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BEHAVIOR OF PRECAST-PRESTRESSED MULTI-COLUMN BENT UNDER CYCLIC LOADING

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ABSTRACT

Recognizing the importance of precast construction, a bridge tee joint was built using precast modules and tested under transverse cyclic loading at the University of California, San Diego (UCSD). The cap beam prestressing which was used as a means of connecting precast modules, was also utilized in the design of joint, and this resulted in considerable reduction of joint reinforcement when compared to an equivalent fully reinforced concrete unit. Following an excellent hysteretic performance of this unit, a further test model representative of a multi-column concrete bent was designed and constructed using precast elements, and tested under transverse cyclic loading. Shear demand in the joints of the latter unit was imposed as high as practicable. The design details and the response of the multi-column test unit are summarized in this paper.

INTRODUCTION

The significance and advantages of precast construction have been long realized. Because of its seismicity, the precast construction is not generally favored by practicing engineers in California. Precast construction has been widely used in parking structures with limited application in low rise buildings. This construction option is rarely considered in the transportation system in California. Among other benefits, introduction of precast bridges will be of economical importance when structures need to be replaced following a major devastating earthquake.

If a number of bridges in a freeway system is brought down by an earthquake, this will have a tremendous economical impact on a city such as Los Angeles and San Francisco. In modern seismic design, structures are designed to perform in a ductile manner, and it is plausible that a significant number of bridges may need replacement following the maximum credible event. Although at a smaller scale, it is appropriate to mention herein that when two segments of the Santa Monica freeway in Los Angeles collapsed in the 1994 Northridge Earthquake, the estimated cost due to closure of the freeway was over a million dollars per day until the replacement structures were put in service [3]. The estimated cost would have easily exceeded by an order of magnitude if several bridges in greater Los Angeles area required replacement. If precast construction procedures are established for concrete bridges, it is expected that replacement structures can be brought in service within a reduced time frame at no compromise to the quality of construction.

As a step towards precast construction of concrete bridges, a multi-column concrete bent was built and tested under transverse cyclic loading at UCSD. A fully prestressed detailing was considered for the bent cap, which facilitated a precast construction procedure to be introduced for multiple column bents and significantly reduced the reinforcement in the joint regions.

SEISIMIC DESIGN OF BRIDGE JOINTS

The current ACI design code [2] and the regulatory document governing bridge design, AASHTO [1], provide no specific guidelines for the design of bridge joints. A joint design approach based upon the maximum joint shear stresses, which was developed empirically based on laboratory tests on building joints, has been recognized as unnecessarily conservative, and causing construction problems due to steel congestion of reinforcing steel in bridge joints [6]. Therefore, alternative efficient details are required for designing cap beam/column connections in concrete bridges.

Design of bridge joints based on force transfer models has been proved to be efficient compared to conventional design methods [4-6]. When a force transfer mechanism is considered for the joint in conjunction with cap beam prestressing, it generally demands no specially-placed joint reinforcement, and only nominal joint steel is provided [6]. This is possible because the cap beam prestressing effectively broadens the joint diagonal strut, permitting all of the longitudinal column reinforcement to be directly anchored into the joint strut and requiring no additional mechanism to clamp the column bars. More details of joint design based on force transfer models may be found in references 4, 5 and 6.

EXPERIMENTAL INVESTIGATION

In the first phase of a research program on the design of bridge joints, three cap beam/column interior joints were built and tested under transverse seismic loading at UCSD [6]. These joints were considered as redesigns of a typical interior joint from the Santa Monica Viaduct in Los Angeles. Maintaining almost identical reinforcement contents in the columns, the cap beams of the test units were designed with conventional reinforcement, partially prestressed and fully prestressed detailing. Joint reinforcement of the test units was varied in a manner consistent with the cap beam detailing. The tee joint with a fully prestressed bent cap was built using precast modules. The joint and column of this model unit was cast monolithically as a single element whereas the cap beam was built as two separate segments. The test unit was formed by connecting beam elements to the joint solely by prestressing. In Fig. 1, the reinforcement detail of the precast tee joint and its hysteretic response under transverse cyclic loading are presented. The performance of the test unit, as indicated by the hysteresis loops, was excellent.

In a well designed bridge joint, the shear demand within the joint is dictated by the longitudinal reinforcement content, ρ_l, of the column framing into the joint. In the above investigation, the value of ρ_l was 1.9 percent which is close to an average value generally used in practice, but ρ_l as high as 4 percent is permissible [5]. Therefore, in the second phase of the research program, a multi-column unit was tested using the proposed design and construction procedures with significantly high longitudinal reinforcement in the columns.

To model the test unit, a three column bent from the Santa Monica Viaduct was chosen as the prototype structure. Longitudinal steel ratios in the columns were increased to 3 and 4 percent in the exterior and interior columns respectively, to impose higher shear demands in the joints. The high joint shear stresses along with the cap beam prestressing were expected to induce average joint principal compression stresses approaching or marginally exceeding . Consistent with current Caltrans practice, a wider cap beam was used, which is necessary to accommodate the joint steel required for longitudinal seismic response.

Fig. 2 shows the overall dimensions and the test setup of the multi-column bent unit, which consisted of two columns with 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 of this unit was cast in two segments, and the whole test unit was assembled by connecting the beam segments to the joints solely by prestressing. The prestressing in this unit and in the precast tee joint was applied with zero eccentricity using Dywidag bars. Unlike the longitudinal direction, the gravity moments are generally small in the transverse direction. Therefore, draped tendons were not considered favorably as one of the objectives of cap beam prestressing was to assist force transfer through the joints. Four hydraulic actuators, two vertically and two side by side horizontally, and a vertical tie-down were attached to the subassemblage to simulate the seismic and gravity forces anticipated in the prototype structure.

The key reinforcement details of the multi-column bent unit is shown in Fig. 3 and the design approach adopted for the joints is described in reference 6. The amount of joint reinforcement provided was about 30 percent of that required based upon the maximum joint shear force design. 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 stresses were expected, two J hooks were placed in conjunction with each vertical joint stirrup to carry transverse tension strain within the joints as a precautionary measure.

Excellent hysteretic behavior obtained for the test unit up to a system ductility of 8 validated the design and construction strategies (see Fig. 4). 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 almost all the joint steel remained elastic throughout the test with some recording strain levels slightly higher the yield strain. The damage to the joints in the test was insignificant, and limited to only minor cracking.

DISCUSSION AND CONCLUSIONS

Precast construction of bridges is not commonly adopted in seismic regions. Recognizing the importance of the precast construction procedure, it was demonstrated that a multi-column bent can be built using precast elements to comply with the capacity design philosophy. A fully prestressed detail was considered for the design of the bent cap and the cap beam prestressing was utilized for connecting precast segments of the multi-column bent.

In the design of cap beam/column connections, the conventional methods demand significantly high joint reinforcement, causing unacceptable congestion in the joint regions. Considering that the cap beam prestressing assists force transfer across the joints, it was shown that a significant reduction in the joint reinforcement can be obtained in multi-column bents with prestressed bent caps. Shear demand imposed in the joints of the test unit was probably a realistic upper bound for concrete bridge structures. Despite that the damage in the joints during the simulated seismic loading was insignificant.

Based on a an excellent ductile response of the multi-column bent test unit, it is concluded that the cap beam prestressing can be used effectively for both facilitating precast construction of the multi-column bent and significantly reducing steel congestion in the cap beam/column joints.

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