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DESIGN OF A SEISMIC UPGRADE FOR OUTRIGGER KNEE JOINTS

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ABSTRACT

Observations after the 1989 Loma Prieta earthquake suggest that older outrigger bridge bents may be susceptible to damage under three dimensional earthquake motions. In particular, older joints are weak and brittle and long outrigger beams may have insufficient torsional capacity.

The performance of the existing outrigger knee joint systems was evaluated by testing two half-scale as-built models. Two upgrade schemes, a ductile and a strong strategy, are proposed and tested on prototype specimens. Upgrade design guidelines are made using the steel jacket implementation of the strong upgrade strategy. A combination of displacement and force based design procedures is recommended to insure that the upgraded outrigger knee joint system satisfies the imposed demands. The recommendations for detailing the steel jacket upgrade and a set of tools for predicting the performance of the upgraded outrigger knee joints complete the guidelines.

KEYWORDS

Reinforced concrete, Seismic upgrade, Beam-column plastic hinge, Design of confinement, Structural joint

INTRODUCTION

The urgent need for seismic upgrading of elevated freeways was underscored by the collapses and extensive damage incurred during the 1989 Loma Prieta earthquake. The California Department of Transportation (Caltrans) initiated a large research effort aimed at devising an effective and economical seismic upgrade strategy for the elevated freeway structures built in the 1950's and 60's. One component of the research effort was the investigation of outrigger beam and knee joint systems found in elevated freeway bents (Figure 1). The investigation had two principal goals: to evaluate the behavior of the existing outrigger knee joint systems under combined transverse and longitudinal loading and to devise and experimentally verify upgrading strategies suitable for improving the seismic performance of existing outrigger knee joints [Stojadinović 95].

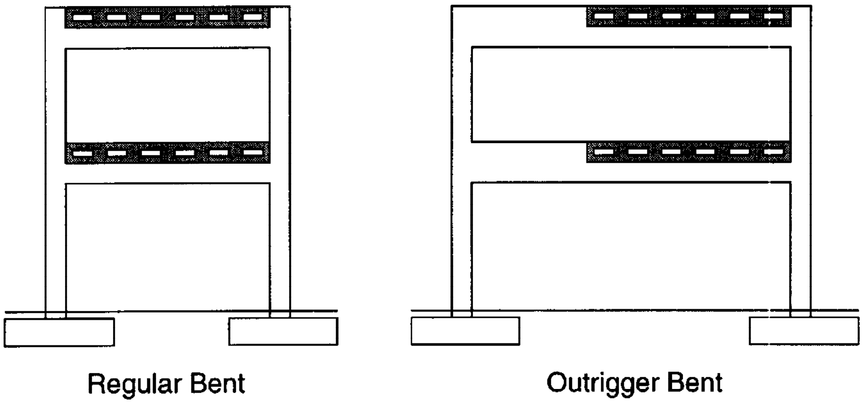

Figure 1: Elevated freeway bents.

Half scale models of typical existing outrigger knee joints were used for experimental evaluation of the behavior of the outrigger knee joint systems. The model/prototype stress identity similitude requirements and the length scale factor of 2 governed the specimen design process. The specimen details and the material properties were chosen to reflect the features of the elevated freeway structures designed in the San Francisco Bay Area during 1950's and 1960's.

For testing convenience the specimens were placed in the loading frame in up-side-down position (Figure 2). The loading pattern was designed to reproduce the overall effects of the earthquake-induced simultaneous bi-directional horizontal motion as well as the effect of gravity and frame action in the bent. The loading was applied in a quasi-static manner by controlling the actuator displacements using a computer. Two types of horizontal displacement patterns were used in the experiments (Figure 2): the clover-leaf pattern and the cross-and-circle pattern. During an experiment, the specimen was subjected to a repeated application of the chosen displacement pattern with a gradually increasing magnitude until failure. The cross-and-circle pattern has the advantage of supplying good planar data as well as three dimensional response data, but it is very demanding in terms of cumulative ductility.

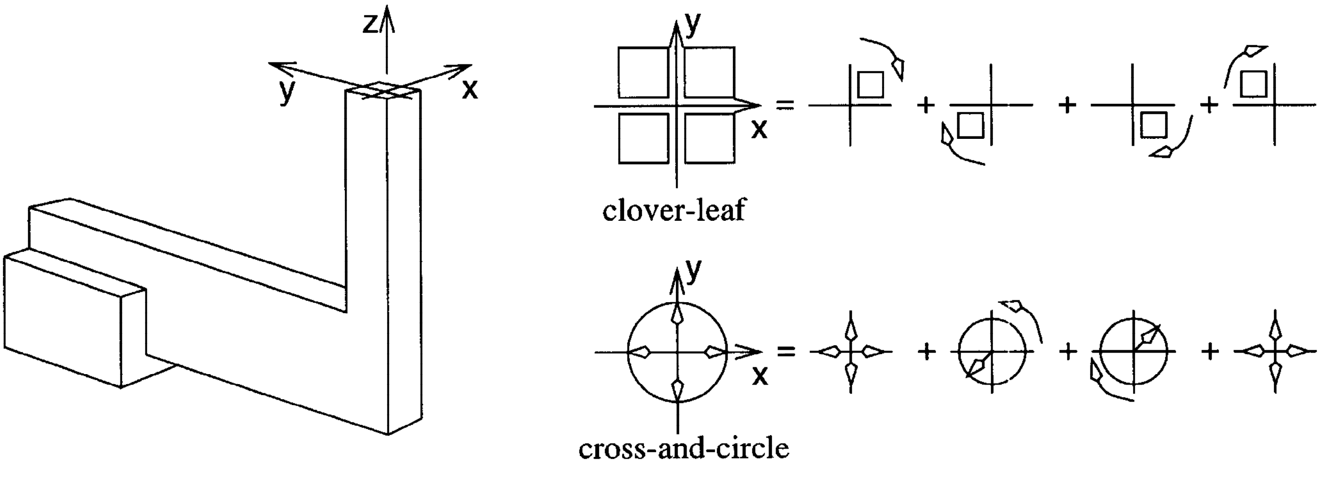

Figure 2: Specimen setup and loading patterns.

AS-BUILT SPECIMENS

The performance of existing specimens was established by testing two specimens, one with a long outrigger beam and the other with a short outrigger beam. The confinement and detailing of the existing outriggers and knee joints is unsatisfactory. The outrigger beam shear reinforcement consists of open stirrups closed with U-caps, placed approximately one quarter of the depth of the beam apart. The longitudinal bars at the bottom of the beam are developed in the knee joint over a length of 20 bar diameters. The joint contains no confining steel, since neither the beam nor the column transverse steel is extended into the joint.

Diagonal cracking appeared on both as-built specimens during the pre-yield cycles. The combination of shear and torsion produced a set of inclined diagonal cracks on the sides of the beam of the long outrigger specimen. The failure of both specimens occurred soon after yielding of column reinforcement. The sides of the joint dilated first, followed by splitting of the layer of column bars from joint core on the exterior face of the joint.

The failure was sudden and brittle (Figure 3). As expected, the unconfined joints were unable to transfer the cyclic joint shears. The long outrigger beam torsional capacity was also found to be inadequate due to the lack of closed stirrups. The deficient details of the existing outriggers contribute to the poor behavior of both as-built specimens.

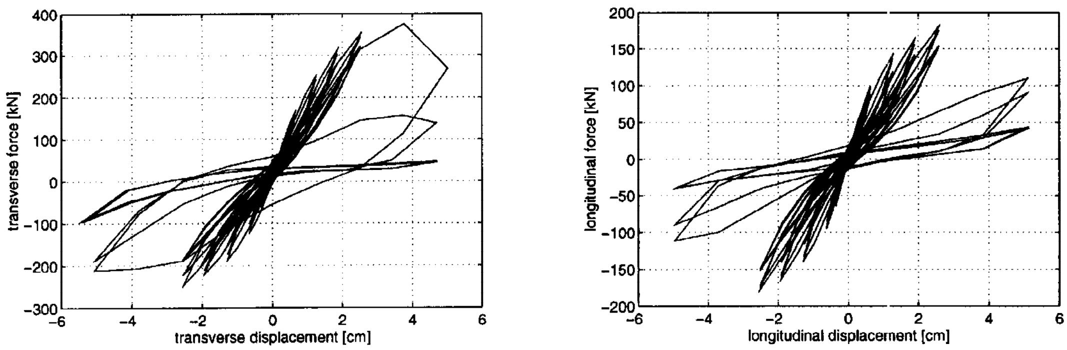

Figure 3: Force/displacement behavior of the short as-built specimen.

PROTOTYPE UPGRADES

The seismic upgrade of existing outrigger knee joints has to prevent their catastrophic failure and to increase their deformation and energy dissipation capacity. The strengthened outrigger knee joints should behave as well as the rest of the upgraded bridge structure and should be easy to inspect and repair after an earthquake. Experiments on the as-built specimens show that the elements of the outrigger knee joint system should be modified to form a stable, ductile, energy dissipating system with a well-controlled failure mechanism. The damage in the knee joint region should be minimized. Two upgrade strategies, designed to accomplish these goals, were proposed: the ductile upgrade strategy and the strong upgrade strategy.

Ductile Upgrade Strategy

The ductile upgrade strategy is designed to increase the stable deformation capacity of the outrigger system. The ductile scheme hinges at multiple locations causing distributed damage throughout the specimen. A plastic hinge forms in the column in response to transverse loading. In the longitudinal direction, hinging occurs in flexure/torsion of the beam.

A reinforced concrete jacket was used on the prototype ductile upgrade. Two 15 centimeter thick side bolsters connected with closed stirrups and T-headed through-bars strengthened the beam. The bolster horizontal reinforcement was wrapped around the outside face of the joint to increase confinement, arrest joint dilation and prevent the column bar bond-splitting failure observed in the as-built tests.

The ductile upgrade prototype behaved as expected, with two distinct plastic hinge zones providing a high level of ductility and energy dissipation. In addition, the forces transferred to the bridge deck were minimized. However, the distributed hinging produced a comparatively large amount of distributed damage, making the upgraded outrigger knee joint system hard to repair after a strong earthquake.

Strong Upgrade Strategy

The strong upgrade strategy was designed to form a stable system with large deformation capacity that concentrated all damage in the column plastic hinge zone. The column was designed to hinge under both transverse and longitudinal loads. The knee joint, the beam and the beam/bridge deck interface were strengthened to the level required to carry the ultimate forces transferred through the column plastic hinge. It should be noted that the forces transfered to the superstructure are larger using this scheme than with the ductile upgrade.

The original strong upgrade prototype used steel jacketing made of 12.5mm A36(USA) plate. The jacket was welded together around the beam and the knee joint, strengthened with threaded through-bars and injected with epoxy. The column of the prototype system was not altered.

As expected, the prototype strong upgrade developed a plastic hinge in the column. The hinge provided the plastic rotation capacity necessary for a ductile behavior of the upgraded system. As a consequence of plastic deformation, virtually all of the damage was concentrated in the column hinge. However, the jacket anchors at the beam/bridge deck interface failed under longitudinal loading, suggesting the final upgrade design must take into account the possibility of significant beam weak axis bending.

FINAL UPGRADE DESIGN

The extent of damage caused by multiple plastic hinge zones makes the ductile upgrade strategy less attractive than the strong upgrade despite its excellent energy dissipation characteristics. The strong upgrade strategy offers a simple ductile solution applicable to outrigger systems with both short and long beams. Therefore, the strong upgrade strategy was chosen for the final design of the outrigger knee joint system upgrades.

Two versions of the final upgrade strategy were tested. A final upgrade employing a post-tensioned reinforced concrete jacket was tested on one long outrigger specimen. The concrete jacket was made up of two 22.5 centimeter thick bolsters resembling the ductile upgrade prototype. Post-tensioning was designed to secure the beam/bridge deck connection and increase the torsional resistance of the beam.

Another final upgrade design (Figure 4), using a 6 mm A572-50(USA) steel plate jacket, was tested on two specimens, one with a long and the other with a short outrigger beam. The jackets were welded together, tied through the middle of the cap beam with one row of threaded through-bars and injected with epoxy. The anchorage of the beam jacket to the bridge deck was carefully detailed to make cap beam post-tensioning unnecessary.

The columns of all three final design specimens were upgraded to achieve large curvature ductility while minimizing the increase in the strength of the column plastic hinge. A grouted cylindrical casing using 3 mm thick A572-50(USA) curved steel plate was placed around the column. The casing was closed from above and below by four pairs of end-plates. The anticipated rotation of the plastic hinge dictated a 2.5 centimeter clearance between the beam jacket and the column casing. The shear capacity of the

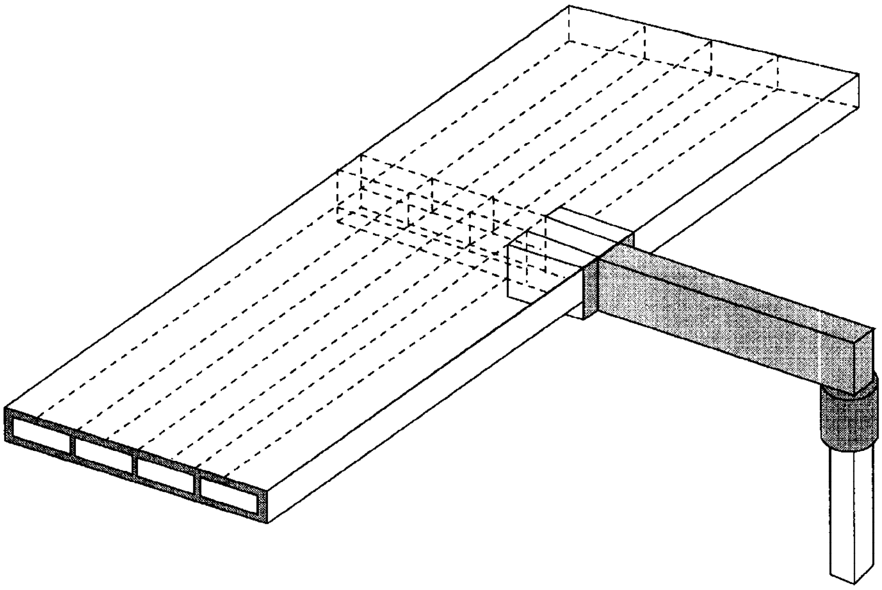

Figure 4: Final upgrade strategy implemented using a steel jacket.

as-built column was determined to be sufficient to hinge the column in bending. Therefore, the steel casing was extended only part-way down the column, along a length determined from the ratio of the ultimate moment capacity of the column hinge and the yield moment strength of the as-built column. Aesthetic or constructibility issues may make a full length column jacket more attractive but it is not needed to achieve the desired system behavior.

The behavior of all three final upgrade specimens was excellent. The strengthened beam and knee joint were sufficiently strong to concentrate virtually all of the damage in the column hinge region. The improvement in the behavior achieved by the strong upgrade is evident from the force/displacement response of the upgraded short outrigger specimen (Figure 5). The specimens maintained significant strength at large deformation and the loops were broad and not pinched.

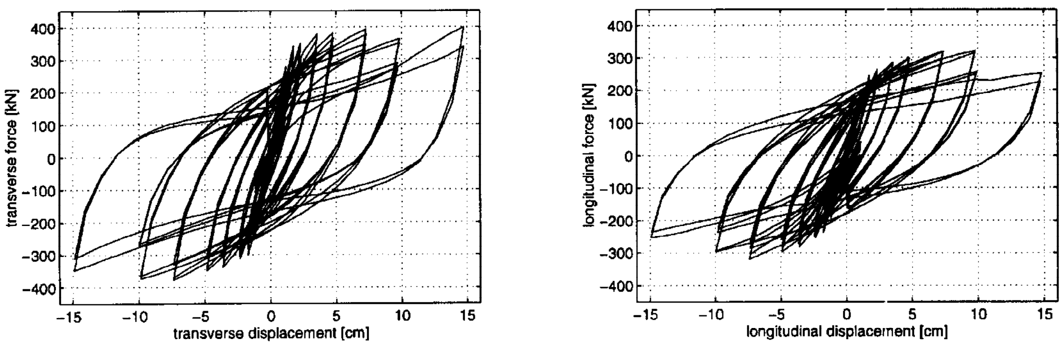

Figure 5: Force/displacement response of the upgraded short outrigger.

The reason for the significantly improved global behavior lies in the ductile moment/curvature response of the upgraded column plastic hinge (Figure 6). Measured response of the upgraded hinge shows stable behavior up to curvature ductility level of 21 and considerable energy dissipation. This behavior was achieved by confining the concrete of the hinge cross section using a steel casing. Even though the casing was quite thin the strains in the casing remained well below yield throughout the experiment.

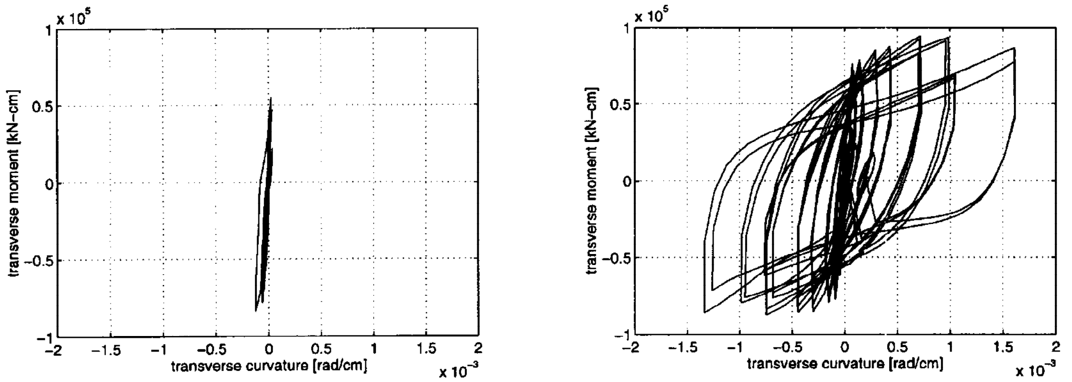

Figure 6: Moment/curvature response of the as-built and the upgraded short outrigger specimen.

DESIGN GUIDELINES AND ANALYSIS TOOLS

Design guidelines [Stojadinović 95] were developed using the information from the experimental and analytical investigation. The guidelines define the necessary steps to design and implement the strong upgrade strategy using a steel plate jacket on existing outrigger knee joint systems. The principal part of the design guidelines is the upgrade design procedure. The procedure has a displacement-based and a force-based part.

The displacement-based part of the design procedure ensures that the upgraded column hinge has sufficient sustained plastic rotation capacity to satisfy the desired outrigger knee joint system drift demand. The design procedure starts by specifying the drift demand on the outrigger knee joint system. The curvature ductility demand on the column plastic hinge is computed using a plastic hinge model under the assumption that all of the system deformation is generated in the hinge zone.

The column hinge confinement is then designed to provide the required curvature ductility. The value of effective confinement pressure is determined iteratively using moment-curvature information from a fiber cross section analysis program. The program employs realistic material models [Mander 84] for unconfined and confined concrete and for the reinforcing steel.

The original section analysis program [Thewalt 94] has been completely rewritten and is now called called APS (Analysis of Plane Sections). The new program has many enhancements over the original version, including: (1) decreased memory demands so that the program can easily run on PC computers; (2) a new solution algorithm that allows for stable force control solution even when multiple stiffness terms go zero or negative; (3) three user definable normalized tolerances to control stress error, path deviation error, and convergence error; and (4) an incremental stiffness update on fiber strain reversals that dramatically improves performance.

Figure 7 shows how the iterative design process is applied to the column hinge cross section of the short upgraded specimen by examining the behavior of an extreme core fiber. Confinement is adjusted until the core concrete does not crush at the desired curvature. The confinement pressure exerted at yield of the column casing was varied from 0 to 5.5 MPa. The improvement in the stress/strain response of the extreme concrete core fiber is reflected in the enhancement of curvature ductility and increase in moment capacity of the column hinge. The dashed line represents the state of the cross section at the design curvature demand level. The circles on the right graph represent the state of the cross section when the first fiber of the concrete core is crushed.

Knowing the ultimate capacity of the upgraded column hinge, including effects like strain hardening, the remaining elements of the upgrade outrigger knee joint system are designed following force-based procedures. The nominal strength capacities of the remaining elements are designed to satisfy the

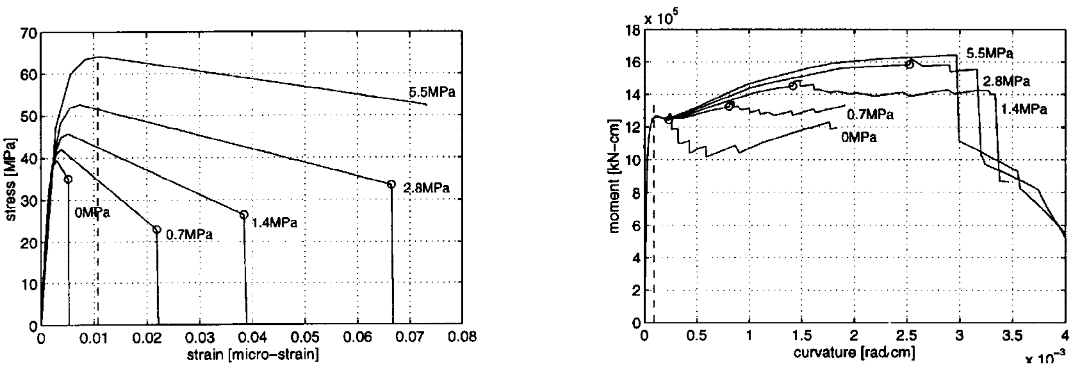

Figure 7: Iterative design of column hinge confinement.

strength demands imposed by the ultimate capacity of the column hinge.

CONCLUSION

The experimental investigation of the as-built outrigger knee joint systems confirmed their vulnerability. The joint region and the torsional strength of the outrigger beam were found to be the primary weak links of the system. Seismic upgrading was found to be necessary to avoid the brittle behavior observed in the as-built tests.

Two upgrade strategies for existing outrigger knee joint systems were proposed and evaluated. The final upgrade strategy is based on the capacity design principle of concentrating the damage in the column plastic hinge and strengthening the remaining elements of the outrigger knee joint system. Variations of the final upgrade design were tested on three specimens and all performed very well.

A demand/capacity procedure for designing the seismic upgrade of existing outrigger knee joints was developed. The design procedure is based on careful detailing of the column plastic hinge to provide adequate and sustained plastic rotation capacity. The design procedure, together with several detailing solutions and section analysis program form a set of design guidelines presented in [Stojadinović 95]. The final report also investigates issues of how the observed local behavior can be included in simplified global nonlinear analyses.

REFERENCES

[Mander 84] J. B. Mander, M. J. N. Priestley, and R. Park. "Seismic design of bridge piers." Technical Report 84-2, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, February 1984.

[Stojadinović 95] B. Stojadinović and C. R. Thewalt. "Upgrading bridge outrigger knee joint systems." Technical Report UCB/EERC-95/03, Earthquake Engineering Research Center, University of California, Berkeley CA 94720, 1995.

[Thewalt 94] C. R. Thewalt and B. Stojadinović. "A stable reinforced concrete section analysis procedure." *ASCE Structural Engineering Journal*, 120(ST10):3012–3024, October 1994.