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ANALYSIS and RETROFIT of FIXED FLARED COLUMNS with GLASS FIBER-REINFORCED PLASTIC JACKETING

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16. Abstract

The main objectives of this study were to develop and analyze a seismic retrofit method for flared columns that are fixed at both ends and consist of a structural flare. The columns of Bridge I-1556 located in Sparks, Nevada, were used in the study. A previous study of the columns with respect to the seismic requirements had shown that the confinement steel is inadequate and the shear capacity near the base of the columns is marginal. Both of these deficiencies were addressed by using a glass fiber-epoxy jacket. Because the columns are flared, a continuous wrap over the flared segments is not appropriate. Therefore, for the flared segments, a series of overlapping straps were recommended. The FHWA and ACI procedures were used in design of the composite jacket. To determine the effectiveness of the retrofit, the as-built and retrofitted columns were analyzed for earthquakes loading using a nonlinear response history analysis computer program called RC-Shake. This program accounts for stiffness and strength degradation of reinforced concrete elements under cyclic loads. The 1994 Sylmar-Northridge earthquake record was used. It was found that the retrofit reduced the displacement ductility demand by 50 percent under an earthquake with PGA of 1.2g.

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Analysis and Retrofit of Fixed Flared Columns with Glass Fiber-Reinforced Plastic Jacketing

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ABSTRACT

The main objectives of this study were to develop and analyze a seismic retrofit method for flared columns that are fixed at both ends and consist of a structural flare. The columns of Bridge I-1556 located in Sparks, Nevada, were used in the study. A previous study of the columns with respect to the seismic requirements had shown that the confinement steel is inadequate and the shear capacity near the base of the columns is marginal. Both of these deficiencies were addressed by using a glass fiber-epoxy jacket. Because the columns are flared, a continuous wrap over the flared segments is not appropriate. Therefore, for the flared segments, a series of overlapping straps were recommended. The FHWA and ACI procedures were used in design of the composite jacket. To determine the effectiveness of the retrofit, the as-built and retrofitted columns were analyzed for earthquakes loading using a nonlinear response history analysis computer program called RC-Shake. This program accounts for stiffness and strength degradation of reinforced concrete elements under cyclic loads. The 1994 Sylmar-Northridge earthquake record was used. It was found that the retrofit reduced the displacement ductility demand by 50 percent under an earthquake with PGA of 1.2g.

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Chapter 1

Introduction

1.1 Introductory Remarks

The seismic design of reinforced concrete highway bridges requires a ductile response of the bridge columns. During an earthquake event, the bridge must be capable of large inelastic deformations without a significant reduction in capacity[10]. In reinforced concrete columns, the most critical type of failure to prevent is brittle failure at plastic hinges due to a lack of adequate confinement steel or inadequate shear capacity[9]. The prevention of shear failure is particularly important when large inelastic deformations occur because plastic hinging reduces the shear capacity of the column. The method used most often for enhancing ductility and shear strength of existing columns is steel jacketing. The use of advanced composite jacketing, typically called fiber-reinforced plastics (FRP), has become increasingly popular over the last 5 years for seismic retrofit of highway bridge columns.

During the January 17, 1994 Northridge earthquake, several highway bridge structures failed in non-ductile shear failure modes. One of these bridges was the SR-118 Mission/Gothic undercrossing that was supported on one-way flared columns. In California and Nevada, the use of one-way and two-way flared columns has been extensive in highway bridges. A series of studies involving an analytical and experimental assessment of seismic vulnerability of flared highway bridge columns and the development of retrofit methods was undertaken at the University of Nevada, Reno. This report considers Bridge I-1556 located in Sparks, Nevada which was previously identified in Ref. 18 as having a potential for shear failure and being deficient with respect to confinement steel.

1.2 Previous Work

Research pertaining to the seismic behavior of reinforced concrete highway bridge columns is quite extensive. Though flared columns are used extensively in bridges, only a few studies have considered their seismic performance. The discussion of previous work that follows is limited to the experimental studies that consider: (1) the seismic performance of flared bridge columns, and (2) the effects of FRP jacketing of reinforced concrete columns.

1.2.1 Flared Bridge Columns

Prior to the 1994 Northridge earthquake very little attention was paid to the seismic performance of flared columns. The shear failure of several columns with non-structural flares in the 1994 Northridge earthquake prompted research to determine their seismic response[8,13].

A preliminary analytical study of the SR-118 Mission/Gothic undercrossing was conducted by the National Institute of Standards and Technology (NIST)[8] and the University of California, San Diego (UCSD)[11]. The main longitudinal reinforcement in the columns was placed in a circular pattern over the height of the column. It was thought the column flares would spall off during severe lateral loading, thus not increasing the flexural capacity of the column. Both studies concluded that the flares contributed to the flexural strength of the columns, and that the supposed spalling of the flare would not occur even though the flares were "architectural."

UCSD continued to investigate these columns with a study completed by Sanchez et al.[13] that consisted of testing both as-built and retrofitted columns with architectural flares. The study suggested a retrofit method of decoupling the effect of the flared portion of the column by cutting the flare at the soffit, leaving a gap between the flare and the soffit. This type of retrofit would not work in columns with structural flares in which the main bars follow the shape of the flares.

Webhe et al.[17] investigated the seismic behavior of four highway bridges with flared columns located in northern Nevada. The one-way flared columns, in general, were constructed using two different reinforcement details. The first type of column is somewhat similar to those that failed during at the Mission/Gothic undercrossing in that they consist of longitudinal steel distributed in a prismatic circular pattern through the core of the column. However, unlike the columns in the Mission/Gothic undercrossing, these columns have heavily reinforced (longitudinal and transverse) flares. In the second type of columns, the primary longitudinal reinforcement follows the column flare without a core longitudinal reinforcement or spirals, and the transverse reinforcement consisted solely of lateral ties. A non-linear analysis was completed in this study that indicated the first type of column has sufficient shear capacity, and would respond well to seismic excitation. However, the second type of column clearly showed an insufficient shear capacity and confinement, indicating probable brittle failure in a seismic event.

The results of the analytical study led to phases two through four of research, which involved the testing of large-scale flared columns at the University of Nevada, Reno. In the second phase, Webhe et al. investigated two forty-percent scale as-built specimens subjected to quasi-static cyclic lateral loads. The results confirmed the need for the development of a retrofit system for the columns. Caywood et al.[3] studied two additional forty-percent scale specimens that were retrofitted with steel jackets and tested under slow cyclic loads. This study showed the steel jackets were effective in retrofitting the test specimens.

Further testing of the flared columns under the response of more realistic dynamic loading was completed in the third and fourth phases of the UNR study. The third phase study was conducted by McElhaney et al.[7], in which two thirty-percent scale specimens were tested. One specimen modeled the as-built columns while the other was retrofitted with a steel jacket. The purpose of the study was to verify the results of the first two studies and quantify the effects of the dynamic loading as compared to the quasi-static loading. The third study showed generally good correlation with the first two studies, while some variation existed due to the dynamic loading. The fourth study considered two FRP retrofitted specimens subjected to shake table loading[6]. This study showed that the FRP retrofit was as effective as steel jacketing in improving the seismic response.

1.2.2 FRP Jacketing of Highway Bridge Columns

The use of advanced composites for seismic retrofit has become an increasingly popular area of research over the last several years. Many studies have considered the effects of FRP jacketing on columns for confinement, flexural behavior, shear strength, and lap splice reinforcement. The research varies widely with respect to the type of composites and configurations used to install the jacketing. This section outlines some of the relevant research to this project relating to highway bridge columns retrofitted with advanced composites.

UCSD was one of the first research institutions to delve into the retrofit of reinforced concrete columns with advanced composites[14]. Seible and Priestley tested four rectangular cantilever columns. The specimens consisted of two retrofitted with a steel jacket and the other two with a glass fiber-epoxy jacket. The jackets were installed in the plastic hinge region at the base of the column. The specimens were tested both in the weak and strong directions to determine the level of flexural increase experienced by the retrofit. The test results showed that the advanced composite and steel jackets performed very well, providing a displacement ductility that exceeded 8. The glass fiber-epoxy jackets showed slightly better confinement than the steel jackets, and were found to be a suitable retrofit method for reinforced concrete columns.

In a study at the University of Arizona, Jin et al.[4] created a glass fiber jacket system that was used to retrofit reinforced concrete columns. The experimental study consisted of ten 0.2-scale, typical pre-1971 reinforced concrete columns, with five circular columns and five rectangular columns. Four as-built specimens and six retrofitted specimens with glass fiber composite jackets were tested. The as-built specimens had serious deficiencies in shear strength and lap splice detail. The results showed that the composite jackets greatly increased the column ductility capacity and shear resistance and prevented bond failure.

In another project, Saadatmanesh et al.[12] used a parametric study to present a method of using fiber-reinforced straps to increase the strength and ductility of reinforced concrete columns. The goal was to improve the seismic performance without increasing the flexural strength. The parametric study indicated that this method of strapping the column was effective in both increasing the shear capacity and in improving the column ductility.

Seible et al.[15] considered both steel jacketing and carbon fiber tow jackets to retrofit prismatic reinforced concrete bridge columns. Four specimens were tested representing one as-built, one steel jacketed, and two carbon fiber jacketed specimens. The carbon-fiber jacketed specimens exceeded the measured displacement ductility and ultimate flexural strength of the steel-jacketed specimens. The carbon-fiber specimens reached a ductility of nearly 10 at failure, while the steel-jacketed column reached a ductility of 8.

In the flared column studies at UNR, two thirty-percent one-way flared columns were retrofitted with FRP jackets consisting of one glass-fiber, epoxy-jacketed specimen and one carbon-fiber epoxy-jacketed specimen[6]. This work is the only case where both non-prismatic reinforced concrete bridge columns and advanced composite jackets were considered. This study showed that the advanced composite jackets increased the shear capacity of the column and improved its seismic response.

1.3 Objective and Scope

The primary objective of this study was to develop and analyze a seismic retrofit system for bridge columns with moment connections at both ends of the column, which incorporated structural flares. The seismic retrofit detail considered was a glass fiber-epoxy jacket to improve confinement and shear strength of the columns.

An analytical study was completed on a full-scale prototype one-way flared reinforced concrete bridge column used in Bridge I-1556 in Sparks, Nevada. Both as-built and retrofitted columns were subjected to a series of earthquakes to determine the effectiveness of the retrofit.

Chapter 2

Description of Bridge and Seismic Retrofit

2.1 Introduction

The purpose of this chapter is to present: (1) description of the bridge being studied and the deficiencies of the columns, and (2) design of FRP jacket for the bridge columns to address the deficiencies.

2.2 Bridge I-1556

2.2.1 Details of Bridge I-1556

Bridge I-1556 is a two-span plate-girder bridge located in Sparks, Nevada. It is an overcrossing located on I-80 at the Sparks Boulevard Interchange. The bridge was constructed in 1989 according to the 1983 AASHTO Standard Specifications[1]. The superstructure consists of eight plate girders supporting a 241-mm thick concrete slab deck. The girders are identical and equally spaced at 3.96 m. The bridge is skewed at 11°.

Seat-type abutments at both ends support the bridge with one four-column bentcap in between. The columns are flared and are rigidly connected to both the footings and bentcap with a full moment connection in both the longitudinal and transverse directions. Figure 2-1 shows a view of one of the columns. Each column is supported by a group of four piles constructed of precast pre-tensioned concrete with a design load capacity of 1960 kN (441 kips) per pile.

The reinforcement detail is identical for all four columns. The longitudinal reinforcement ratio varies along the height of the column from 1.05 to 1.6 percent. The longitudinal reinforcement follows the parabolic shape of the column elevation resulting in different cross sections and longitudinal steel ratios. The number of the longitudinal bars also varies with the height of the column.

Figures 2-2 and 2-3 show the column elevation and reinforcement details, respectively. Note that the lower 1.83 m (6 ft.) of the columns has constant cross section and is not flared. The main longitudinal reinforcement consists of 20 - ϕ36 mm (#11) bars that extend throughout the column height. In addition 12 - ϕ23 mm (#7) bars are placed along the upper flared segment of the column from 3.65 m to 6.7 m from the footing. The transverse reinforcement consists of lateral ties and crossties of ϕ16 mm (#5) bars at 102 mm vertical spacing.

The specified material properties for the steel and concrete are shown in Table 2-1. For the analysis in this study, the concrete strength was increased to reflect estimated increase in strength over time since the placing of the concrete. The concrete compressive strength of the prototype column was 27.6 MPa (4.0 ksi) in 1989. The estimated increase in strength over the ten years since placing of the concrete is 32.4 MPa (4.7 ksi).

A previous evaluation of the columns of Bridge I-1556 showed that plastic hinges would form at column ends because the columns are fixed at both ends[18]. The study also revealed that in flared columns with hinged base the plastic hinge would form at some distance from the top end of the column. With respect to the lateral steel, the study showed that the column ties in Bridge I-1556 are inadequate in terms of (a) confinement and (b) shear strength at the plastic hinge at the bottom of the columns. In the study Ref. 6, a method to apply FRP jackets on flared columns, was developed. In the next section both the confinement and shear problems of the columns in Bridge I-1556 are discussed and the FRP design is described.

2.3 Design of FRP Jacket

The use of FRP jackets to retrofit highway bridge columns is becoming more accepted due to the high strength, light weight, and relative ease of application. The typical wrap consists of a fiber-reinforced plastic (FRP), which combines a fabric-reinforcing material with a bonding agent. The fabric-reinforcing material provides the composite wrap with its primary strength, while the bonding agent holds the reinforcing material together. The reinforcing material consists of uni-directional fibers which are arranged into a laminate by overlapping layers of reinforcing material in any direction to achieve the required strength.

The most common reasons for seismic retrofit of bridge columns using FRP jackets are to improve the shear capacity and confinement. The deficiencies of the columns and the retrofit design with respect to both of these issues are discussed in this section.

2.3.1 Design of FRP Jacket for Shear Strength Enhancement

The jacket was designed through consideration of the capacity and demand at the predicted plastic hinge location. The nominal shear capacity of the column (V_n) was calculated by including contribution from concrete (V_c), and the transverse steel (V_s), using the CALTRANS method[2]. This method was chosen because it accounts for the reduced concrete strength capacity of the plastic hinge. The concrete shear strength includes the effects of compressive axial stress, displacement ductility demand, and level of column core confinement. The shear demand was calculated based on moment capacity and location of the plastic hinges.

The jacket thickness was designed for the difference between the column shear capacity and demand. The jacket design shear strength is outlined in Eq. 2-1.

$$V_{Design} = W_0 \cdot V_{Demand} - f \cdot (V_c + V_s) \qquad (2\text{-}1)$$

This equation considers both an over-strength safety factor *(W_0)* and a strength reduction factor *(f)* to account for the uncertainties of seismic loading effects and accurate estimation of shear capacity. The octagonal shape of the column was approximated as a circular column to account for the contribution of the jacket in a conservative manner. The Federal Highway Administration (FHWA) composite jacket design procedures were used to find the required thickness of the jacket[16]. The FHWA design equation was modified to only include passive confinement effects of the jacket. Equations (2-2) and (2-3) were used to derive the thickness of the jacket based on the jacket design shear, assuming a circular column relationship.

$$V_{Design} = \frac{p}{2} \cdot \left(\left(t_p \cdot E_p \right) \cdot e_p \right) \cdot D \cdot cot(q) \qquad (2\text{-}2)$$

$$t_j = \frac{2}{p} \cdot \left(\frac{V_{Design}}{\left(E_p \cdot e_p \cdot D \cdot cot(q) \right)} \right) \qquad (2\text{-}3)$$

Where: t_p = *Thickness of FRP jacket (passive component)*

E_p = *Young's modulus of FRP jacket (passive component)*

e_p = *Design strain of FRP jacket (passive component)*

D = *Effective depth of FRP jacket*

q = *Design shear crack failure inclination (assumed to be 45 degrees)*

The FHWA method models the jacket as hoop reinforcement with the jacket area equivalent to the thickness of the jacket with a spacing height of unity (1 mm or 1 in). The thickness of the jacket (t_j) is calculated using Eqs. (2-1) through (2-3), given the plastic hinge location and composite wrap properties (Table 2-3). The calculated thickness must be rounded up to the typical minimal thickness of the installed jacket including epoxy therefore providing additional strength beyond that of the original design.

The jacket was designed to provide additional shear capacity near the footing at the predicted plastic hinge region. An overstrength factor of W_0 from 1.5 to 2 has been used. In this study a value of 1.8 was used. The strength reduction factor was assumed to be $f = 1$. The material properties assumed for the jacket are shown in Table 2-2.

The glass fiber-epoxy has a typical layer thickness of 1.27 mm. Based on Eq. (2-1) through (2-3) a thickness of 12.5 mm was found which required ten layers of the glass fiber-epoxy wrap. Reference 18 showed that the inflection point of the columns under the ultimate condition will be at 1.83 m (6 ft.) from the footing. The jacket was designed to reinforce the prismatic portion of the column from the footing to 1.83 m (6 ft.) above the footing in two sections of 0.91 m (3 ft.). In the prismatic portion of the column, the jacket can be wrapped continuously around the perimeter of the column.

2.3.2 Design of FRP Jacket for Confinement

Several confinement steel design procedures are available for reinforced concrete columns. Four sets of design provisions specified in the following codes were used to design the confinement steel. These codes were: the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials Load and Resistance Factor Design (AASHTO-LRFD), the California Department of Transportation (Caltrans), and the Applied Technology Council panel 32 (ATC-32). The tie bar configurations and the size were kept the same as those in the actual columns (Fig. 2-3). The codes were used to determine the required spacing and to evaluate the extent of deficiencies of the column ties with respect to confinement requirements.

Table 2-3 lists the required tie spacing for different codes at different cross sections that are shown in Fig. 2-3. The ties running in the narrow direction of the column controlled the design for Sec. 1-1. The spacing for Sec. 2-2 and 3-3 was controlled by the ties in the wide direction of the column section. It can be seen that the AASHTO code requires the smallest spacing (the highest amount of confinement steel), while the requirements for the other three codes are similar. The actual spacing of the column ties is 100 mm (4 in.).

According to ACI, only Sec. 1-1 would require retrofit. The Caltrans and ATC-32 indicate that the existing confinement steel is sufficient and no retrofit is necessary. Using the AASHTO requirements and the design properties for glass FRP shown in Table 2-2, the number of wraps were determined. The effectiveness factor of the composites for the column was assumed to be 0.75 because the column cross section is non-circular. The confinement provided by the existing ties was taken into account. It was found that the columns would require 13 wraps in Sec. 1-1 (plastic hinge at the top of the column) and 5 wraps elsewhere. Based on the ACI code, the number of wraps for Sec. 1-1 would be only 4. The reason for the difference between the AASHTO and ACI results is in the coefficient of a lower bound confinement steel requirement in both codes. The ratio of the tie bar area and spacing according to the AASHTO version of this equation is:

$$A_{sh}/s = 0.12\ h_c\ (f'_c/f_y) \qquad (2\text{-}4)$$

Where h_c = core section dimension perpendicular to the ties

This equation is an older version of the ACI code formula. In the current ACI code, the coefficient has been reduced to 0.09, thus resulting in a 25 percent reduction. Because a good portion of the required confinement is already provided by the existing ties, the 25 percent difference in the total confinement requirement translates into a large difference in the number of composite wraps that are required for the two codes.

Considering that the ACI results are similar to those of Caltrans and ATC-32 in addition to the fact that these codes are more up to date, it is reasonable to conclude that the appropriate number of wraps to provide confinement in Sec. 1-1 is four and that no wraps are needed elsewhere. As was shown in Sec. 2.3.1, however, Sec. 3-3 needs to be strengthened by 10 wraps due to its low shear capacity.

2.3.3 Combined FRP Jacket Design

Based on Sec. 2.3.1 and 2.3.2, it is recommended that 4 layers of glass fiber composites be placed over the entire height of the column plus an <u>additional</u> 6 layers placed over the lower 1.83 m (6 ft.) of the columns. All the layers in the lower 1.83 m (6ft.) can be wrapped continuously. The installation on the rest of the column height should be in the form of partial straps similar to those used in Ref. 6 for use on the columns of Bridge 1250 (the Airport Viaduct) in Reno, Nevada. Figure 2-4 shows the composite jacket. Note that a 50-mm (2-in.) gap is recommended at both column ends.

The shear capacity of the column with and without the retrofit jacket is shown in Fig. 2-5. In this graph the shear capacity of the 4-layer composite jacket over the upper 4.9-m of the column is included, even though confinement and not shear controlled the FRP design. Nonetheless, the presence of the 4-layer jacket will enhance the shear capacity. It can be seen in the figure that the FRP jacket increased the margin against shear failure considerably.

Chapter 3

Analytical Procedure and Results

3.1 Introduction

The as-built and retrofitted columns described in Chapter 2 were subjected to the Sylmar Hospital earthquake to determine the effectiveness of the retrofit. This chapter describes the analytical procedure and presents the results.

3.2 Analysis Procedure

One column was used in the analysis assuming that its ends were fixed against rotation. The analysis was done in the strong direction of the columns. The actual piers have four columns. Under lateral loads, column axial forces vary because of the overturning effects. The increase in the axial load increases the moment capacity and the associated column shear. This effect was account for in analyzing both the retrofitted and as-built columns.

The analysis consisted of two parts both taking into account the nonlinearity of the columns. First a static pushover analysis was completed to find the basic load-displacement relationship for each column. In the second analysis, the basic load-displacement properties were used in a nonlinear dynamic of the columns subjected to ground motions. This section describes each analysis and the results.

3.2.1 Pushover Analysis

Computer program RCMC was used to determine the moment curvature relationships for different cross sections[19]. From the pushover analysis the dynamic response of the column was calculated treating the column as a single-degree-of-freedom (SDOF) system. The confined concrete properties were used in the analyses assuming Mander's model. Also included was the increase in the flexural strength due to the transverse strength of the FRP jacket. This was done despite the fact that there is a small gap at the end of the composite jacket and that, theoretically, the plastic moment should form in the gap region. In reality, however, the plastic hinge is distributed over a certain length that extends into the composite jacket. Past studies have shown that the transverse capacity of the composite, even though it is relatively small, contributes to the flexural strength of columns[6]. Primarily the epoxy matrix controls the strength properties of the FRP sheets in the transverse direction. Table 2.2 lists the values used in the analysis. The axial load was taken equal to 6750 kN (1515 kips) based on a previous push-over analysis of the bent[18]. The results from RCMC were idealized by a series of bilinear relationships to facilitate the push-over analysis. Figure 3-1 shows the RCMC results and the idealized curves.

The analysis of the as-built column was conducted taking into account the moment and curvature variations along the column height. The initial stiffness and the load associated with plastic hinge formation at both ends of the column were calculated. Based on past shake-table performance of flared column models, it was assumed that the as-built column strength degradation starts at a displacement ductility of 5. In absence of an established method to estimate the descending slope, it was assumed that this slope is the average of the initial and post-yielding stiffness of the column. The load-displacement relationship for the as-built column is shown in Fig. 3-2. The coordinates of different key points and the stiffnesses for different branches are listed in Table 3.1.

The load-displacement relationship for the retrofitted column was constructed by first assuming that the FRP jacket would increase the initial stiffness of the column by approximately 30 percent. This figure was based on past experience in FRP jacketed columns for which the increase in the stiffness has been reported to be in the range of 20 to 50 percent. The "yield" moment associated with point 1 in Fig. 3.1 was found assuming plastic hinges at both column ends and using the results from RCMC analysis. To determine the displacement at the start of strength degradation, the measured ductility capacity for FRP jacketed flared columns reported in Ref. 6 was used. It was assumed that the displacement ductility for this point is 7.5. Following a procedure similar to that used for the as-built column, the stiffness of the descending branch was assumed to be the average of the initial and post-yielding stiffnesses. The load-deflection relationship and the numerical values for the curve are shown in Fig. 3.1 and Table 3.1, respectively.

3.2.2 Dynamic Analysis

The computer program RC-Shake was used to analyze the equivalent SDOF system representing each column subjected to ground motions. An in-depth discussion of the parameters of RC-Shake can be found in Ref. 5. The 1994 Northridge earthquake as measured at the Sylmar Hospital was applied to the SDOF system by adjusting the peak ground acceleration (PGA) of the motion original motion from 100 to 250 percent. The measured PGA was 0.6 g. This meant the PGA used in the analysis was 0.6g to 1.5g. The viscous damping was assumed to be 5 percent. The mass was the tributary dead load for each column. The computer program incorporates a modified version of the Q-Hyst model to account for the variation of the force and displacement. The model takes into account stiffness and strength degradation.

Figures 3-3 to 3-6 show the displacement histories of the top of the as-built and retrofitted columns for different earthquake amplitudes. The maximum displacements, ductilities, and drift ratios are listed in Table 3-2. Because the yield displacements of the two columns were nearly the same (Table 3-1), the effect of retrofit on all three parameters listed in Table 3-2 was nearly the same. It can be seen that under 1xSylmar earthquake neither column yielded. However, the peak displacement of the retrofitted column was approximately 30 percent less than that of the as-built column. The as-built column reached a ductility of 1.3 under the 1.5xSylmar whereas the retrofitted column still remained elastic. Under 2xSylmar the ductility demand in the retrofitted column was only one-half of the as-built column. The displacement history in Fig. 3-6 shows that when the earthquake amplitude was increased to 2.5xSylmar (PGA= 1.5g), the as-built column became unstable whereas the retrofitted column reached a moderate ductility demand of 2.5.

The hysteresis curves for the four earthquake runs are shown in Figs. 3-7 to 3-10. The linear behavior of both columns under 1xSylmar can be seen in Fig. 3-7. Figure 3-9 shows the considerable difference in energy dissipation demand for the two columns through the large area within the hysteresis loops for the as-built column versus the relatively small area for the retrofitted one. Finally, the unstable behavior of the as-built column under 2.5xSylmar can be observed in Fig. 3-10.

The aforementioned results clearly demonstrate the effectiveness of the retrofit jackets. The composite jacket improved the shear strength and confinement and was able to withstand an earthquake with a PGA of 1.5g with only a moderate ductility demand.

Chapter 4

Summary and Conclusions

4.1 Summary

The main objectives of this study were to develop and analyze a seismic retrofit system for the columns of Bridge I-1556 located in Sparks, Nevada. The bridge pier consists of four one-way flared columns with moment connections at both ends of the column. A previous evaluation of the bridge columns with respect to the seismic requirements had shown that the confinement steel is inadequate and the shear capacity near the base of the columns is marginal. Both of these deficiencies were addressed in developing a retrofit strategy. The seismic retrofit detail considered in this study was a glass fiber-epoxy jacket. Because the columns are flared, a continuous wrap over the flared segments is not appropriate, as it will lead to an undesirable increase in the flexural capacity of the columns. Therefore, for the flared segments, a series of overlapping straps was recommended. The FHWA and ACI procedures were used in design. The composite properties were based on the values reported by Fyfe and Associates for their glass FRP wraps. For the prismatic part of the column, a continuous wrap is appropriate. It was found that ten layers are necessary over the prismatic part of the columns and four layers elsewhere.

To determine the effectiveness of the retrofit, the as-built and retrofitted columns were analyzed for earthquakes loading using a nonlinear response history analysis computer program. The moment-curvature relationships for the columns were determined by using a moment-curvature analysis program called RCMC. Program RC-Shake was used to determine the response histories. This program accounts for stiffness and strength degradation of reinforced concrete elements under cyclic loads. The 1994 Sylmar-Northridge earthquake record was used. The peak amplitude of the ground acceleration (PGA) was varied from 0.6g (1xSylmar) to 1.5g (2.5xSylmar). It was found that the retrofit reduced the displacement ductility demand by 50 percent under an earthquake with PGA of 1.2g. Under the 2.5xSylmar record (PGA= 1.5g), the as-built column became unstable whereas the retrofitted column remained stable and had a moderate ductility demand of 2.5.

4.2 Conclusions

- The analytical study of the columns of Bridge I-1556 showed that the columns were vulnerable with respect to shear in the lower part of the columns when subjected to loads in the plane of the pier. The columns were also deficient with respect to the current confinement steel requirements.
- Four layers of glass fiber reinforced plastic wraps are needed over the entire height and additional six layers are needed in the lower part of the columns. These numbers are based on fibers with properties shown in Table 2-2.
- The FHWA shear design and ACI confinement steel design provisions were found to be appropriate for the columns.
- The nonlinear dynamic analysis of the as-built and retrofitted columns showed substantial improvement in the seismic behavior of the columns.

References

1. American Association of State Highway and Transportation Officials, "Standard Specifications for Highway Bridges," 15th Ed, Washington, D.C., 1992.

2. California Department of Transportation, "Memo to Designers, 20-4," Engineering Service Center, Earthquake Engineering Branch, November 1998.

3. Caywood, C., Saiidi, M. S., and Sanders, D. H., "Seismic Retrofit of Flared Bridge Columns with Steel Jackets," Report No. 98-2, CCEER. Department of Civil Engineering, University of Nevada, Reno, June 1998.

4. Jin, L., Saadatmanesh, H., and Ehsani, M.R., "Seismic Retrofit of Existing Reinforced Concrete Columns by Glass-Fiber Composites," Proceedings of the Third Materials Engineering Conference (Infrastructure: New Materials and Methods of Repair), San Diego, California, pp. 758-763, November 1994.

5. Laplace, P., "Shake Table Testing of Flexure Dominated Reinforced Concrete Bridge Columns," M.S.C.E. Thesis, Department of Civil Engineering, University of Nevada, Reno, August 1999.

6. Martinovic, F., M. Saiidi, D. Sanders, and F. Gordaninejad, "Dynamic Testing of Non-Prismatic Reinforced Concrete Bridge Columns Retrofitted with FRP Jackets," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-4, January 2000.

7. McElhaney, B., "Shake Table Testing of Flared Bridge Columns with Steel Jacket Retrofit," M.S.C.E Thesis, Department of Civil Engineering, University of Nevada, Reno, August 1999.

8. "1994 Northridge Earthquake: Performance and Structures, Lifelines, and Fire Protection Systems," United States Department of Commerce, National Institute of Standards and Technology, Special Publication 862, May 1994.

9. Park, R., and Paulay, T., "Reinforced Concrete Structures," John Wiley & Sons, New York, 1975.

10. Preistley, M.J.N., Seible, F., and Calvi, G. M., "Seismic Design and Retrofit of Bridges," John Wiley & Sons, 1996.

11. Priestley, M.J.N., Seible, F., and Uang, C.M., "The Northridge Earthquake of January 17, 1994: Damage Analysis of Selected Bridges," Report No. SSRP-94/06, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego, La Jolla, California, February 1994.

12. Saadatmanesh, H., Ehsani, M.R., and Li, M.W., "Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps," ACI Structural Journal, Vol. 91, No. 4, pp. 434-447, July-August 1994.

13. Sanchez, A.V., Seible, F., and Priestley, M.J.N., "Solutions to Seismic Performance Problems of Flared Bridge Columns," Proceedings of the Second Symposium on Practical Solutions for Bridge Strengthening and Rehabilitation, The National Science Foundation, Kansas City, Missouri, pp. 93-102, March 24-25, 1997.

14. Seible F., and Priestley, M. J., "Retrofit of Rectangular Flexural Columns with Composite Fiber Jackets," Proceedings of the Second Annual Seismic Research Workshop, Sacramento, California, March 1993.

15. Seible, F., Priestley, M.J.N., Hegemier, G.A., and Innamorato, D., "Seismic Retrofit of RC Columns with Continuous Carbon Fiber Jackets," Journal of Composites for Construction, ASCE ,Vol. 1, No. 2, pp.52-62, May 1997.

16. U.S. Department of Transportation, "Seismic Retrofitting Manual for Highway Bridges," Federal Highway Administration, Pub. No. FHWA-RD-94-052, May 1995.

17. Wehbe N., and Saiidi, M.S., "Effects of Confined Core on Seismic Vulnerability of Reinforced Concrete Column with Structural Flares," ACI Special Publication (SP-187), Seismic Response of Concrete Bridges, 1998.

18. Wehbe, N.I, Saiidi, M.S., and Sanders, D. H., "Effects of Confinement and Flares on the Seismic Performance of Reinforced Concrete Bridge Columns," Report No. 97-2, CCEER. Department of Civil Engineering, University of Nevada, Reno, September 1997.

19. Wehbe, N., and M. Saiidi, "User's Manual for RCMC v 1.2- A Computer Program for Moment-Curvature Analysis of Confined and Unconfined Reinforced Concrete Sections," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-6, May 1999.

Tables

Table 2 - 1 Bridge I-1556 Material Properties

	Specified	Estimated Actual
Concrete Compressive Strength	27.6 MPa (4 ksi)	32.4 MPa (4.7 ksi)
Steel Yield Stress	414 MPa (60 ksi)	414 MPa (60 ksi)

Table 2 - 2 Composite Jacket Properties

	DESIGN	SPECIFIED
Tensile Modulus	20,700 MPa (3,000 ksi)	27,600 MPa (4,000 ksi)
Ultimate Strain	0.006	0.02
Ultimate Tensile Strength	124 MPa (18 ksi)	552 MPa (80 ksi)
Strength at 90 degrees	34 MPa (5 ksi)	34 MPa (5 ksi)
Laminate Thickness	13 mm (0.51 in.)	13 mm (0.51 in.)
Modulus at 90 degrees	2,600 MPa (375 ksi)	2,600 MPa (375 ksi)

Table 2 - 3 Confinement Steel Spacing Requirements, mm (in.)

	ACI	AASHTO	ATC-32	CALTRANS
Section 1-1	88 (3.5)	66 (2.6)	102 (4.0)	115 (4.5)
Section 2-2	105 (4.1)	79 (3.1)	101 (4.0)	111 (4.4)
Section 3-3	105 (4.1)	79 (3.1)	101 (4.0)	111 (4.4)

Table 3 - 1 Load-Displacement Properties

	As-Built	Retrofitted
Displacement at point 1 mm (in)	21.3 (0.84)	20.8 (0.82)
Force at point 1 KN (kips)	2887.0 (649.1)	3665.2 (824.0)
Stiffness for Branch 0-1 KN/mm (kips/in)	135.5 (774.0)	176.2 (1006.0)
Displacement at point 2 mm (in)	106.5 (4.2)	156.0 (6.1)
Stiffness for Branch 1-2 KN/mm (kips/in)	3.4 (19.3)	4.4 (25.2)
Stiffness for the Descending Branch	-69.5 (-396.6)	-90.3 (-515.7)

Table 3 - 2 Maximum Displacements and Ductilities

	Peak Displacement, mm (in)			Displacement Ductility			Drift Ratio %		
	As-built	Retrofit	% Reduction	As-built	Retrofit	% Reduction	As-built	Retrofit	% Reduction
1.0 x Sylmar	17.4 (0.7)	12.4 (0.5)	29	0.8	0.6	27	0.3	0.2	29
1.5 x Sylmar	33.2 (1.3)	18.6 (0.7)	44	1.6	0.9	43	0.5	0.3	44
2.0 x Sylmar	56.5 (2.2)	26.3 (1.0)	53	2.7	1.3	52	0.8	0.4	53
2.5 x Sylmar	147.5 (5.8)	52.2 (2.1)	65	6.9	2.5	64	2.2	0.8	65

Figures

Figure 2 - 1 A View of the Edge Column in Bridge I-1556

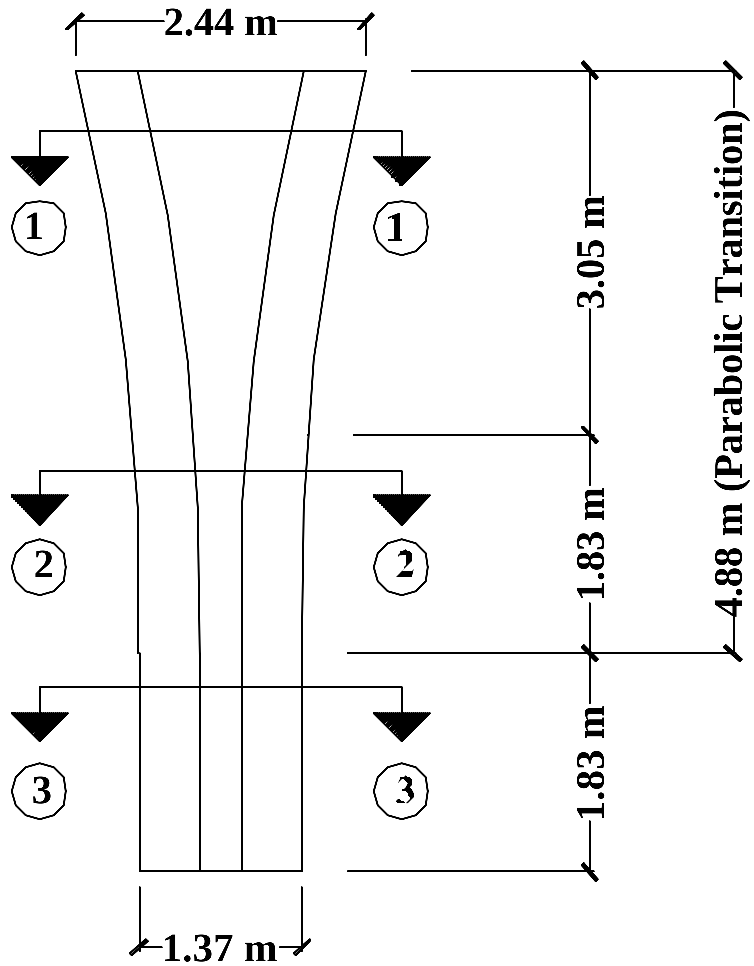


Figure 2 - 2 Elevation of Columns in Bridge I-1556

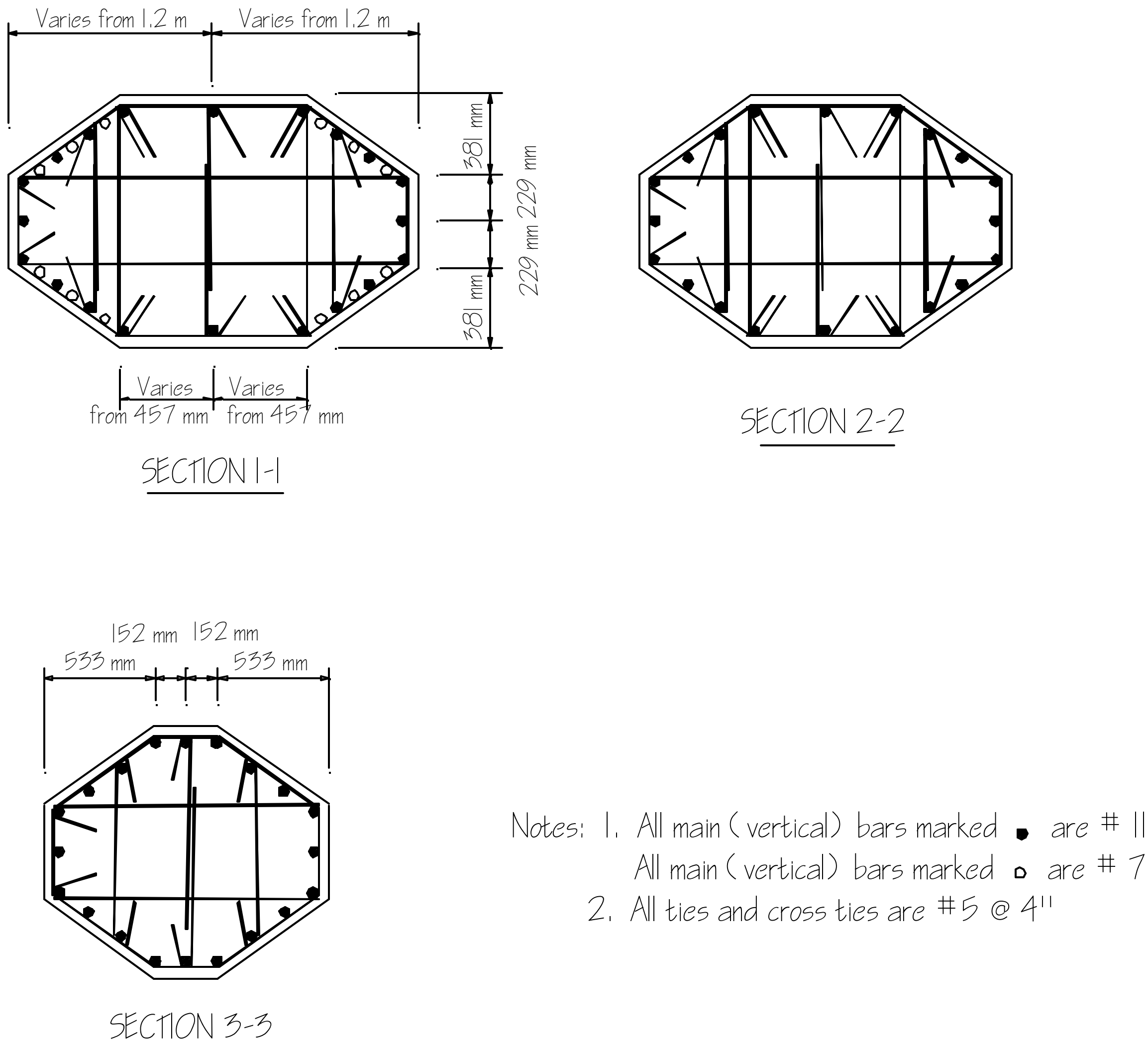


Figure 2 - 3 Reinforcement Detail of Typical Column on I-1556

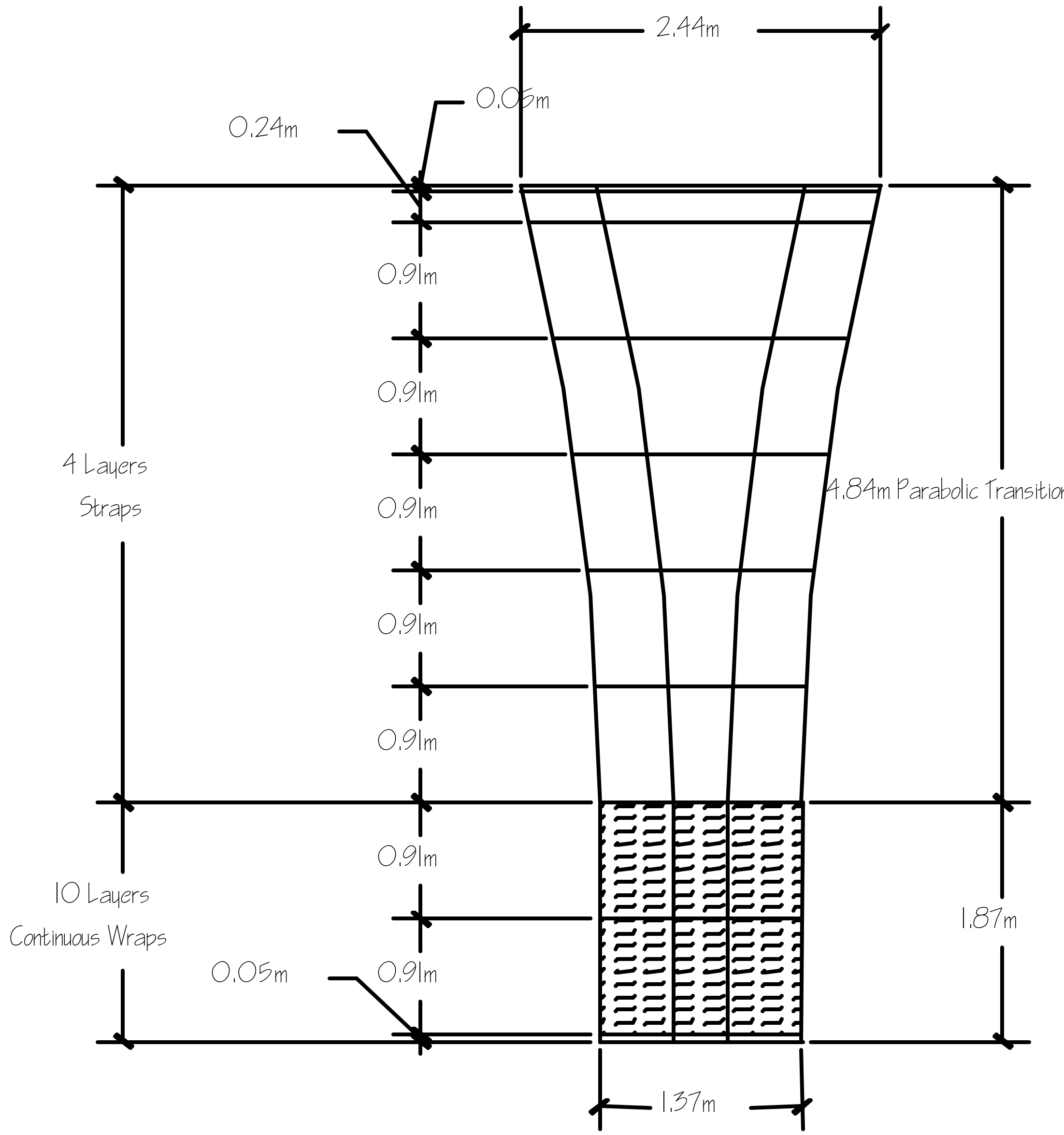


Figure 2 - 4 Glass Fiber-Epoxy Jacket Elevation

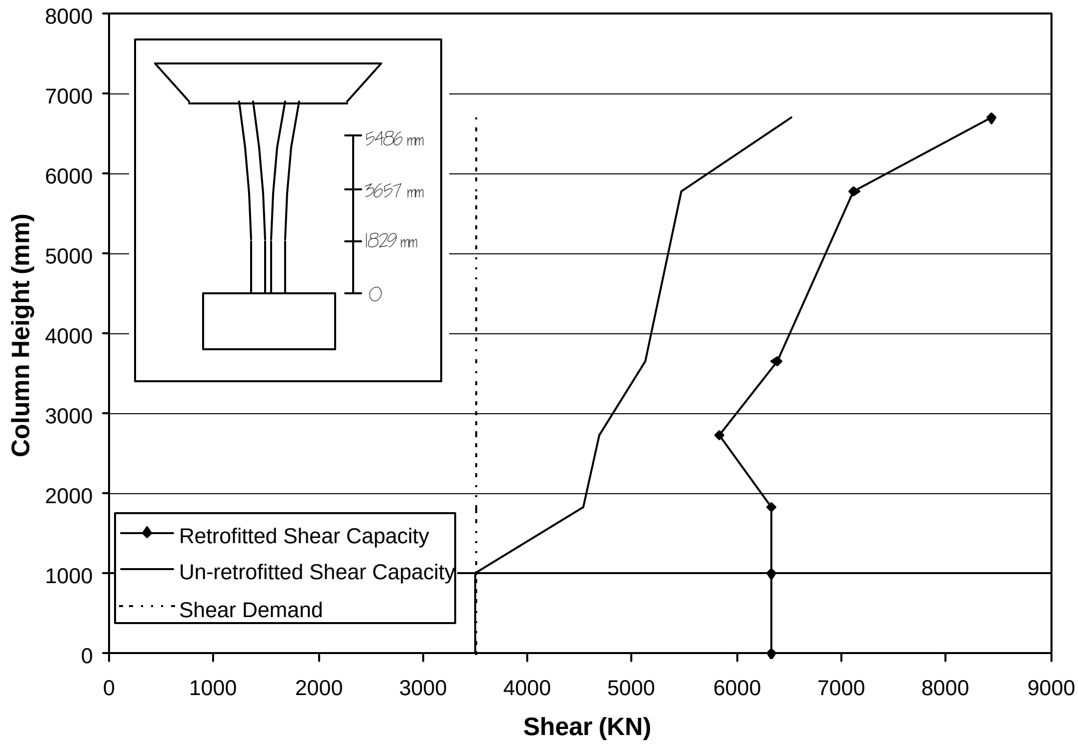
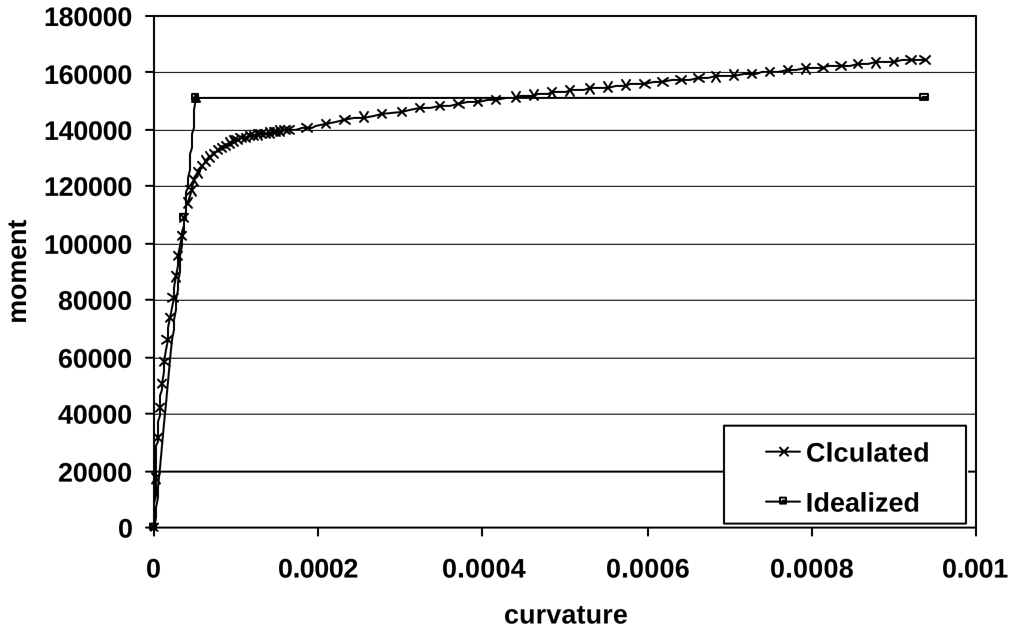
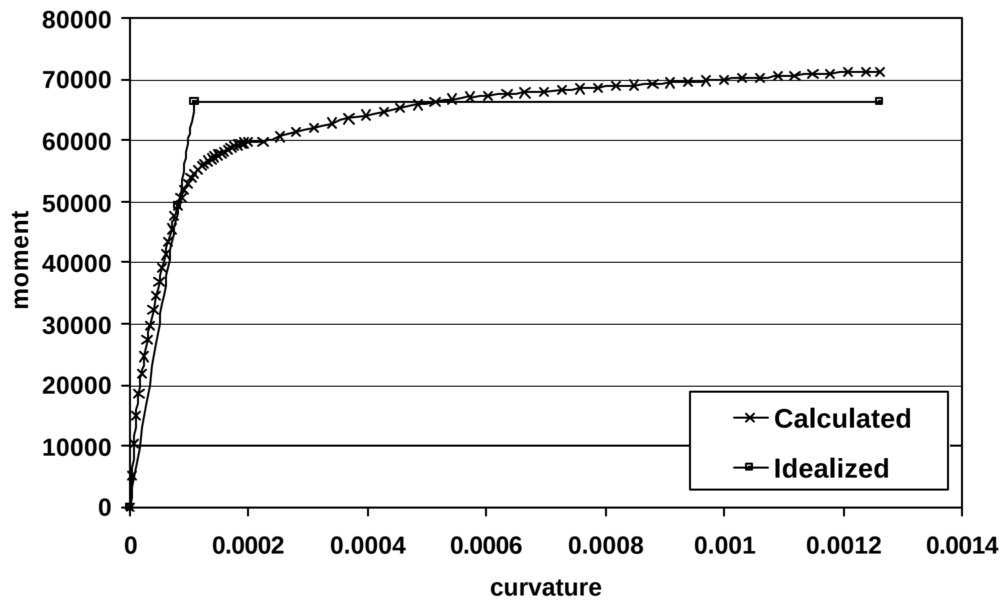


Figure 2-5 Shear Demand and Capacities for the As-Built and Retrofitted Columns



(a) Top of the Column



(b) Base of the Column

Figure 3 - 1 Moment-Curvature Relationships for the ends of the Jacketed Column

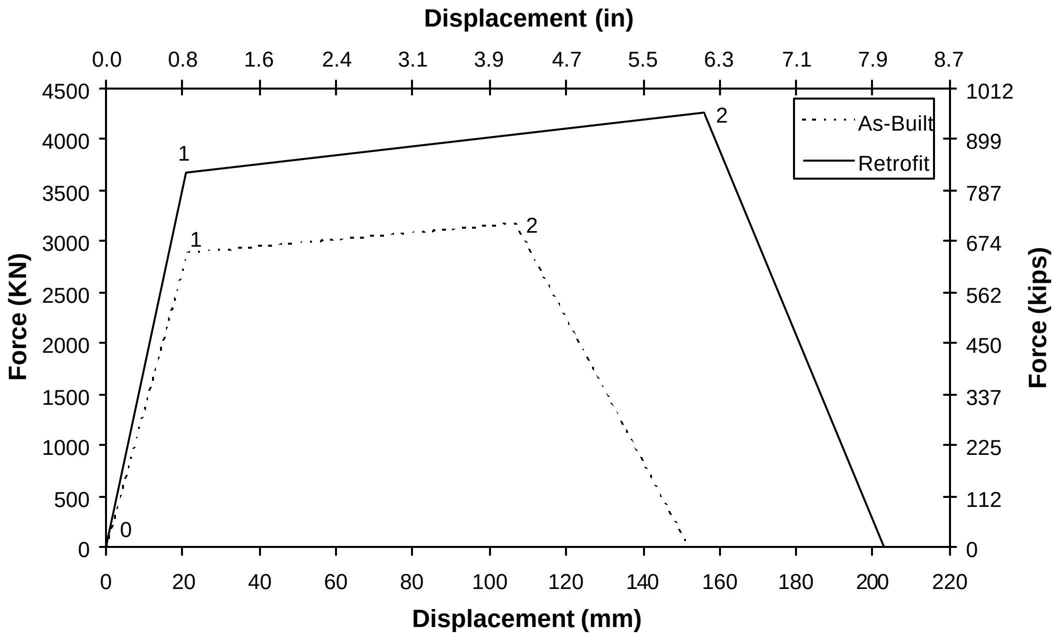


Fig. 3-2 Force vs. Displacement Envelopes for As-Built and Retrofitted Columns

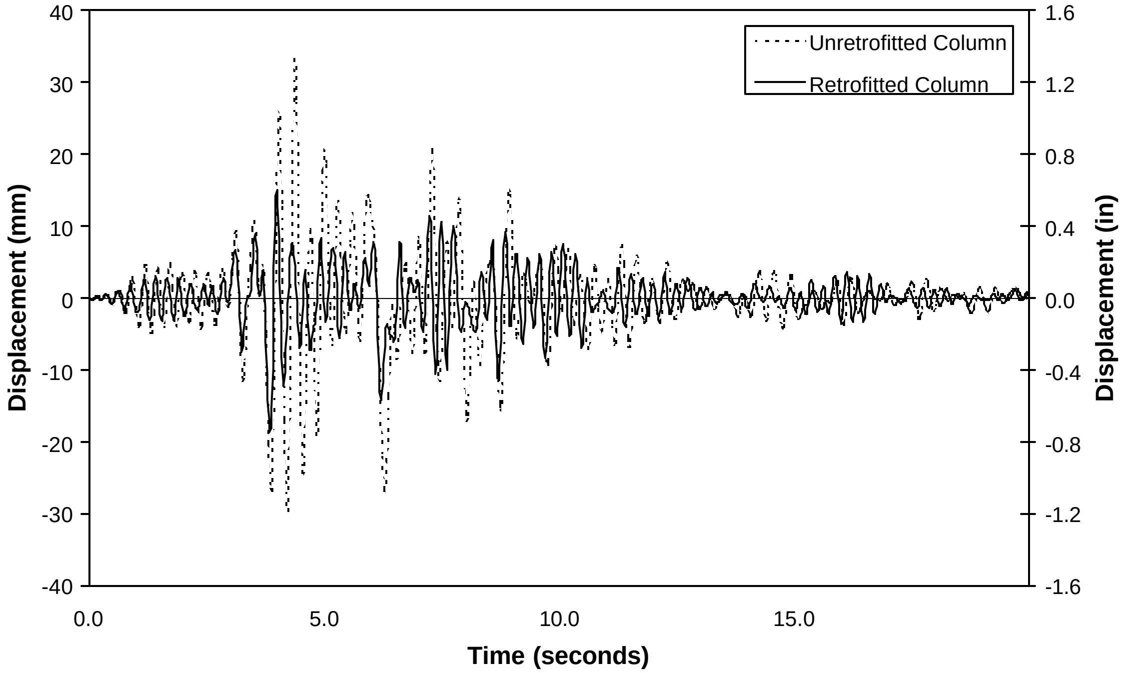


Fig. 3-4 Comparison of Displacement History for 1.5 x Sylmar Event

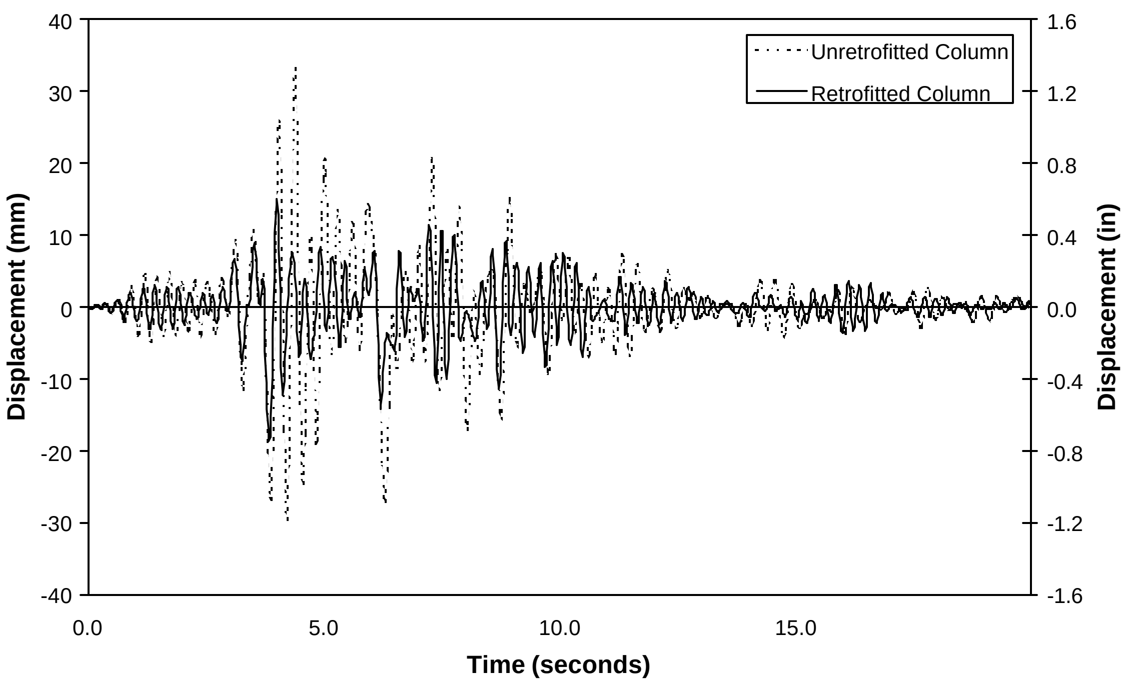


Fig. 3-4 Comparison of Displacement History for 1.5 x Sylmar Event

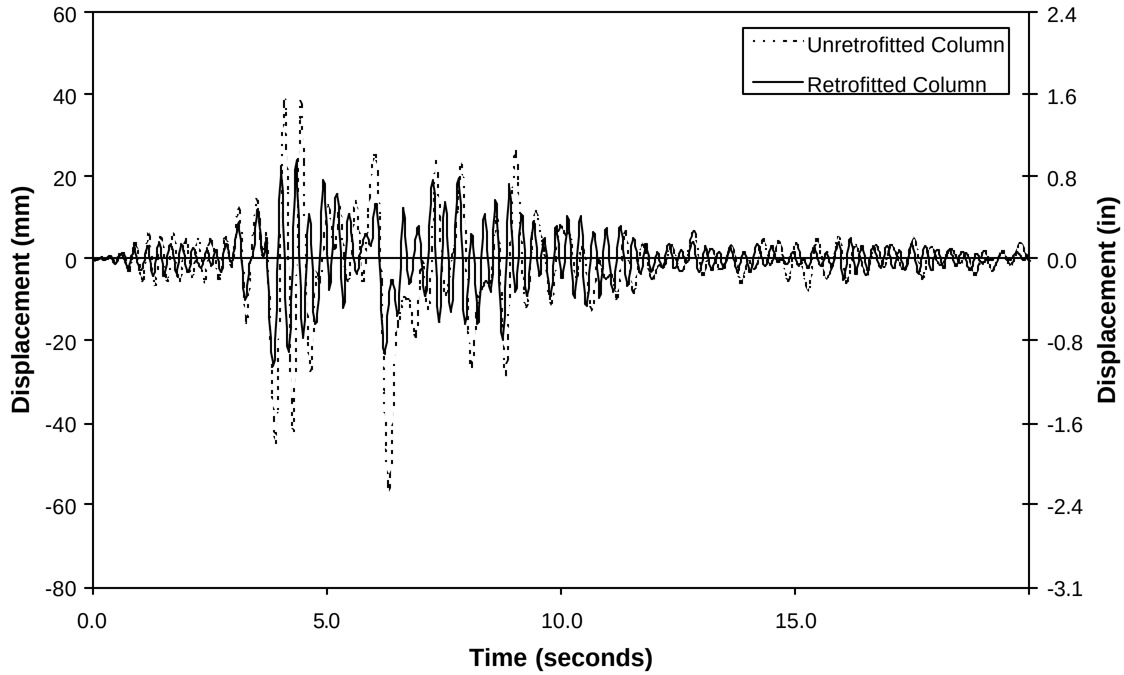


Fig. 3-5 Comparison of Displacement History for 2.0 x Sylmar Event

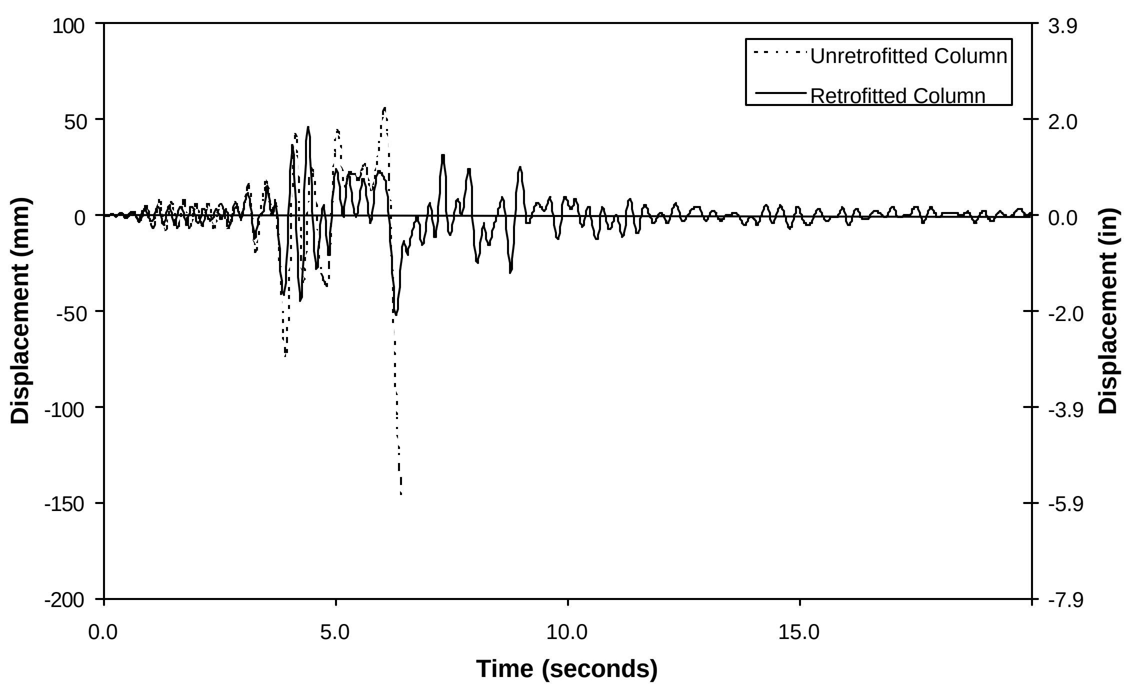


Fig. 3-6 Comparison of Displacement History for 2.5 x Sylmar Event

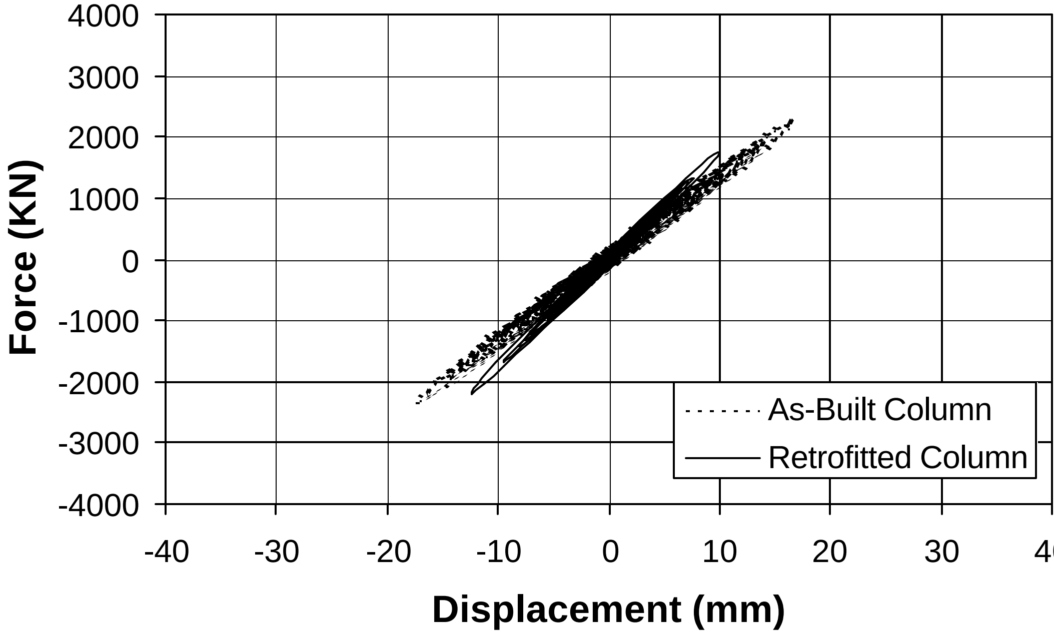


Figure 3 - 7 Comparison of Hysteresis Curves for 1.0 x Sylmar

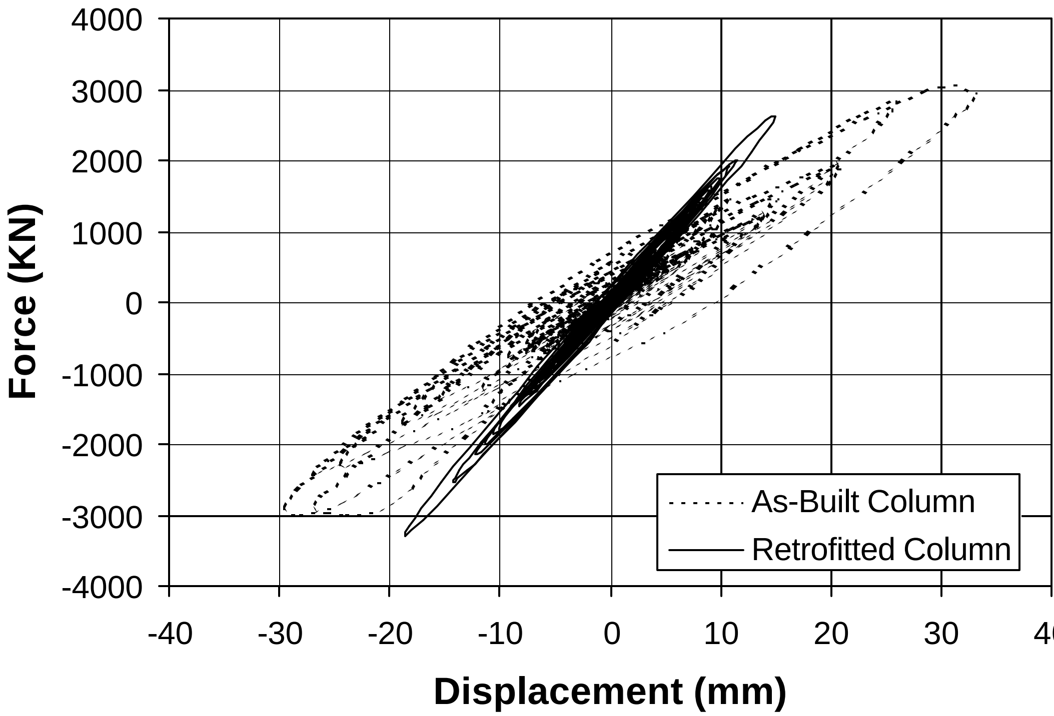


Figure 3 - 8 Comparison of Hysteresis Curves for 1.5 x Sylmar

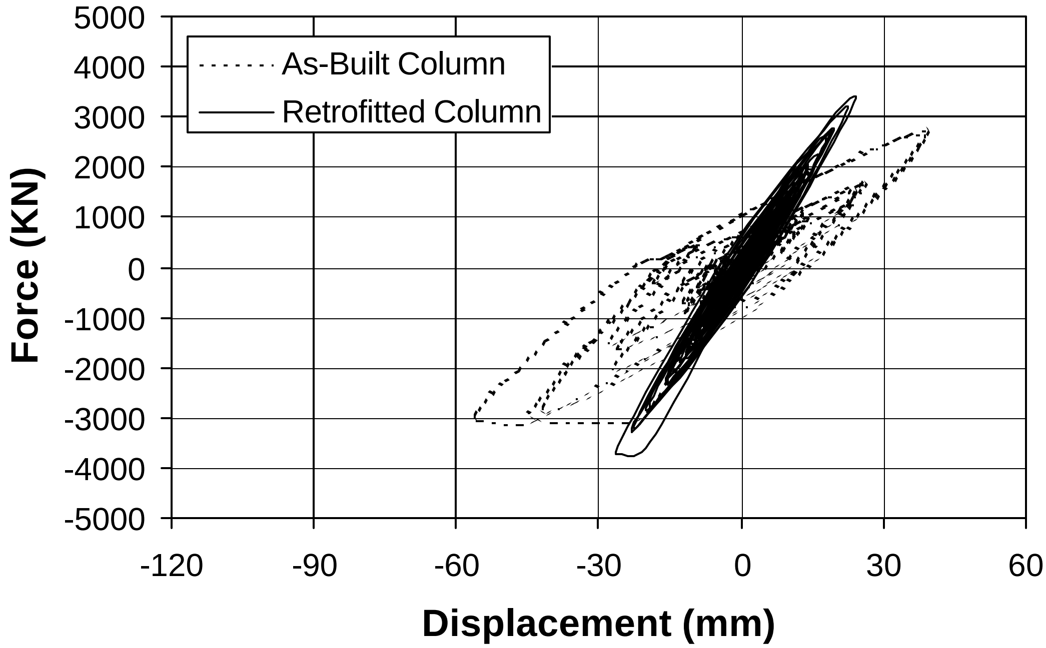


Figure 3 - 9 Comparison of Hysteresis Curves
for 2.0 x Sylmar

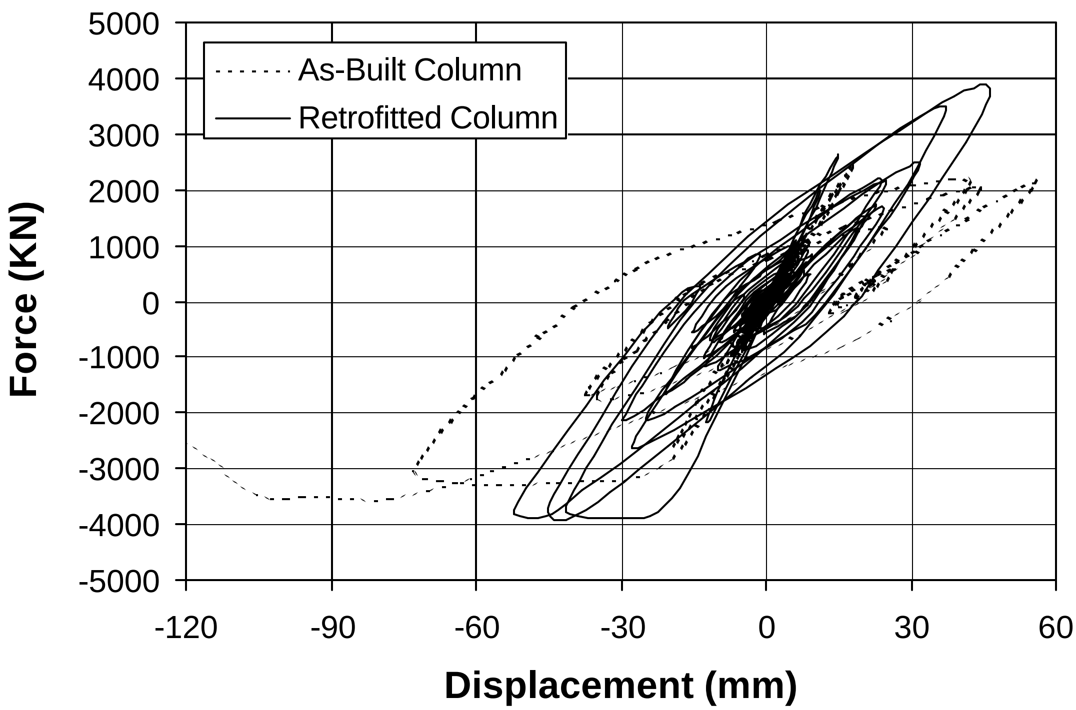


Figure 3 - 10 Comparison of Hysteresis Curves
for 2.5 x Sylmar

LIST OF CCEER PUBLICATIONS

Report No.	Publication
CCEER-84-1	Saiidi, M., and R. Lawver, "User's Manual for LZAK-C64, A Computer Program to Implement the Q-Model on Commodore 64," Civil Engineering Department, Report No. CCEER-84-1, University of Nevada, Reno, January 1984.
CCEER-84-2	Douglas, B. and T. Iwasaki, "Proceedings of the First USA-Japan Bridge Engineering Workshop," held at the Public Works Research Institute, Tsukuba, Japan, Civil Engineering Department, Report No. CCEER-84-2, University of Nevada, Reno, April 1984.
CCEER-84-3	Saiidi, M., J. Hart, and B. Douglas, "Inelastic Static and Dynamic Analysis of Short R/C Bridges Subjected to Lateral Loads," Civil Engineering Department, Report No. CCEER-84-3, University of Nevada, Reno, July 1984.
CCEER-84-4	Douglas, B., "A Proposed Plan for a National Bridge Engineering Laboratory," Civil Engineering Department, Report No. CCEER-84-4, University of Nevada, Reno, December 1984.
CCEER-85-1	Norris, G. and P. Abdollaholiaee, "Laterally Loaded Pile Response: Studies with the Strain Wedge Model," Civil Engineering Department, Report No. CCEER-85-1, University of Nevada, Reno, April 1985.
CCEER-86-1	Ghusn, G. and M. Saiidi, "A Simple Hysteretic Element for Biaxial Bending of R/C in NEABS-86," Civil Engineering Department, Report No. CCEER-86-1, University of Nevada, Reno, July 1986.
CCEER-86-2	Saiidi, M., R. Lawver, and J. Hart, "User's Manual of ISADAB and SIBA, Computer Programs for Nonlinear Transverse Analysis of Highway Bridges Subjected to Static and Dynamic Lateral Loads," Civil Engineering Department, Report No. CCEER-86-2, University of Nevada, Reno, September 1986.
CCEER-87-1	Siddharthan, R., "Dynamic Effective Stress Response of Surface and Embedded Footings in Sand," Civil engineering Department, Report No. CCEER-86-2, University of Nevada, Reno, June 1987.
CCEER-87-2	Norris, G. and R. Sack, "Lateral and Rotational Stiffness of Pile Groups for Seismic Analysis of Highway Bridges," Civil Engineering Department, Report No. CCEER-87-2, University of Nevada, Reno, June 1987.
CCEER-88-1	Orie, J. and M. Saiidi, "A Preliminary Study of One-Way Reinforced Concrete Pier Hinges Subjected to Shear and Flexure," Civil Engineering Department, Report No. CCEER-88-1, University of Nevada, Reno, January 1988.
CCEER-88-2	Orie, D., M. Saiidi, and B. Douglas, "A Micro-CAD System for Seismic Design of Regular Highway Bridges," Civil Engineering Department, Report No. CCEER-88-2, University of Nevada, Reno, June 1988.
CCEER-88-3	Orie, D. and M. Saiidi, "User's Manual for Micro-SARB, a Microcomputer Program for Seismic Analysis of Regular Highway Bridges," Civil Engineering Department, Report No. CCEER-88-3, University of Nevada, Reno, October 1988.
CCEER-89-1	Douglas, B., M. Saiidi, R. Hayes, and G. Holcomb, "A Comprehensive Study of the Loads and Pressures Exerted on Wall Forms by the Placement of Concrete," Civil Engineering Department, Report No. CCEER-89-1, University of Nevada, Reno, February 1989.

CCEER-89-2 Richardson, J. and B. Douglas, "Dynamic Response Analysis of the Dominion Road Bridge Test Data," Civil Engineering Department, Report No. CCEER-89-2, University of Nevada, Reno, March 1989.

CCEER-89-2 Vrontinos, S., M. Saiidi, and B. Douglas, "A Simple Model to Predict the Ultimate Response of R/C Beams with Concrete Overlays," Civil Engineering Department, Report NO. CCEER-89-2, University of Nevada, Reno, June 1989.

CCEER-89-3 Ebrahimpour, A. and P. Jagadish, "Statistical Modeling of Bridge Traffic Loads - A Case Study," Civil Engineering Department, Report No. CCEER-89-3, University of Nevada, Reno, December 1989.

CCEER-89-4 Shields, J. and M. Saiidi, "Direct Field Measurement of Prestress Losses in Box Girder Bridges," Civil Engineering Department, Report No. CCEER-89-4, University of Nevada, Reno, December 1989.

CCEER-90-1 Saiidi, M., E. Maragakis, G. Ghusn, Y. Jiang, and D. Schwartz, "Survey and Evaluation of Nevada's Transportation Infrastructure, Task 7.2 - Highway Bridges, Final Report," Civil Engineering Department, Report No. CCEER 90-1, University of Nevada, Reno, October 1990.

CCEER-90-2 Abdel-Ghaffar, S., E. Maragakis, and M. Saiidi, "Analysis of the Response of Reinforced Concrete Structures During the Whittier Earthquake 1987," Civil Engineering Department, Report No. CCEER 90-2, University of Nevada, Reno, October 1990.

CCEER-91-1 Saiidi, M., E. Hwang, E. Maragakis, and B. Douglas, "Dynamic Testing and the Analysis of the Flamingo Road Interchange," Civil Engineering Department, Report No. CCEER-91-1, University of Nevada, Reno, February 1991.

CCEER-91-2 Norris, G., R. Siddharthan, Z. Zafir, S. Abdel-Ghaffar, and P. Gowda, "Soil-Foundation-Structure Behavior at the Oakland Outer Harbor Wharf," Civil Engineering Department, Report No. CCEER-91-2, University of Nevada, Reno, July 1991.

CCEER-91-3 Norris, G., "Seismic Lateral and Rotational Pile Foundation Stiffnesses at Cypress," Civil Engineering Department, Report No. CCEER-91-3, University of Nevada, Reno, August 1991.

CCEER-91-4 O'Connor, D. and M. Saiidi, "A Study of Protective Overlays for Highway Bridge Decks in Nevada, with Emphasis on Polyester-Styrene Polymer Concrete," Civil Engineering Department, Report No. CCEER-91-4, University of Nevada, Reno, October 1991.

CCEER-91-5 O'Connor, D.N. and M. Saiidi, "Laboratory Studies of Polyester-Styrene Polymer Concrete Engineering Properties," Civil Engineering Department, Report No. CCEER-91-5, University of Nevada, Reno, November 1991.

CCEER-92-1 Straw, D.L. and M. Saiidi, "Scale Model Testing of One-Way Reinforced Concrete Pier Hinges Subject to Combined Axial Force, Shear and Flexure," edited by D.N. O'Connor, Civil Engineering Department, Report No. CCEER-92-1, University of Nevada, Reno, March 1992.

CCEER-92-2 Wehbe, N., M. Saiidi, and F. Gordaninejad, "Basic Behavior of Composite Sections Made of Concrete Slabs and Graphite Epoxy Beams," Civil Engineering Department, Report No. CCEER-92-2, University of Nevada, Reno, August 1992.

CCEER-92-3 Saiidi, M. and E. Hutchens, "A Study of Prestress Changes in A Post-Tensioned Bridge During the First 30 Months," Civil Engineering Department, Report No. CCEER-92-3, University of Nevada, Reno, April 1992.

CCEER-92-4 Saiidi, M., B. Douglas, S. Feng, E. Hwang, and E. Maragakis, "Effects of Axial Force on Frequency of Prestressed Concrete Bridges," Civil Engineering Department, Report No. CCEER-92-4, University of Nevada, Reno, August 1992.

CCEER-92-5 Siddharthan, R., and Z. Zafir, "Response of Layered Deposits to Traveling Surface Pressure Waves," Civil Engineering Department, Report No. CCEER-92-5, University of Nevada, Reno, September 1992.

CCEER-92-6 Norris, G., and Z. Zafir, "Liquefaction and Residual Strength of Loose Sands from Drained Triaxial Tests," Civil Engineering Department, Report No. CCEER-92-6, University of Nevada, Reno, September 1992.

CCEER-92-7 Douglas, B., "Some Thoughts Regarding the Improvement of the University of Nevada, Reno's National Academic Standing," Civil Engineering Department, Report No. CCEER-92-7, University of Nevada, Reno, September 1992.

CCEER-92-8 Saiidi, M., E. Maragakis, and S. Feng, "An Evaluation of the Current Caltrans Seismic Restrainer Design Method," Civil Engineering Department, Report No. CCEER-92-8, University of Nevada, Reno, October 1992.

CCEER-92-9 O'Connor, D., M. Saiidi, and E. Maragakis, "Effect of Hinge Restrainers on the Response of the Madrone Drive Undercrossing During the Loma Prieta Earthquake," Civil Engineering Department, Report No. CCEER-92-9, University of Nevada, Reno, February 1993.

CCEER-92-10 O'Connor, D., and M. Saiidi, "Laboratory Studies of Polyester Concrete: Compressive Strength at Elevated Temperatures and Following Temperature Cycling, Bond Strength to Portland Cement Concrete, and Modulus of Elasticity," Civil Engineering Department, Report No. CCEER-92-10, University of Nevada, Reno, February 1993.

CCEER-92-11 Wehbe, N., M. Saiidi, and D. O'Connor, "Economic Impact of Passage of Spent Fuel Traffic on Two Bridges in Northeast Nevada," Civil Engineering Department, Report No. CCEER-92-11, University of Nevada, Reno, December 1992.

CCEER-93-1 Jiang, Y., and M. Saiidi, "Behavior, Design, and Retrofit of Reinforced Concrete One-way Bridge Column Hinges," edited by D. O'Connor, Civil Engineering Department, Report No. CCEER-93-1, University of Nevada, Reno, March 1993.

CCEER-93-2 Abdel-Ghaffar, S., E. Maragakis, and M. Saiidi, "Evaluation of the Response of the Aptos Creek Bridge During the 1989 Loma Prieta Earthquake," Civil Engineering Department, Report No. CCEER-93-2, University of Nevada, Reno, June 1993.

CCEER-93-3 Sanders, D.H., B.M. Douglas, and T.L. Martin, "Seismic Retrofit Prioritization of Nevada Bridges," Civil Engineering Department, Report No. CCEER-93-3, University of Nevada, Reno, July 1993.

CCEER-93-4 Abdel-Ghaffar, S., E. Maragakis, and M. Saiidi, "Performance of Hinge Restrainers in the Huntington Avenue Overhead During the 1989 Loma Prieta Earthquake," Civil Engineering Department, Report No. CCEER-93-4, University of Nevada, Reno, June 1993 (in final preparation).

CCEER-93-5 Maragakis, E., M. Saiidi, S. Feng, and L. Flournoy, "Effects of Hinge Restrainers on the Response of the San Gregorio Bridge During the Loma Prieta Earthquake," (in final preparation) Civil Engineering Department, Report No. CCEER-93-5, University of Nevada, Reno.

CCEER-93-6 Saiidi, M., E. Maragakis, S. Abdel-Ghaffar, S. Feng, and D. O'Connor, "Response of

Bridge Hinge Restrainers During Earthquakes -Field Performance, Analysis, and Design," Civil Engineering Department, Report No. CCEER-93-6, University of Nevada, Reno, May 1993.

CCEER-93-7 Wehbe, N., Saiidi, M., Maragakis, E., and Sanders, D., "Adequacy of Three Highway Structures in Southern Nevada for Spent Fuel Transportion, Civil Engineering Department, Report No. CCEER-93-7, University of Nevada, Reno, August 1993.

CCEER-93-8 Roybal, J., Sanders, D.H., and Maragakis, E., "Vulnerability Assessment of Masonry in the Reno-Carson City Urban Corridor," Civil Engineering Department, Report No. CCEER-93-8, University of Nevada, Reno, May 1993.

CCEER-93-9 Zafir, Z. and Siddharthan, R., "MOVLOAD: A Program to Determine the Behavior of Nonlinear Horizontally Layered Medium Under Moving Load," Civil Engineering Department, Report No. CCEER-93-9, University of Nevada, Reno, August 1993.

CCEER-93-10 O'Connor, D.N., Saiidi, M., and Maragakis, E.A., "A Study of Bridge Column Seismic Damage Susceptibility at the Interstate 80/U.S. 395 Interchange in Reno, Nevada," Civil Engineering Department, Report No. CCEER-93-10, University of Nevada, Reno, October 1993.

CCEER-94-1 Maragakis, E., B. Douglas, and E. Abdelwahed, "Preliminary Dynamic Analysis of a Railroad Bridge," Report CCEER-94-1, January 1994.

CCEER-94-2 Douglas, B.M., Maragakis, E.A., and Feng, S., "Stiffness Evaluation of Pile Foundation of Cazenovia Creek Overpass," Civil Engineering Department, Report No. CCEER-94-2, University of Nevada, Reno, March 1994.

CCEER-94-3 Douglas, B.M., Maragakis, E.A., and Feng, S., "Summary of Pretest Analysis of Cazenovia Creek Bridge," Civil Engineering Department, Report No. CCEER-94-3, University of Nevada, Reno, April 1994.

CCEER-94-4 Norris, G.M. and Madhu, R., "Liquefaction and Residual Strength of Sands from Drained Triaxial Tests, Report 2," Civil Engineering Department, CCEER-94-4, University of Nevada, Reno, August 1994.

CCEER-94-5 Saiidi, M., Hutchens, E., and Gardella, D., "Prestress Losses in a Post-Tensioned R/C Box Girder Bridge in Southern Nevada," Civil Engineering Department, CCEER-94-5, University of Nevada, Reno, August 1994.

CCEER-95-1 Siddharthan, R., El-Gamal, M., and Maragakis, E.A., "Nonlinear Bridge Abutment , Verification, and Design Curves," Civil Engineering Department, CCEER-95-1, University of Nevada, Reno, January 1995.

CCEER-95-2 Norris, G.M., Madhu, R., Valceschini, R., and Ashour, M., "Lique faction and Residual Strength of Loose Sands from Drained Triaxial Tests," Report 2, Civil Engineering Department, Report No. CCEER-95-2, University of Nevada, Reno, February 1995.

CCEER-95-3 Wehbe, N., Saiidi, M., Sanders, D., and Douglas, B., "Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement,"Civil Engineering Department, Report No. CCEER-95-3, University of Nevada, Reno, July 1995.

CCEER-95-4 Martin, T., Saiidi, M., and Sanders, D., "Seismic Retrofit of Column -Pier Cap Connections in Bridges in Northern Nevada," Civil Engineering Department, Report No. CCEER-95-4, University of Nevada, Reno, August 1995.

CCEER-95-5 Darwish, I., Saiidi, M., and Sanders, D., “Experimental Study of Seismic Susceptibility Column-Footing Connections,” Civil Engineering Department, Report No. CCEER-95-5, University of Nevada, Reno, September 1995.

CCEER-95-6 Griffin, G., Saiidi, M., and Maragakis, E., “Nonlinear Seismic Response of Isolated Bridges and Effects of Pier Ductility Demand,” Civil Engineering Department, Report No. CCEER-95-6, University of Nevada, Reno, November 1995.

CCEER-95-7 Acharya, S., Saiidi, M., and Sanders, D., “Seismic Retrofit of Bridge Footings and Column-Footing Connections,” Report for the Nevada Department of Transportation, Civil Engineering Department, Report No. CCEER-95-7, University of Nevada, Reno, November 1995.

CCEER-95-8 Maragakis, E., Douglas, B., and Sandirasegaram, U., “Full-Scale Field Resonance Tests of a Railway Bridge,” A Report to the Association of American Railroads, Civil Engineering Department, Report No. CCEER-95-8, University of Nevada, Reno, December 1995.

CCEER-95-9 Douglas, B., Maragakis, E., and Feng, S., “System Identification Studies on Cazenovia Creek Overpass,” Report for the National Center for Earthquake Engineering Research, Civil Engineering Department, Report No. CCEER-95-9, University of Nevada, Reno, October 1995.

CCEER-96-1 El-Gamal, M.E. and Siddharthan, R.V., “Programs to Computer Translational Stiffness of Seat-Type Bridge Abutment,” Civil Engineering Department, Report No. CCEER-96-1, University of Nevada, Reno, March 1996.

CCEER-96-2 Labia, Y., Saiidi, M., and Douglas, B., “Evaluation and Repair of Full-Scale Prestressed Concrete Box Girders,” A Report to the National Science Foundation, Research Grant CMS-9201908, Civil Engineering Department, Report No. CCEER-96-2, University of Nevada, Reno, May 1996.

CCEER-96-3 Darwish, I., Saiidi, M., and Sanders, D., “Seismic Retrofit of R/C Oblong Tapered Bridge Columns with Inadequate Bar Anchorage in Columns and Footings,” A Report to the Nevada Department of Transportation, Civil Engineering Department, Report No. CCEER-96-3, University of Nevada, Reno, May 1996.

CCEER-96-4 Ashour, M., Pilling, P., Norris, G., and Perez, H., “The Prediction of Lateral Load Behavior of Single Piles and Pile Groups Using the Strain Wedge Model,” A Report to the California Department of Transportation, Civil Engineering Department, Report No. CCEER-96-4, University of Nevada, Reno, June, 1996.

CCEER-97-1-A Rimal, P. and Itani, A. “Sensitivity Analysis of Fatigue Evaluations of Steel Bridges”, Center for Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada Report No. CCEER-97-1-A, September, 1997.

CCEER-97-1-B Maragakis, E., Douglas, B., and Sandirasegaram, U. “Full-Scale Field Resonance Tests of a Railway Bridge,” A Report to the Association of American Railroads, Civil Engineering Department, University of Nevada, Reno, May, 1996.

CCEER-97-2 Wehbe, N., and M. Saiidi, “User’s Manual for RCMC v. 1.1, A computer Program for Moment-Curvature Analysis of Confined and Unconfined Reinforced Concrete Sections,” Civil Engineering Department, University of Nevada, Reno, November, 1997.

CCEER-97-3 Darwish, I., M. Saiidi, G. Norris, and E. Maragakis, “Determination of In-Situ Footing Stiffness Using Full-Scale Dynamic Field Testing,” A Report to the Nevada Department of Transportation, Structural Design Division, Carson City, Nevada, Report No. CCEER-97-3, University of Nevada, Reno, October 1997.

CCEER-97-4 Wehbe, N., and M. Saiidi, “User’s manual for RCMC v. 1.2 : A Computer Program for Moment-Curvature Analysis of Confined and Unconfined Reinforced Concrete Sections,” Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-97-4, November, 1997.

CCEER-97-5 Isakovic, T., M. Saiidi, and A. Itani, “Influence of new Bridge Configurations on Seismic Performance,” Department of Civil Engineering, University of Nevada, Reno, Report No. CCEER-97-5, September, 1997.

CCEER-98-1 Itani, A., Vesco, T. and Dietrich, A., “Cyclic Behavior of “as Built” Laced Members With End Gusset Plates on the San Francisco Bay Bridge” Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada Report No. CCEER-98-1, March, 1998.

CCEER-98-2 G. Norris and M. Ashour, “Liqueficiation and Undraned response evaluation of Sands from Drained Formulation.”

CCEER-98-3 Qingbin, Chen, B. M. Douglas, E. Maragakis, and I. G. Buckle, "Extraction of Nonlinear Hysteretic Properties of Seismically Isolated Bridges from Quick-Release Field Tests", Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-98-3, June, 1998.

CCEER-98-4 Maragakis, E., B. M. Douglas, and C. Qingbin, "Full-Scale Field Capacity Tests of a Railway Bridge", Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-98-4, June, 1998.

CCEER-98-5 Itani, A., Douglas, B., and Woodgate, J., “Cyclic Behavior of Richmond-San Rafael Retrofitted Tower Leg”. Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno. Report No. CCEER-98-5, June 1998

CCEER-98-6 Moore, R., Saiidi, M., and Itani, A., “Seismic Behavior of New Bridges with Skew and Curvature”. Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno. Report No. CCEER-98-6, October, 1998.

CCEER-98-7 Itani, A and Dietrich, A, “Cyclic Behavior of Double Gusset Plate Connections”, Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-98-5, December, 1998.

CCEER-99-1 Caywood, C., M. Saiidi, and D. Sanders, “ Seismic Retrofit of Flared Bridge Columns With Steel Jackets,” Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-1, February 1999.

CCEER-99-2 Mangoba, N., M. Mayberry, and M. Saiidi, “Prestress Loss in Four Box Girder Bridges in Northern Nevada,” Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-2, March 1999.

CCEER-99-3 Abo-Shadi, N., M. Saiidi, and D. Sanders, "Seismic Response of Bridge Pier Walls in the Weak Direction", Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-3, April 1999.

CCEER-99-4 Buzick, A., M. Saiidi, "Shear Strength and Shear Fatigue Behavior of Full-Scale Prestressed Concrete Box Girders", Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-4, April 1999.

CCEER-99-5 Randall, M., M. Saiidi, E. Maragakis and T. Isakovic, "Restrainer Design Procedures For

Multi-Span Simply-Supported Bridges", Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-5, April 1999.

CCEER-99-6 Wehbe, N. and M. Saiidi, "User's Manual for RCMC v. 1.2, A Computer Program for Moment-Curvature Analysis of Confined and Unconfined Reinforced Concrete Sections", Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-6, May 1999.

CCEER-99-7 Burda, J. and A. Itani, "Studies of Seismic Behavior of Steel Base Plates," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-7, May 1999.

CCEER-99-8 M. Ashour and G. Norris, "Refinement of the Strain Wedge Model Program," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-99-8, March 1999.

CCEER-99-9 A. Dietrich and A. Itani, "Cyclic Behavior of Laced and Perforated Steel Members on the San Francisco-Oakland Bay Bridge," Civil Engineering Department, University, Reno. December 1999.

CCEER 99-10 A. Itani, A. Dietrich, "Cyclic Behavior of Built Up Steel Members and their Connections," Civil Engineering Department, University of Nevada, Reno. December 1999.

CCEER 99-11 A. Itani, J. Woodgate, "Axial and Rotational Ductility of BuiltUp Structural Steel Members," Civil Engineering Department, University of Nevada, Reno December 1999.

CCEER-99-12 Sgambelluri, M., Sanders, D.H., and Saiidi, M.S., Behavior of One-Way Reinforced Concrete Bridge Column Hinges in the Weak Direction, Report No. Department of Civil Engineering, University of Nevada, Reno, December 1999.

CCEER-99-13 Laplace, P., Sanders, D.H., Douglas, B, and Saiidi, M, Shake Table Testing of Flexure Dominated Reinforced Concrete Bridge Columns, Report No. Department of Civil Engineering, University of Nevada, Reno, December 1999.

CCEER-99-14 Ahmad M. Itani, Jose A. Zepeda, and Elizabeth A. Ware "Cyclic Behavior of Steel Moment Frame Connections for the Moscone Center Expansion," December 1999.

CCEER 00-1 Ashour, M., and Norris, G. "Undrained Lateral Pile and Pile Group Response in Saturated Sand", Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-1, May 1999. January 2000.

CCEER 00-2 Saiidi, M. and Wehbe, N., "A Comparison of Confinement Requirements in Different Codes for Rectangular, Circular, and Double-Spiral RC Bridge Columns," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-2, January 2000.

CCEER 00-3 McElhaney, B., M. Saiidi, and D. Sanders, "Shake Table Testing of Flared Bridge Columns With Steel Jacket Retrofit," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-3, January 2000.

CCEER 00-4 Martinovic, F., M. Saiidi, D. Sanders, and F. Gordaninejad, "Dynamic Testing of Non-Prismatic Reinforced Concrete Bridge Columns Retrofitted with FRP Jackets," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-4, January 2000.

CCEER 00-5 Itani, A., and M. Saiidi, "Seismic Evaluation of Steel Joints for UCLA Center for Health Science Westwood Replacement Hospital," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-5, February 2000.

CCEER 00-6 Will, J. and D. Sanders, "High Performance Concrete Using Nevada Aggregates," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-6, May 2000.

CCEER 00-7 French, C., and M. Saiidi, "A Comparison of Static and Dynamic Performance of Models of Flared Bridge Columns ," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER-00-7, October 2000.

CCEER 00-8 Itani, A., H. Sedarat, "Siesmic Analysis of the AISI LRFD Design Example of Steel Highway Bridges," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER 00-08, November 2000

CCEER 01-1 Ah Sha, H., D. Sanders, M. Saiidi, "Early Age Shrinkage and Cracking of Nevada Concrete Bridge Decks, "Civil Engineering Department, University of Nevada, Reno, Report No. CCEER 01-01, May 2001

CCEER 01-2 Ashour, M. and G. Norris, "Pile Group program for Full Material Modeling an Progressive Failure." Civil Engineering Department, University of Nevada, Reno, Report No. CCEER 01-02, July 2001

CCEER 01-3 Itani, A., C. Lanaud, and P. Dusicka, "Non-Linear Finite Element Analysis of Built-Up Shear Links." Civil Engineering Department, University of Nevada, Reno, Report No. CCEER 01-03, July 2001

CCEER 01-4 Saiidi, M., J. Mortensen, and F. Martinovic, "Analysis and Retrofit of Fixed Flared Columns with Glass Fiber-Reinforced Plastic Jacketing," Civil Engineering Department, University of Nevada, Reno, Report No. CCEER 01-4, August 2001

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