I-370 Failure Analyses of T-Shape Concrete Bridge Piers under Eccentric Loadings

S. Member JSCE, Kyushu University, Toshihiro Ebihara
Member JSCE, Kyushu University, John Bolander Jr.
Member JSCE, Kyushu University, Hiroshi Hikosaka
Member JSCE, Struct. Engrg. Centr., Masayuki Satake

INTRODUCTION

A series of experimental tests was performed to investigate the nonlinear behavior of T-shape concrete bridge piers under eccentric loadings. Details concerning the experimental setup and results, along with preliminary numerical calculations, have been reported [1, 2]. This paper focuses on certain challenging aspects of the numerical analyses of these structures. Of particular interest is the modeling of bonding actions between the concrete and steel reinforcing. We propose a nonlinear stress-slip model which is based on nonlocal measures of damage.

FINITE ELEMENT IDEALIZATION AND SOLUTION PROCEDURE

Fig. 1 shows the finite element idealization of the Series A test specimens and boundary conditions. Loading P is applied incrementally with Newton-Raphson type iterations to restore equilibrium over each increment. Four-node isoparametric elements represent the concrete assumed to be in a plane stress state. Concrete cracking and plasticity are simulated by adjusting the material response coefficients at appropriate sampling points. Concrete cracking is modeled with a smeared approach; damage parameter ω controls the material softening normal to a cracking plane (Fig. 2).

Considering the structural shape and reinforcing layout, it would not be appropriate to smear the steel behavior over the concrete continuum. Therefore, all reinforcing steel is modeled using discrete truss-type elements with elastic-plastic (strain-hardening) response. Conventional link-type elements (Fig. 3) are used to model the bonding action between concrete and the main reinforcement bars. Normal to the bar direction, the link is given a very high stiffness K_{nn} to simulate zero relative displacement in that direction. Tangential to the bar direction, the link stiffness K_{tt} is adjusted by means of a nonlinear stress-slip relation, as described below.

BOND STRESS-SLIP MODELING

Various tests have provided useful information for modeling bond stress-slip relations, yet most studies have focused on cases of well-confined concrete. Such experimental results account for the effects of damage local to the bar caused by actions of the bar lugs against the concrete. For practical analyses of reinforced concrete structures, however, the effects of damage caused by global effects (e.g. structurally induced cracking) should also be reflected in the stress-slip relations.

Here we propose a bond stress-slip relation which is dependent on a nonlocal measure of damage surrounding the region in question. Two bounding stress-slip relations are used, corresponding to well confined concrete and unconfined concrete [3], respectively (Fig. 4). More precisely, the bond stress-slip relation at node point J is dependent on ω_J^*, a weighted average of the damage surrounding point J (Fig. 5).

$$\omega_J^* = \frac{1}{V_J}\int_V \alpha(\mathbf{x}_J)\omega(\mathbf{x}_J)dV \quad ; \quad V_J = \int_V \alpha(\mathbf{x}_J)dV$$

Here, $\alpha(\mathbf{x}_J)$ is a weighting function which tends towards zero with increasing distance from point J. During finite element calculations, these integrals are computed as discrete sums over the element sampling points. ω_J^* is used to transition between the two bounding curves, as shown in Fig. 4.

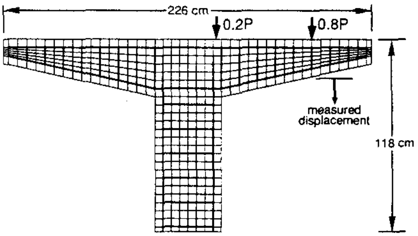

Fig. 1 Finite element modeling

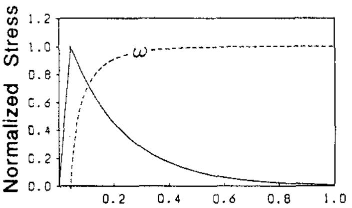

Fig. 2 Exponential softening model

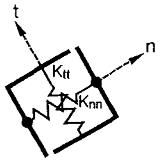

Fig. 3 Bond link element

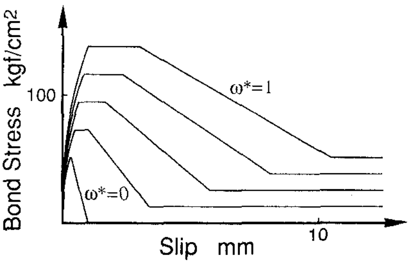

Fig. 4 Variable stress-slip model

Link stiffness K_{tt} is then set equal to the secant stiffness defined by the current stress-slip point on this response curve.

ANALYSIS RESULTS

Load-displacement response of the test specimens and numerical model, with and without bond links, is shown in Fig. 6. Cracking patterns given by the experimental and numerical model are compared in Fig. 7 at the selected load stages shown in Fig. 6. There is good agreement between these results, although formation of diagonal cracking in the panel zone occurs too soon in the numerical model. Notably, smeared crack models which consider strain softening give fairly realistic representations of cracking.

Including the link elements not only effects the global response, but also has a profound effect on the local cracking patterns. When not allowing bond slip, the stiffness of the reinforcing steel artificially restricts softening of the concrete and unnatural cracking formations result (Fig. 7). These concerns are especially critical when using smaller elements, as we do here, since a longer softening branch is required to consume proper fracture energy during cracking.

Similar results have been obtained for the other specimens in the test series. Particularly good agreement is seen with respect to global load-deflection response and final cracking distributions. Failure in the numerical model occurs by concrete crushing, accompanied by severe diagonal cracking and sometimes pullout of the main tensile reinforcing near the top of the column. However, the test results generally did not show such distress in the compressive region and only a few cases showed mild tendency of slippage. Future work will center on improving the bond stress-slip modeling, including a dependency on damage orientation, and will look at other effects such as 3-dimensional behavior to help explain these discrepancies.

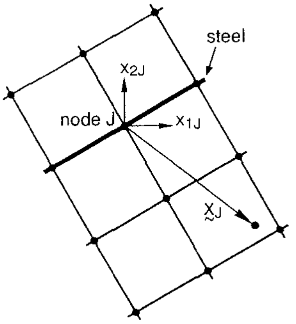

Fig. 5 Averaging about node J

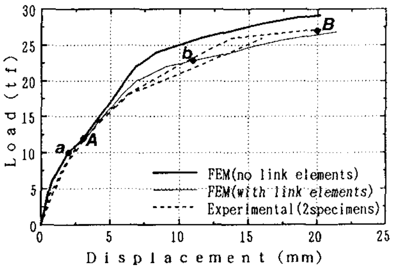

Fig. 6 Load-displacement response

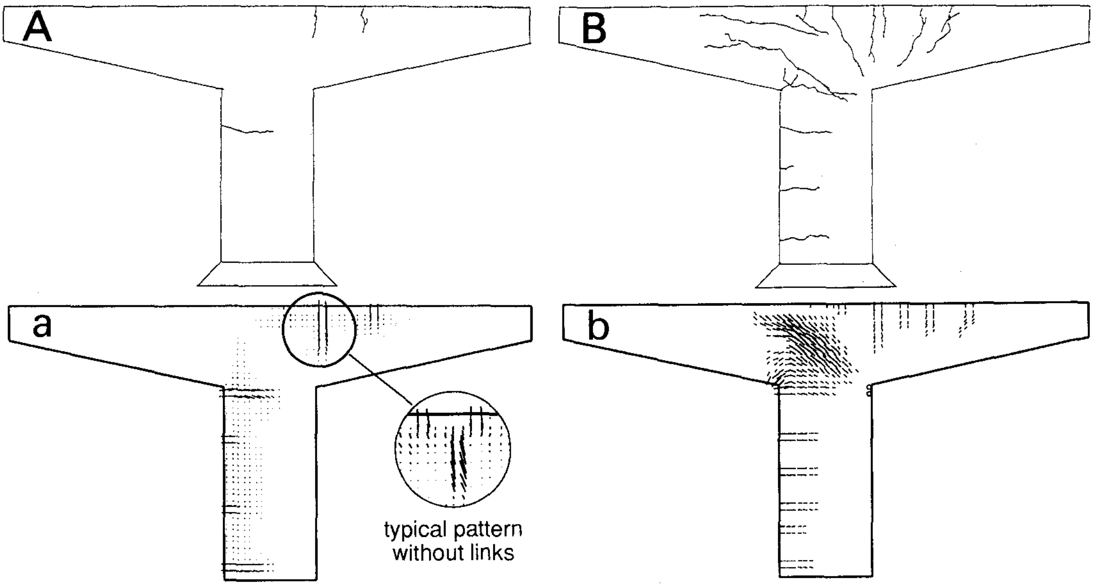

Fig. 7 Experimental (top) and numerical (bottom) cracking patterns

References

[1] Hikosaka, H, et al., J. of Struct. and Mat. in C. E., KABSE and JSCE Seibu-Branch, 1992.
[2] Joh, H, et al., Proc. 47th Annual JSCE National Convention, Division 1, Sendai, 1992.
[3] Eligehausen, R, et al., EERC Report No. UBC/EERC 83-23, Univ. of Calif., Berkeley, 1983.