. Engng Res. Lab.*, Calif. Inst. Tech.

Kubo,T, and et al. (1998), "A note on inelastic responses of a building structural system subjected to intense cyclic loadings during a strong earthquake ground motion", *Trans. of Tokai Division Technical Meeting, Archi. Inst. Japan*, Vol. 36, pp. 201-204. (in Japanese)