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The Seismic Rehabilitation of Reinforced Concrete Highway Bridges

Introduction

Bridges are ubiquitous in today's built environment, carrying highways through cities and countries and serving as the transportation lifeline of modern society. Without bridges, transportation would cease and commerce would halt. Thus, the importance of highway bridges cannot be underestimated, and bridges must be designed to adequately withstand the forces of devastating earthquakes. The vitality of transportation networks must be ensured and the safety of the users of transportation infrastructure must be guaranteed.

This report will present a detailed discussion of the rehabilitation of reinforced concrete highway bridges. The need for seismic retrofit of existing bridges will first be discussed, citing previous design practice and documented structural response to past earthquakes. Next, the current practices for retrofitting the various components of reinforced concrete bridges will be examined. Lastly, the concepts of seismic retrofit will be applied through the analysis and virtual rehabilitation of a simple span highway bridge structure. SAP2000 finite element analysis software will be used to perform a time history analysis on a representative reinforced concrete highway bridge before seismic rehabilitation and after rehabilitation. The exact method(s) of retrofit and specific bridge components that will be retrofitted and analyzed are yet to be determined.

The Need for Rehabilitation

The majority of all highway bridges contain a major reinforced concrete structural component, either in the footing foundations, abutments, pier groups, or superstructure, and a significant number of highway bridges are comprised entirely of reinforced concrete. Additionally, the transportation networks in most developed countries located within earthquake regions are already well-established, and most bridges within these networks have been in service for many years, even before seismic-resistant design was seriously considered. Thus, the topic of seismic rehabilitation of reinforced concrete bridges is of particular interest for the sake of public safety and economic well-being.

Performance Inadequacies

It is made clear in the following section that many existing reinforced concrete bridges have not performed satisfactorily when subject to seismic loads.

Two main reasons exist for the inadequate performance of highway spans during earthquakes. The first is the inherent lack of redundancy in bridge structures. Highway bridges, being purely functional structures designed to carry loads as efficiently and economically as possible, lack the redundant systems common in buildings. Thus, the individual bridge components must be carefully designed to withstand seismic forces since secondary structural systems are not present in case of failure.

The second reason for the inadequate performance of highway spans is an insufficient knowledge of seismic forces at the time of design and construction coupled with an incomplete understanding of the mechanics of reinforced concrete and corresponding reinforced concrete design principles. An elastic design philosophy employed prior to the 1970's resulted in many of the deficiencies of reinforced concrete highway bridges subject to seismic loading. First, the deflection of individual bridge components was greatly underestimated due to the use of the gross concrete section instead of the cracked section in performing deflection analyses. Second, the shapes of moment diagrams for various bridge components were miscalculated due to a misunderstanding of the interaction between seismic loads and gravity forces. The erroneous location of points of inflection on moment diagrams leads to an incorrect placement of longitudinal reinforcement in members. Finally, the importance of inelastic deformation in response to major earthquakes was not considered. Thus, adequate levels of ductility and corresponding energy dissipation mechanisms were not incorporated into the bridge structures, and bridges were severely damaged by seismic events (Priestley, 3-4).

A Note on Plastic Analysis

As mentioned in the previous section, an elastic design philosophy was initially used for the seismic design of reinforced concrete structures. However, it is beneficial to consider the non-linear inelastic behavior of reinforced concrete structures subjected to seismic forces to account for structural ductility and energy dissipation. Thus, the various methods of rehabilitation discussed in this report are based upon plastic failure phenomenon and the formation and location of plastic hinges.

Plastic analysis is used for non-linear analysis and ultimate strength design. Its advantages include a more accurate estimate of maximum loads and corresponding safety factors, applicability to complicated structural analyses, and adaptability to large, unpredictable stresses, such as earthquake loads.

The basic theory of plastic analysis includes a redistribution of stresses within a structural member after elastic yielding in the material has occurred. Since portions of the structural member that have reached the elastic limit can no longer support additional load, stresses are distributed to the member portions that still retain strength capacity in the elastic region. When the member has reached its complete elastic capacity, plastic hinges develop in the locations of maximum bending moment. Any additional moment causes the hinges to rotate, and structural failure ensues (McCormac, 586).

Problems and Failures

Much seismic damage has occurred to reinforced concrete highway bridges in earthquake regions, and many spans have suffered complete failure. Seismic damage and failure in highway bridges can be categorized according to the type of failure mechanism and major components of the bridge, including displacement, abutment slumping, column failure, cap beam failure, joint failure, footing failure, and failure of steel components. Since displacement and column failures seem to cause the most significant and costly damage in bridges, the mechanisms causing these failures will be described in detail.

Displacements

Displacements are a major cause of highway bridge span damage and failure during earthquakes. Displacement failure due to seismic excitation is the result of concrete bridge design using elastic theory. The underestimated lateral forces and overestimated gross-section stiffness resulted in the inadequate design of superstructure seats and lateral clearance between adjacent structures (Priestley, 5). Two displacement damage mechanisms of interest that are prevalent in reinforced concrete bridges are unseating and pounding. Excessive displacements in the longitudinal direction can result in bridge failure via the unseating of the superstructure, while displacements in the transverse direction can result in pounding damage through cyclic contact with an adjacent structure.

Unseating failure is particularly problematic for simply supported highway bridges when earthquake forces occur in the longitudinal direction. If seats or corbels located at the abutments or on the piers do not possess sufficient length in the longitudinal direction, then the entire superstructure span can become unseated, resulting in sudden bridge collapse. This failure mechanism can be enhanced for either tall pier columns or for adjacent pier frames of unequal height. In the case of tall piers, column rotation about the base enhances displacements at the location of maximum height of the superstructure. Adjacent pier frames of varying heights have different fundamental frequencies, and thus displacements are increased if the frames respond out of phase with respect to each other when subject to seismic excitation.

Pounding of bridge structures due to inadequate displacement considerations can also result in severe bridge damage. If a small clearance envelope exists between the bridge and adjacent structures, then damage can occur through cyclic pounding as the earthquake occurs in the transverse direction, creating shear forces and imposing brittle failure. This damage can be amplified if the adjacent structure is of a different height or stiffness. The different fundamental frequency of the adjacent structure can result in out of phase motion with the bridge, amplifying shear forces and corresponding pounding damage.

Column Failures

The study of column failure during seismic activity is significant because collapse of a supporting column within a pier group will likely result in the failure of the entire bridge structure.

The two primary failure mechanisms that occur in columns are flexural failure and shear failure. The mechanics of these failures are discussed below.

The remainder of the report is outlined below:

A. Complete column failure section
B. Discuss retrofit in detail for various bridge components
C. Perform SAP time history analysis
    1. Analyze “typical” reinforced concrete highway bridge
    2. Apply approximate retrofit technique and compare results

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