Copyright © 1996 Elsevier Science Ltd
Paper No. 1303. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

IN-PLANE SEISMIC RESPONSE OF JOINTS IN MULTI-COLUMN BENTS OF CONCRETE BRIDGES

J. M. INGHAM[1], S. SRITHARAN[2], M. J. N. PRIESTLEY[2], AND F. SEIBLE[2]

[1] Department of Civil and Resource Engineering, University of Auckland, Private Bag 92019, Auckland, New Zealand.

[2] Division of Structural Engineering, Department of Applied Mechanics and Engineering Sciences, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0085, USA.

ABSTRACT

Experimental investigations were conducted on the in-plane seismic response of both exterior (knee) and interior (tee) large-scale beam-column bridge joint sub-assemblies. These investigations were supported by parallel analytical studies based on rational joint force transfer models. Utilising design strategies developed from the preliminary investigations, two further units incorporating new design techniques were tested. The application of headed reinforcement in the first unit and cap beam prestressing in the second unit greatly reduced congestion of joint reinforcement, when compared with the equivalent joints designed using conventional methods. Excellent response was obtained for both new designs, confirming the validity of the rational design procedure.

KEYWORDS

Concrete bridge; seismic response; beam-column joint; force transfer mechanism; strut and tie modeling; joint compression strut; headed reinforcement; cap-beam prestressing; precast construction.

BACKGROUND

Bridge damage which occurred during a number of earthquakes in the State of California since 1971 has motivated research on the seismic response of reinforced concrete bridge components, with the objective of developing retrofit and new design strategies. An accelerated Bridge Seismic Retrofit Program (Roberts, 1991) was implemented in California following the 1989 Loma Prieta earthquake, leading initially to the installation of hinge and joint cable restrainers, and subsequently to the use of column jackets to improve shear strength and flexural deformation characteristics. More recently, the California Department of Transportation (Caltrans) has supported a number of investigations into the seismic response of both column-footing and column-cap beam connections.

The two investigations reported herein were motivated by the poor response of a considerable number of reinforced concrete freeway bridge joints during the Loma Prieta Earthquake (Housner, 1990). Eight exterior cap beam-column bridge knee joint units (Ingham *et al.*, 1994a,b) and four interior cap beam-column bridge tee joint units (MacRae *et al.*, 1994, Sritharan *et al.*, 1995) were tested, employing as-built, repaired, retrofitted, or redesigned joint details. Results from these tests indicated that poor seismic performance could be expected for many pre-1970 as-built bridge joints in the State of California, and confirmed the comparative efficiency of new designs and retrofit measures incorporating reinforced, partially prestressed, and fully prestressed cap beams.

Research Significance

The seismic design of reinforced concrete bridges in California is now based upon the capacity design philosophy (Priestley *et al.*, 1996), requiring that joint damage is minimised during an earthquake, so that structural collapse is prevented and subsequent joint repair is not required. However, the current United States concrete design code (American Concrete Institute, 1992) and the regulatory document governing bridge construction (AASHTO, 1989) provide little direction in the design of such joints. Furthermore, guidelines provided in other design standards (e.g. Standards New Zealand, 1995) are primarily derived for building frames, and lead to excessive congestion of reinforcement when applied to bridge joints. Results from the research described in this paper provide alternative rational methods for design of the joint regions to reduce reinforcement congestion.

FORCE TRANSFER MODELS

The fundamental premise of the proposed rational design procedure is that the magnitude and distribution of forces acting at the joint boundaries in conjunction with the formation of plastic modes of deformation can be accurately identified, and that with appropriate detailing, these forces can be readily distributed through the joint in association with the development of a joint diagonal strut. However, it has been demonstrated (Ingham, 1995) that the manner in which these forces are distributed through a reinforced concrete bridge joint is greatly influenced by both geometric and reinforcement detailing within the joint, so that a rational assessment of the joint force flow is required for each joint design.

Two basic mechanisms are available for the distribution of forces through a reinforced concrete bridge joint: the joint strut mechanism, and the reinforcement truss mechanism. When the full benefit of the joint strut mechanisms is not utilised, or when joint detailing prevents effective development of the diagonal joint strut, it follows that joint demands must be supported primarily by specially-placed joint reinforcement, which will frequently lead to excessive congestion of joint reinforcement.

For the two test units discussed herein, efforts were made to increase the capacity and maximise the effectiveness of the joint strut mechanism, consequently reducing the required volume of specially-placed joint reinforcement. Joint strut capacity was enhanced by increasing the strut depth using two different strategies. In the case of the bridge knee joint unit, the effective use of headed reinforcement resulted in superior delineation of the force paths through the joint, and allowed the joint strut depth to be increased, so that no specially-placed joint reinforcement was required. In the case of the multi-column bridge bent unit comprised of both a knee and a tee joint, the application of cap beam prestressing effectively increased the joint strut depths, and only a minimal quantity of specially-placed joint reinforcement was provided. In both cases, excellent test unit response demonstrated the validity of the new design procedure.

Joint Stress Levels

In both the New Zealand code approach and the ACI code approach, the maximum input to the joint is correlated to the limiting uniform joint shear stress. In the New Zealand code, the maximum recommended uniform joint shear stress is related to the concrete compression strength (f_c'), while in the ACI code the maximum recommended uniform joint shear stress is related to the concrete tension strength ($\sqrt{f_c'}$). However, when conducting a rational assessment of the force flow through a joint, both code procedures are of little relevance. Instead, an investigation of the principal tension and compression stresses developed within the joint is recommended. In the assessment of poorly detailed joints, joint response will be dictated by joint cracking, so joint stress levels should be related to the maximum joint principal tension strength (Priestley *et al.*, 1996). Furthermore, in well detailed joints in which a substantial component of the total demand upon the joint is supported by the joint strut mechanism, joint strut strength will dictate response, and joint demand should be related to the maximum joint principal compression strength.

Joint Strut Capacity

When conducting a rational assessment of the demand upon the joint diagonal strut it is necessary to define the strut geometry, and in particular the critical strut cross-section, based upon the distribution of flexural forces and prestress anchors acting at the joint strut boundaries, and if applicable, the distribution of headed reinforcement. Demand can then be compared with the capacity estimated using procedures such as those of Vecchio and Collins (1986), which have been adapted by Kuchma (1994) to incorporate the influence of out-of-plane confinement. In particular, it is important to recognise that strut capacity will significantly diminish as the transverse tension strains increase within the joint.

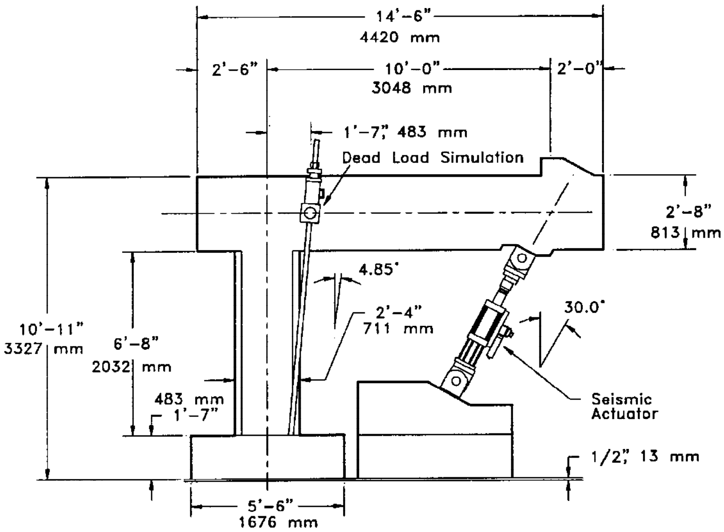

Fig. 1. Configuration of Knee joint test set-up.

BRIDGE KNEE JOINT UNIT WITH HEADED REINFORCEMENT

In a previous investigation (Ingham *et al.*, 1994a,b) eight large-scale bridge knee joint units were tested under simulated seismic cyclic loading, and were divided into two categories dependent upon their column geometry. The units having a rectangular column configuration represented a pre-1970 as-built joint, a haunched joint repair, an external prestress retrofit of the as-built joint incorporating no conventional joint reinforcement, and a redesign of the as-built joint requiring a considerable volume of specially-placed joint reinforcement. Similarly, the units having a circular column configuration represented a recently completed as-built joint, a haunched joint repair, a retrofit using a reinforced concrete jacket about the as-built joint, and a redesign of the as-built joint utilising internal prestressing of the cap beam and joint. The configuration of the test set-up is shown in Fig. 1.

Upon completion of the investigation discussed above, a bridge knee joint unit utilising headed reinforcement, but no conventional joint-shear reinforcement, was designed and tested (Ingham *et al.*, 1995). The configuration of this unit replicated that used for the rectangular column redesign unit, facilitating direct comparison. For both units a column plastic hinge developed at the joint interface for both positive and negative joint moments, while the longitudinal cap beam reinforcement remained nominally elastic. Reinforcement details for the joint with conventional reinforcement are shown in Fig. 2, and for the joint with headed reinforcement are shown in Fig. 3. A simplified representation of the force transfer mechanisms assumed to develop within the joint of the unit with headed reinforcement is shown in Fig. 4, where the influence of the reinforcement heads upon the geometry of the joint diagonal strut can be clearly identified.

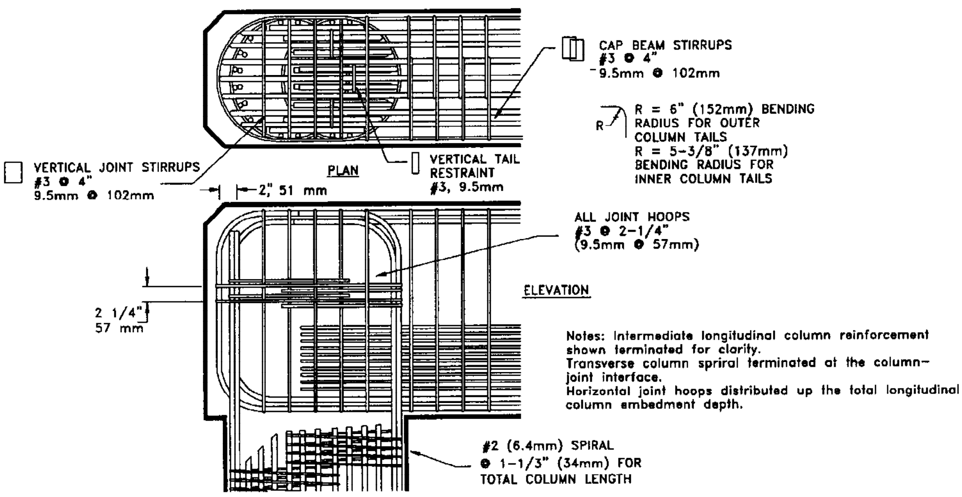

Fig. 2. Reinforcement details for the bridge knee joint unit with conventional reinforcement.

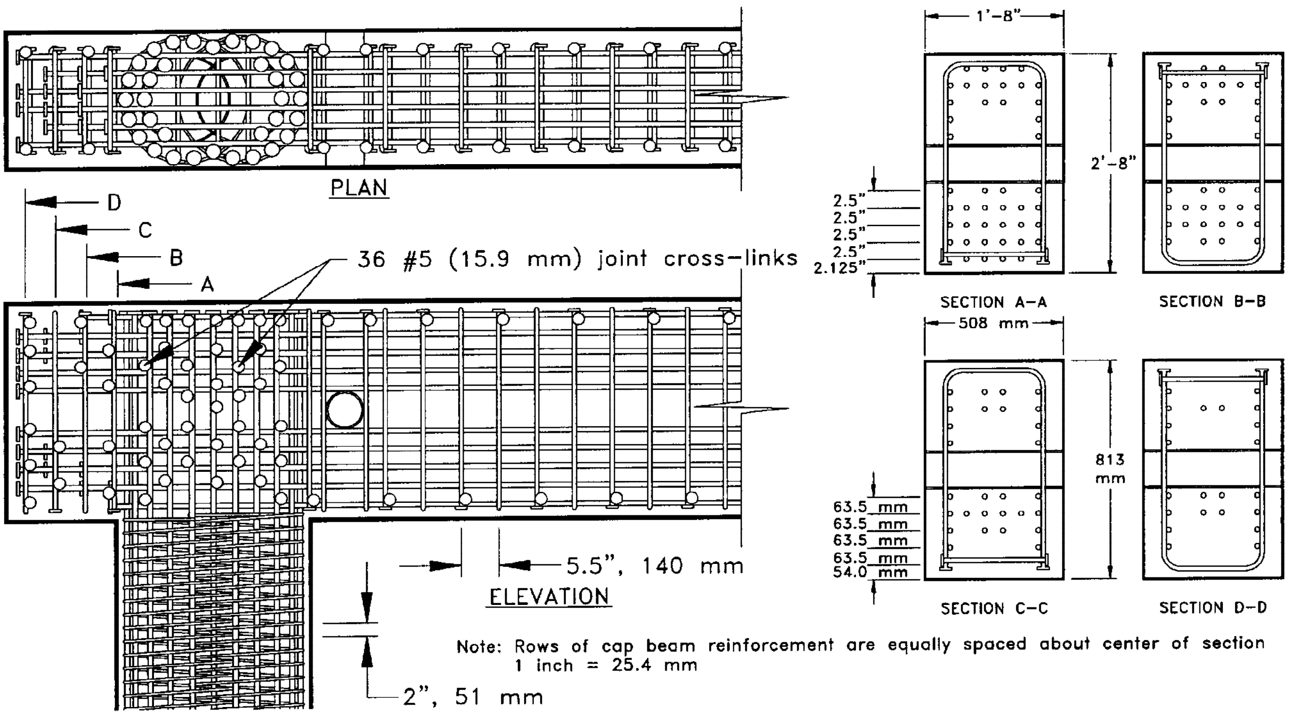

Fig. 3. Reinforcement details for the bridge knee joint unit with headed reinforcement.

Results

In Fig. 5 results are presented, establishing the satisfactory response of the bridge knee joint unit with headed reinforcement. In Fig. 5a the force-displacement history shows that ductile response was attained, with strength degradation eventually developing during repeated cycling at the maximum range of the seismic actuator (see Fig. 1). More importantly, Fig. 5b shows a comparison of the force-displacement envelopes for the unit with conventional reinforcement, and the unit with headed reinforcement. Clearly, the response of the two units was very similar, even though the unit with headed reinforcement contained no specially-placed joint reinforcement. In Fig. 5c the joint shear stress-shear strain curve is plotted, showing that the maximum joint shear stress exceeded the recommended limits of both the ACI and NZ codes, and that satisfactory joint response was developed prior to eventual deterioration under repeated cycling at the maximum displacement level (see also Fig. 5a). Finally, Fig. 5d shows strain gauge profiles measured along an embedded longitudinal column bar in tension for applied joint-opening actions. Clearly significant strain penetration was measured, even prior to first yielding of the longitudinal column reinforcement at the column-joint interface (the critical flexural section). Fig. 5d also shows that at large ductility levels, yield strains were measured 187 mm (7 in., $9d_b$) from the end of the bar, indicating the beneficial influence of headed reinforcement, and confirming the assumed force transfer mechanism (see Fig. 4a).

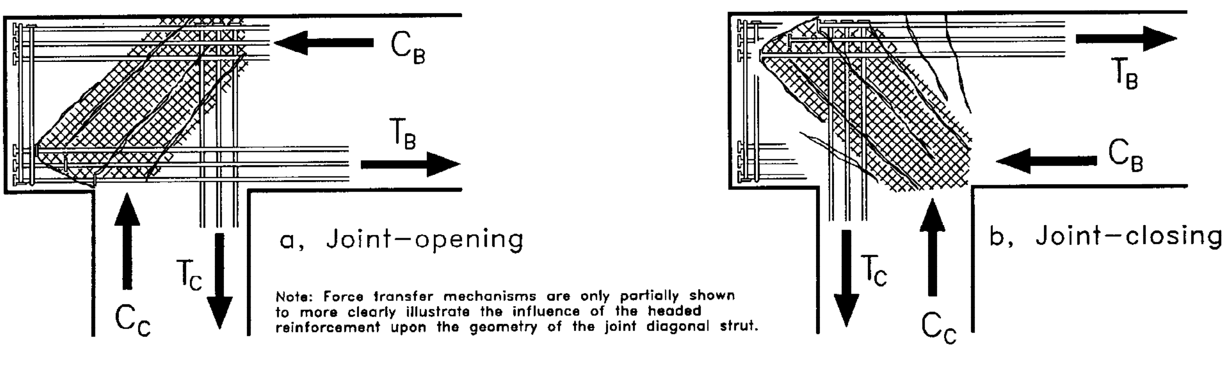

Fig. 4. Partial representation of the developed joint force transfer mechanisms.

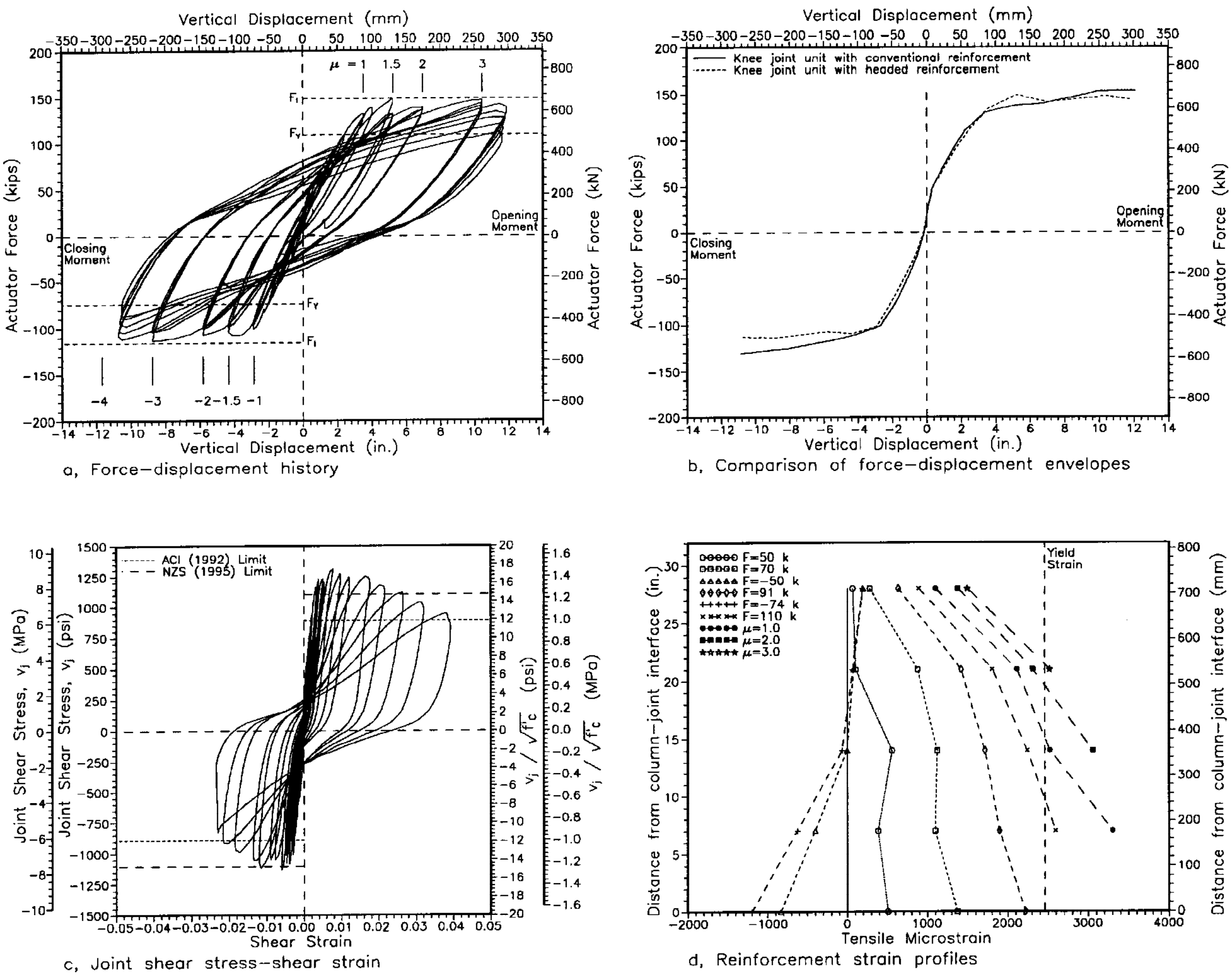

Fig. 5. Test results for the Bridge Knee Joint unit with Headed Reinforcement.

MULTI-COLUMN BRIDGE BENT UNIT WITH CAP BEAM PRESTRESSING

As part of the preliminary beam-column bridge tee joint investigation, it was demonstrated (Sritharan *et al.*, 1995) that cap beam prestressing permitted both a considerable reduction of joint reinforcement, and facilitated precast multi-column bridge bent construction. To rigorously test this type of design approach, a half scale multi-column bent having dimensions representative of a three column bent from the Santa Monica Viaduct in Los Angeles, California, was tested under transverse seismic loading (Sritharan and Priestley, 1995). Longitudinal steel ratios in the columns were increased to 3 and 4 percent respectively in the exterior and interior columns, to impose higher shear demands in the joints. The high joint shear stress along with the cap beam prestressing was expected to induce maximum principal compression stress approaching or marginally exceeding $0.3f_c'$. Consistent with current Caltrans practice, a wider cap beam was used, necessary to accommodate joint steel required for longitudinal seismic response.

Fig. 6 shows the overall dimensions and the test set-up of the multi-column bent unit, which consisted of two columns having pin-supported bases. The two joints, representing a knee connection on the right and a tee connection on the left, were built monolithically with the columns. The cap beam was cast in two segments, and the whole test unit was assembled by attaching the beam segments to the joints solely by prestressing. Four hydraulics actuators, two vertically and two side by side horizontally, were attached to the subassemblage to simulate the seismic forces anticipated in the prototype structure.

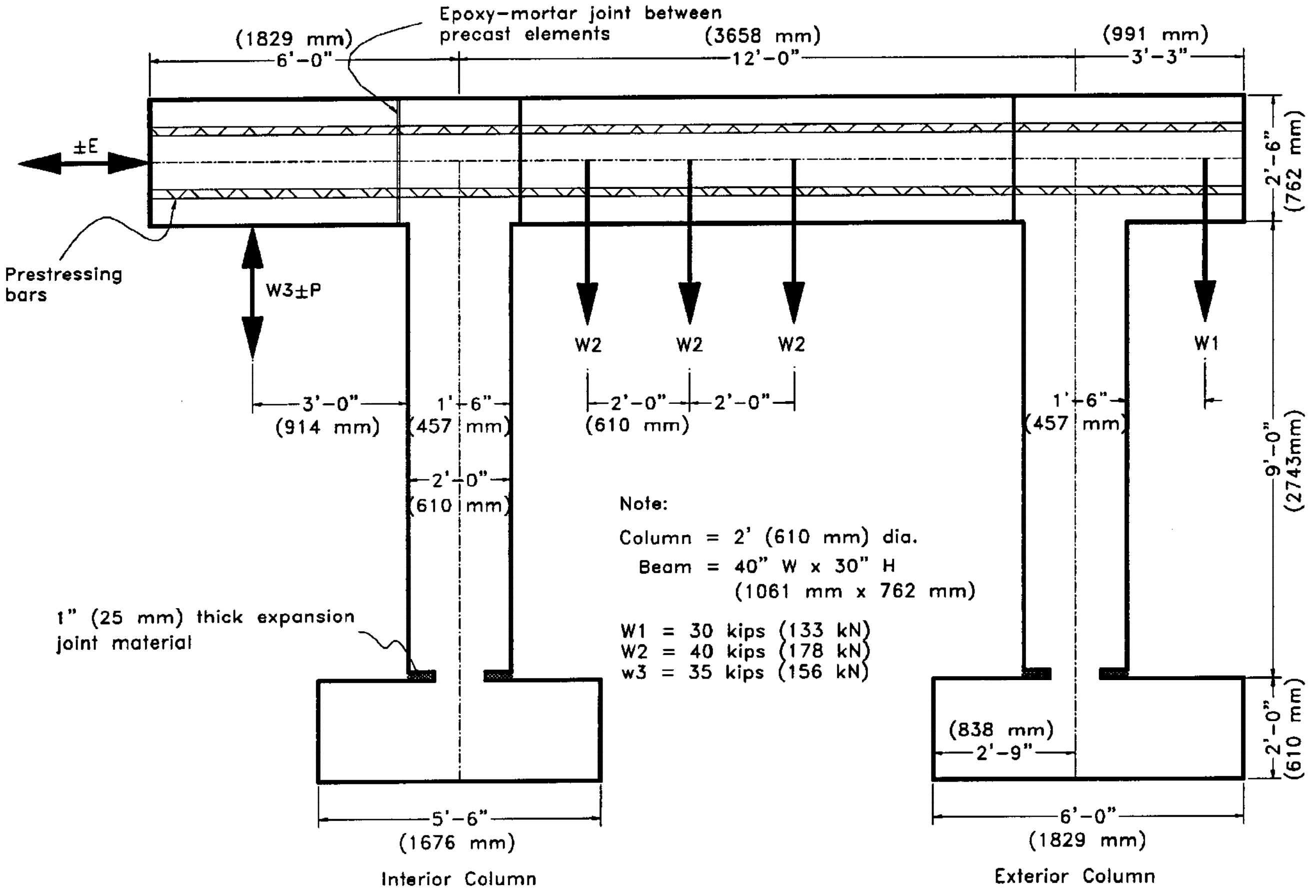

Fig. 6. Overall dimensions and test set-up of Multi-Column bridge bent test.

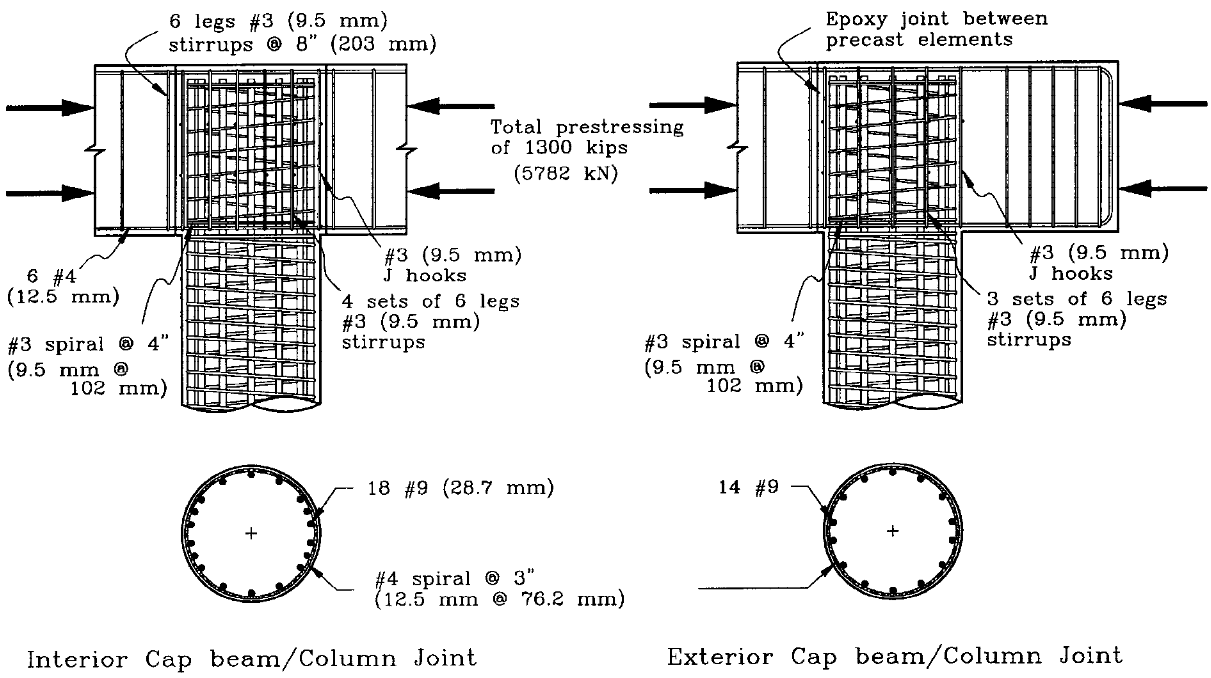

Fig. 7. Reinforcement details for the Multi-Column Bridge Bent Unit.

The key reinforcement detail of the Multi-column bent unit is shown in Fig. 7. The amount of joint reinforcement provided was about 30 percent of conventional design, consistent with the recommendation of Priestley *et al.* (1996). The cap beam was considerably wider than the columns, and hence the outer legs of the vertical stirrups were deemed ineffective as joint reinforcement, but were required to confine beam concrete. Since high joint shear stress was expected, as a precautionary measure, two J hooks were placed in conjunction with each vertical joint stirrup to carry transverse tension strain within the joints.

Excellent hysteretic behaviour obtained for the test unit up to a system ductility of 8 validated the design and construction strategies (see Fig. 8). The first indication of significant strength reduction in the force-resisting ability of the system was noted at ductility 8, attributable to buckling and fracturing of longitudinal column reinforcement. Strain gauge measurements showed that all the joint steel remained elastic throughout the test. The damage to the joints in the test was insignificant, and limited to only minor cracking.

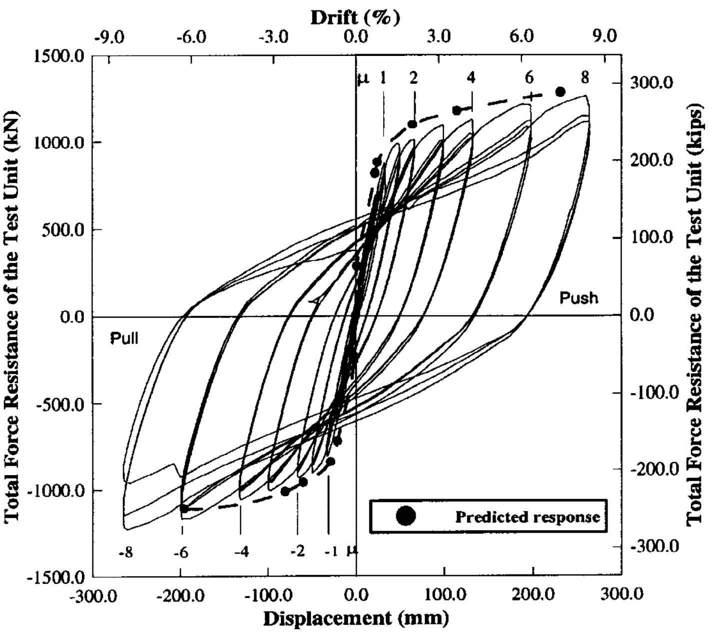

Fig. 8. Force-displacement history for the Multi-Column Bridge Bent Unit.

CONCLUSIONS

The seismic design of cap beam-column connections in typical bridge structures using procedures developed for reinforced concrete building frames demands a large reinforcement content within the joint, leading to congestion problems. An alternative design strategy is to use rational joint force transfer models, where the effectiveness of the concrete strut mechanism can be maximised.

Current code recommendations limiting joint input on the basis of a maximum uniform joint shear stress are of little relevance when conducting a rational assessment of joint demand. Instead, the maximum joint principal tension stress is relevant when assessing the probable performance of poorly detailed joints, and the maximum joint principal compression stress is relevant when assessing the capacity of joint force transfer mechanisms dependent primarily upon the development of a joint diagonal strut.

Bridge Knee Joint Unit with Headed Reinforcement

The bridge knee joint unit with headed reinforcement contained no conventional joint-shear reinforcement, but satisfactorily supported joint stress levels in excess of maximum code limits. It also closely matched the force-displacement response measured for a unit with significant quantities of specially-placed joint reinforcement which had performed according to current capacity-design principles. It is thus concluded that the functionality of headed reinforcement was clearly demonstrated.

Experimental data from the bridge knee joint unit with headed reinforcement confirmed that the assumed force transfer mechanisms developed as anticipated. It is concluded that headed reinforcement allows greater delineation of force paths, which is of considerable benefit when using rational joint force transfer models.

Multi-Column Bridge Bent Unit with Cap Beam Prestressing

Shear demand imposed in the joints of the test unit was probably a realistic upper bound for concrete bridge structures. Detailing of the joints was performed assuming cap beam prestressing assists force transfer through the joints, thereby requiring significantly less reinforcement than with conventional designs. Based on an excellent ductile response of the multi-column bridge bent unit, it is thus concluded that the cap beam prestressing can be used effectively to reduce steel congestion within the joints.

A precast cast construction opted for the test unit demonstrated that multi-column concrete bents with fully prestressed cap beam can be built efficiently using precast elements to comply with the capacity design philosophy.

ACKNOWLEDGEMENT

The experimental research reported herein was conducted in the Charles Lee Powell Structural Systems Laboratory at the University of California at San Diego. The assistance of the technical staff of this facility is gratefully acknowledged. Funding for the exterior beam-column knee joint unit and the multi-column bridge bent unit was provided by Headed Reinforcement Corporation (HRC) and the California Department of Transportation (Caltrans) respectively. Conclusions in the paper are those of the authors and should not be construed to have endorsement from the financial sponsors.

REFERENCES

AASHTO (1989). Standard Specifications for Highway Bridges. Fourteenth Edition. Washington D. C.

American Concrete Institute (1992). Building Code Requirements for Reinforced Concrete, ACI 318-89 (Reapproved 1992). Detroit. Michigan.

Housner, G. W. (1990). Competing Against Time - Report to Governor George Deukmejian from the Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake.

Ingham, J. M., M. J. N. Priestley and F. Seible (1994a). Seismic Performance of Bridge Knee Joints - Volume 1, Rectangular Column/Cap Beam Experimental Results. SSRP-94/12. Department of Applied Mechanics and Engineering Sciences. University of California at San Diego. La Jolla. California.

Ingham, J. M., M. J. N. Priestley and F. Seible (1994b). Seismic Performance of Bridge Knee Joints - Volume 2, Circular Column/Cap Beam Experimental Results. SSRP-94/17. Department of Applied Mechanics and Engineering Sciences. University of California at San Diego. La Jolla. California.

Ingham, J. M. (1995). Seismic Performance of Bridge Knee Joints. Doctoral Dissertation. Department of Applied Mechanics and Engineering Sciences. University of California at San Diego. La Jolla. California.

Ingham, J. M., M. J. N. Priestley, F. and Seible (1995), Bridge Knee Joint with Headed Reinforcement. *Pacific Conference on Earthquake Engineering*. Melbourne. Australia. 3. 217-225.

Kuchma, D. A. (1994). Compressive Response of Reinforced Concrete Confined by T-Headed Reinforcement. *Headed Reinforcement Workshop*. St. John's, Newfoundland.

MacRae, G. A., M. J. N. Priestley and F. Seible (1994). Santa Monica Viaduct Retrofit - Large-Scale Column-Cap Beam Joint Transverse Test, Preliminary Report. SSRP TR - 94/02. Department of Applied Mechanics and Engineering Sciences. University of California at San Diego. La Jolla. California.

Priestley, M. J. N., F. Seible, and M. Calvi (1996, in press). Seismic Design and Retrofit of Bridges. John Wiley & Sons. New York.

Roberts, J. E. (1991). Research Based Seismic Design and Retrofit of California Bridges, *First Annual Seismic Research Workshop*, Sacramento, California. 1-10.

Sritharan, S. and M. J. N. Priestley (1995). Response of a Three Column Bent with a Prestressed Cap Beam under Seismic Loading. Unpublished Report to Caltrans. University of California at San Diego. La Jolla. California.

Sritharan, S., M. J. N. Priestley and F. Seible (1995). Performance of Newly Designed Cap beam/Column Interior Joints under Cyclic Loading. *Pacific Conference on Earthquake Engineering*. Melbourne. Australia. 3. 207-216.

Standards New Zealand (1995). Concrete Structures Standard, NZS 3101:Part 1 and 2:1995.

Vecchio, V. J. and M. P. Collins (1986). The Modified Compression-Field Theory for Reinforced Concrete Elements subjected to Shear, *J. ACI*. 83(2). 219-231.