Post-Earthquake Evaluation and Emergency Repair of Earthquake-Damaged RC Bridge Columns Using CFRP Materials

RESULTS: The objective of the study was to develop a rapid and effective repair method using carbon fiber reinforced polymer (CFRP) materials for earthquake-damaged bridge columns. A database of 33 columns tested under seismic loads was developed and five distinct damage states were identified. Five standard and sub-standard models were tested, repaired, and retested at the University of Nevada, Reno (UNR) through a research project funded by the California Department of Transportation (Caltrans). The significant outcome of this study was a series of charts indicating the number of required CFRP layers inside and outside the plastic hinge zones based on the observed damage state, column dimensions, and the longitudinal steel ratio. These charts along with the proposed repair procedure enable rapid repair of earthquake-damaged columns and quick opening of bridges to traffic. In addition, a simple analytical method was developed to determine pushover curves for repaired columns. Project Website: http://wolfweb.unr.edu/homepage/saiidi/caltrans/emergrepair.html

Why We Pursued This Research

Current seismic design practice in bridge engineering for standard bridges allows for damage to bridge columns during moderate and strong earthquakes. The target performance under the maximum credible earthquake is “no-collapse”, realizing that the structure would undergo considerable nonlinearity associated with extensive concrete damage, yielding of bars, or even rupture of some of the bars. For the more frequent earthquakes, the target response is repairable damage that would allow for relatively rapid restoration of the bridge and the highway network. The level of damage to different columns of a bridge varies depending on the intensity of the ground shaking, type of earthquake, and the force/deformation demand on individual members.

Based on the inspection of the damaged columns engineers have to determine whether the bridge is sufficiently safe to be open to traffic without repair, whether it is repairable within a reasonable time frame, or if it needs to be replaced. They should also recommend repair methods for the columns. Any delay in opening of the bridge to traffic can have severe consequences on the passage of emergency vehicles, detour lengths, and traffic congestion in the area. Rapid and effective repair methods are needed to enable quick opening of the bridge to minimize impact on the community.

What We Did

This study consisted of three main phases: (1) Development of simple criteria for apparent damage states and correlating them to seismic response parameters, (2) Experimental and analytical studies of the original and repaired column models, and (3) Development of rapid repair design recommendations.

In the first phase of the study, detailed data from 33 bridge column models, mostly tested on shake tables, were evaluated to determine correlation between the apparent damages and seismic response parameters. Five distinct damage states were proposed based on the apparent damage (Fig. 1). The damage states were flexural cracks (DS-1), first spalling and shear cracks (DS-2), extensive cracks and spalling (DS-3), visible lateral and/or longitudinal bars (DS-4), and start of core failure indicating imminent failure of the column (DS-5). Six response parameters were defined in terms of drift, frequency, strains, yielding, and ultimate displacements. Two approaches were used to correlate the damage states and the response parameters. In the first approach, the correlation was identified for five different column categories based on seismic design, shear demand, and ground motion type. In the second approach, all the columns were studied in a single category to achieve a larger data base. To consider the effect of data scatter, a probabilistic approach using fragility functions was utilized and fragility curves were developed to correlate damage states and response parameters.

In the second phase of the study, two standard columns, one standard 2-column bent, and two substandard columns were tested on a shake table, repaired using CFRP fabrics, and retested on the shake table to evaluate the repair performance.

The repair process consisted of straightening the column, removing the loose concrete, epoxy injection of cracks, concrete repair using a fast-set, non-shrink mortar, CFRP wrapping, and accelerated curing of CFRP under elevated temperature for 24 hours followed by a day of curing under ambient temperature (Fig. 2). The total repair and curing time for one column was three to four days, including two days of curing for CFRP.

The original standard columns were tested to DS-5 and repaired to restore the confinement and the shear strength. The original sub-standard columns were tested to reach DS-2 or DS-3 and repaired to restore and upgrade the confinement and shear strength to meet the current SDC. Due to the severely inadequate transverse steel for shear and confinement and the lap-splice at the column base, the original sub-standard
columns could not reach higher damage states. All the repaired columns were tested on a shake table until failure.

Figure 1 - Five damage states

Based on extensive analysis of the measured data and analytical studies, repair design recommendations were made in the third phase to aid bridge maintenance engineers in quickly coming up with a decision about the number of layers of CFRP based on the apparent damage and basic information about the bridge column fixity, size, and reinforcement.

Research Results

The following items present the main conclusions of the study:
- Fragility curves provide means for performance based design and performance based assessment of bridge columns for different damage states.
- The proposed repair method is practical and can be used for emergency repair of earthquake-damaged concrete columns.
- Accelerated curing of CFRP for 48 hours is effective in providing the required strength.
- To repair earthquake-damaged standard RC bridge columns, it is recommended that the shear strength and confinement be restored for a target displacement ductility of five.
- To repair earthquake-damaged sub-standard RC bridge columns, the shear strength needs to be upgraded to match the plastic shear corresponding to overstrength moment capacity. Furthermore, confinement needs to be provided to inhibit splice failure and to obtain the target displacement ductility of five. The existing retrofit design criteria should be used to design for confinement.
- The strength and displacement ductility capacity of columns are fully restored by the proposed rapid repair procedure; however, due to stiffness degradation of steel and concrete during the earthquake, the stiffness of the columns can not be fully restored with repair.
- Pushover analysis of repaired columns needs to account for inherent softening of column. Using the modified steel properties developed in this study, it is possible to obtain a reasonable estimate of the pushover response of repaired columns.

Reference