

INFLUENCE OF GIRDER DUCTILITY ON THE SEISMIC SAFETY OF TWO-STORY RC VIADUCTS USING SUBSTRUCTURED PSEUDODYNAMIC TEST METHOD

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ABSTRACT

In this paper, substructure pseudo-dynamic test method is used effectively to study the influence of the member ductility provided in the first-level girder on the total seismic response of two-story reinforced concrete (RC) viaducts. From the results, it is shown that the ductility demand on the critical first-story columns can be reduced by providing the first-level girders with sufficiently large ductility. Moreover, even with eventual strength degradation or even complete failure of the 1st-level girder, seismic safety of the total structure can be ensured as long as sufficient energy absorption capacity is provided for the 1st-story girder during response in the strong earthquake duration.

KEYWORDS

Substructured Pseudodynamic Test, Reinforced Concrete Viaducts, Seismic Design, Nonlinear Earthquake Response, Ductility Demand

INTRODUCTION

In recent years, many reinforced concrete (RC) framed bridge pier structures have been constructed for expressways, commuter railways and high-speed Shinkansen railways. Unlike single piers supporting simple bridges, damage to some portions does not necessarily lead to collapse of the whole structure. In order to fully understand the seismic behavior and safety of such structures, it is necessary to understand how the characteristics (strength, stiffness, ductility, ...) of its constituent member elements affect the response of the total structure, and how the failure process progresses from each member to collapse of the total structure. However, seismic response behavior of the whole structure as well as a part of the structure such as the first-level girder is not yet completely understood. Moreover, the required strength and ductility that should be provided for each member of the structure in order to achieve a rational earthquake-resistant design of this type of structures are not yet well established.

Owing to this deficiency in our understanding of the seismic behavior of this type of structures, several framed structures constructed in Japan had been damaged, in particular during the 1978 Off-Miyagi Earthquake and most recently the January 1995 Hyogo-ken Nanbu Earthquake. During the January 1995 earthquake, many viaducts supporting the Shinkansen (bullet train) tracks were severely damaged. In many of the damaged portions, columns of the upper levels as well as the lower levels completely collapsed whereas the connecting girders at the first level did not suffer any visible damage (Photo 1).

In this paper, a pseudo-dynamic test method combining a non-linear response analysis based on one-component model with an online loading test is carried out on two-story R/C viaduct models. In order to verify the influence of first-level girder on the response properties of the whole framed structure, the first-level girder was loaded as an experimental member in order to obtain accurately the highly nonlinear restoring forces, while the response of the other members was numerically simulated. In this manner, the required strength and ductility that should be given to the first-level girder can be properly studied and identified as to how they affect the response of the total structure.



Photo 1 Damage to RC Viaducts Due to 1995 Hyogo-ken Nanbu Earthquake

SUBSTRUCTURE PSEUDO-DYNAMIC TESTING SYSTEM

Although many numerical and experimental studies have been conducted on the inelastic behavior of column members as well as girder members, few experimental researches have been done on the response behavior of complete structures in which some members may undergo extensive inelastic deformation during severe earthquake and thus affecting significantly the total response behavior and structural integrity of the complete structure. This is due to the cost and scale of conducting such large tests.

Pseudo-dynamic test method is a computer-controlled experimental technique in which direct numerical time integration is used to solve the equations of motion. The computed displacements at each step are statically imposed on a specimen through computer-controlled load actuators in order to measure its restoring forces at the current deformation state. The measured restoring forces are then fed into the equations of motion to compute the next set of displacements. In the basic pseudo-dynamic test, specimen modeling the complete system is fabricated and loaded. Incorporating substructuring concept, it is possible to test only the critical members in obtaining the inelastic seismic response of the whole structure.

A complete structural system is considered to be divided into analytical substructures and experimental substructures. Portions of the structure that are as yet difficult to model mathematically are taken as the experimental substructures. The remaining portions are taken as the analytical substructures in which presently available analytical models are applicable to describe their restoring-force characteristics. The set-up of the pseudo-dynamic test system used in this study is shown in Fig. 1.

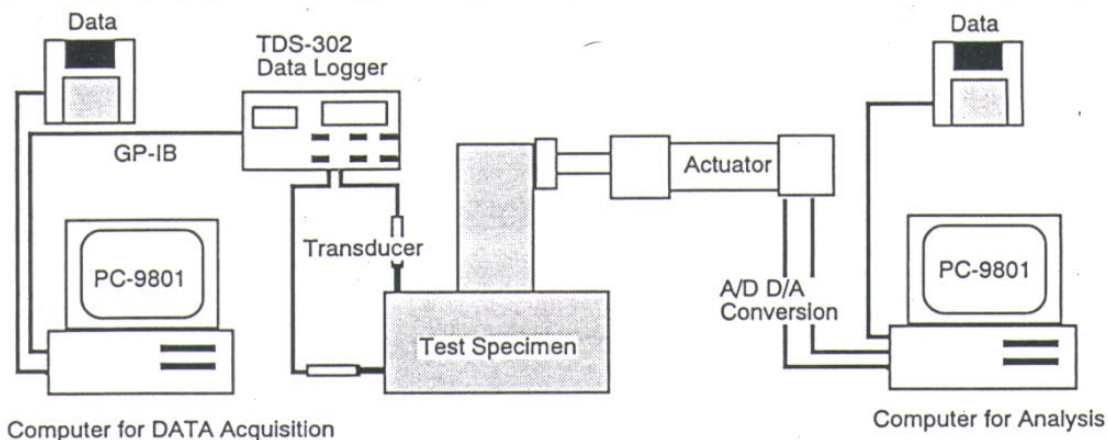


Fig 1 Setup of Substructured Pseudodynamic Test System

For numerical integration, a study has shown that a class of so-called mixed (explicit-implicit) integration methods originally developed for finite-element analysis of structure-fluid interaction has been found to be

suitable for substructured pseudo-dynamic tests. Nakashima et al (3) found that the constitutive operator splitting (OS) method is the most effective for substructure pseudo-dynamic tests in terms of both solution stability and accuracy. The numerical integration used in the previous study is improved by adopting the OS method and has been implemented in the present study. A simplified flowchart of substructure pseudo-dynamic test method adopting the OS method is shown in Fig. 2.

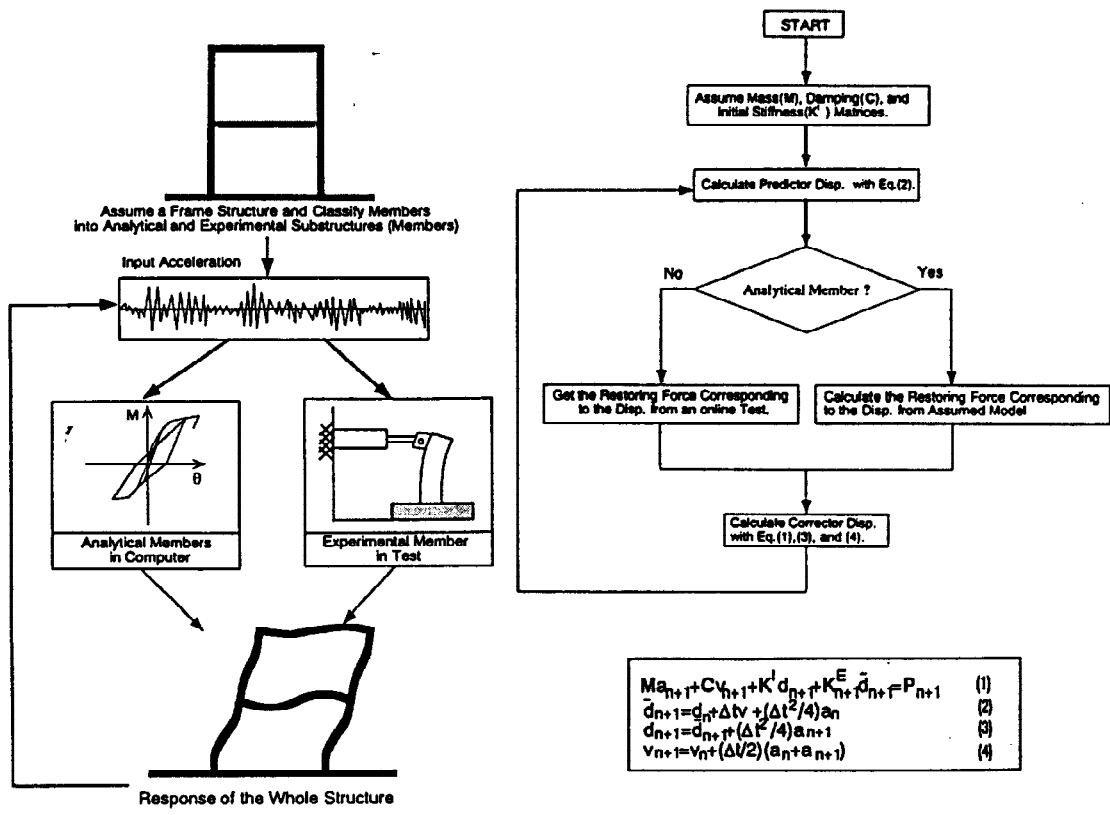


Fig 2 Procedure of Substructured Pseudodynamic Test System

EARTHQUAKE RESPONSE STUDY ON 2-STORY VIADUCT STRUCTURE

Structural Model

The structure studied is a two-story RC frame which is intended to represent a portion of the typical viaducts used in elevated railway tracks of the Tohoku-Shinkansen (bullet) trains. The scaled prototype maintained the strength ratio and the stiffness ratio of the different members as designed and constructed in the real structures. The upper girder supports the tracks and are designed to be fairly rigid. In this study, an elastic member with very large stiffness is used to model the upper girder. In contrast to some two-story bridge piers supporting two-tier lanes in expressways, the first-level girders in this type of railway viaducts are used as tie girders for the high piers.

With a very rigid upper girder and a yielding first-level girder, plastic hinges are allowed to be formed at the bottom ends of lower columns, upper ends of upper columns, and at both ends of first-level girders. With proper design utilizing the plastic behavior of the first-story girder, seismic safety of the critical columns can be enhanced. For this investigation, it is important to understand the sequence of formation of the plastic hinges and to understand how the initiation and final failure of the first-level girder affecting the total structural response.

Member modeling for each member of the 2-story framed viaduct structure is made using the so-called one-component member model in which a member is assumed to be composed of a central elastic member with inelastic hysteretic springs at the ends in which inelastic deformations are assumed to be concentrated. The effect of finite joint sizes on the member stiffness is considered. In this study, the consistent mass matrix is used and a value of 2% is assumed for each mode of modal damping. In this study, an integration time step of 0.001 second was used.

Except for the 1st-story girder which is treated as the experimental substructure, all the members were

analytically modeled using one-component member models. For the hysteretic modeling of the inelastic springs, Takeda model is used. In addition, degradation of strength is modeled based on a previous study (4) as shown in Fig. 3. For the primary skeleton load-deformation property, available member ductility is estimated using the study of Ishibashi et al (5).

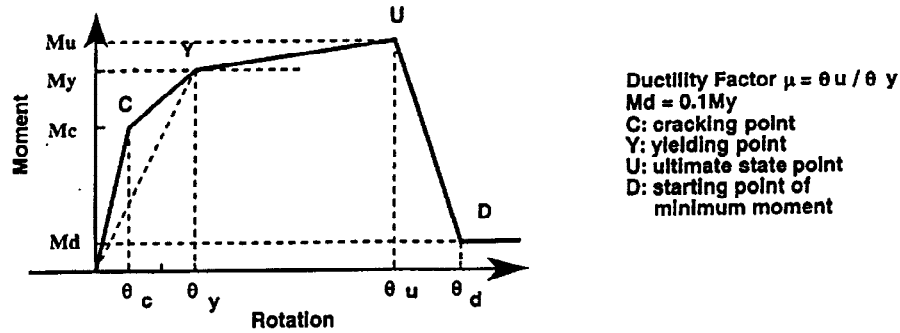


Fig 3 Primary Curve of Load-Deformation Model Considering Strength Degradation

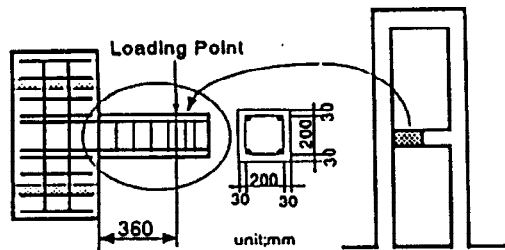


Fig 4a Frame and Test Model

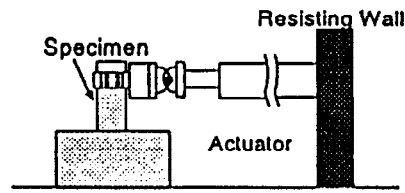


Fig 4b Setup of Test Specimen

Specimens

The first-level girder is taken as the experimental substructure (Fig. 4a) for the reason that this member is expected to undergo extensive plastic deformation with severe strength and stiffness degradation which cannot be accurately characterized by currently available analytical models. From the online loading test, an accurate restoring force based on its current deformation state can be obtained. For a linearly varying moment distribution and asymmetrical at the center, the first-level girder may be considered to be composed of identical cantilevered member satisfying compatibility and equilibrium conditions at the center. The loading setup is shown in Fig. 4b, in which a cantilevered specimen securely fixed at the base is loaded laterally at its tip by a servo-hydraulic actuator.

A total of 5 specimens were fabricated in this study, with one specimen used for cyclic loading test and four specimens for substructure pseudo-dynamic tests. Concrete strength and yield strength of the reinforcements used in the specimens are given in Table 1. All the specimens have the same geometric dimensions, but member ductility is differed by providing different amount of transverse reinforcements (Table 2). Calculated ductilities of the specimens using Ishibashi's equation (5) are 5.3 and 3.6, but these values were not necessary in the actual pseudo-dynamic tests.

Table 1 Strength of Reinforcement and Concrete

Concrete compressive strength (MPa)		34.6
yielding strength of reinforcements (MPa)	D13	372.8
	D6	399.2
	D3	235.6

Specimen CL-1 was subjected to repeated cyclic loads. The displacement amplitude for each cycle was defined by multiples of the yield displacement with 5 repetitions for each cycle. Specimens PD-1 to PD-4 were used for substructured PSD test in which effect of small and large member ductilities under different intensity of input earthquakes were compared (Table 2). In this study, 20 sec of the El Centro NS record of the 1940 Imperial Valley Earthquake was used.

Table 2 Summary of Test Variables

specimen	test type	tensile reinfo.	transverse reinfo.	pitch (cm)	calculated ductility factor	max. inp. accel. (cm/sec ²)	1st nat. period (sec)
CL-1	cyclic load.	D13	D6	8	5.3	----	----
PD-1	PSD test		D6	8	5.3	400	0.148
PD-2			D3	10	3.6		
PD-3			D6	8	5.3		
PD-4			D3	10	3.6		

Test Results

Fig. 5 shows the hysteretic load-deformation behavior of the specimen CL-1 subjected to cyclic lateral loading. It is observed that under severe loading, the specimen shows unsymmetrical plastic deformation behavior with differing levels of strength degradation in the positive and negative directions. In one direction (positive as shown in the figure), behavior typical of stable strength degradation is exhibited; while in the other direction, sudden and abrupt strength degradation typically of the shear type is exhibited. From the obtained data on strains, it is known that the main steel reinforcements had already yielded or were about to yield when the strength had degraded to about 80% of the maximum strength. From the experimental result of this cyclic loading test, ductility in the positive direction may be judged to have a value of about 5.0; but the behavior in the negative direction gives a ductility of only about 2.5. Although it is not possible to generalize using results from one test, it can be said that predicting inelastic cyclic behavior up to ultimate state is complicated and very much dependent on the nature of loading and its previous inelastic history.

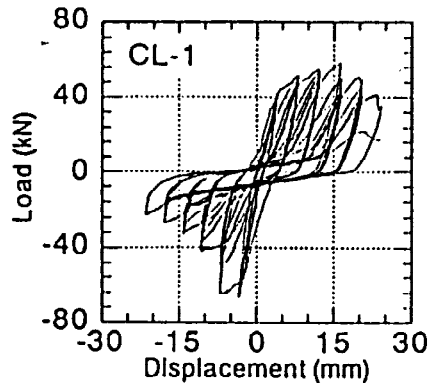


Fig. 5 Load-Displacement Behavior Under Cyclic Loading

Comparing results from PD-1 (1st-level girder has larger member ductility) and PD-2 (1st-level girder has smaller member ductility) which were both subjected to the same earthquake intensity level of 400 gal, the effects of the differences in stiffness and strength deterioration on the response of the other members as well as on the total structural response are well manifested. Fig. 6 shows the moment-rotation response of the respective first-story girders. First-level girder of frame model PD-1 has higher ductility and responded in a stable manner showing no strength degradation for the duration of the earthquake motion (Fig. 6a). On the other hand, the first-level girder of model PD-2, having a smaller member ductility, deteriorated severely in both strength and stiffness especially on the side of the negative direction (Fig. 6b). While this severe strength degradation of the girder member does not necessarily mean collapse of the total structure, it may have a large influence on the subsequent response of the other members of the structure in particular the first-story columns.

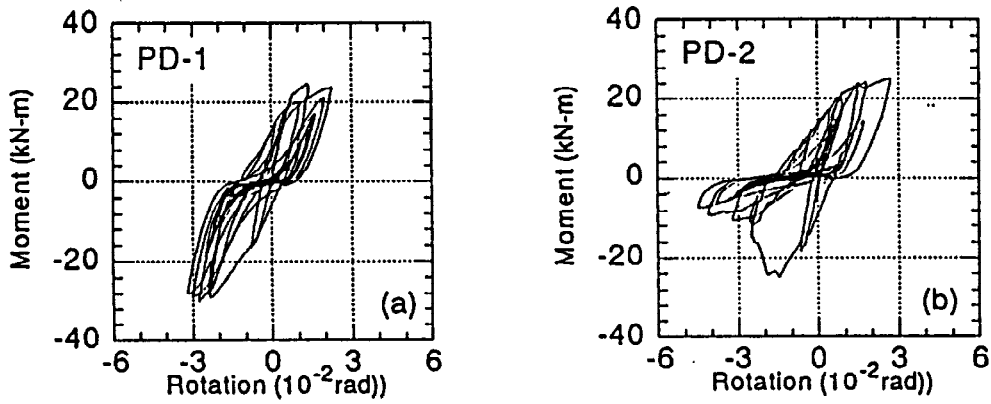


Fig. 6 Moment-Rotation Behavior of 1st-Level Girder (PD-1 and PD-2)

By comparing the respective 1st-story column response (Fig. 7) of the respective model, it is observed that a very large ductility demand was imposed on the first-story columns after severe strength degradation in the small ductility case. In the tests conducted, large ductility was numerically given to the first-story columns for the purpose of checking the effect of degrading 1st-story girders on the other members. In real structures, however, such large ductility demand may not be attainable especially in column members which are subjected to both axial and bending loads and are thereby the most critical members in the safety of the total structure. Conversely speaking, it is better to reduce the ductility demand on the critical first-story columns by providing the first-level girders with sufficiently large ductility. Moreover, even with eventual strength degradation or even complete failure of the 1st-level girder, seismic safety of the total structure can be ensured as long as sufficient energy absorption capacity is provided for the 1st-story girder during response in the strong earthquake duration.

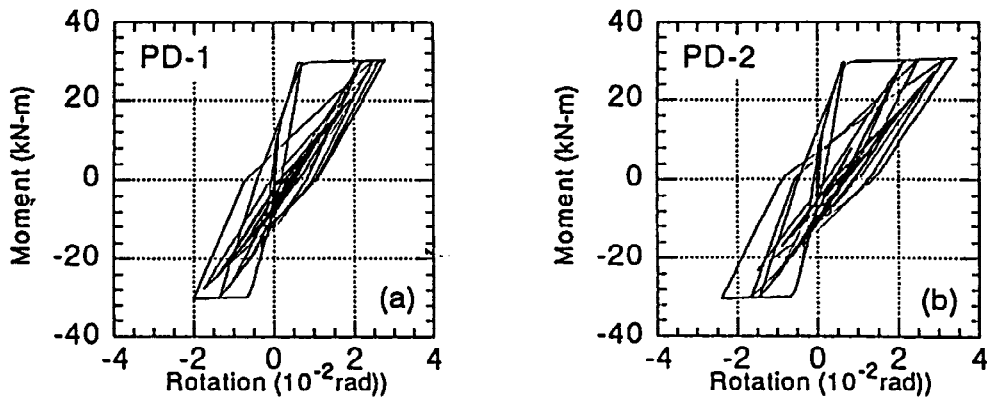


Fig. 7 Moment-Rotation Behavior of 1st-Level Pier (PD-1 and PD-2)

Fig. 8 shows the base shear-displacement response of PD-1 and PD-2. Base shear-displacement curves are usually plotted to show response of shear building model. In the case here, however, these are plotted to show the unstable effect of sudden and abrupt degradation (Fig. 8b) of the 1st-story girder even if the columns were to sustain the maximum strength capacity. Therefore, if strength degradation of 1st-story girder is to occur eventually, it will be better to design the member with stable and gentle degradation.

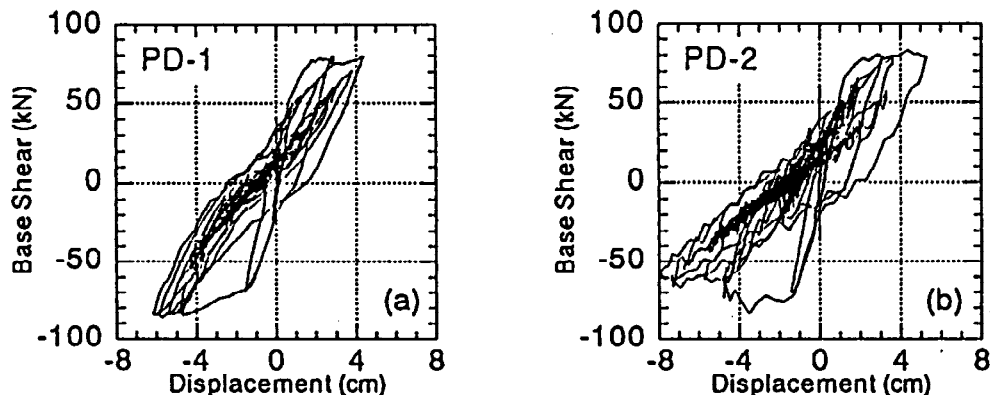


Fig. 8 Base Shear-Displacement Curves (PD-1 and PD-2)

The same set of frame models was subjected to a higher level of earthquake intensity (530 gal) for PD-3 and PD-4. The results will not be presented fully here, but are summarized along with the previous two cases in Table 3. Same as in the previous observations, the larger member ductility of the 1st-story girder (PD-3) resulted in enhancing safety of the columns even with subsequent deterioration (Fig. 9a). With a smaller ductility and subjected to a very severe earthquake, strength degradation in one direction occurs very early; and on subsequent reversal of loading to the other direction, maximum strength was never attained and resulted in a very unpredictable response (Fig. 9b) totally different from the prediction made using the skeleton curve obtained from the results of cyclic loading test (CL-1).

Table 3 Ductility Demand on 1st and 2nd Level Piers and 1st-Level Girder

specimen	1st story column (lower)		2nd story column (upper)		1st story girder	
	+	-	+	-	+	-
PD-1	4.60	3.29	4.20	2.89	2.04	2.88
PD-2	5.66	3.94	5.71	3.59	2.45	4.06
PD-3	6.20	5.66	6.17	5.51	5.28	5.91
PD-4	4.87	7.08	4.84	7.04	6.76	4.65

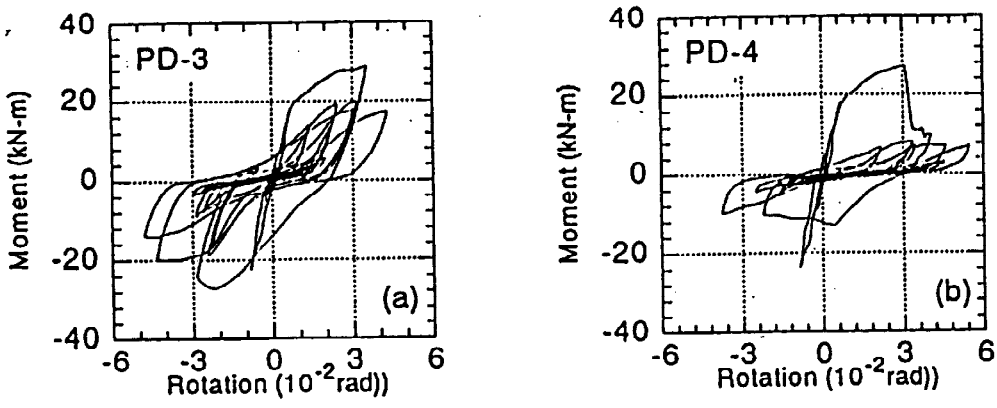


Fig. 9 Moment-Rotation Behavior of 1st-Level Girder (PD-3 and PD-4)

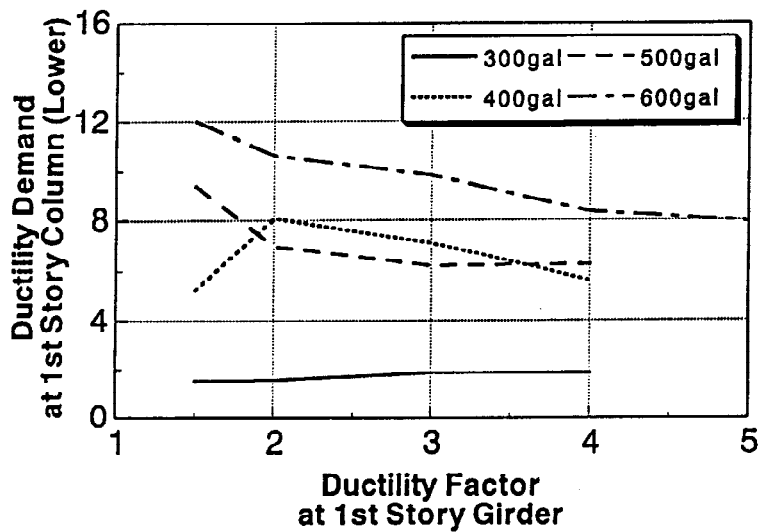


Fig. 10 Ductility Demand on Piers with Increasing 1st-Level Girder Ductility Provided

Lastly, to further investigate the influence of the ductility provided to the 1st-level girder on the ductility demand on the 1st-story piers, numerical simulations were conducted. The results in Fig. 10 shows the case of the viaduct subjected to various levels of input earthquake intensities. Although subject to the accuracies of the analytical models used, the results indicate a decreased ductility demand on the critical piers with a larger girder ductility of above 4.

SUMMARY AND CONCLUSIONS

A new technique of pseudo-dynamic test system for R/C two-story frame structures is developed in which the first-level girder is tested and the other members are analytically simulated using one-component models in obtaining the inelastic earthquake response of the whole structure. Substructure pseudo-dynamic test method is fully developed and applied to investigate the effect of member ductility of the first-level girder

on the total structural response of a two-story RC bridge pier framed structure. Compared to the previous implementation, an improved numerical integration scheme is adopted and complete experimental/numerical tests were conducted on 4 structural models subjected to strong earthquakes. Based on the test results, the following conclusions can be drawn:

- The ductility demand on the critical first-story columns can be reduced by providing the first-level girders with sufficiently large ductility. Moreover, even with eventual strength degradation or even complete failure of the 1st-level girder, seismic safety of the total structure can be ensured as long as sufficient energy absorption capacity is provided for the 1st-story girder during response in the strong earthquake duration.
- Substructure pseudo-dynamic test method is an effective and efficient tool to investigate the effect of a member undergoing extensive inelastic deformation on the earthquake response of the total structure.

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