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Shear Failure Analysis of RC Bridge Piers Subjected to Strong Ground Motions

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Abstract

This study presents the analysis of cracking phenomena related with the shear failure mechanism that may occur in RC bridge piers when these are subjected to strong ground motions. As it was emphasized by the 1995 Great Hanshin Earthquake, the shear failure mechanism occurs in a complex form, in which the degradation of concrete depends strongly on the evolution of the crack pattern (typically diagonal) which in turn is highly dependent on the shear transfer across the cracks. On this way, a Finite Element analysis of a RC Bridge Pier which meets similar characteristics with respect to those ones that sustained severe shear failure under the effects of the 1995 Great Hanshin Earthquake, is carried out herein in order to determine both the extend and characteristics of the failure zone as well as the base shear and displacements in the failure stage. Nonlinearities of concrete material are considered by means of the stress-strain relationship for tension and compression.

Keywords *: Bridge piers, Reinforced Concrete, Cracking, Shear failure, Structural response*

1. Introduction

The large number of RC piers that collapsed due to shear failure during the 1995 Great Hanshin Earthquake emphasized the need for a better understanding of the complex shear transfer mechanism that leads to the shear cracking phenomena in RC bridge piers subjected to cyclic reversals. However, it is the lack of crispness (or inherent fuzziness) in the shear failure mechanism that causes difficulty in determining quantitatively the contribution of concrete to shear strength which is given mainly by the combined strength of complex mechanisms such as the aggregate interlock along crack interfaces and dowel action of reinforcement across the cracks among others more. By this way, the characterization of concrete cracking which may lead to nonlinearity in response is made herein on basis of the above-mentioned in order to evaluate the seismic response of RC bridge piers (T-shape RC single-column bents) in which failure is caused predominantly by shear mechanism.

2. Theoretical background

During strong earthquakes, the shear failure mechanism in RC bridge piers is expected to occur in zones subjected to reversed cyclic high-intensity shear loads as a result of inelastic seismic response. Some characteristics of the shear failure mechanism are : considerable concrete crushing, not many cracks visible before rebars violently ripped out (brittle failure), diagonal cracking and minimal inward rotation which contrasts with the large rotations that occur in flexural failure. It is also important to point out that yield strength of reinforcement bars in certain regions (particularly where inelastic and reversible strains occur) can be developed to the point at which associated deformations such as slip or pull-out occur.

Because fracture of concrete[1] is governed by tensile mechanism, the bi-linear softening model described by Eq. 1 and shown in Fig. 1 are used herein to represent the cracking of concrete in tension.[2]

$$f'_t = 0.62\,(f'_c)^{1/2}\quad \text{(MPa)} \qquad (1)$$

$$\varepsilon_{ot} = f'_t / E$$

$$\varepsilon_{ut} = 9.2\,\varepsilon_{ot}$$

where,

f'_t = Tensile strength of unconfined concrete

ε_{ot} = Tensile cracking strain of concrete (initial tensile strain threshold)

ε_{ut} = Ultimate tensile strain of concrete.

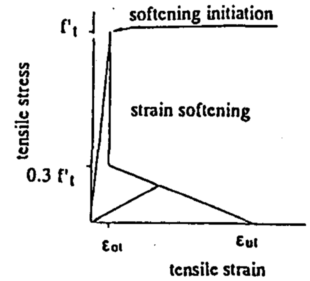

Fig. 2 Stress-strain relationship for concrete in tension

By the other hand, Fig. 3 shows the failure envelope that defines the cracking in compression.[3]

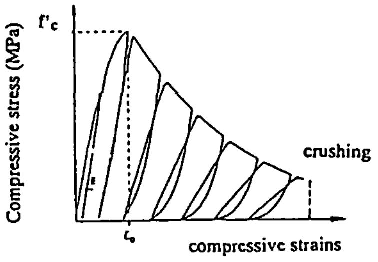

Fig. 3 Stress-strain model for concrete in compression

The state of tension-shear stress in the cracking stage is governed by the *yield condition* given by Eq. 2

$$\sigma_n^2 + \tau_{nt}^2 / \alpha^2 - f_t'^2 = 0 \qquad (2)$$

The dependence of the yield condition (See Eq. 2) on the shear stress τ_{nt} introduces in the stress-strain matrix for the cracking stage the term between principal normal stresses and shear strains as well as the term that takes into account the shear stiffness.[4]

3. Model Problem

A RC bridge pier which sustained severe shear failure during the 1995 Great Hanshin Earthquake is considered herein as a model problem. This RC pier belong to the supporting structure of the Hanshin Expressway viaduct located in Nishinomiya City, Kobe. Its geometrical characteristics are shown in Fig. 3.

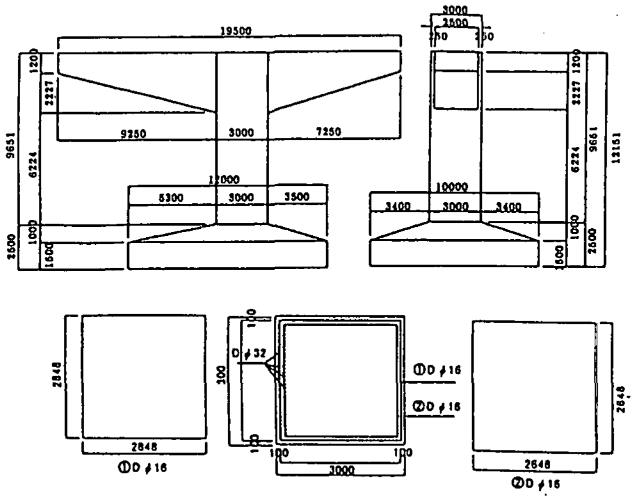

Fig. 3 Geometrical characteristics of the RC bridge pier

The concrete material has the following characteristics: $\gamma_c = 2500$ kgf/m^3, $f'_c = 270$ kgf/cm^2 and $E_c = 2.65\text{x}10^5$ kgf/cm^2. The finite element mesh considered is shown in Fig. 4.

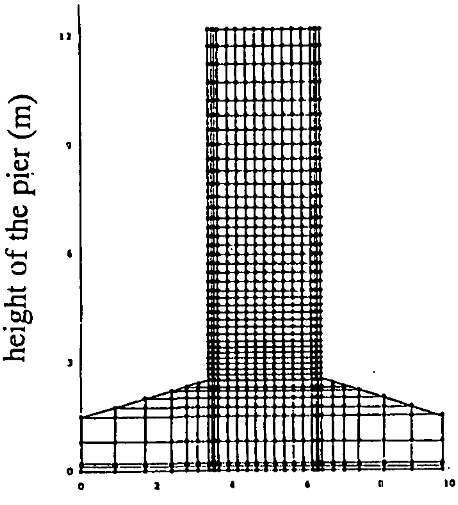

Fig. 4 Finite element mesh for the model problem in the longitudinal direction of the bridge

The analysis is carried out by using a uniform piece-linear wave of 4 seconds of duration with peak acceleration of 400 gals as depicted in Fig. 5. The input motion is applied at the pier base and in the longitudinal direction of the bridge.

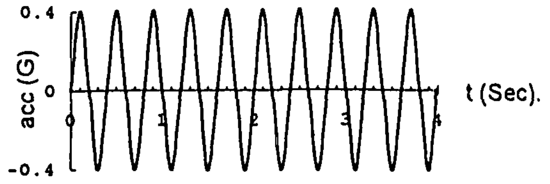

Fig. 4 Input motion

4. Analytical results

At first, the strength characteritics of this RC pier are presented in order to quantify the design forces and displacements at each of the three main stages (cracking, yielding and ultimate state) it is showed in Fig. 5:

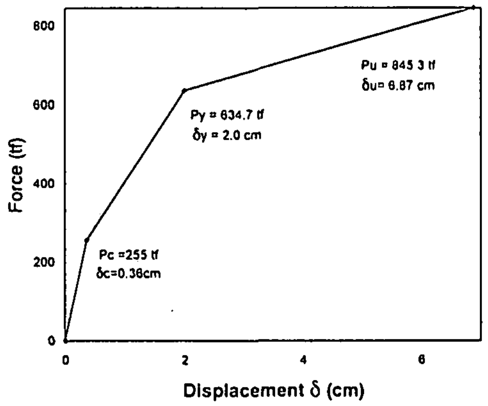

Fig. 5 Force-displacement for cracking, yielding and ultimate stages

The design values for lateral forces are given as follows:

$P_s = 559$ tf (Ultimate lateral load)
$M_{max} = 5818$ tf-m
$V = 510$ tf (Specification for shear strength, JSCE)
$P_a = 559$ tf (Lateral resistant force) , and;
$P_{ud} = 603$ tf-m (Design value for ultimate lateral load)
From these design parameters it can be concluded that:

$P_u > P_s$ and $P_{ud} > P_s > V$

$0.26.\ W.\ K_{h_c} = 854$ tf $> P_a$

Hereafter, the analytical results of this study are presented. and discussed. The initial stage of cracking results in horizontal cracks which, with varying load, extended in diagonal manner as can be seen in Fig. 6. Cracks tend to migrate to zones at which the cracking stage has not still been reached because balance of the shear is transferred across the cracks.

By the other hand, Fig. 7 shows the resultant maximum stresses that correspond to the crack pattern depicted in Fig. 6. As can be seen, the surfaces or stress distributions are steep near the face of the pier and flatter upward in diagonal form creating zones of traction in which the maximum stresses in tension are reached producing the cracking of concrete. This form of degradation of concrete strength in the diagonal direction (traction stresses distributed diagonally) is the cause for extending the shear failure. At this stage, only the stresses in the outermost layer exceeded the yield stress. In this context, these yielded bars become also in another source for crack formation, specially when these are subjected to compressive stresses during the cyclic motion. It will cause the shear force to be transmitted by dowel action.

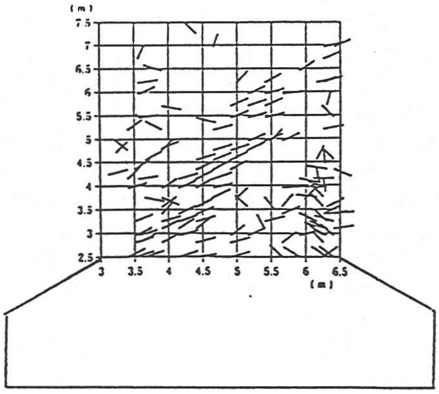

Fig. 6 Resultant crack pattern in the final stage

From Fig. 7, it is also possible to observe that a high compression zone is located at one of the corners of the base pier.

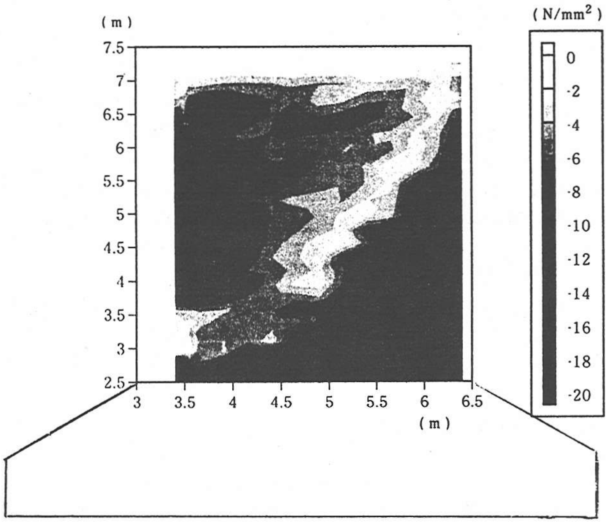

Fig. 7 Distribution of maximum stresses that corresponds to the crack pattern of Fig. 6

In other aspect, the maximum displacement at the top part of the pier in the longitudinal direction is about 6 cm, as shown in Fig. 8. This maximum displacement is hazardous, especially, because it occurs in the longitudinal direction, so, it can cause also the restrainers of bearing supports to be sheared off.

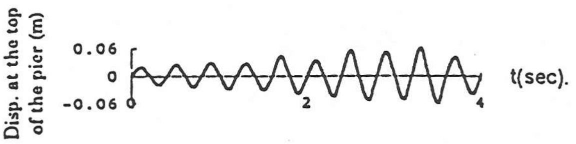

Fig. 8 Displacement at the top of the RC bridge pier

It must also be quoted that when the maximum displacement at the top of the pier was reached, maximum deformations at the base and its vecinity exceeded the elastic values.

Another important fact is related with the variation of rotation. It is because the inelastic rotation should not exceed the rotational capacity in order to prevent shear failure or minimize the risk of collapse caused by shear failure mechanism. By this way, Fig. 9 shows how sensitive is the the variation of rotation at the pier base respect to the base shear.

In fact, Fig. 9 shows that the base shear may change strongly even for small variation in the base rotation. It may be the result of new cracks extending in the vicinity of spalled zones as well as crack widening, and also due to the slip between the reinforcing steel bars and surrounding concrete.

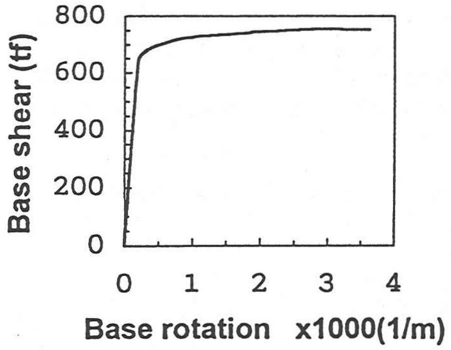

Fig. 9 Variation of base shear respect to rotations at the pier base

The next point is referred to the variation of base shear with respect to the displacement at the top of the pier. As shown in Fig. 10, it is possible to observe that displacement at the top of the pier vary proportionally until maximum base shear is reached, and then, remain almost constant despite the increase in its value. It may indicate that the effects of shear forces on the degradation of concrete during cyclic loading is important in the lower part of the pier (because change of rotations as shown in Fig. 9) rather than in the upper part in which displacements become a very important parameter.

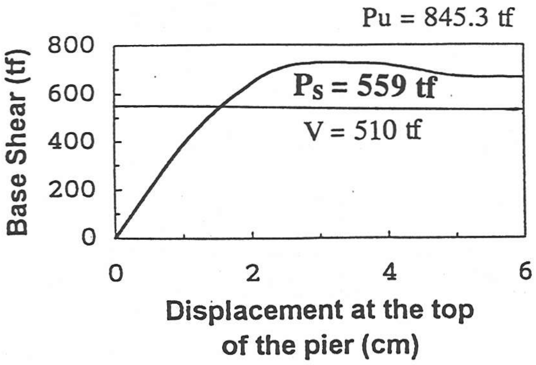

Fig. 10. Base shear versus displacement at the top of the RC pier

Regarding to the understanding of stresses generated in the stirrups (square hoops) after cracking, it is necessary to remember, firstly, that full confinement is only applied near the corners of such stirrups because the pressure of the concrete tends to bent the column faces outward. And, secondly that, shear reinforcement is provided to resist the difference between the total shear force and the contribution of the concrete V_c. On this basis, a brief explanation on stresses generated in stirrups are presented in the following. As can be observed in Fig. 11(a) the stress generated in the stirrups at the height corresponding to 0.15 m above the pier base level (h=0.15 m), becomes important just at the ends of the pier face (σ = 2300 Kgf/cm^2), but yielding is not reached. This trend continues until reach the height 0.90 m above the pier base, is just at this level at which yielding of strirrup is reached. The yielded point is located near the pier face (See Fig. 11(b). This yielded point implies unstability in the structural analysis which is out of the scope herein. On the same way, although not yielded, stirrups located at heights between 0.90m and 2.45 m, are subjected to considerable stresses which in some cases are quite near to the yielding point such as the case of the stirrup located 2.45 m above the pier base, see Fig. 11(c). For stirrups located above 2.45 m, the stresses have low values.

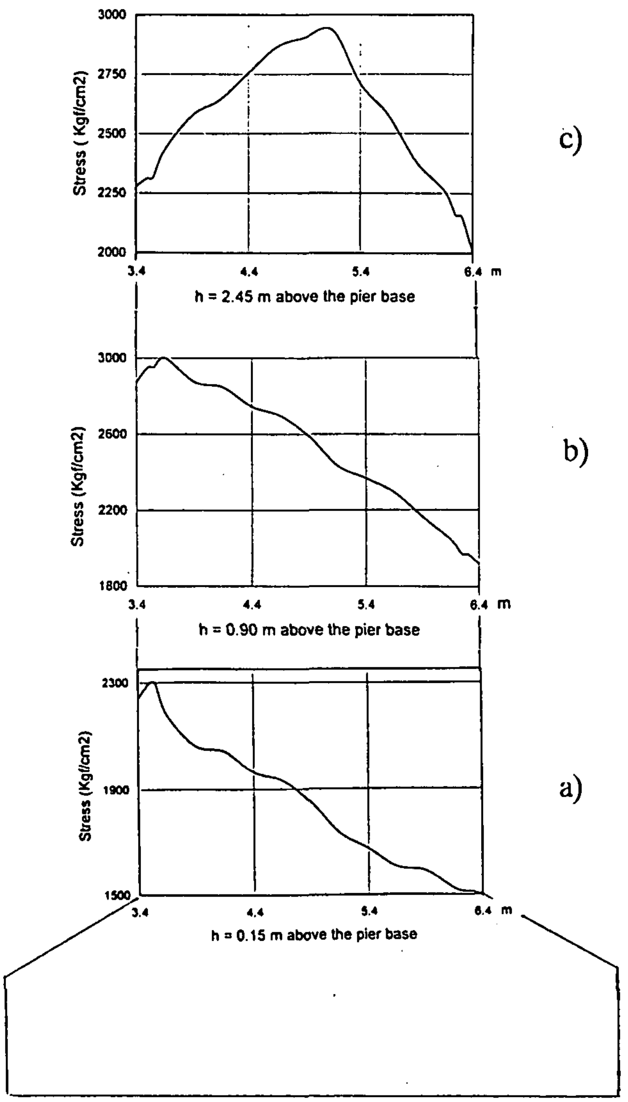

Fig. 11 Stresses in stirrups

Conclusions

Based on results of this study the following conclusions can be drawn:

(1) The shear distribution after concrete has cracked as well as the relation between the shear force with other parameters may be useful to interpretate some facts of the shear failure mechanism that otherwise would be difficult to realize.

(2) This study has shown also that cracking is very sensitive to the variation of stresses due to reduction of strength and stiffness. Thus, a control of the shear transfer mechanism appears to be a key point to consider in the structural design of new RC bridge piers in order to ensure enough strength as well as moderate cracking during an strong earthquake.

(3) From this study, it is possible to quote that the quantification of stresses and deformations (See Figs. 6 and 7), can provided a better idea about how shear failure occurs.

(4) From the design point of view, it should be emphasized that as important to consider close spacing for the shear reinforcement is how it should be detailed in order to enhance force transfer more efficiency in ways that formed diagonal cracks not result in failure.

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