

Seismic behavior of reinforced concrete columns and improvement by vertical prestressing

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SUMMARY

The reinforced concrete columns designed under traditional seismic codes were heavily damaged in Kobe area by 1995 Kobe Earthquake. The reason of this fact is that the earthquake was the near field earthquake. The maximum acceleration in horizontal direction was equivalent to the acceleration of the gravity. The author has proposed an idea of introducing vertical prestressing in the reinforced concrete columns from the stand point of the utilization of the inherent performance in prestressed concrete members which have superior restoration capability at unloading. This paper describes the seismic performance and design, evaluation of the damage under the near field earthquake, and the utilization of vertical prestressing in the concrete columns.

1 INTRODUCTION

The reinforced concrete columns designed according to traditional seismic design codes were heavily damaged in Kobe area by the Kobe Earthquake of 1995 (1995 Hyogoken-Nanbu Earthquake). The reason of this fact is that the earthquake of M7.2 was the near field earthquake, the epicenter of which was near Kobe City. This area was struck by a severe earthquake in 1596, about 400 years ago, which destroyed Kobe and Kyoto areas. More than 40,000 lives were said to be claimed by this 1596 Earthquake. However, this historical fact had almost been ignored so far due to the very scarce historical event. It should be noted that seismic design must be performed with reference to historical data of earthquakes in the area including more than 1000 years of seismic records.

On the other hand, the down town area of Osaka suffered by strong ground motion of Kobe Earthquake was not damaged due to the distance from the epicenter and to the structural performance designed under traditional seismic design codes. This means that the traditional seismic design codes were quite effective to the Osaka area. This fact should be much more recognized as an effect of the traditional seismic codes.

The maximum horizontal acceleration of a near field earthquake is equivalent to the acceleration of the gravity, say 981 gals, so that the structures must be designed to survive under this enormous seismic disturbance in the case of a near field earthquake. Based on the tragic experience in the Great Hanshin Seismic Disaster due to Kobe earthquake of 1995, two types of earthquake such as the near field earthquake and the distant huge interplate earthquake are considered in seismic design codes in Japan. The up-to-date seismic code will be based on the performance design criteria in which serviceability limit state and ultimate limit state of the structure during and after the earthquake are evaluated under the two types of earthquake. Ductility design of reinforced concrete structures has been adopted so far to deal with the severe earthquake by utilizing energy absorption. However, large residual deformation cannot be avoided under large plastic deformation. Hence, considering the serviceability of the structure after the earthquake, residual deformation should be limited to some extent.

The author has proposed an idea of introducing vertical prestressing in the reinforced concrete columns from the stand point of the utilization of the inherent performance in prestressed concrete

members which have superior restoration capability at unloading. The author has successfully investigated the effect of prestressing in the column against earthquake loadings to eliminate large residual deformation after the earthquake. This paper describes the seismic performance and design, evaluation of the damage in reinforced concrete columns under the near field earthquake, and the enhancement of the seismic performance of concrete columns by introducing the vertical prestressing.

2 SEISMIC DESIGN AND SEISMIC PERFORMANCE

The traditional seismic design was based on the static seismic coefficient of 0.2 of gravity in the horizontal direction in Japan after the 1923 Kanto Earthquake. After the experience of the 1978 Miyagiken-oki Earthquake, the shear design was improved in the Concrete Specification of the JSCE in 1980. In the same time the Highway Bridge Specification stipulated the ultimate strength capacity of reinforced concrete columns against an earthquake response of 1.0G (G: gravity) in the horizontal direction. It should be noted that the structures designed after 1980 based on the improved codes were found to perform well without severe damages in the Kobe Earthquake.

In 1986, JSCE revised the Concrete Specification to adopt the limit state design method in which a new seismic design rule was specified [1]. The new seismic design rule was based on the performance design criteria where the performance of the concrete structure should be considered not only for the safety during the earthquake but also for the serviceability of the structure after the earthquake. It should be noted that this rule was stipulated before the Kobe Earthquake.

After the Kobe Earthquake, the seismic design has been emphasized on the near field earthquake. In 1996 the Highway Bridge Specification stipulated the horizontal seismic response of 2.0G in maximum for the evaluation of the ultimate flexural capacity of reinforced concrete columns [2]. The specification also specified the acceptable residual deformation of one hundredth radian after the earthquake. This is quite reasonable to the serviceability of the structure after the earthquake. Designing the concrete structure safely and economically to satisfy above mentioned seismic code, introduction of seismic isolators or seismic-proof devices might be preferable. The introduction of vertical prestressing in the reinforced concrete columns is expected to be quite effective for the case.

3 EVALUATION OF FAILURES DUE TO NEAR FIELD EARTHQUAKE

The primary cause of serious failure of structures in Kobe area due to the 1995 Kobe Earthquake attributes definitely to the ultra-high intensity of the seismic ground motion which was not specified in the design codes at the time of construction. Various individual phenomena of failures such as disconnection of hoop reinforcement, large diagonal shear cracks, buckling of longitudinal reinforcement in columns, etc. were the result of mechanical behavior of failures, and are not thought to be the primary cause of the failure of the structure. Furthermore, the proper description for the collapse or falling down of structures has not always been available and even wrong description can often be seen in intuitive reports. However, it is quite important to evaluate properly the most probable behavior of failing processes in the valuable and bitter experience of the Great Hanshin Seismic Disaster for providing the future seismic countermeasure.

Here, the collapse of the expressway viaducts in Kobe, which is one of the most well-known collapse by the Kobe Earthquake of 1995 is evaluated to express the proper mechanical behavior of the collapse due to the near field earthquake. The viaduct was elevated expressway structure which was a 18-span prestressed concrete girder of Gerber type, in which piers and girders were connected as mushroom shape. The total length was 635m and each span length was 35m. The width was 20.25m and the height of the top surface from the bottom of footing was 15.0m. The typical size of the column was 3.1m in diameter of solid circular cross section and approximately 10m in height. The structure was designed for horizontal seismic coefficient of 0.2 and vertical one of ± 0.1 . The one third of longitudinal reinforcement was terminated at the height of 2.5m from the top surface of the footing.

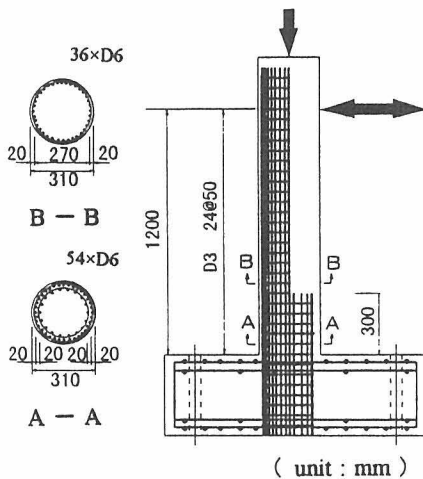


Figure 1. Specimen for pseudo dynamic test.

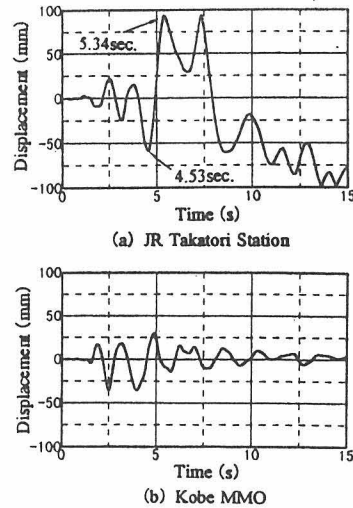
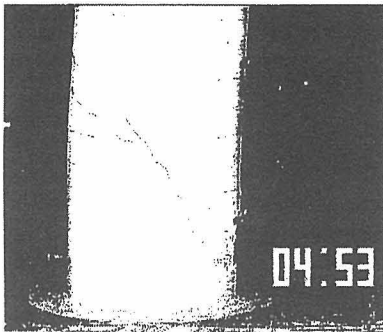
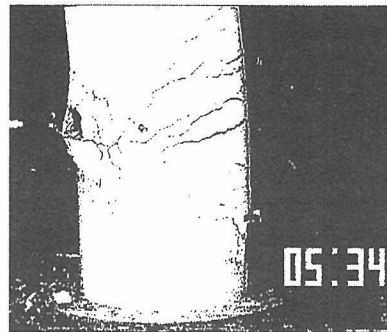


Figure 2. Experimental time history response.



(a) Time at 4.53 second



(b) Time at 5.34 second

Figure 3. Cracking behavior under Kobe MMO motion.

Fig. 1 is the test specimen which is approximately one tenth of the actual structure. Pseudo dynamic tests were performed with two acceleration records of the Kobe Earthquake, i.e., JR Takatori Station and Kobe Maritime Meteorological Observatory (Kobe MMO) the maximum accelerations of which were 666 gals and 818 gals, respectively [3].

Fig. 2 shows the experimental results of the response where (a) and (b) in the figure show the response under the seismic wave of JR Takatori Station and the one under the Kobe MMO, respectively.

Fig. 3 shows the cracking behavior of the specimen under the record of JR Takatori Station at the time of 4.53 sec. and 5.34 sec. as shown in Fig. 2a. The specimen was impaired seriously with large residual deformation and almost lost its horizontal resistance after 15 seconds duration. On the other hand, Fig. 2b shows that the specimen was well survived without significant residual deformation under Kobe MMO seismic ground motion although the specimen had heavily cracked. The threshold of the damage of the specimens was the flexural crack at the termination point of longitudinal reinforcement and the insufficient hoop reinforcement was allowed to decrease the ductility under seismic loading. Through these tests, it was clarified that the collapsed viaduct was due not to the ground motion of Kobe MMO but to that of the type of JR Takatori Station motion. The ground condition of the viaduct site is similar to that of JR Takatori Station rather than that of

Kobe MMO. Therefore, from the experimental results and the ground condition, it is not reasonable to connect directly the collapse of the viaduct and the Kobe MMO seismic record having maximum acceleration of 818 gals.

The experimental results were recorded in video tapes in the form of real time scale seismic response by using videoization technique [4]. Therefore, it is possible to see repeatedly the seismic response of structures such as ongoing failing process under the near field earthquake.

4 VERTICAL PRESTRESSING IN COLUMNS

It has not been common in the column to introduce prestressing because the column always sustains vertical loads. However, after the bitter experience of Kobe Earthquake of 1995 columns are expected to resist large horizontal ground acceleration which is comparable to that of gravity. As prestressing is quite effective to enhance the flexural performance of concrete beams under gravitational condition, the similar effect can be obviously expected in the vertically prestressed concrete column in the case of the near field earthquake. On the other hand, the prestressed concrete member has its inherent flexural performance of the restoration capability at unloading. This is significantly desired to prevent from large residual deformation after the earthquake. The prestressed concrete member has nonlinear load-deflection relationship which makes the member avoid the amplifying phenomenon of vibration under seismic motion. It should be noted that this nonlinearity exists under elastic behavior of the prestressing cables and eventually inherent restoration in deflection can be performed. The above mentioned structural characteristic was firstly ascertained in the experiment on the connection of precast beam segment and columns by vertical prestressing in Shigenobu Viaduct Project [5]. The basic study was carried out after that to examine the applicability of this desirable performance of vertical prestressing.

Fig. 4 shows the experimental result where parameters are level of prestress (0, 3.5, 7.0 MPa) and external axial stress (1.0, 4.0 MPa). The specimen was a single column with footing loaded in horizontal direction with constant axial force. The cross section of the specimens was

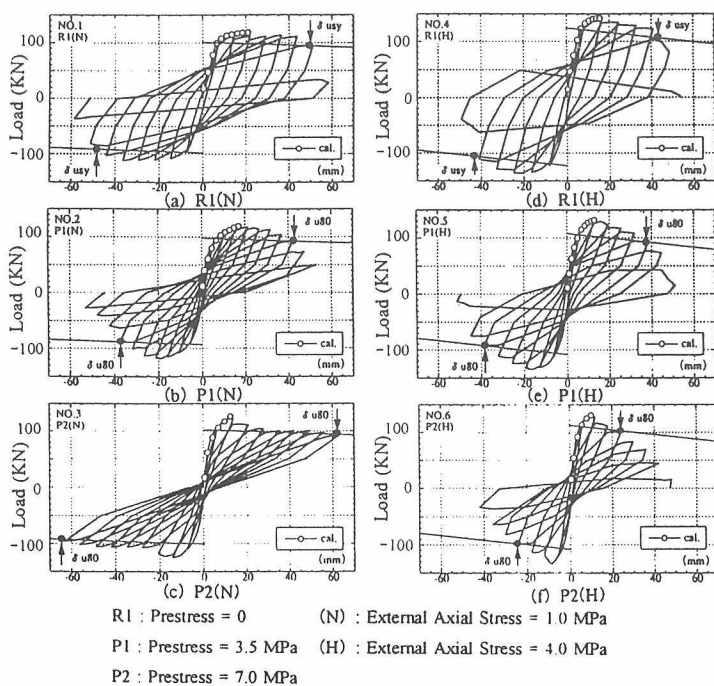


Figure 4. Experimental result of load - deflection curve.

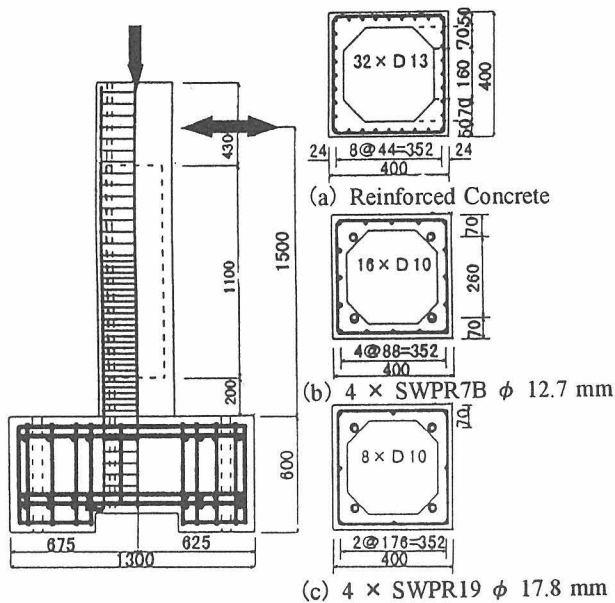


Figure 5. Specimen having hollow cross section.

300mm \times 300mm square and the height of horizontal loading point from the top of footing was 1000mm. Prestressing cables were unbonded. The specimens were designed to have the flexural capacity by additionally installing ordinary longitudinal reinforcement. The experiment shows that residual deformation is proportional to the sharing ratio of ordinary reinforcement in flexure. Prestressing of both 3.5 MPa and 7.0 MPa are quite effective for ductility and residual deformation with 1.0 MPa of axial stress. On the other hand, prestressing of 7.0 MPa makes the specimen brittle with axial stress of 4 MPa. This brittleness may be caused on the small amount of vertical reinforcement in the compressive zone. The strength of concrete at the time of experiment was 35 MPa [6]. In order to investigate the utilization of vertical prestressing in the actual structures, a systematic research has been carried out in Japan Prestressed Concrete Engineering Association under the chairmanship of the author. Twenty five single column type specimens were made for the experiments of reversed cyclic loading and pseudo dynamic test. Parameters are such as the level of prestress, concrete strength, axial stress, bonding condition of cables, type of cross section, etc.

Fig. 5 shows the specimens having hollow cross section for the pseudo dynamic test [7]. The specimen having cross section (b) in Fig. 5 was prestressed with 4 MPa together with external axial stress of 1.0 MPa while the specimen having cross section (a) was non prestressed with the same external axial stress.

Figs 6 and 7 show the time history response of above mentioned specimens. The seismic motion in this test was Kobe MMO. The specimens were designed against the near field earthquake under the new seismic code stipulated in 1996 [2]. The experiment shows that the vertical prestressing is quite effective to the response against the near field earthquake having favorable restoration behavior while reinforced concrete specimen has large residual deformation. The calculated response by using a specific model could express good simulated results as shown in the figures.

Various types of vertical prestressing for bridge piers are demonstrated in Fig. 8. Adequate volume of longitudinal reinforcement seems to be necessary together with the vertical prestressing for any type in the figure. Even in the case of precast segment as shown F in Fig. 8, vertical reinforcement might be needed to maintain ductility during severe earthquakes although the vertical reinforcement is not connected between the segments.

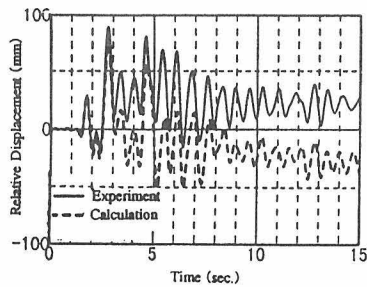


Figure 6. Time history response of reinforced concrete specimen under Kobe MMO motion.

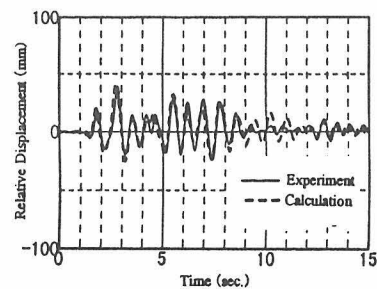


Figure 7. Time history response of reinforced concrete specimen prestressed with 4 MPa under Kobe MMO motion.

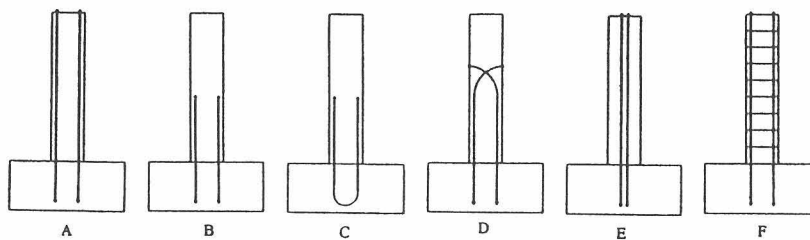


Figure 8. Various types of vertical prestressing for Bridge Piers (F: precast segmental construction).

5 CONCLUSION

1. From the bitter experience caused by Kobe Earthquake of 1995, it is essential to construct and maintain concrete structures against near field earthquakes as well as against distant interplate earthquakes.
2. The pseudo dynamic test showed the phenomenon of the collapse of expressway viaduct by using JR Takatori Station Motion instead of Kobe MMO motion.
3. Vertical prestressing was assured to be effective to concrete piers against near field earthquakes. In particular, the inherent performance of restoration capability in prestressed concrete is quite favorable to eliminate residual deformation after severe earthquakes.

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