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Improving Seismic Performance of Outrigger Knee Joints

Amélioration de la résistance sismique des portiques de support d'autoroutes surélevées

Verbesserung des seismischen Verhaltens von Brückenauslegerverbindungen

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SUMMARY

Improving the seismic performance of bridge outrigger knee joint systems became imperative after the 1989 Loma Prieta earthquake. The existing outrigger knee joints were experimentally evaluated on half-scale specimens. Two upgrade strategies were proposed and tested on prototype specimens. The "strong" strategy was chosen for the final upgrade design, tested on three specimens and recommended in the form of upgrade design guidelines.

RÉSUMÉ

A la suite du séisme de Loma Prieta en 1989, il a fallu revoir la conception des portiques de support des autoroutes surélevées. Les connections entre la colonne et la poutre de support ont particulièrement souffert. Des connections de conception traditionnelle ont été testées en laboratoire a l'échelle 1:2. Deux stratégies de renforcement ont été proposées et testées sur différents prototypes. La stratégie "forte" a été adoptée comme solution finale. Cette stratégie a été testée sur trois spécimens additionnels et recommande un renforcement des directives de projet.

ZUSAMMENFASSUNG

Nach dem Loma Prieta Erdbeben im Jahre 1989 wurde ersichtlich, dass Verbesserungen des seismischen Verhaltens an Brückenauslegerverbindungen unbedingt erforderlich sind. Bis zu dem Zeitpunkt übliche Brückenauslegerverbindungen wurden experimentell an Modellen im Maßstab 1:2 getestet. Zwei Verbesserungsstrategien wurden vorgeschlagen und in Modellversuchen getestet. Die "starke" Strategie wurde schließlich für den endgültigen Verbesserungsentwurf gewählt. Nach dem Testen dieser Strategie an drei Modellen wurden Richtlinien zum Verbesserungsentwurf empfohlen.

1 INTRODUCTION

The catastrophic collapse of the Cypress Viaduct during the Loma Prieta 1989 earthquake emphasized the vulnerability of elevated freeway bridge structures. One track of the joint California Department of Transportation and University of California at Berkeley research project is the investigation of outrigger beam and knee joint systems found in elevated freeway bents (Figure 1). This project has two principal goals: to evaluate the behavior of the existing outrigger and knee joint systems under a combined transverse and longitudinal loading and to devise and experimentally verify upgrading strategies and repair techniques suitable for improving the seismic performance of outrigger knee joints [1].

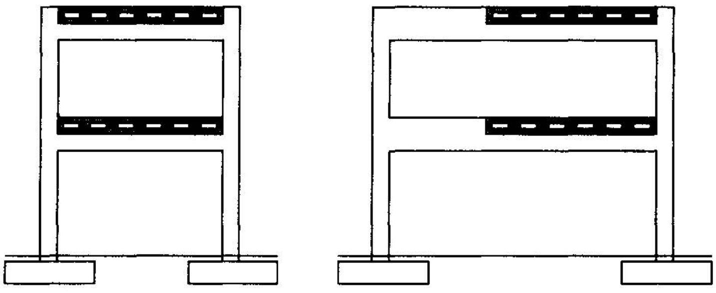

Figure 1: Elevated freeway bents.

2 EXPERIMENT SETUP

The outrigger knee joint specimens are scaled models of the existing outrigger knee joint systems. The length scale factor of 2 and a model/prototype stress identity similitude requirements governed the specimen design process. The choice of materials and the specimen details reflect the features of the elevated freeway structures designed in the San Francisco bay area during 1950's and 1960's.

The specimens were placed in the loading frame in up-side-down position to facilitate loading and anchoring (Figure 2). The actuator displacements were computer controlled to apply the loading in a quasi-static manner. The loading pattern, designed to simulate the outrigger knee joint earthquake loading, models the simultaneous horizontal motion in both directions, the effect of the frame action and the dead load of the bridge. Two types of horizontal displacement patterns were used in the experiments (Figure 2): the clover-leaf pattern and the cross-and-circle pattern. A test was made up of repeated application of the chosen load pattern, with the magnitude of the horizontal displacement increasing in multiples of the yield displacement value until failure.

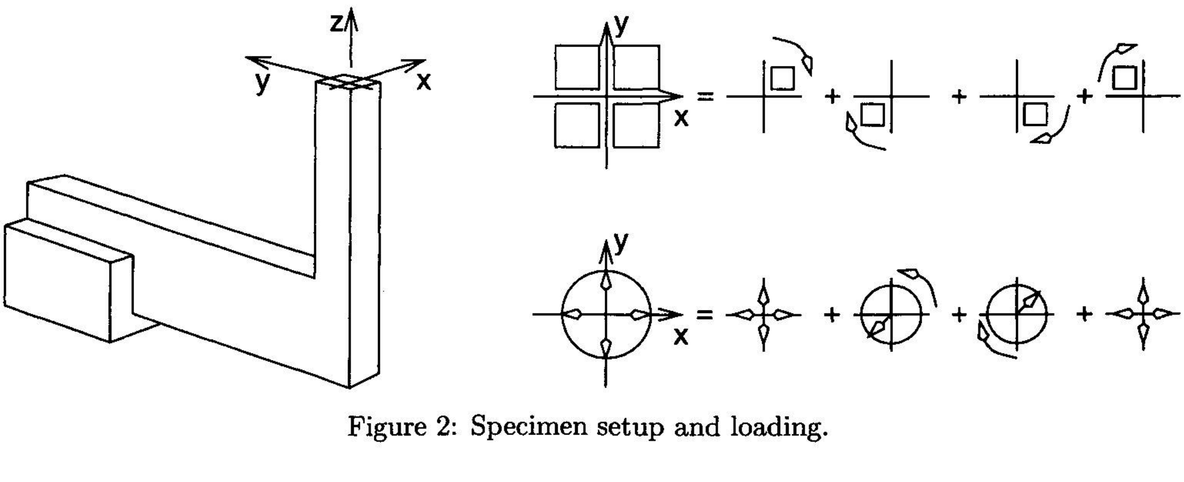

Figure 2: Specimen setup and loading.

3 AS-BUILT SPECIMENS

Performance of exiting outrigger knee joints was evaluated using two half-scale specimens, one with a long outrigger beam the other with a short outrigger beam. Compared to the current practice, confinement and detailing of the outriggers and knee joints is unsatisfactory. The outrigger beam shear reinforcement consists of hoops closed with a U-cap, placed approximately one quarter of the depth of the beam apart. The development length of the bottom beam bars into the joint is approximately 20 bar diameters. The joint contains no confining steel.

The deficient details of the existing outriggers contribute to the poor behavior of both as-built specimens [2]. The specimens developed diagonal cracks in the joint area during the pre-yield cycles. The combination of shear and torsion produced a set of inclined diagonal cracks to form on the sides of the long beam. The failure of both specimens occurred slightly after yielding of the column reinforcement and beam hoops. The sides of the joint dilated and then the layer of column bars on the outside face of the joint split away from the joint core.

The failure was sudden and brittle, as seen from the force/displacement response graphs for the short-span outrigger specimen (Figure 3). As expected, the unconfined joints were unable to transfer the cyclic joint shears, and the outrigger torsion capacity was inadequate due to the lack of closed stirrups.

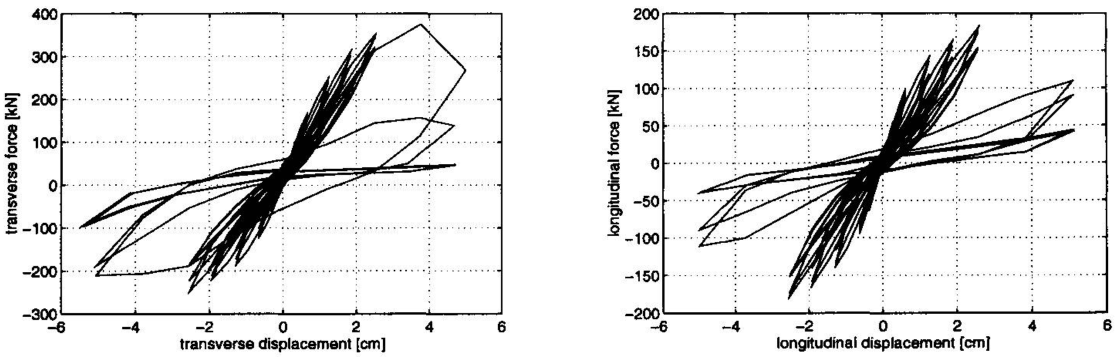

Figure 3: Force/displacement behavior of the short as-built specimen. Displacement of 3.6 centimeters corresponds to a drift ratio of 1%.

4 PROTOTYPE UPGRADES

Systematic upgrading of the outrigger knee joint system is necessary to elevate the performance of the system to a level implied by the current earthquake-resistant design practice. The goal of upgrading is to prevent catastrophic failure and to enhance the deformation and energy dissipation capacity of the outrigger knee joint system so that it behaves as well as the rest of the upgraded bridge structure [3]. The elements of the system should be strengthened to form a stable, ductile, energy dissipating system with a well-controlled failure mechanism. Furthermore, the strengthened outrigger knee joint system should be easy to inspect and repair after an earthquake.

The experiments on the as-built specimens show that the capacity of the joint region must be increased to limit damage there. The strength and stiffness of the outrigger beam for both bending and torsion must be improved. Jacketing the system elements was chosen to accomplish both of these goals. Starting from these common points, two upgrade strategies were proposed: The ductile upgrade strategy; And the strong upgrade strategy.

4.1 Ductile Upgrade Strategy

Ductile upgrade strategy is designed to produce multiple plastic hinges in the outrigger and knee joint system. In transverse direction, for both joint opening and joint closing, a plastic hinge is expected remaining elements of the outrigger and knee joint system are strengthened to the capacity required to sustain the designed plastic hinges.

The prototype ductile upgrade was made using a concrete jacket. Two 15 cm 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.

The ductile upgrade prototype behaved according to expectations. The two distinct plastic hinge zones provided 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 damage, suggesting that an upgraded outrigger and knee joint system may be hard to inspect and repair after a strong earthquake.

4.2 Strong Upgrade Strategy

The fundamental premise of the strong upgrade strategy is to form a single plastic hinge in the column for both the transverse and the longitudinal loading directions. The knee joint, the beam and the beam/bridge deck interface of the outrigger and knee joint system are strengthened to the level required to sustain the forces transferred through the column plastic hinge.

A steel jacket made of 12.5 mm A36 steel plate was used in the strong upgrade prototype. The jacket was welded together around the beam and the knee joint, strengthened with post-tensioned through-bars and injected with epoxy. The column of the outrigger knee joint system was not altered.

As expected, the prototype strong upgrade developed a plastic hinge in the column. The hinge insured ductile behavior of the upgraded system, with the damage concentrated in the column base. The forces generated in the column hinge under longitudinal loading caused failure of the jacket anchors at the beam/bridge deck interface, suggesting the final upgrade design must take into account the possibility of significant beam weak axis bending.

5 FINAL UPGRADE DESIGN

Despite the good energy dissipation behavior and the ability to sustain the dead load after severe deformations, the extent of damage caused by multiple plastic hinge zones makes ductile upgrade strategy less suitable for fulfilling the upgrade design goals. The strong upgrade strategy offers a sufficiently 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 strong upgrade strategy were tested. A strong 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. The post-tensioning was designed to secure the beam/bridge deck connection and increase the torsional resistance of the beam.

Another strong upgrade design, using a 6 mm A572-50 steel plate jacket, was tested on two specimens, one with a long and the other with a short outrigger beam (Figure 4). The jackets were welded together, tied with post-tensioned through bars and injected with epoxy. The anchorage of the beam jacket to the bridge deck was carefully detailed without the use of post-tensioning.

The columns of all three final design specimens were enhanced to achieve large curvature ductility with the smallest possible increase in the strength of the column plastic hinge. A grouted cylindrical steel casing was placed around the column. The casing is 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 as-built column was determined to be sufficient to carry the shear force required to hinge the column in bending. Therefore, the steel casing was extended only part-way down the column. The length of the steel casing was determined by considering the ultimate moment capacity of the column hinge and the yield moment strength of the as-built column.

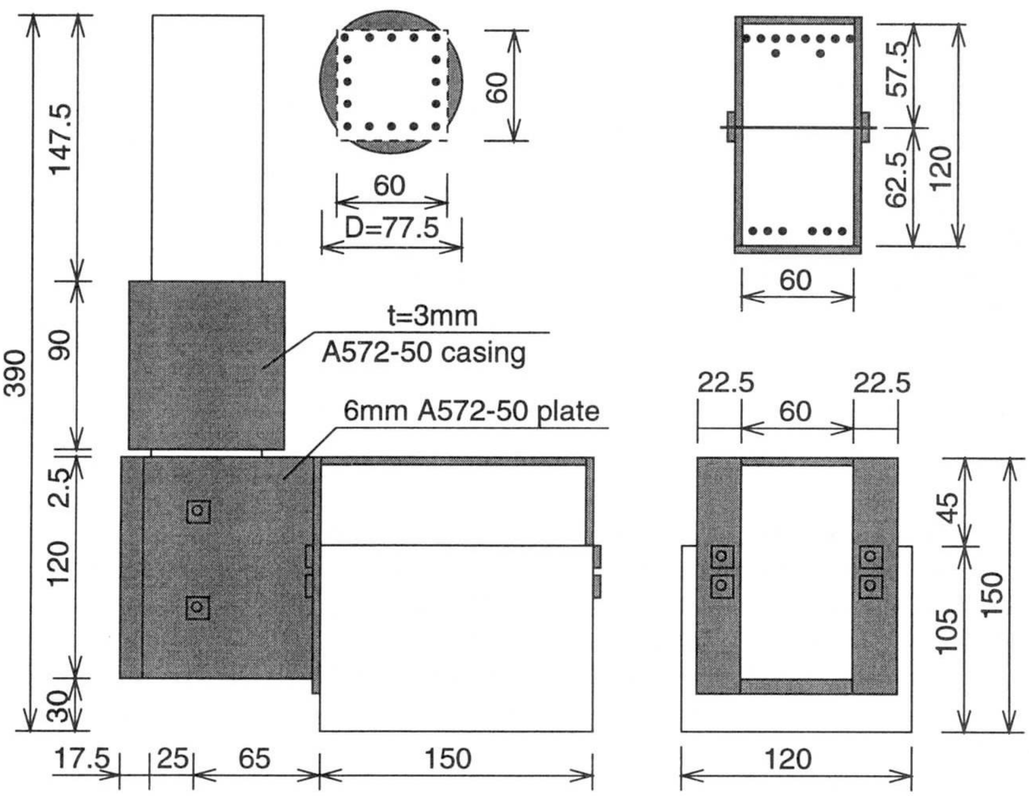

Figure 4: Final design of the strong steel jacket upgrade.

The behavior of all three specimens complied fully with the upgrade design goals. The strengthened beam and knee joint were sufficiently stiff to make the bi-directional plastic hinge form at the base of the column. The curvature ductility achieved in the hinges was 21. The damage in all three specimens was concentrated in the column hinge. 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) and the comparison of tip displacement ductility and drift measures for all seven specimens (Table 1).

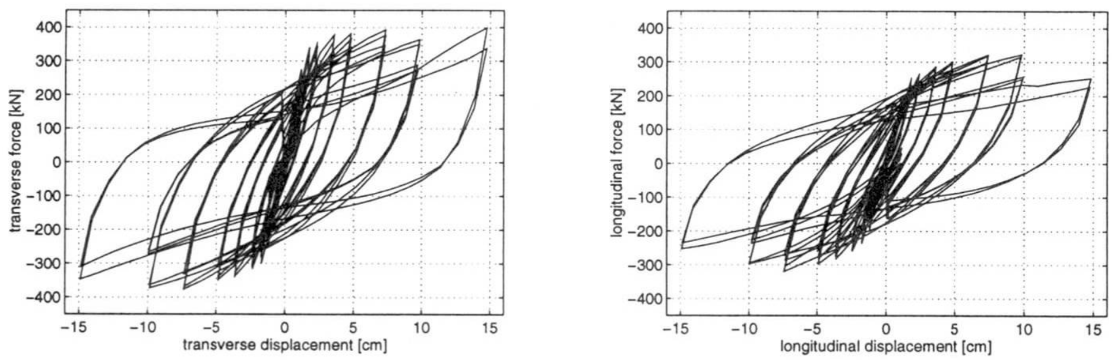

Figure 5: Force/displacement response of the upgraded short outrigger.

6 CONCLUSIONS

The results of the investigation on improving the seismic performance of outrigger knee joint systems were summarized in the form of seismic upgrade design guidelines. The guidelines define the necessary steps to implement the strong upgrade strategy using a steel plate jacket on existing outrigger knee

specimen	transverse		longitudinal	
	displ. ductility	drift [%]	displ. ductility	drift [%]
as-built long	1.5	1.04 (2.78)	5.33	1.39 (2.78)
as-built short	2.0	1.04 (1.39)	1.33	0.69 (1.39)
ductile prototype	5.5	5.56 (5.56)	6.0	2.78 (5.56)
strong prototype	6.0	2.78 (4.16)	4.0	2.78 (4.16)
strong concrete	12.0	2.78 (4.16)	12.0	2.78 (4.16)
strong steel long	12.0	2.78 (5.56)	12.0	2.78 (4.16)
strong steel short	12.0	2.78 (4.16)	12.0	2.78 (4.16)

Table 1: Specimen ductility and drift measures. The bracketed drift values are computed at the largest displacement level achieved during the test.

Particular attention is directed to detailing the column plastic hinge zone. The thickness of the cylindrical column casing is determined to provide the effective confinement pressure needed to achieve the desired drift of the outrigger knee joint system. The necessary column hinge curvature ductility is calculated first, using the desired drift and assuming all of the deformation is generated in the column plastic hinge. Given the curvature demand, a program for non-linear analysis of reinforced concrete cross-sections, AFcS [4], is used to design the confinement of the hinge cross-section. Using Mander's model for confined concrete [5], the level of confinement is adjusted to enable the hinge cross section to achieve the necessary curvature ductility while keeping the largest strain in the concrete core below the crushing strain level.

In addition to providing design tools and detailing recommendations, the guidelines emphasize the fundamental principles of capacity design in the seismic upgrade setting. The guidelines complete the research loop by providing results in a form useful to practicing engineers.

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