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EARTHQUAKE RESPONSE OF STRENGTHENED BRIDGE PIER DURING THE 1995 SOUTH HYOGO EARTHQUAKE

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ABSTRACT

Many bridge piers constructed more than 20 years ago collapsed during the 1995 South Hyogo earthquake on January 17, 1995 in Japan. New seismic code for the Japanese highway bridges had recommended to strengthen those old bridge piers to avoid severe shear failure at their mid-height where the reinforcement steel bars had been terminated. Some reinforced concrete piers had been already strengthened using the steel jacketing method before that earthquake, and suffered few damage during the earthquake. The adjacent pier to the strengthened pier had been left unstrengthened until the earthquake notwithstanding the necessity of strengthening, and had shear failure at its mid-height. The bridge piers are usually strengthened or repaired after the earthquakes (Kawashima *et al.*, 1990; Mahin and Moehle, 1990; Ohuchi *et al.*, 1992), but few strengthened piers experienced severe earthquakes until then. Therefore, this case gives the valuable data to verify the seismic strengthening effect of the steel jacketing method for the reinforced concrete bridge piers. This paper numerically analyzed the earthquake response of the strengthened bridge pier during the 1995 South Hyogo earthquake to verify the effectiveness of the strengthening. The results showed that the numerically calculated force-displacement relation and the earthquake response of the strengthened pier showed more room for the ultimate state than the original one.

KEYWORDS

1995 South Hyogo Earthquake; Strengthening; Reinforced Concrete Bridge Pier; Steel Jacketing; Estimation of Earthquake Response; Survived Structure.

STRENGTHENED BRIDGE PIER

The subject of the numerical simulation is the T-shaped reinforced concrete bridge pier of the highway viaducts shown in Fig. 1. The cross section of the original pier was circle of 2.7m in diameter. This pier was constructed in 1967 according to the old seismic code for the Japanese highway bridges, and was strengthened in 1986 according to the seismic code of 1980. The steel jackets of 12 mm thick was wrapped around the pier and bonded with epoxy resin to the pier.

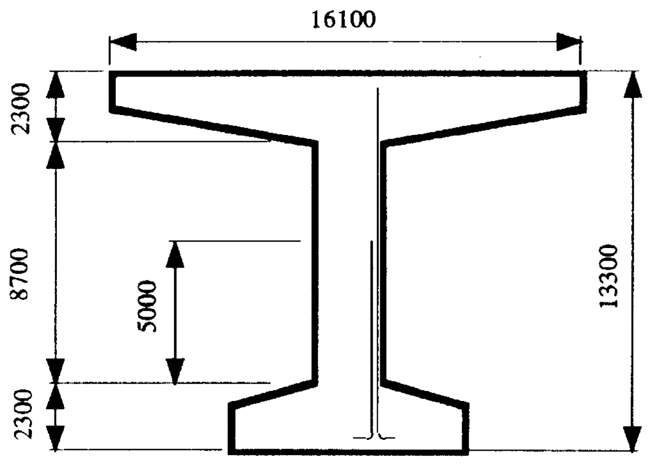


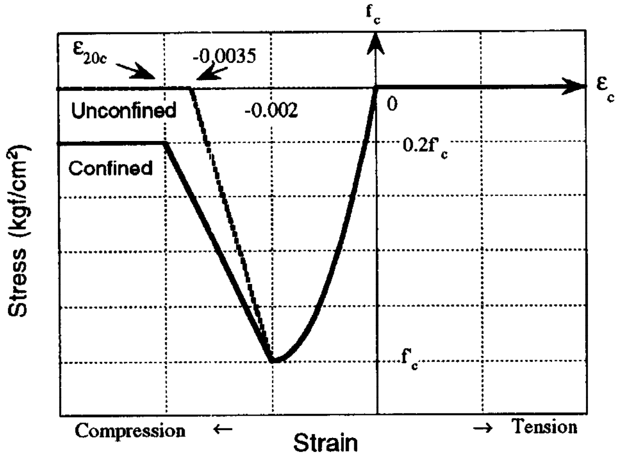
Fig. 1 T-shaped Bridge Pier Model.

This pier was located only 10 km far from the epicenter of the 1995 South Hyogo earthquake, and the many structures was heavily damaged in the vicinity of this pier. The seismic intensity of this zone was level VI on the seven-level Japanese intensity scale. This pier looked like having no damage as far as seen from outside. However, some slips between the steel jacket and the concrete were found by hammering tests. The slips may have occurred because of the inelastic response of the steel jacket.

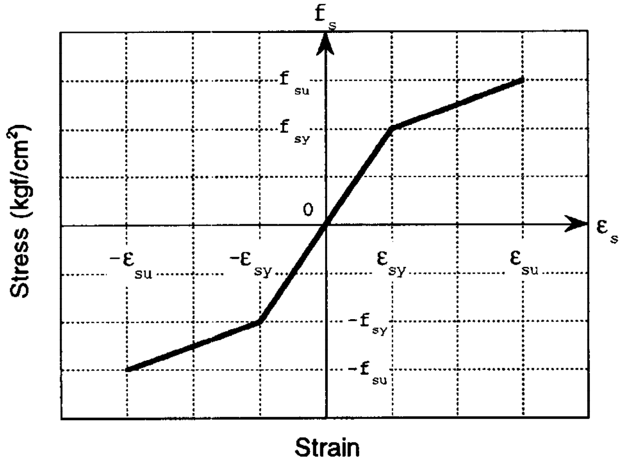
MOMENT-CURVATURE RELATIONSHIP

The moment-curvature relationship for some sections of the pier was calculated using the fiber modeling technique extended to handle the effect of the grouted epoxy resin (Izuno *et al.*, 1993). The each section was divided into several fiber elements and the moment was calculated for the assumed curvature considering the constitutive laws of the concrete, the steel and the epoxy resin shown in Fig. 2. The Kent-Park model (Kent and Park, 1971) was assumed for the concrete, the bilinear relation between stress and strain was assumed for both the reinforcing bars and the steel jackets, and the linear relation was assumed for the grouted epoxy resin.

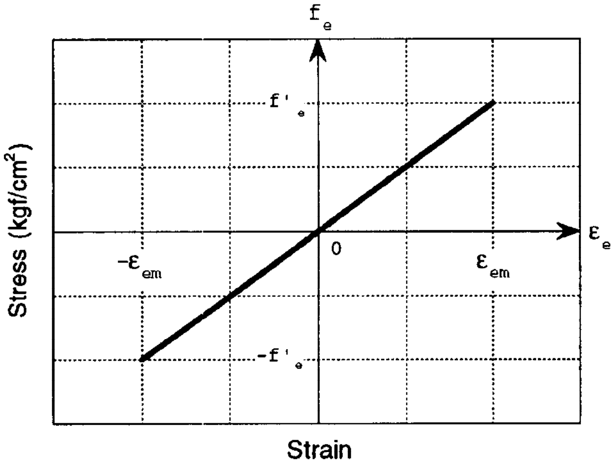
Figure 3 shows the calculated moment-curvature relationship for the original pier and the strengthened pier. Figure 3 (a) shows the relationship for each section when one section shows cracks of the concrete; Figure 3 (b) shows the relationship when the reinforcing steel of one section begins to yield; Figure 3 (c) shows the relationship when the core concrete of one section begins to crush under compression. Though the all limit state occurs at the bottom of the pier, the safety margin for the original pier is small at its mid-height where the reinforcing steel had been terminated especially for the case of Fig. 3 (b). The safety margin becomes large after strengthening for the case of Figs. 3 (b) and (c); it is obvious for the case of Fig. 3 (c).



(a) concrete

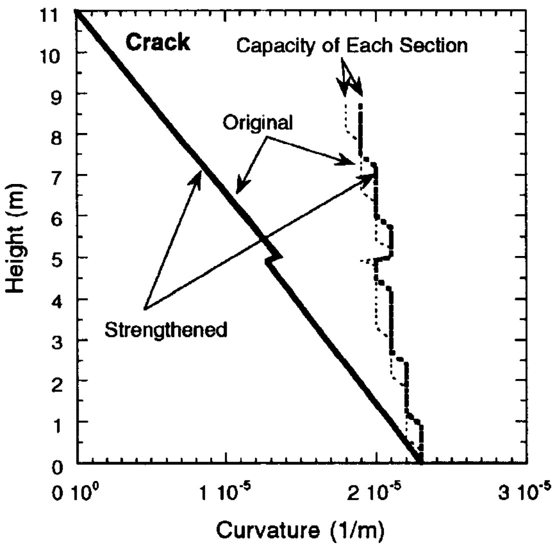


(b) steel

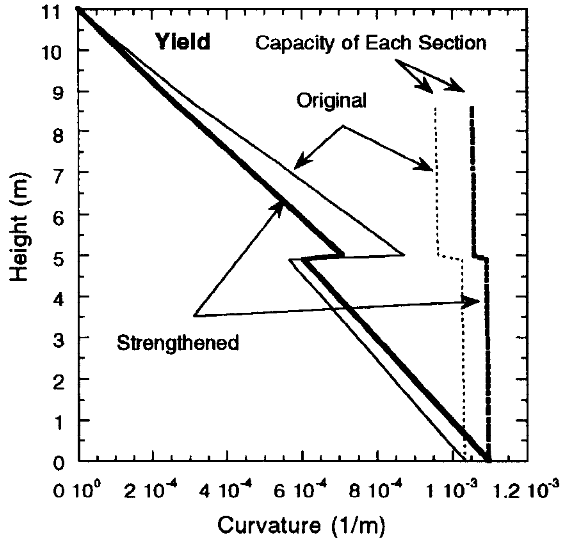


(c) epoxy resin

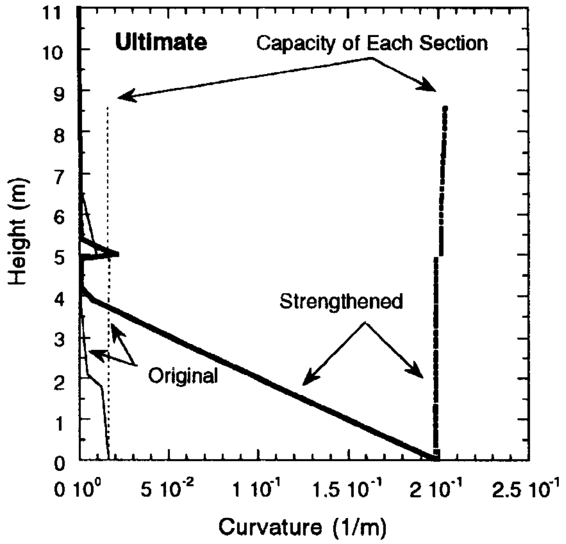
Fig. 2 Assumed stess-strain relationship.



(a) crack of concrete



(b) yield of steel



(c) crush of concrete

Fig. 3 Moment-curvature relationship.

FORCE-DEFORMATION RELATIONSHIP

Figure 4 shows the calculated force-deformation relationship of original and strengthened piers. The maximum point for the original pier shown in Fig. 4 is when the cover concrete begins to crush. The definition of other points in Fig. 4 are similar to the moment-curvature relationship; the crack point is when one section shows cracks of the concrete, the yield point is when the reinforcing steel or the steel jacket begins to yield, and the ultimate point is when the core concrete begins to crush under compression. The relationship of the strengthened pier shows the twice larger yield strength than the original pier, moreover, the ultimate point shows the twice larger strength and the 10 times larger deformation than the original pier. This relationship shows that the strengthening succeeded in adding the ductility for the ultimate state of the pier.

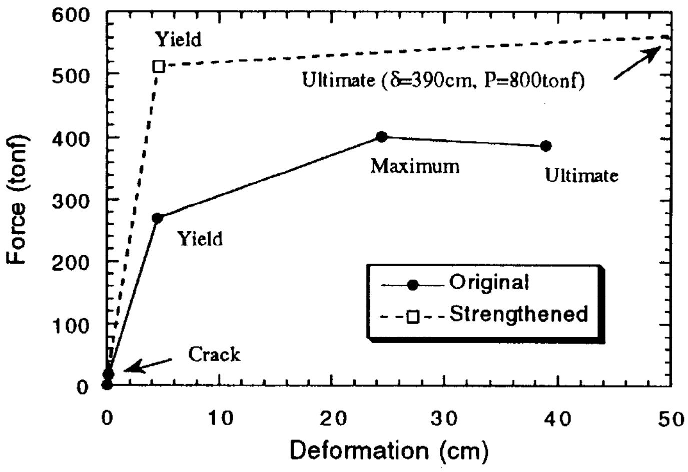


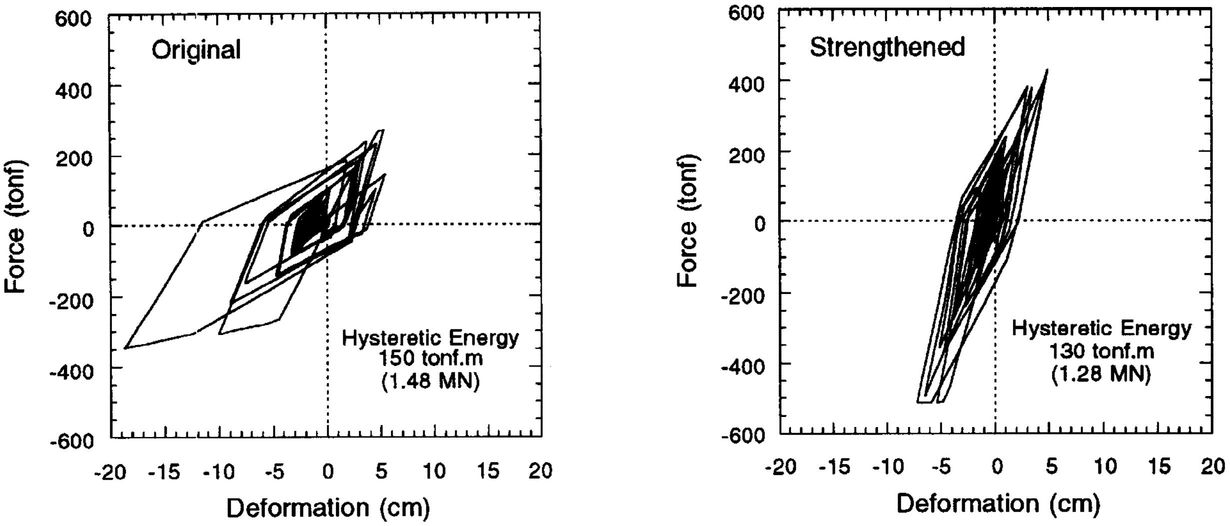
Fig. 4 Force-Deformation Relationship for Original and Strengthened Piers.

ESTIMATION OF EARTHQUAKE RESPONSE

The pier was modeled as the 1-d.o.f. system using the inelastic spring of the degrading trilinear hysteretic model having the skeleton curve of Fig. 4. The input earthquake record is selected as the N-S component of the Kobe Marine Observatory record for the 1995 South Hyogo earthquake whose maximum acceleration was 818 gal.

Figure 5 shows the hysteretic response of both the original and the strengthened piers. Though the maximum response of the strengthened pier shows 1.5 times larger force than the original pier, there is still room for its ultimate state. The response of the strengthened pier remains almost linear response, but the original pier shows quite inelastic response. The maximum displacement response of the strengthened pier shows 40% of that of the original pier, and the absorbed hysteretic energy of the strengthened pier shows 85% of that of the original one.

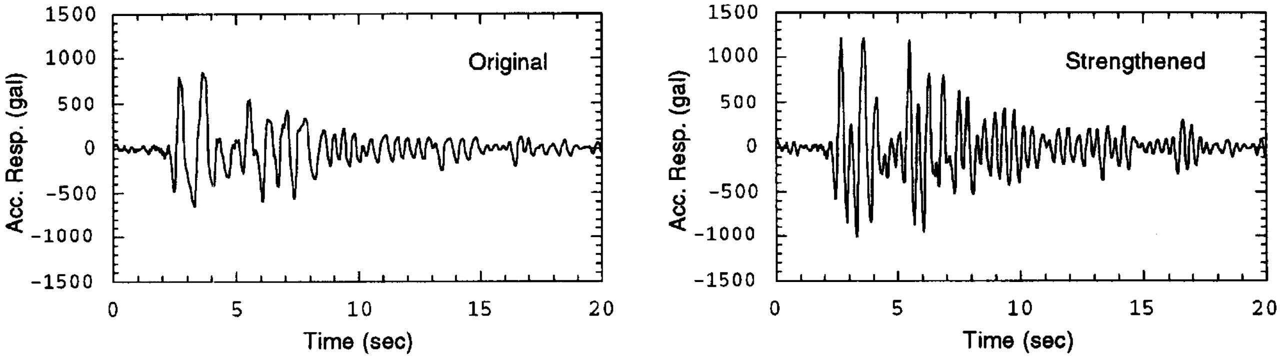
Figure 6 shows the acceleration response time histories of the original and the strengthened pier; Fig. 6 (a) is for the original pier and Fig. 6 (b) is for the strengthened pier. The strengthened pier shows larger



(a) original pier

(b) strengthened pier

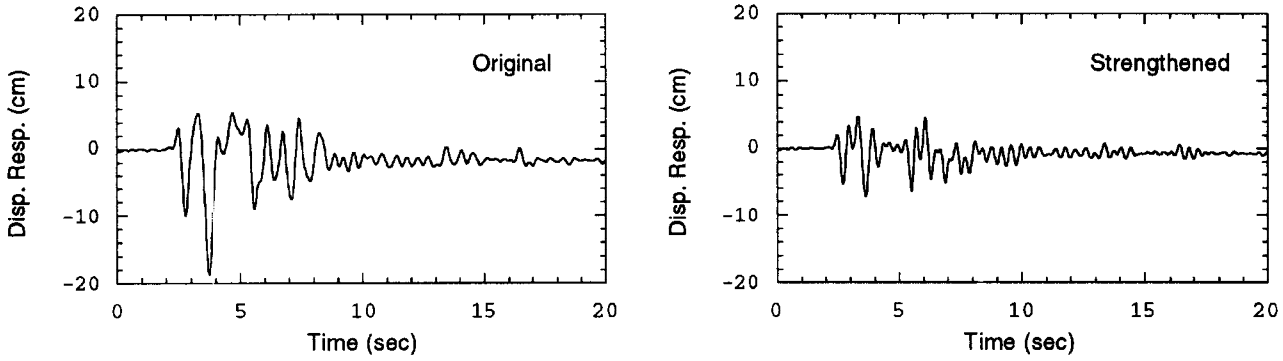
Fig. 5 Estimated hysteretic responses.



(a) original pier

(b) strengthened pier

Fig. 6 Acceleration response-time histories.



(a) original pier

(b) strengthened pier

Fig. 7 Displacement response-time histories.

acceleration response because of the almost linear response and of the shorter natural period. Figure 7 shows the displacement response time histories; Fig. 7 (a) is for the original pier and Fig. 7 (b) is for the strengthened pier. The original pier shows the large residual deformation after the response. The original pier deforms considerably at the 2nd large response at 4 second in Fig. 7 (a). This may cause the failure of the original pier soon after the beginning of the earthquake. The strengthened pier of Fig. 7 (b) shows the little residual deformation and almost half displacement response of that of the original pier.

CONCLUSIONS

The seismic design of the new structures is of course an important problem, however, the seismic enhancement of the existing structures is also an important problem considering the safety of the city.
This study numerically analyzed the earthquake response of the strengthened bridge pier during the 1995 South Hyogo earthquake to verify the effectiveness of the strengthening. The main conclusions are as follows;

1) The bridge pier which had been strengthened using the steel jackets had large safety margin at the mid-height where the reinforcing steel had been terminated.

2) The strengthened pier had larger ultimate strength and quite larger deformation capacity than the original pier.

3) The strengthened pier might respond smaller than the original pier; 40% in displacement response and 85% in the absorbed hysteretic energy.

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