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Shear Failure Analysis of RC Bridge Piers During Strong Ground Motions : A Deformation Approach

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OBJECTIVE

This study aims to analyze the performance of a typical RC bridge pier that sustained severe shear failure during the Jan. 17, 1995 Hyogo-Ken Nambu Earthquake earthquake. For this purpose, an approach based on the estimation of deformations considering the material nonlinearities is presented. The results obtained herein highligth two facts for analizing the shear cracking. One is refering to ***the determination of the extend of the yielding regions*** , and the other is regarding to ***the deformation capacity of the section from the onset of yielding of reinforcement until the collapse.***

1. ANALYTICAL BASIS

To analize the shear failure of RC bridge piers, it is necessary to define clearly the main factors that contribute to the shear transfer. Such factors are: the tension stiffening of the concrete, the effect of aggregate interlock and dowel action at cracks, the bond effect at the steel-concrete interface and the yielding of both the longitudinal and transverse reinforcement (ties). The knowledge of extreme forms of collapse, that is, final stage of cracking or yielding may not help much if it is intended to analize (describe) the progressive failure of concrete. In what follows, a brief explanation concerning to the main factors that contribute to the shear transfer mechanism are briefly reviewed.

1.1 Tensile Stresses and Cracking

The tensile envelope curve used herein is depicted in Fig.1. The softening part of this envelope is composed by two lines: a initial "*steep decay of stresses*" in order to represent the brittle cracking and a "*soft stress decay*" for representing the transfer coming from reinforcement crossing the crack. As depicted in Fig. 1. Failure of concrete to compression under cyclic loading is calculated bearing in mind the ultimate strength envelope. Crushing of concrete is assumed to occur when the concrete loss completely its load-carrying capacity. The area under the softening curve represents the fracture energy G_f absorbed until complete fracture occurs. The stress decay produced in a crack is usually assumed to occur due to the shear transfer between crack faces or due to the development of a crack band with decreasing stiffness and strength. In view of that, the crack extension is evaluated in two ways, one is, by considering the maximum energy release rate, while the other is by considering maximum principal stresses. The characteristic crack opening, "*w*", and the characteristic crack length "*l*" (Hilleborg et al, 1976) are defined by Eq. 1, These expressions could be useful for evaluation purposes when controlling the crack dimensions.

$$w = G_f / f'_t \quad , \qquad l = E\,G_f / f'_t \qquad (1)$$

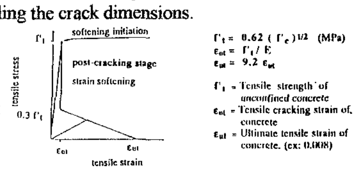


Fig. 1 Tensile stress-strain curve for the concrete material

1.2 Agreggate Interlock and Dowel Action

In the Finite element analysis considered herein the shear strain in the cracking stage is expressed as:

$$\Delta\gamma^{cr}_{nt} = (\sigma_{nt} / G)(1/\beta) \qquad (2)$$

where n = direction normal to the crack (mode I)
t = tangential direction to the crack (mode II)
σ = stress ; γ = shear strain

The term "β" is called the shear retention factor, it takes into account the continuously decreasing of shear stiffness during the cracking phenomena, The factor "β" derived experimentally by Bazant Z. and also by Pruijssers(1988) is taken into account herein because its dependence from both the crack-opening (normal direction) strain as well from the maximum aggregate size (d_{max}) in mm.

$$\beta^{-1} = (1/4762)\,\varepsilon_{nn} - (1/1346)\,\varepsilon_{nn} \quad \text{for} \quad \delta_t/\delta_n < 1/3 \qquad (3)$$

$$\beta^{-1} = 1 + p\,\varepsilon_{nn} \quad ; \quad p = 2500 / \left\{ d_{max}^{\,0.14} \left[0.76 - 0.16\,\varepsilon_{nn}/\gamma_{nt}\,(1 - \exp(-6\,\gamma_{nt})) \right] \right\} \quad \text{for} \quad \delta_t/\delta_n < 2/3 \qquad (4)$$

The dowel action mechanism of shear transfer is difficult to represent with accuracy (i.e. axial stiffness) because of the interaction of bending effects with the tensile stresses developed at the crack. It leads to implement integration points at which cracking is evaluated. The localization criteria that makes meaningful the use of the strain-softening is described herein by Eq. 5, *it is called the "yielding criteria"*.

$$f = \sigma_n^2 + \tau_n^2/\alpha^2 - f_t^2 = 0 \qquad (5)$$

By introducing all of the above-mentioned considerations in the stiffness matrix of an element, it results in the governing equation for the cracked stage.

2. CASE STUDY

A RC bridge pier with the dimensions shown in Fig. 2 is analized, compressive strength of the 3 cm maximum aggregate concrete is 270 kg/cm^2. The layout of reinforcement is also shown in Fig. 2. Deformed bars of 32 mm and 16 mm diameter of f_y=3000 kg/cm^2 were used for the longitudinal reinforcement and ties respectively. The RC bridge pier was subjected for 10 sec to a sinusoidal base motion with 400 gals of peak-acceleration. The Finite Element model is depicted in Fig. 3. Both, the longitudinal and transversal reinforcement are represented by the vertical and horizontal lines of the finite element model depicted in Fig. 3.

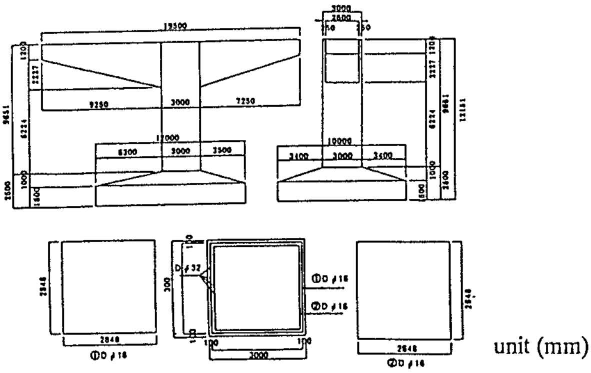


Fig. 2 Geometric and structural detailing of the RC pier

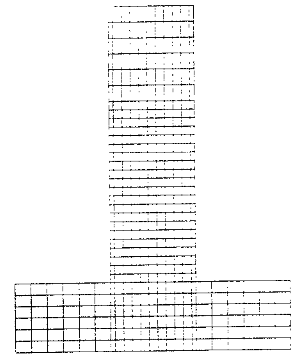
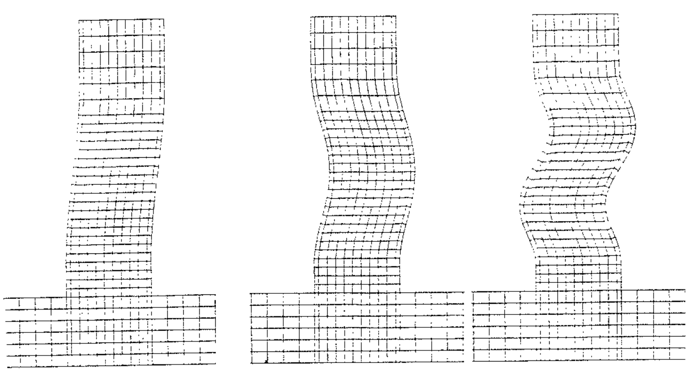


Fig. 3 Finite Element Model

3. DISCUSSION OF RESULTS AND CONCLUSIONS

Fig. 4 depicts the variation of deformation of the RC bridge Pier for t= 1.5 sec, t=4.6 sec, and t=7.3 sec respectively. From Fig. 4, it can be observed that strength allocated to the concrete near the base of the pier, diminishes progressively with cyclic reversals applied because the high deformations of both, steel reinforcement and concrete, specially from 1.50m height from the base. For instance, Fig. 4a (t=1.5 sec) shows the deformation stage when the concrete tensile stress is first reached, it means when the first crack occurs (at 1.50 m height from the base), it is necessary to indicate that displacement at the point in which it intersects with its transversal component "beam" (at 6.2 m from the base of the pier, of the pier) was 1.86 cm. For a better understanding, it should be remembered once more again, that, deformation of longitudinal and transversal lines represent the deformation of longitudinal and transversal reinforcement. On the other hand, Fig. 4b shows the large deformation at t= 4.6 sec in the diagonal direction (prevalence of tension stage on the compression one) at almost the midheight of the pier at which the horizontal displacement was 2.1 cm. From this Figure it is implicit that tension stiffening by means of the mechanic interlock between the concrete and steel bars starts to gain importance. Going further, Fig. 4c shows the deformation of the pier at t= 7.3 sec , it shows explicitely the deformation of steel bars including the ties. From this figure, it can be concluded that: ***Diagonal tension in RC Bridge Piers subjected to strong ground motions, start to develop primarily from the base of the pier and in some degree (depending on the size of the pier) from the intersection between the column itself with the beam component of the pier, it is due to the large rigidity of the base of the pier as well as of the upper part of the pier***. Consequently, ***the shear cracks that extend diagonally are the result of the interaction of shear-compression and shear-tension mechanisms in zones where the shear deformation capacity depend strongly on the boundary conditions of both the lower and the upper part of the RC bridge pier.*** All the state of stresses produced in a RC bridge pier during a strong ground motion, are in between the tension and compression states, therefore, evaluation of shear failure mechanism should be done necessarily by taking into account a "yield condition" for controlling the states of shear-tension or shear-compression need to be considered apropiately. Finally Fig. 5 shows the distribution of shear stresses developed at the pier at t= 7.3 sec, from this figure it is possible to observe that the ties confining the concrete are seriously exposed to yield, under this circumstance, concrete degradation will degenerate in the shear failure of this RC bridge pier. These results highligth two facts for analizing the shear cracking. One is refering to ***the determination of the extend of the yielding regions*** , and the other is regarding to ***the deformation capacity of the section from the onset of yielding of reinforcement until the collapse.***



a) t= 1.5 sec **b)** t= 4.6 sec **c)** t= 7.3 sec

Fig. 4 Deformation of the whole RC bridge pier showing the deformation of both Long steel bars as well as ties

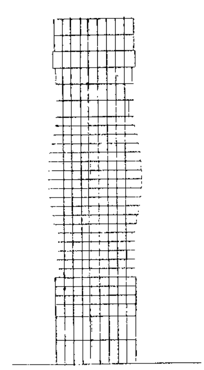


Fig. 5 Distribution of Shear Stresses

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