第Ｖ部門

Evaluation of the Main Factors that Contribute to the Shear Failure of RC Bridge Piers During Strong Ground Motions

Shiro Takada *
Hidenori Morikawa **
Freddy Duran C. ***

OBJECTIVE

It is intended herein to evaluate the main factors that contribute to the shear failure of RC Bridge piers during strong ground motions. For this purpose, a RC bridge pier that sustained shear failure during the Jan. 17,1995 is considered for the analytical study which is conducted by a Finite Element analysis. Results show that the evaluation of the shear transfer mechanism is necessary to identify the main factors that contribute to shear failure such as effect of aggregate interlock, effects of dowel action, effects of confining reinforcement in large size cross-sections, and theeffects of concrete strength given by the tension stiffening.

1. INTRODUCTION

On view of the extensive shear failure occured to RC bridge piers during the Jan. 17,1995 Hyogo-Ken Nambu Earthquake, it is intended herein to evaluate the main factors that contributed to such extensive damage to RC bridge piers. A number of analytical studies have been conducted by several researchers in order to evaluate the damage to the RC bridge piers caused by this earthquake. However, most of them use analytical plattforms that simplify key factors such as the shear retention factor which in some form helps to take into account the aggregate interlock and dowel action. Previous studies conducted by the authors have shown that the understanding of the " internal shear transfer mechanism" may help strongly in the identification of factors that contribute to the shear failure of RC bridge piers during earthquakes.

2. ANALYTICAL BACKGROUND

In order to understand the meaning of the several factors that contribute to the shear faiure of RC bridge piers during ground motions, it is necessary to provide a brief analytical background on this matter. The need for a better understanding the seismic analysis of RC bridge piers has spurred great interest in developing numerical tools to model the failure characteristics of the Reinforced Concrete under dynamic effects. As failure of RC members implies effects of cracking, it is of immediate necessity to focus in the understanding of cracks, specially the "shear cracks". In classical Fracture Mechanics a shear crack is one in which the crack plane is coincident with the plane of principal shear stress, however, in RC bridge piers shear cracks occur in regions of high shears but does not follow the principal shear stress. For understaning of this fact, the main aspects of the cracking analysis performed herein are outlined in the following:

The first solution is a static non-linear stress analysis. Specifically any isotropic material may exhibit a bi-linear stress-strain relation. The stress analysis reports the principal tensile stresses for each element at the four Gauss points ($\sigma 1$, $\sigma 2$, $\sigma 3$ and $\sigma 4$ with normal direction angles $\alpha 1$, $\alpha 2$, $\alpha 3$, and $\alpha 4$, respectively).

The cracking is governed by the tensile properties of the concrete material. The tensile (See Fig.1) and compressive strength of concrete are used to set the tension cutoff condition in the failure criteria given by Eq. 1

$$F(\sigma, \varepsilon_{np}) = \sigma_n^2 + \tau_{nt}^2/\alpha^2 - f_t^2 = 0 \qquad (1)$$

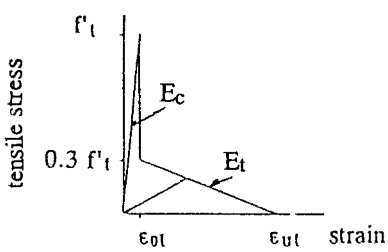

Fig. 1 Tensile stress-strain relationship of concrete

Nodal displacements are converted into strains which are checked against the allowable strain. Failure will occur when any isotropic element reaches a pre-specified maximum allowable strain. On the same way stresses are checked against the failure criteria. A progressive failure analysis is performed when stresses exceed those given by the failure criteria. The exceeded stresses are converted to an excess force vector. The stiffness matrix of the cracked concrete is then determined by taking into account this failure criteria and the tensile-strain softening diagram which in turn is defined by the tensile strength, fracture energy which is the area below the softening curve and the descendent part of the diagram., then, the isotropic element matrix changes to the following form:

The structure is then analized with the new stiffness matrix to determine if any further failure is induced. If further failure does not occur, the analysis continues with the next step of loading. This process continues until failure occurs. The ultimate load-carrying capacity of the structure is then determined..

$$\begin{bmatrix}\sigma_n\\ \sigma_t\\ \tau_{nt}\end{bmatrix}=\begin{bmatrix}E_{11}(1-4E_{11}c\sigma_n^2) & 0 & -4cE_{11}G\sigma_n\tau_{nt}/\alpha^2\\ & E_{11} & 0\\ Symm & & G(1-4c\,G\tau_{nt}^2/\alpha^4)\end{bmatrix}\begin{bmatrix}\varepsilon_n\\ \varepsilon_t\\ \gamma_{nt}\end{bmatrix}$$

$$c = 1/(4f'_t\sigma_n hE_n + 4\sigma_n^2E_n + 4\tau_{nt}^2G/\alpha^4)$$

$$E_{11} = E/(1-\nu)^2 \qquad (2)$$

α = Parameter from the plastic condition

* Principal Professor, Faculty of Civil Engineering, Kobe University - JAPAN
** Associate Professor, Faculty of Civil Engineering, Kobe University - JAPAN
*** Graduate Student

3. CASE STUDY

A RC bridge pier that collapsed during the Jan. 17, 1995 Hyogo Ken Nambu Earthquake is considered for analytical investigation. The RC bridge pier is 3m x 3m cross section, with longitudinal reinforcement given by double layers of 32mm diam-steel reinforcing bars. The confinement is given by 16 mm diam-bars at about 30 cm-centers. The concrete material has the following characteristics: f'c = 270 kg-f/cm2 and Ec=1.89 x10E05 kgf/cm2. The yield strength of both longitudinal bars and stirrups(hoops) are taken as fy = 3000 kgf/cm2. A piece-linear input motion with 0.4 G of peak acceleration is applied at the base of the pier in the longitudinal direction.As the size, distribution and roughness of aggregates will affect greatly the progressive material failure, the maximum aggregate size is assumed to be herein as 19 mm, so, the crack band width used in the analysis is h =19 x 3 = 57 mm. A Finite Element analysis is carried out to investigate mainly the main factors that contribute to the shear failure of RC bridge piers.

4. RESULTS AND DISCUSSION

Shear retention Factor

As has been previously pointed out, the understanding of the shear failure mechanism may help to much to analyze the shear cracking phenomena, on this way, the effect of dowel action and aggregate interlock are first evaluated, it will be done through the variation of the shear retention factor β (See Fig. 2). For this purpose three analysis are performed, one for β=0.25 that corresponds to 0.25Ge, the second for β=0.90 that simulates almost fully interlock between crack surfaces, and the third, that corresponds to β= 0.01 which simulates almost frictionless crack surfaces.

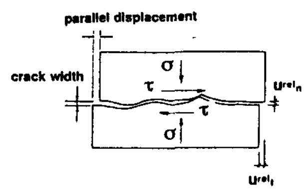

Fig. 2 Aggregate interlock

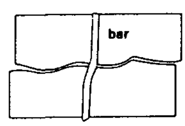

Fig. 3 Dowel action

From Figs. 4, 5 and 6, it is possible to observe that the effect of β on the final crack pattern is remarkable specially in the direction of the cracks as well as in their location. It is possible to observe that when β decreases then the inclination of cracks also decrease. Indeed, the consideration of the coupling of normal stress and shear strain in the diagonal term of the matrix for cracked concrete affects greatly the orientation and distribution of stresses.

By the other hand, Figs. 4, 5 and 6 also shows the significative presence of crack patterns that exhibit tension as well as lateral compression. It means that cracking and plasticity occur at some locations, this type of cracking also known as "splitting" obligates to consider a failure plasticity model such as the expressed in Eq. 1 , which will permit to take into consideration a plasticity formulation which is suitable to apply at zones in which the simultaneous effects of high tension with significant lateral compression occurs.

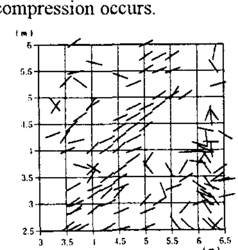

Fig. 4 Shear Retention Factor
β = 0.90

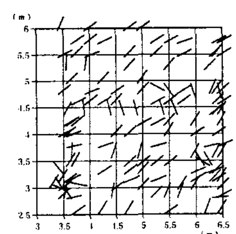

Fig. 5 Shear Retention Factor
β = 0.25

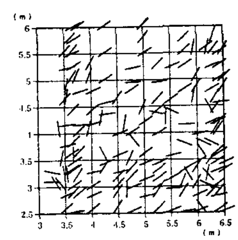

Fig. 6 Shear Retention Factor
β=0.01

Shear Reinforcement

The "arch action" of the stirrups during tension creates zones of stress concentration specially at the column-faces in the vicinity of the corners of the stirrups as can be seen from Fig. 7. While during compression, the middle parts of the column-faces (See Fig. 8) are subjected to high stresses which will cause spalling of concrete and compression cracks with low inclination. The stresses produced in the stirrups will vary strongly if the number of these are few, in addition, under cyclic loads, these stirrups may debond and even slip, then to be subjected to unexpected deformations that could lead to yielding of these. Fig. 9 shows stresses of stirrups obtained analytically at a heigh equal to 0.15m above the base of the pier.

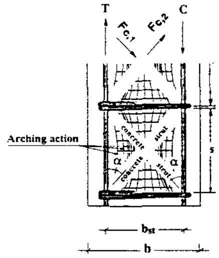

Fig. 7 Arch action in Tension

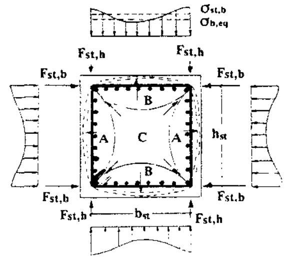

Fig. 8 Arch action in compression

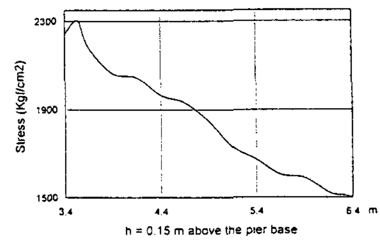

Fig. 9 Stirrup stress at h =0.15m from the base