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Seismic performance evaluation of multi-column bridge bents retrofitted with different alternatives using incremental dynamic analysis

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ABSTRACT

A comprehensive study has been carried out to numerically investigate the performance of a three column bridge bent retrofitted with different options. The bridge bent represents a typical case of vulnerable bridges since it was built in the early sixties with minimal seismic design requirements. This study evaluates four different retrofitting provisions, namely carbon fiber reinforced polymer (CFRP) jacketing, steel jacketing, concrete jacketing, and engineered cementitious composite (ECC) jacketing for improving the seismic performance of this non-seismically designed bridge bent. Finite element methods have been implemented in this study where each retrofitting technique has been modeled and numerically validated with the experimental results. Analytical models of those retrofitted bridge bents have been developed using finite element analysis tools and verified against experimental results. Nonlinear static pushover analyses have been performed to compare their performances in terms of performance criteria such as the displacement and base shear at cracking, yielding, and crushing. Incremental dynamic time history analyses have been performed to assess the dynamic behavior of the retrofitted bents and to generate required data for performance-based evaluations. The performance-based assessment study employed 20 near fault ground motions to compare the performance of these retrofitting strategies in terms of maximum drift (%), residual drift, and ductility demand. The results indicated that both the CFRP and ECC jacketing were effective in reducing the anticipated damage of the retrofitted bridge bent.

1. Introduction

Highway bridges constitute a significant portion of highway infrastructures. Aging and deterioration of these bridges have increased the need for effective maintenance, repair, rehabilitation, and retrofitting. Increased traffic volume, harsher environment, all these factors render those aged bridges incapable of carrying the design load. Moreover, concrete cracking, rebar corrosion, non-seismic detailing make these older bridges vulnerable during a seismic event. These bridges might have inadequate stiffness, strength or deformation capacity to resist seismic loads as required by the current codes and guidelines [1–3]. Many bridges were designed without any earthquake resistance criterion since they were built prior to earthquake resistant design codes; others were designed to resist horizontal actions but without the principles of the capacity design or were built at a site in an area where the seismic hazard has been re-evaluated and increased [2,3].

The replacement or demolition of these deficient bridges will be a costly undertaking. Alternatively, retrofitting of these bridges could be more convenient to meet the current seismic and traffic demand. Various rehabilitation techniques are available to upgrade the seismic performance of existing RC structures. The major techniques for structural rehabilitation of RC bridges include encasing of columns and beam column joints with steel [4,5], fiber reinforced polymer (FRP) jacket [6,7], textile reinforced mortar (TRM) jacket [8,9], reinforced concrete (RC) jackets [10]. In recent years, innovative technologies such as engineered cementitious composites (ECC) jacketing [11,12] and prestressing wires along with traditional solutions have become available to the practitioners for structural retrofitting by either enhancing the seismic capacity or reducing the demand. These options may be significantly different with respect to various aspects such as costs, time, structural performances, architectural impact, and occupancy disruption [13,14]. In the last two decades, FRPs have attracted the attention of researchers and bridge owners as an alternative material for retrofitting reinforced concrete bridge elements. More recently, a newly developed jacketing technique, comprising textile carbon fiber in a mortar matrix, also known as Textile-Reinforced Mortars (TRMs) have emerged as a promising solution for the strengthening of RC columns and bridge piers [8,9]. The use of ECC, a high performance high strength concrete with its special tensile properties

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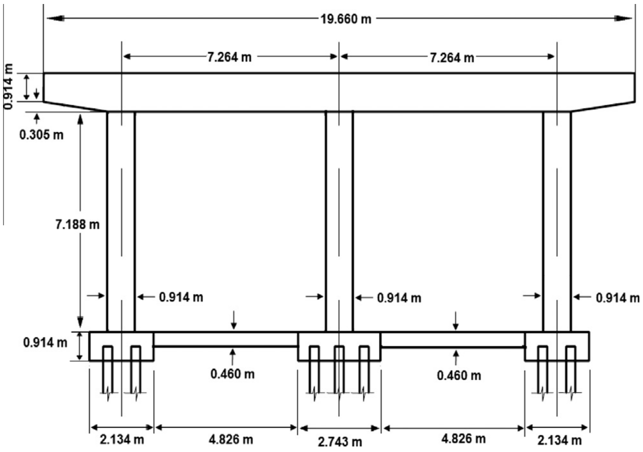

Fig. 1. South Temple Bridge bent dimensions (adapted from [6]).

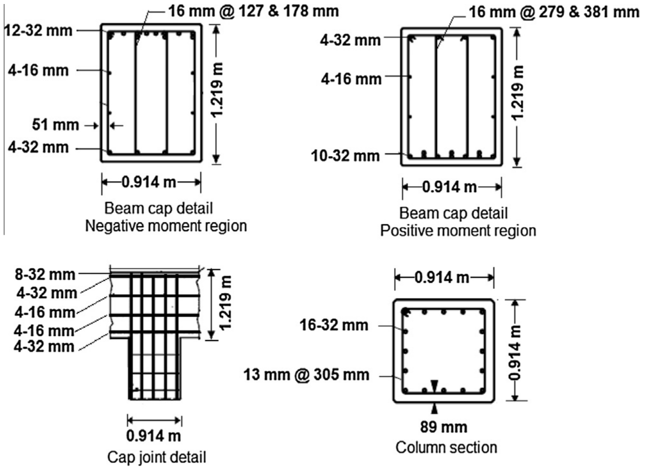

Fig. 2. South Temple Bridge bent reinforcement details (adapted from [6]).

is gradually gaining popularity among the practitioners in earthquake engineering. For instance, the Glorio Roppongi high-rise apartment building in Tokyo contains a total of 54 ECC coupling beams (2 per story) intended to mitigate earthquake damage [15]. Because of its improved tensile and strength properties, ECC warrants its use in seismic retrofitting.

Recently, there is a growing interest in the research community to investigate the performance of different retrofitting techniques for improved seismic performance of bridge bents. Roy et al. [16] developed and experimentally validated a performance based design guideline for CFRP retrofitted bridge bent. Silva and Sritharan [17] investigated the seismic performance of concrete bridge bent with steel shell columns. Walkenhauer et al. [18] experimentally investigated the seismic performance of a cruciform-shaped column jacketed with CFRP. They concluded that CFRP jacketing was adequate to provide sufficient shear strength. Billah et al. [19] conducted fragility analysis to compare the relative vulnerability of a bridge bent retrofitted with four different retrofitting techniques. In another study, Billah and Alam [20] developed a performance based prioritization method for selecting a suitable retrofitting technique for a concrete bridge bent. Recently, Bournas and co-workers [8,9] developed a new jacketing technique, known as textile reinforced mortar, which has shown promising performance for retrofitting of concrete bridge pier.

The objective of this study is to compare the performance of a non-seismically designed multi-column bridge bent retrofitted with different rehabilitation techniques, namely CFRP jacketing, steel jacketing, concrete jacketing, and engineered cementitious composites (ECC) jacketing. Here, nonlinear finite element analysis has been implemented to conduct the study, which was first validated with the experimental results of each category of retrofitting. The performance of different retrofitted bridge bents are compared in terms of performance criteria such as the displacement and base shear at cracking, yielding, and crushing using static pushover analysis (SPO). As the inelastic characteristics of retrofitted bridge bents may differ significantly from regular bridge systems under severe ground motions, the present study focuses on quantifying seismic inelastic demands and capacities of bridge bents retrofitted with different retrofitting techniques using incremental dynamic analysis (*IDA*). The behavior and response of these retrofitted structures were examined by subjecting representative nonlinear analytical models of the retrofitted bents to an ensemble of 20 earthquake ground motions scaled to different intensity levels. With respect to an intensity measures (*IM*), such as peak ground acceleration (*PGA*), the maximum response quantities in terms of governing engineering demand parameters (*EDP*), such as the maximum deflection or drift, residual drift, and ductility demand of the structure have been estimated to compare the performance of four retrofitted bridge bents.

2. Bridge bent details

In order to evaluate the performance of the different retrofitting schemes, the bridge bent in the northbound lanes of the South Temple Bridge is considered in this study [6]. The bridge was considered seismically deficient as it had inadequacy in the amount of reinforcement and seismic detailing. This bridge bent was retrofitted by Pantelides and Gergely [6] using CFRP jacketing. They developed design equations for CFRP jacketing and performed both experimental study and analytical verification of their results. The bent consists of three columns and a bent cap as shown in Fig. 1. A concrete deck of 21.87 m span was supported by two bents and each bent supported eight steel girders. A gravity load of 240 kN was carried by each steel girder. Reinforcement details of the column, bent cap, and joints are shown in Fig. 2. The bent column had inadequate transverse reinforcement in the lap-splice region. Transverse hoops in the bent cap joints were absent, and columns had insufficient tie spacing in the plastic hinge regions, which is the most vulnerable portion of a column. The reinforcing steel in the bridge bent had yield strength of 275 MPa, while the compressive strength of the concrete was 21 MPa.

2.1. Details of retrofitting techniques

Four different retrofit techniques specifically concrete jacketing, steel jacketing, CFRP jacketing, and ECC jacketing have been implemented along the height of the pier to retrofit the seismically deficient multi-column bridge bent. In order to design the four different retrofitting techniques, a response spectrum analysis was carried out to determine the design base shear. As the bridge bent was located in Salt Lake City, Utah, USA, the design response spectrum for this location was obtained which is shown in Fig. 3 [21]. Determining the time period and modal mass participation factors from eigenvalue analysis, the design base shear for each retrofitted bridge bent was estimated. Fig. 4 shows the schematic diagram of different retrofitting techniques adopted in this study.

In this study the CFRP composite jacket retrofitting technique has been implemented from Pantelides and Gergely [6], which has a tensile strength of 628 MPa, initial stiffness of 6.5×10^4 MPa and ultimate axial strain of 10 mm/m. The material is a carbon fiber/epoxy resin composite with 48,000 fibers per tow unidirectional carbon fibers. The number of tows per 25.4 mm of sheet (pitch) was 6.5, and the width of the carbon fiber sheets was