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Guide for the Selection of Rapid Repair Systems for Earthquake-Damaged Reinforced Concrete Bridge Columns

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16. Abstract

This guide addresses the selection of systems for rapidly repairing earthquake-damaged reinforced concrete bridge columns with different types and levels of damage. Recent studies in the technical literature on repair have demonstrated that different techniques can be a viable option for restoring the use of earthquake-damaged RC bridge columns, even those columns that have been severely damaged. Furthermore, other studies have confirmed the feasibility of implementing certain repair techniques within a short timeframe, thereby making them suitable for the purpose of rapid repair. In order to design and implement the repair, the damage extent and type of damage must be quantified, and an appropriate repair system must be identified. This guide helps identify appropriate repair systems corresponding to the damage observed. The guide also helps enables bridge engineers and inspectors to make rapid, effective, and cost-beneficial decisions regarding post-earthquake repair of bridge columns, which are critical to the transportation industry.

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List of Abbreviations

Externally bonded (EB)
Fiber reinforced polymer (FRP)
Mid-America Transportation Center (MATC)
Missouri University of Science & Technology (Missouri S&T)
Near surface mounted (NSM)
Nebraska Transportation Center (NTC)
Reinforced concrete (RC)
Shape memory alloy (SMA)

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Abstract

This guide addresses the selection of systems for rapidly repairing earthquake-damaged reinforced concrete bridge columns with different types and levels of damage. Recent studies in the technical literature on repair have demonstrated that different techniques can be a viable option for restoring the use of earthquake-damaged RC bridge columns, even those columns that have been severely damaged. Furthermore, other studies have confirmed the feasibility of implementing certain repair techniques within a short timeframe, thereby making them suitable for the purpose of rapid repair. In order to design and implement the repair, the damage extent and type of damage must be quantified, and an appropriate repair system must be identified. This guide helps identify appropriate repair systems corresponding to the damage observed. The guide also helps enable bridge engineers and inspectors to make rapid, effective, and cost-beneficial decisions regarding post-earthquake repair of bridge columns, which are critical to the transportation industry.

Field of Application

The main objective of this guide is to present the most rapid and effective systems for repairing earthquake-damaged reinforced concrete bridge columns. The influence of different variables, such as damage type and damage severity, are evaluated to select the most effective repair system(s).

The repair systems considered in this guide are limited to those that are characterized by a relatively rapid installation and/or whose effectiveness has been confirmed through research and/or experimentation. Systems that have been shown to be the most suitable for repairing reinforced concrete columns damaged by different actions, such as bending moment, shear, and torsion, and different damaged levels are indicated.

Chapter 1 Introduction

According to current seismic design criteria, columns are the primary energy dissipating elements of a bridge during an earthquake, while the other structural components of the bridge such as cap beams, girders, and abutments are designed to remain elastic during a seismic event without any damage. Therefore, the repair of earthquake-damaged reinforced concrete (RC) bridges usually involves repair of the columns.

During an earthquake, RC bridge columns may sustain damage such as concrete cracking, concrete spalling, concrete crushing, reinforcing bar yielding, tie opening, bar splice failure, bar fracturing, and/or bar buckling. These types of damage can be localized in different regions of the column, such as at the column-footing or column-cap beam joint, or can be distributed along the length of the member.

Immediately after a seismic event occurs, bridges considered essential for the transportation industry and for carrying out emergency operations should be inspected by bridge engineers in order to evaluate the extent and the degree of damage and to compare the current performance with the performance requirement of the structure. If the current performance is not significantly affected by the damage, it is possible to use the bridge without repair. Otherwise, if the performance verification of the structure fails, it is necessary to determine if the bridge can be repaired to the desired performance level. If so, it is necessary to select an appropriate repair system and then design the repair reinforcement. If it is not possible to repair the structure to the original or the desired level, the performance requirement must be reduced, and restrictions on the use of the structure must be applied. Only afterwards will it be possible to select a repair system and design the repair reinforcement. The repair system should be applied to the structure only after verifying that the repaired structure is able to return to the fully operative state or to a desired state of operation, otherwise a different repair system must be selected, thus iterating the process described above.

The major difference between a permanent repair and an emergency (or rapid) repair of an earthquake-damaged bridge is that a permanent repair aims to restore the strength and deformation capacity of the damaged members to their initial state, whereas an emergency repair is designed to prevent further damage and restore the minimum functionality of the structure, making it capable of accommodating essential traffic for disaster mitigation, as described above (ATC-18 1997). Moreover, emergency repair should be carried out rapidly in order to restore at least the minimum level of functionality of the bridge as soon as possible. Low use of labor as well as availability of the repair materials are qualities that define the most suitable systems to be used in emergency situations.

Figure 1.1 illustrates the process for selecting a rapid repair system for a bridge damaged by a seismic event. This logical process is valid for essential bridges that must be repaired (i.e., the option to abandon the bridge is not allowed).

Many systems have been developed and tested for rapidly repairing RC bridge columns. This guide summarizes and evaluates available repair systems in terms of applicability to different damage types, effectiveness, and ease of application. Recommendations in this guide have been developed based on results of experimental studies carried out by different researchers to quantify the damage extent and type of damage and to identify the appropriate repair system corresponding to the damage observed.

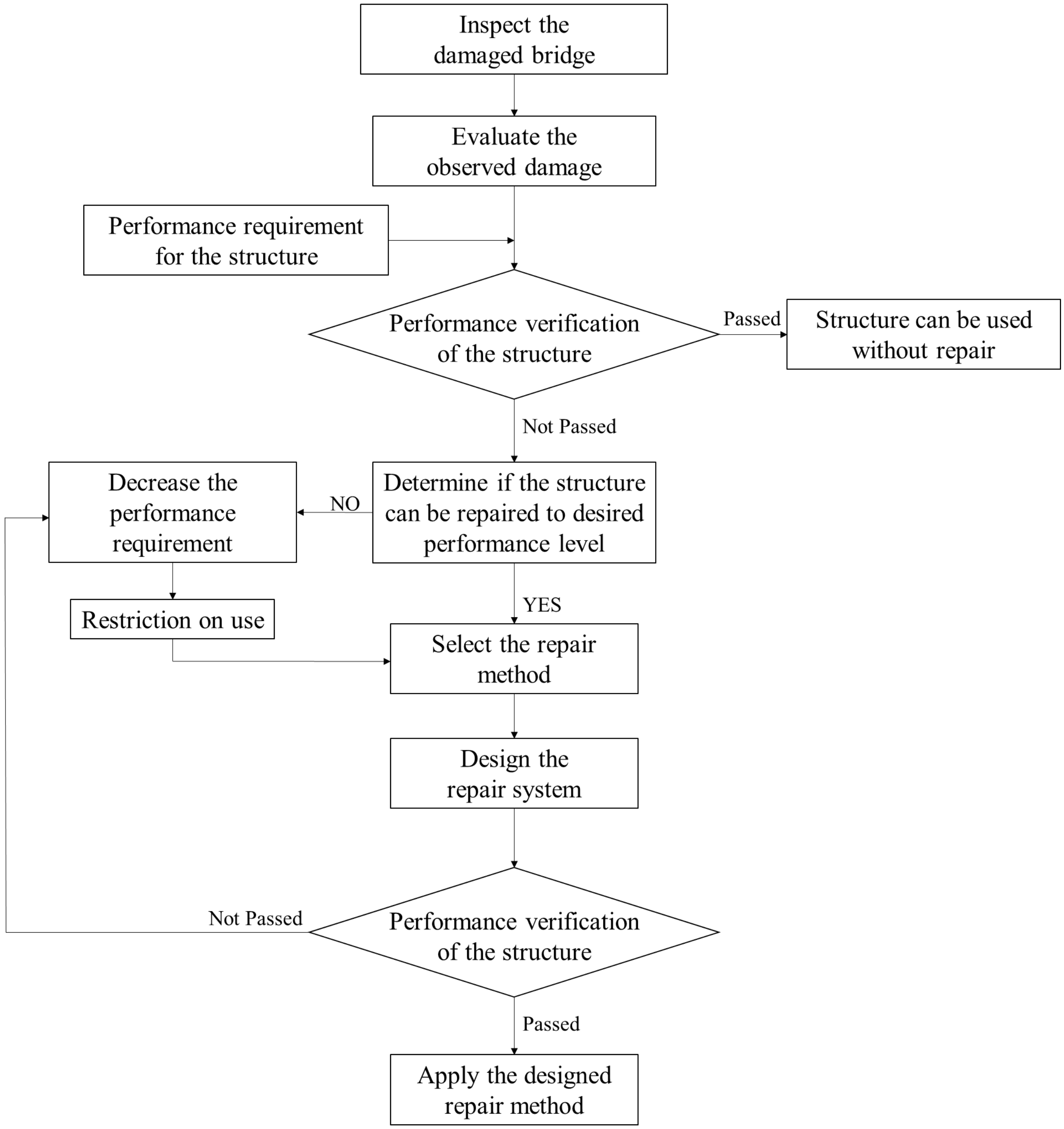


Figure 1.1 Flow chart describing the process for selecting a rapid repair system for earthquake-damaged bridges

Chapter 2 Summary of Literature on Repair of Earthquake-Damaged Reinforced Concrete Bridge Columns

The literature search conducted in this work, and summarized in the tables presented in Appendix A, revealed that a considerable number of studies concerning the repair of RC bridge columns has been conducted. On the other hand, very little information has been published about evaluation criteria, repair selection process, and general guidance for repairing earthquake-damaged RC bridge columns.

In order to determine the most effective systems to repair RC bridge columns damaged by seismic loading, an extensive literature search was conducted, and a database of test results was developed. Based on the information gathered, the studies were divided into two groups: 1) experimental works on repair of damaged columns that did not have fractured longitudinal reinforcing bars, and 2) experimental works on repair of damaged columns with fractured longitudinal reinforcing bars. This distinction is fundamental for understanding the effectiveness of the repair systems for RC columns with different levels of damage, especially since fracture of reinforcement is an ultimate limit state and generally constitutes member failure.

Research reported in the literature has involved different repair techniques and materials ranging from "classical" repair systems, such as RC jacketing and steel jacketing, to systems that have recently become popular such as FRP jacketing, and to more innovative systems such as the addition of NSM-FRP bars or SMA spirals. These methods are discussed in more detail in Chapter 5.

The tables presented in Appendix A are an extension of the work by He et al. (2015). For each experimental test collected during the literature search, the parameters deemed to be most relevant were summarized including the scale of the column test specimen, the column cross-sectional shape, the axial load index, the applied loading(s), the apparent damage after testing of the as-built member, the repair system utilized, and the improvement made by the repair system in terms of strength, ductility, and/or stiffness. This information was used to determine the suitability of different repair systems for a given damage type and severity as discussed in Chapter 6.

The references listed in Appendix A can be used as a starting point if more in-depth information on specific repair systems is needed.

Chapter 3 Reinforced Concrete Bridge Column Properties

3.1 Overview

The columns of a bridge are structural elements that support the superstructure and transfer the loads to the foundation below. In most bridges, columns are the primary elements that resist the lateral loads acting on the bridge.

The main geometrical parameters that characterize an RC bridge column are the shape of the cross section and the height. Cross sectional shapes commonly used for RC bridge concrete columns are circular, square, and rectangular, and sometimes hexagonal and octagonal. The cross section can be solid or hollow, and the dimensions may be constant or vary along the column height (as in the case of a flared column). The column height is used to classify the column as short or slender based on the slenderness ratio, defined as the ratio between the effective length factor times the unsupported length divided by the radius of gyration (Kl_u/r). The result of this ratio governs the behavior of the column when compressed. A short column is defined as a column whose axial load capacity is governed primarily by the strength of the materials and geometry of the cross section, whereas a slender column is one whose axial load capacity is significantly reduced due to moments resulting from lateral deflection.

The geometrical characteristics of RC bridge columns discussed above influence the selection of the most appropriate repair system and its design. For example, a circular cross section is relatively easy to wrap with FRP sheets (such as in the case of FRP jackets), whereas the sharp corners of rectangular cross-sections can damage the fibers when they are tensioned, which necessitates rounding of corners prior to application. Moreover, the confining action of a circular cross section is more effective than for non-circular shapes.

The flexural behavior of an RC column is characterized by the sectional geometry, material strengths, longitudinal reinforcement ratio, aspect ratio (slenderness ratio), and axial load ratio, while the shear behavior is influenced by the sectional geometry, material strengths, concrete components (e.g., maximum aggregate size), and transverse reinforcement ratio. In addition, design details are crucial, which vary based on the age of the bridge and the code requirements at the time at which it was designed. Therefore, the design of a repair system should consider the information gathered during the visual inspection of the damaged bridge as well as the original design details and the maintenance/strengthening/retrofit works carried out over its life.

The era in which the bridge was designed can provide significant indications about the design provisions utilized and the typical vulnerability of the bridge, thus making it easier to identify the mechanisms that caused the damage. The construction age of a bridge (and of any structural strengthening/retrofit carried out on it afterwards) can, therefore, provide an indication of its performance, where newer bridges are generally less affected by earthquake damage than older bridges.

Earthquakes that have occurred in the U.S. during the past century have caused extensive damage and casualties, which has led to a substantial evolution of design codes and the seismic design provisions. The events that have most significantly influenced this evolution are the 1925 Santa Barbara earthquake, the 1971 San Fernando earthquake, the 1989 Loma Prieta earthquake, and the 1994 Northridge earthquake. These earthquakes have led to changes to the seismic design of bridges as discussed in the sections that follow.

3.2 Bridges Designed Before 1974

In 1906, after the San Francisco earthquake, engineers became aware of the seismic risk to structures. Despite the large number of casualties, estimated between 700 and 3000, and the destruction of approximately 28,000 buildings (USGS n.d.), the 1906 San Francisco earthquake did not stimulate an explicit code response because the damage caused by the ground motion was completely overcome by the fire. Only after the 1925 Santa Barbara earthquake did the post-earthquake investigators who examined the damaged structures call for regulatory change (Theodoropulous 2006). The first code concerning the seismic design provision for bridges was developed in California by the California State Highway Association in 1940 and by the American Association of State Highway Officials (AASHO, now the American Association of State Highway Transportation Officials, AASHTO) in 1941 in which ground motion effects were modeled simply as a lateral force proportional to the mass of the structure of unspecified value (Todd et al. 1994). Until 1965, the lateral seismic design force was 6% of the structural dead load, and later was increased to 13% (Caltrans 2006).

3.2.1 Flexural Behavior of RC Columns

RC columns of bridges designed before 1974 typically fail in shear due to inadequate transverse reinforcement. For this reason, if subjected to actions caused by an earthquake, such columns generally do not reach their full flexural capacity, and therefore, the longitudinal bars remain elastic. Even if the column is able to reach the yielding moment of the section, the few stirrups placed within the plastic hinge region would not provide acceptable ductility, leading to a sudden collapse.

Another reason why it is difficult to reach the yielding moment in columns designed before 1974 is due to inadequate lap splice of the longitudinal reinforcement. The common practice was to splice the bars at locations of high flexural demand (e.g., right above the footing) using a length of only 20 bar diameters. It was also common practice to anchor the longitudinal bars in the footing without using 90-degree hooks and with an embedment length of only 20 bar diameters. Columns designed with such short lap splice length or embedment length can exhibit brittle failure due to the slipping or pullout of the bars.

(a) (b)

Figure 3.1 Pullout (a) and buckling (b) failure of bridge damaged in the 1971 San Fernando earthquake (Caltrans 2006).

3.2.2 Shear Behavior of RC Columns

Before 1974 RC bridge columns were typically designed with transverse reinforcement consisting of #4 bars spaced at 12 in., regardless of the size of the column or of the longitudinal reinforcement. Therefore, fracture of transverse reinforcement as well as local buckling of the longitudinal bars are common. In the case of a low transverse reinforcement ratio, aggregate interlock becomes the main shear resisting mechanism. However, dynamic loading can create wide cracks in the column reducing the aggregate interlock effect. For these reasons shear typically governs the failure mechanism, which occurs in a brittle manner, for columns of bridges built before 1974.

Figure 3.2 Shear failure of a bridge damaged in the 1971 San Fernando Earthquake due to the low thickness and high spacing of the transverse reinforcement (Caltrans 2006).

3.2.3 Typical Characteristics of RC Columns

- Longitudinal bars with lap splice length of typically 20 bar diameters
- Longitudinal bars with lap splice location in regions of high flexural demand (i.e., often right above the footing)
- Longitudinal bars with embedment length into the footing of typically 20 bar diameters and without 90-degree hooks
- Transverse reinforcement of #4 at 12 in. regardless size of column or longitudinal bars (Moehle and Eberhard 2000, Caltrans 2006)
- Transverse reinforcement that is not anchored into the concrete core (i.e., no 135 deg. hooks)
- Transverse reinforcement that does not provide adequate confinement to the concrete core, particularly in large columns

3.2.4 Typical Vulnerabilities of RC Columns

- Failure due to buckling, slippage, or pullout of longitudinal reinforcement
- Foundation anchorage failure, especially for bridges supported by piers with a single column
- Shear failure due to inadequate transverse reinforcement

3.3 Bridges Designed Between 1974-1994

The next step in the evolution of bridge design provisions was due to the 1971 San Fernando earthquake. Damage caused by the ground motion to the structures that met the code requirements exceeded expectations, which led to an increase in performance requirement. Thus, the lateral seismic design force was increased to 30% of the structural dead load (Caltrans 2006). Moreover, bridge design was required to take into account the dynamic response of the structure as well as the ductility and the relative stiffness of the members. More stringent detailing requirements became a function of the fault proximity and the site condition. Although all these requirements were incorporated in the 1974 Caltrans Code and the 1975 AASHTO Specification (Todd et al. 1994), it took a few years for them to be fully implemented. As a result, all bridges that were severely damaged by the 1994 Northridge earthquake were built between 1964 and 1976. Therefore, some caution is required when evaluating the vulnerabilities of bridges built during that time period, especially in the case of flared columns. Before 1994, flares were assumed to be non-structural elements, and therefore the resulting change in column stiffness and strength was not considered. The extensive damage caused by the 1989 Loma Pieta earthquake made it necessary to review and improve the minimum performance levels, detailing requirements, and design provisions. Unfortunately, the 1994 Northridge earthquake occurred before the improvements were concluded.

3.3.1 Flexural Behavior of RC Columns

Due to the revised design provisions, columns of bridges built between 1974 and 1994 are typically able to reach the yielding moment of the section. On the other hand, inadequate confinement of the plastic hinge regions amplifies the strength degradation due to cyclic load. Buckling of the longitudinal bars due to the fracture of transverse reinforcement is also common.

Figure 3.3 Failure due to strength degradation at plastic hinge regions of bridges damaged in the 1994 Northridge Earthquake (Caltrans 2006).

3.3.2 Shear Behavior of RC Columns

Bridge columns built between 1974 and 1994 were typically designed with sufficient transverse reinforcement to reach the full flexural capacity. However, the effect of the cyclic degradation as well the effect of the buckling of the longitudinal bars were not considered. Shear failure in the plastic hinge region is common.

(a) (b)

Figure 3.4 Shear failure of bridges damaged in the 1994 Northridge Earthquake. In (b) the use of a flare created a "short column" that is very sensitive to shear actions (Caltrans 2006).

3.3.3 Typical Characteristics of RC Columns

- Longitudinal bar lap splices prohibited in regions of high flexural demand
- Transverse reinforcement typically #4 at 6 in.
- Transverse reinforcement that does not provide adequate confinement to the concrete core, particularly in large columns
- No additional transverse reinforcement within the joint or plastic hinge region

3.3.4 Typical Vulnerabilities of RC Columns

- Shear failure at the plastic hinge regions due to inadequate transverse reinforcement and poor confinement

- Shear failure due to the effects of non-structural elements (e.g., channel walls, column flares)

3.4 Bridges Designed After 1994

The new generation of seismic design codes include recommendations about capacity design and ductility approach. The purpose is to ensure a ductile flexural failure of the columns only, while all other bridge elements are to remain elastic. For this reason, the number of expansion joints were minimized as well as the use of column flares, the required shear capacity of joint connections was increased, and anti-buckling reinforcement was provided. When the 1994 Northridge earthquake occurred, the damaged bridges were mainly those built before 1974 and that had not been retrofitted. This observation validated the evolution of the code during the second half of the last century.

3.4.1 Flexural Behavior of RC columns

Bridge columns designed after 1994 were designed to exhibit ductile behavior. The transverse reinforcement provided is generally adequate to allow the longitudinal reinforcement to reach the full flexural capacity, and it also prevents the buckling of longitudinal bars.

3.4.2 Shear Behavior of RC Columns

According to the capacity design, a column built after 1994 has very closely spaced transverse confinement, especially in the plastic hinge regions. Therefore, the column should fail in a ductile way due to bending moment actions.

3.4.3 Typical Characteristics of RC columns

- Lap splice of longitudinal bars prohibited in plastic hinge regions
- Adequate joint reinforcement is provided
- Specific reinforcement is provided within plastic hinges regions

Chapter 4 Reinforced Concrete Bridge Column Damage Classification

This section describes and classifies the type and level of damage reported on earthquake-damaged bridge RC columns. The most common types of damage, such as concrete cracking, concrete spalling, reinforcing bar yielding, bar buckling, and bar fracturing are described in Section 5.1. In Section 5.2, the type of damage is associated to different damage levels.

4.1 Damage Types

4.1.1 Concrete Flexural, Shear, and Torsional Cracking

Concrete cracking occurs when the tensile stress reaches the tensile strength of the concrete. For RC columns subjected to bending moment, the typical crack pattern is represented by flexural cracks that are generally perpendicular to the longitudinal axis of the column emanating from the tensile face. For columns under a combination of bending moment, shear, and/or torsion, the direction of cracks is inclined to the longitudinal axis of the column (Belarbi et al. 2010). If shear action is predominant, the cracks appear on opposite faces of the column and are generally parallel to one another. If torsional action is predominant, the cracks spiral around the column in a continuous manner, and thus the cracks on opposite faces of the column are generally perpendicular to one another.

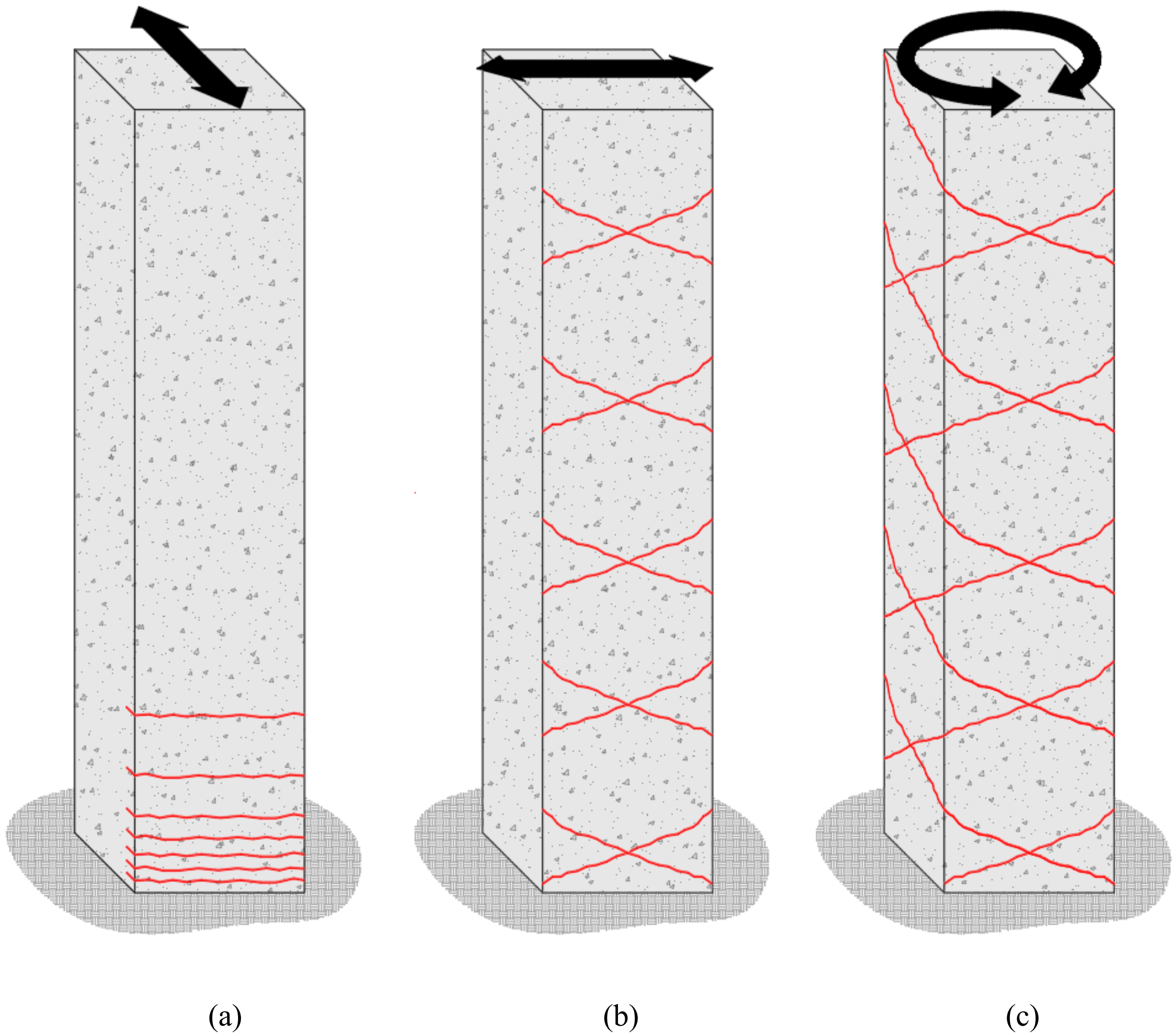


Figure 4.1 (a) Flexural cracking, (b) shear cracking, (c) torsional cracking

4.1.2 Concrete Cover Spalling

Spalling of the concrete cover can be described as detachment of the concrete outside of the reinforcing bar cage. The extent of spalling depends on many factors such as the thickness of the clear cover, shape of the cross section, and longitudinal reinforcement ratio. If the longitudinal and/or transverse reinforcing bars are relatively close each other, they can create a preferential section of failure between the cover concrete and the core concrete.

In plastic hinge regions, spalling of the cover concrete occurs following yielding of longitudinal reinforcement. Therefore, the extent of the spalling is an important factor to consider in designing the minimum length of the repair. Although concrete cover spalling is a symptom of moderate damage, repair of spalling can be performed easily.

4.1.3 Concrete Splitting

Bond failure of longitudinal reinforcement will often exhibit splitting cracks, which are oriented in the axial direction of the column and along the longitudinal reinforcing bars. Concrete splitting cracks also appear on the surface of RC columns that have endured compressive action equal to or larger than their axial load capacity. The typical pattern is represented by short parallel cracks oriented along the column's longitudinal axis. This type of damage may be observed for those columns subjected to an earthquake with a large vertical component.

4.1.4 Longitudinal Reinforcing Bar Yielding

In general, yielding of the longitudinal reinforcement starts on the tension side of the element and gradually spreads to adjacent bars around the column (Belarbi et al. 2010). Longitudinal bar yielding in plastic hinge regions is generally followed by concrete cover spalling.

4.1.5 Longitudinal Bar Buckling

The longitudinal bars can buckle due to the nature of cyclic loading that occurs during an earthquake (Belarbi et al. 2010). Bar buckling occurs after extensive spalling of the concrete cover and significant degradation of the core concrete, making the reinforcement no longer able to withstand the compressive stresses. Therefore, buckling of the longitudinal reinforcement is a sign of imminent collapse.

4.1.6 Longitudinal and Transverse Reinforcing Bar Fracture

Fracture of longitudinal or transverse reinforcement is a serious indication that the column was subjected to a loading condition that exceeded its strength, thus leading to failure. In both cases the core has been compromised, and the element is no longer capable of supporting additional load.

4.2 Damage Levels

ATC-32 (1996) classified damage in terms of three levels described as minimal, repairable, and significant. Minimal and repairable damage were not quantitatively defined in ATC-32, although significant damage was used to describe columns with a permanent offset, yielded reinforcement, or major concrete spalling.

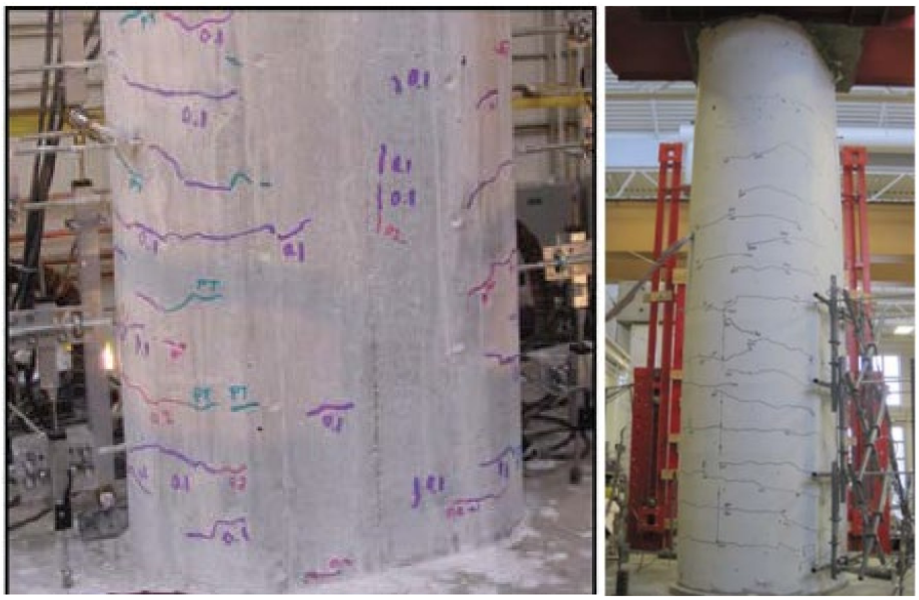
More recently, the severity of damage to an RC column is often described using damage states. Different researchers have associated damage states with a visual description of damage and/or objective criteria. Dutta and Mander (1999) defined five different damage states to categorize the severity of damage in an RC bridge element, ranging from almost no damage to collapse, where each state corresponds to a given drift limit. However, this scale is a function of the column design since the same drift ratio can cause different damage to a non-seismically designed column compared with a seismically designed column. Billah and Alam (2012) modified the previous damage scale using ductility demand limits instead of drift limits, thus making the scale usable for any type of column. This approach, although accurate and in a certain way capable of defining unambiguous categories, is difficult to use on site to evaluate the damage caused by a seismic event. For instance, it may be incorrect to assume that the measured residual drift (after the seismic event) is the maximum drift value experienced by the column during the event. Similarly, it may not be appropriate to assume that the drift is solely the result of the last earthquake (disregarding potential pre-existing conditions), or to assume that the residual drift is due entirely to damage and has not been influenced by support conditions (e.g., rotation of the column due to sagging foundation).

A descriptive formulation of damage states, where the severity of the damage is associated with a visible damage condition and mechanism (although subjected to interpretation) is the only approach that can be used in every condition. The study performed by Vosooghi and Saiidi (2010), which was based on the review of shake test data from 30 RC bridge columns, allowed to identify five damage states corresponding to five apparent levels of damage. The damage states were defined as follows: DS-1: flexural cracks; DS-2 first spalling and shear cracks; DS-3: extensive cracks and spalling; DS-4: visible transverse and longitudinal bars; DS-5: imminent failure. However, if the seismic event is so strong that results in column failure, where the contribution of the damaged column to the strength of the bridge structure is null, is not possible to identify the damage state using the abovementioned scale. For this reason, the damage states scale proposed by Vosooghi and Saiidi (2010) is expanded with a sixth state: DS-6: member failure. In addition, an additional damage state has been added to classify structural elements that, following a seismic event, exhibit damage that does not affect the performance: DS-0.

A brief description of each individual damage states is provided below. Table 5.1 summarizes the information presented and explained in this section.

DS-0. Damage state DS-0 applies to RC columns that show barely visible cracks that are not necessarily attributable to the effect of the seismic event. Columns that show a damage condition classified as DS-0 do not need repair work.

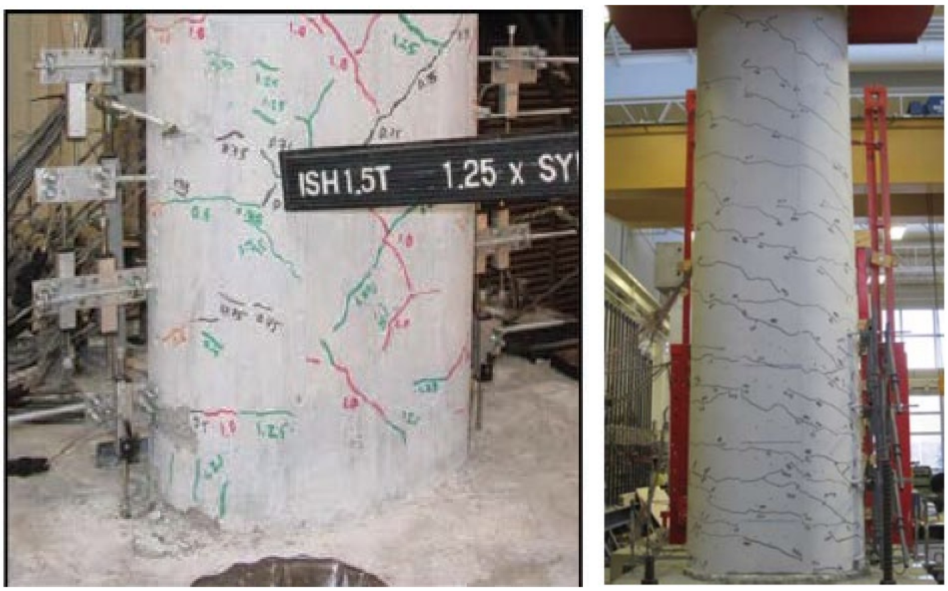
DS-1. Damage state DS-1 is assigned to RC columns that exhibit flexural cracks after the seismic event. Repairing a column in this state should be evaluated with a cost-benefit analysis because it may not be necessary.



(a) (b)

Figure 4.2 Examples of columns with damage state DS-1: flexural cracks: (a) from Vosooghi and Saiidi (2010); (b) from Li (2012)

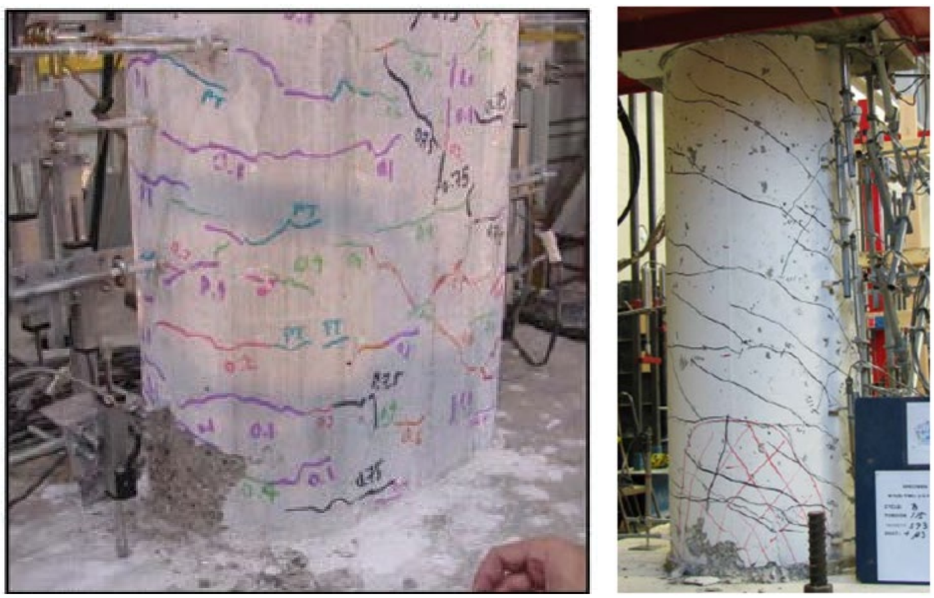
DS-2. Under damage state DS-2 minor spalling and shear cracks are observed on the column surface. Columns that show a damage condition classified as DS-2, if repaired, are subjected to repairs capable of minor improvement.



(a) (b)

Figure 4.3 Examples of columns with damage state DS-2: first spalling and shear cracks (a) from Vosooghi and Saiidi (2010); (b) from Li (2012)

DS-3. In damage state DS-3, a large number of cracks of significant width are present, and concrete spalling occurs in a relatively large region. Columns that show a damage condition classified as DS-3 are subjected to repairs capable of minor improvement.



(a) (b)

Figure 4.4 Examples of columns with damage state DS-3: extensive cracks and spalling (a) from Vosooghi and Saiidi (2010); (b) from Prakash (2009)

DS-4. Under damage state DS-4, the transverse reinforcement and possibly the longitudinal reinforcement are visible. This indicates a loss of unconfined concrete. Columns in this damage state may be subjected to repairs capable of moderate improvement.

(a) (b)

Figure 4.5 Examples of columns with damage state DS-4: transverse and logitudinal bars visible (a) from Voosoghi and Saiidi (2010); (b) from Li (2012)

DS-5. A column in damage state DS-5 is at risk of imminent failure. The damage also effects the confined core concrete. There may be signs of buckling of the longitudinal reinforcement. Columns that show a damage condition classified as DS-5 need to be intensively repaired with one or more repair systems capable of significant improvement.

(a) (b)

Figure 4.6 Examples of columns with damage state DS-5: imminent failure (a) from Vosooghi and Saiidi (2010); (b) from Li (2012)

DS-6. Under damage state DS-6, the confined core is compromised. Longitudinal bar buckling as well as longitudinal and transverse reinforcement fracture may be present. Repairing a column in this condition requires extensive use of different repair systems, and therefore, if possible, need for replacement of the element should be evaluated. In the case of a rapid repair, a lower performance level may be required, even with intensive repair.

(a) (b)

Figure 4.7 Examples of columns with damage state DS-6: column failure (a) fractured rebar; (b) local buckling (Li 2012)

Table 4.1 Damage classification and repair required

Damage level	Damage classification	Damage description	Repair
DS-0	None	Barely visible damage	No repair
DS-1	Minor	Flexural cracks	Possible repair
DS-2	Minor/moderate	Minor spalling and shear cracks	Possible/minimum repair
DS-3	Moderate	Large cracks and spalling	Minimum repair
DS-4	Moderate/serious	Visible reinforcement	Moderate repair
DS-5	Serious	Core damage	Intensive repair
DS-6	Critical	Buckling or fracture of the reinforcement	Intensive repair/ replacement

Chapter 5 Reinforced Concrete Bridge Column Repair Systems

5.1 Overview

The repair systems discussed in this guide include those that have been experimentally tested and reported in the literature for repairing RC bridge columns (see Chapter 2 and Appendix A). This section describes the different systems that have been used, organized first by different repair materials (Section 5.2), and then by different repair techniques available (Section 5.3). Pros and cons of the different repair materials and techniques are discussed. Figure 5.1 shows the repair materials and systems discussed in Sections 5.2 and 5.3. Finally, Section 5.4 provides a brief discussion of emerging systems that have been used to reinforce and/or repair RC members but that have not been tested on elements having the same scale as real bridge columns.

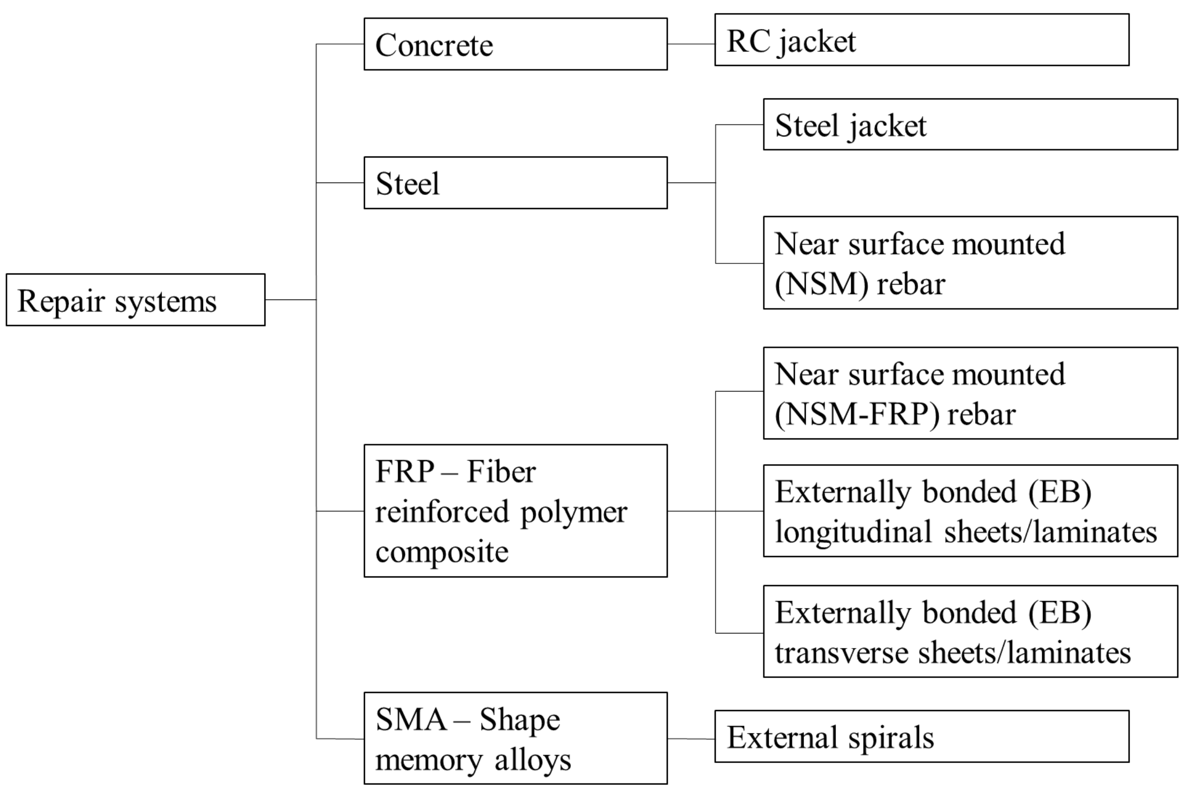


Figure 5.1 Repair systems for repairing damaged RC bridge columns

5.2 Repair System Primary Materials

5.2.1 Concrete

Concrete is the most compatible material for repairing RC members. Concrete (or grout or mortar) is widely used to repair minor spalling, and it has also been used to strengthen RC columns by enlarging the cross section with an RC jacket. The latter involves placing an additional layer of concrete around the existing member, together with longitudinal and/or transverse (i.e., stirrups) reinforcing bars, to improve the flexural and/or shear strength of the column. In this way, it is possible to maintain a high degree of compatibility between the repair system and the substrate in terms of deformation. Moreover, resistance to delamination and durability are better compared to other types of materials (Narayanan et al 2012). On the other hand, concrete has a relatively large unit weight and a relatively low strength-to-weight ratio, which can result in an increase in size and weight of the repaired member. These are significant disadvantages of this method since the stiffness and dynamic response of the column are altered. In addition, formwork is required in most applications. Another drawback is the hardening time required by conventional concrete, which makes it difficult to use in a rapid repair. This disadvantage can be overcome, where possible, by using a concrete (or grout or mortar) with a rapid setting time and/or with a higher strength than necessary such that it is able to gain sufficient strength after a short period of time.

5.2.2 Steel

Since the 1960s, steel has been used in different ways to repair RC bridge columns. Steel has good material performance and exhibits isotropic behavior, which make it easily adaptable to most configurations. Furthermore, steel can be used in both tension and compression. However, steel requires protection or constant treatment since it is subjected to oxidation, which effects its resistance over time. Steel has a large unit weight and a moderate strength-to-weight ratio, both of which are larger than that of concrete.

Traditional repair techniques, such as applying external steel hoops, spirals, straps, and continuous jacketing around the column cross section, have been used widely and effectively and have become common practice in many countries for increasing the strength and ductility of columns (El-Hacha and Mashrik 2012). Although hoops, spirals, and straps are relatively easy to handle and install, they do not apply a uniform confining pressure to the element due to the discontinuity of the reinforcement along the column length. Continuous steel jackets, on the other hand, can apply a uniform confinement along the column length and have the advantage of preventing spalling of the cover concrete, which is one of the main reasons for deterioration of bond and buckling of reinforcing bars in RC columns. However, continuous steel jackets have certain disadvantages, such as the addition of mass to the structure, although the increase in mass is typically less than that of RC jackets due to the lower jacket thickness required. Also, installation of steel elements, especially continuous jackets, can be labor intensive and sometimes difficult to implement on site.

Steel bars or plates can also be applied in the longitudinal (axial) direction of the column by bonding them to the surface, or by inserting them into grooves made in the concrete surface column and subsequently filling the groove with mortar or epoxy resin (Hasan et al. 2016). These applications are used to enhance the flexural strength of the column.

5.2.3 Fiber Reinforced Polymer (FRP) Composites

FRP composites are made from continuous fibers embedded in a polymer matrix. The function of the fibers is to carry tensile stresses, while the function of the matrix, generally an epoxy resin, is to wrap and protect the fibers and to transfer the stress from the member to the fibers.

Fiber types commonly used (or researched) in RC column repair applications include glass, carbon, aramid, or a combination of these. The fibers can be arranged in different configurations: uniaxial (with fibers oriented in one direction), biaxial (with fibers oriented in two orthogonal directions), or quadriaxial (with fibers oriented in various directions along the plane of the composite). Moreover, the composite can be installed with fibers in different directions in order to optimize the mechanical properties of the composite in the direction(s) required. The type of materials used and the arrangement of fibers determine the engineering design parameters such as the elastic modulus, tensile strength, and elongation at failure. However, the main parameter that characterizes the composite material is not the tensile strength, which is typically much larger than the strength of the element to be reinforced, but rather its elastic modulus. The higher the elastic modulus of the fibers, the higher the stiffness they provide.

FRP composites can be provided in the form of dry fiber sheets + matrix, precured laminates, or precured shapes. Dry fiber sheets are installed using a wet-layup procedure, which involves saturating the fiber sheets in the resin and applying them to the surface of the member. This allows for flexibility of shape and form. Precured laminates, where the fibers are pre-impregnated with resin using an industrial extrusion process called pultrusion, are generally more rigid, but some thin laminates can be bent to form a curve. In addition, precured rigid elements are available in the form of plates and bars. These elements can be installed onto the surface of the column, or can be inserted into grooves cut into the concrete surface, and are bonded to the element using epoxy resin. It should be noted that in externally bonded applications, surface treatment (i.e., roughening the surface) is necessary to achieve a good bond between the concrete and FRP composite, which is necessary to transfer stresses between the substrate to the composite.

The most important advantages of FRP composites, compared with traditional repair materials such as concrete and steel, are their light weight, small increase in mass and cross section, high strength-to-weight ratio, high-stiffness-to-weight ratio, ease and speed of application, durability, low maintenance due to the high resistance to corrosion agents and to weathering resistance, low thermal conductivity and thermal expansion, and high adaptability to different element shapes (ACI 440.2R 2017). Despite these advantages, there are certain drawbacks due mainly to the use of organic resins used to bind the fibers such as high cost of epoxy resin and of specialized workers for application, poor fire resistance, hazard for workers during installation, lack of vapor permeability, inability to apply onto wet surfaces or at temperature less of 10°C or more than 30°C, and susceptibility to ultraviolet (UV) radiation (ACI 440.2R 2017). Moreover, epoxy resin degrades quickly under high temperature, releasing toxic fumes.

5.2.4 Shape Memory Alloys (SMAs)

Shape memory alloys (SMAs) are materials capable of undergoing large inelastic deformation and regaining their undeformed shape when subjected to heating. This effect is observed when the SMA is deformed below the martensite finish temperature and then regains its original shape when heated above the austenite finish temperature. If the SMA is constrained and not able to fully recover its original shape, stress is generated in the material, which can provide a prestress to the strengthened member. It is therefore essential to use a SMA with martensite finish and austenite finish temperatures far from the environmental (in-service) temperature range.

SMAs are usually available in the form of strips, bars, and wires and are used to confine and/or reinforce damaged regions of RC columns. Due to the unique characteristic of SMAs, if they are arranged in spirals or hoops around the column cross section, they can generate an active confinement to the damaged region. The ability to provide active confinement is an advantage over other conventional systems that provide passive confinement only. On the other hand, SMAs are a relatively new material, and the high cost of SMAs limits their use. Furthermore, there is currently no information available about the durability of the material and the effect of degradation on its performance.

5.3 Repair System Techniques

5.3.1 RC Jackets

Most contractors that are capable of constructing RC structures are also able to construct RC jackets since this technique does not require specialized workers or equipment. Moreover, the general procedure used to design an RC column can be used to design an RC jacket. The number and diameter of the steel reinforcing bars as well the size of the jacket depend on the performance requirement for the structural element. Since this technique can also provide passive confinement to the column (if transverse reinforcement is provided in the jacket), it is possible to increase the effectiveness of the method by reducing or temporarily eliminating the axial load on the column before applying the RC jacket by raising the overlying deck, which requires the necessary construction equipment.

If the damage to the column is significant, it is important to restore the verticality of the column and remove the loose concrete within the plastic hinge region. Otherwise, the application of the method begins with preparing the surface of the substrate by removing all loose concrete cover and drilling holes to insert connectors to hold the longitudinal reinforcement (as needed). If the column exhibits damage at the footing, it may be necessary to anchor the longitudinal steel bars into the foundation. It is generally not required to roughen the concrete surface or use bonding agents (Julio et al. 2005). Formwork is placed to constrain the fresh concrete. Once the longitudinal and transverse reinforcement have been positioned, a low shrinkage concrete is usually used for the jacket and for replacing the concrete that was removed from the column. The reason for this is because concrete jacket shrinkage has been found to reduce the strength of the composite column, especially for columns with large axial loads (Lampropoulos and Dritsos 2011). If this method is used as a rapid repair, a high-early strength concrete should be considered in order to achieve the target strength in a short period of time.

- *Pros:* Can be used to improve the flexural, shear, and compressive strength of the column; relatively easy to design and implement; does not require specialized workers; wide range of applicability; materials are readily available.
- *Cons*: Increases the column mass and cross-sectional dimensions.

5.3.2 Steel Jackets

Steel jackets in the form of external steel hoops, spirals, straps, and continuous jacketing have been used for several decades. This technique can allow for increasing the flexural and shear strength of the column without significantly increasing the cross-sectional dimensions of the column. Since this technique provides passive confinement to the column, it is possible to increase the effectiveness of this technique by reducing or temporarily eliminating the load on the column by raising the overlying deck before applying the steel jacket, which requires the necessary construction equipment. Continuous thin light-gage steel jackets have also been used in combination with steel cables, where the jacket was used to distribute the compression stresses generated by cables that were wrapped around the column and then pretensioned in order to apply active confinement (see Figure 5.3). Continuous steel jackets can also be used as stay-in-place formwork, if replacement of concrete is needed.

If the damage to the column is significant, it is important to restore the verticality of the column and remove the loose concrete within the plastic hinge region. Otherwise, the jacket can be installed around the existing column. After installing the steel jacket, the space between the RC column and jacket is typically filled using an epoxy resin. This increases the bond between the concrete substrate and the steel jacket and provides a contact surface allowing immediate activation of the passive confinement.

Steel is vulnerable to environmental degradation. Therefore, steel jackets should be coated (e.g., painted).

- *Pros:* Can be used to improve the flexural, shear, and compressive strength of the column.
- *Cons:* Confining pressure is not uniform in the case of discontinuous reinforcement (e.g., hoops, spirals, straps); increases the column mass (in the case of continuous steel jackets); steel must be protected to avoid environmental degradation.

Figure 5.2 Column repaired with hybrid steel jacket (Fakhairifar et al 2015a)

5.3.3 Near Surface Mounted (NSM) Rebar

This method consists of inserting regular steel reinforcing bars into grooves that are cut into the surface of the column, and then filling the grooves with cement mortar or epoxy resin. This method can be used to increase or restore the flexural strength of the column.

If the damage to the column is significant, it is important to restore the verticality of the element and remove the loose concrete within the plastic hinge region. If the column exhibits damage at the footing, it may be necessary to anchor NSM rebars oriented in the column longitudinal (axial) direction into the foundation.

- *Pros:* Can be used to improve the flexural strength of the column; NSM rebar has the same properties as the internal reinforcement; NSM rebar contributes in both tension and compression zones; unlike FRP bars, steel rebar exhibits plastic behavior; does not increase the column mass or cross-sectional dimensions; materials are readily available.

- *Cons.* NSM rebars have a lower strength than NSM FRP bars; this technique is often coupled with other types of reinforcement.

5.3.4 Near Surface Mounted Fiber Reinforced Polymer (NSM FRP) Bars

This method consists of inserting FRP bars into grooves that are cut into the surface of the column, and then filling the grooves with epoxy resin. This method can be used to increase or restore the flexural strength of the column.

If the damage to the column is significant, it is important to restore the verticality of the element and remove the loose concrete within the plastic hinge region. If the column exhibits damage at the footing, it may be necessary to anchor NSM FRP bars oriented in the column longitudinal (axial) direction into the foundation.

- *Pros:* Can be used to improve flexural strength of the column; NSM FRP bars contribute in both tension and compression zones; NSM FRP bars have a higher ultimate strength than NSM rebar; does not increase the column mass or cross-sectional dimensions.
- *Cons:* This technique is often coupled with other types of reinforcement; FRP bars do not exhibit plastic behavior.

5.3.5 Externally Bonded (EB) Longitudinal Fiber Reinforced Polymer (FRP)

FRP composite with fibers oriented in the column longitudinal (axial) direction can be bonded to the surface of an RC column to restore its flexural strength. The FRP composite can be in the form of dry fiber sheets + matrix or precured laminates.

If the damage to the column is significant, it is important to restore the verticality of the column. Before applying the FRP composite, all defects and loose concrete should be removed and replaced with non-shrink mortar. Concrete cracks may or may not be injected using epoxy resin. The surface of the column should be roughened, cleaned (e.g., using compressed air), and dried completely before installing the FRP to ensure proper bonding (Faella et al. 2011). Certain FRP systems require the use of a primer that is applied to the concrete surface in order to enhance the bond between the concrete and FRP. Then for the case of dry fiber sheets, an initial layer of epoxy adhesive is applied to the concrete. The fiber sheets are soaked in the resin to impregnate the fibers. The saturated fiber sheets are then installed one at a time using a wet-layup procedure directly onto the surface of the column, and another layer of matrix is applied to cover the fibers. Using a special roller, the fibers are smoothed onto the surface of the column to eliminate air pockets and ensure proper impregnation of epoxy. The application procedure can be repeated several times depending on the number of fiber layers required. If the column exhibits damage at the footing, it may be necessary to anchor the FRP sheet to the foundation using a mechanical device or similar. However, design of the anchorage should be treated with caution, as limited success has been reported in the literature (He et al. 2013).

For the case of precured FRP laminates, an initial layer of epoxy adhesive is applied to the substrate, and the laminates are then bonded to the surface. If the column exhibits damage at the footing, it may be necessary to anchor the FRP laminates to the footing (e.g., by embedding them into the foundation, Yang et al. 2015b).

- *Pros:* Can be used to improve the flexural strength of the column; does not increase the column mass or cross-sectional dimensions; fast installation.

- *Cons:* Requires concrete surface preparation; EB FRP is generally less effective than NSM FRP since EB FRP contributes only in tension zone; requires specialty labor; materials may not be readily available.

5.3.6 Externally Bonded (EB) Transverse Fiber Reinforced Polymer (FRP)

The application of FRP with fibers wrapped around the column in the transverse direction and bonded to its surface can be used to increase the shear and torsional strength. Since this technique also provides confinement to the column, it is possible to increase the effectiveness of the technique by reducing or temporarily eliminating the axial load on the column before applying the FRP by raising the overlying deck. In addition, some researchers (e.g., Nesheli and Maguro 2006) have attempted to increase the effectiveness of the method by pre-tensioning the fiber wraps in order to apply active confinement (see Figure 5.4a). The FRP composite can be in the form of dry fiber sheets + matrix or thin precured laminates.

Before applying the FRP composite, all defects and loose concrete should be removed and replaced with non-shrink mortar. Concrete cracks may or may not be injected using epoxy resin. The surface of the column should be roughened, cleaned (e.g., using compressed air), and dried completely before installing the FRP sheets to ensure proper bonding (Faella et al. 2011). If the column has a non-circular cross section, it is essential to round the corners to prevent local failure of the fibers at the column corners (see Figure 5.4b). Certain FRP systems require the use of a primer that is applied to the concrete in order to enhance the bond between the concrete and FRP. Then for the case of dry fiber sheets, an initial layer of epoxy adhesive is applied to the concrete. The fiber sheets are soaked in the resin to impregnate the fibers. The saturated fiber sheets are then installed one at a time using a wet-layup process directly onto the surface of the column, and another layer of matrix is applied to cover the fibers. Using a special roller, the fibers are smoothed onto the surface of the member to eliminate air pockets and ensure proper impregnation of epoxy. The application procedure can be repeated several times depending on the number of fiber layers required.

For the case of thin precured FRP laminates, an initial layer of epoxy adhesive is applied to the concrete. Then the laminate is wrapped around the column and bonded to the surface. Continuous precured FRP laminates can also be used as a stay-in-place formwork, if replacement of concrete is needed (Yang et al. 2015b). This method can only be used on columns with circular or elliptical cross-sections.

(a)

(b)

Figure 5.3 (a) Prestressed FRP wraps (Nesheli and Meguro 2006), (b) FRP jacket (b). Note the rounded column corners at the jacket location.

- *Pros:* Can be used to improve the compressive, shear, and torsional strength of the column; does not increase the column mass or cross-sectional dimensions; fast installation.
- *Cons:* Requires concrete surface preparation including rounding corners; requires specialty labor; material may not be readily available.

5.3.7 Shape Memory Alloy (SMA) Spirals

This method consists of wrapping SMA wires around the RC column cross section in order to provide confinement (see Figure 5.5). After the material is heated, active confining pressure is provided to the column.

Before applying the SMA spirals, all loose concrete cover should be removed and replaced with non-shrink mortar. The SMA wires are stretched during their martensitic phase, and then they are wrapped around the column and anchored at the ends of the wire. In order to activate the shape memory effect, the wires are then heated above the austenite finish temperature. The restraint of the substrate prevents the SMA spirals from recovering their initial shape, thus generating a tensile stress in the wires that results in active confinement of the column.

This method can only be used on columns with circular or elliptical cross-section (Choi et al. 2015). In addition, the high cost of SMA material generally limits the application to the plastic hinge region only.

- *Pros:* Generate active confinement, does not increase the column mass or cross-sectional dimensions; fast installation.
- *Cons:* High cost of SMA material; material may not be readily available; can only be used on columns with circular or elliptical cross-section.

Figure 5.4 SMA active confinement (Jung et al. 2018)

5.4 Emerging Materials and Methods

This section describes several emerging materials and methods that have recently been investigated for repair or strengthening of RC members. These methods are not included in Sections 4.1-4.3 above since, at present, their application has not yet been widely studied or demonstrated on RC bridge columns and thus requires investigation.

5.4.1 Fiber Reinforced Polymer (FRP) Wires

FRP wires have been used to increase the strength, ductility, and stiffness of RC columns with circular cross sections. Choi et al. (2015) demonstrated the use of small GFRP wires (diameter of 1 mm) wound around severely damaged RC columns. The wires were pre-tensioned with a small force during the winding process, and no adhesive was used to bond the wires to the surface. Promising results were achieved in terms of strength, ductility, and stiffness. The use of this method is reserved for columns with circular or elliptical cross-sections.

Figure 5.5 RC column reinforced with externally wound FRP wires (Choi et al. 2015)

5.4.2 Externally Bonded (EB) Fabric Reinforced Cementitious Matrix (FRCM) Composites

Fabric (or fiber) reinforced cementitious matrix (FRCM) composites are a relatively new type of composite used for external strengthening applications, similar to EB FRP composites. They can be used to strengthen RC members in flexure, shear, and torsion, and can provide confinement to the member. The main difference between FRCM and FRP composites is the matrix, which for FRCM is an inorganic mortar instead of an organic resin for FRP. Use of an inorganic matrix results in increased compatibility with the substrate and decreased hazard for the installers. In addition, FRCM systems have higher temperature and fire resistance, better vapor permeability, and better UV radiation resistance than FRP systems, and they can be applied onto wet surfaces and at lower temperatures (ACI 549.4R 2013). Similar to FRP composites, other advantages are that they are light weight, non-invasive, and easy to install. On the other hand, the inorganic matrix does not fully penetrate and impregnate the dry fiber, making the adhesion between fibers and matrix the main drawback of FRCM technology. This characteristic influences the mechanical behavior and the performance of FRCM composite. As a result, most fabrics used in FRCM are in the form of bidirectional fiber sheets. Fiber types including carbon, glass, basalt, polyparaphenylene benzobisoxazole (PBO), and flax, have been investigated.

FRCM composites are installed using a wet layup process. Rounding of the column corners is required for noncircular cross sections if the fibers are wrapped around the member.

5.4.3 Externally Bonded (EB) Steel Reinforced Grout (SRG) Composites

The term SRG, steel reinforced grout, it is used to refer to an inorganic matrix composite with continuous steel fiber cords. The steel fiber cords are high strength twisted wire strands and are provided in unidirectional sheets. SRG can be used in external strengthening applications, similar to FRCM and FRP composites. They have been used to strengthen RC members in flexure, and shear, and can provide confinement to the member. Similar to FRCM composites, the use of an inorganic matrix can address some of the drawbacks associated with FRP composites such as increased compatibility with the substrate and decrease the hazard for the installers. In addition, SRG systems have higher temperature and fire resistance, better vapor permeability, and better UV radiation resistance than FRP systems, and they can be applied onto wet surfaces and at lower temperatures. Similar to FRP and FRCM composites, other advantages are that they are light weight, non-invasive, and easy to install.

SRG composite is installed using a wet layup process. The steel sheets have the advantage that they do not require rounding of column corners for noncircular cross sections (Sneed et al. 2018).

5.4.4 Externally Bonded (EB) Steel Reinforced Polymer (SRP) Composites

SRP composite is a composite system that combines continuous high strength steel fiber cords and a polymeric matrix. The steel fiber cords are high strength twisted wire strands and are provided in unidirectional sheets. SRP can be used in external strengthening applications, similar to FRP and SRG composites. They have been used to strengthen RC members in flexure, and shear, and can provide confinement to the member. Similar to FRP composites, drawbacks are due mainly to the use of organic resins used to bind the fibers such as high cost of epoxy resin and of specialized workers for application, poor fire resistance, hazard for workers during installation, lack of vapor permeability, inability to apply onto wet surfaces or at high/low temperatures, and susceptibility to ultraviolet (UV) radiation.

SRP composite is installed using a wet layup process. The steel sheets have the advantage that they do not require rounding of column corners for noncircular cross sections.

Chapter 6 Repair System Selection

6.1 Summary

The previous sections regarding RC bridge column repair systems and damage classification are preparatory for determining the most suitable rapid repair technique. Since it is possible to reach the same result with different strategies, and it is not possible to provide targeted suggestions without knowing the characteristics and vulnerabilities of the bridge, the type and level of damage sustained by the columns, the skills of the available workforce, and the availability of repair materials after the seismic event, the considerations formulated in this section are of a general nature.

Table 6.1 summarizes the suitability of different repair systems for a given damage type and severity to aid in the selection. The effectiveness of the repair system, the time required to carry out the repair, and the cost of the implementation were evaluated for each repair system considering the type and level of damage. The parameter *Effectiveness of the system* reflects a judgement on the appropriateness of the repair system to restore or enhance the performance of an RC bridge column for a given damage type, and for a given damage severity. The effectiveness of the repair system was determined based on analysis of the results of the experimental tests reported in Appendix A. The *Time* parameter takes into account the speed of application, as well as the time required to achieve a target strength of material, which are important for a rapid repair. The third parameter is the *Cost,* since a complete evaluation of the performance of any repair technique cannot be separated from a cost estimation. This parameter considers the cost of the repair material relative to other repair materials.

6.2 Discussion

This section discusses the values given in Table 6.1 for each repair system.

RC Jackets. RC jacketing has proven to be a robust method to repair or to increase the strength of RC bridge columns. It shows good performance in repairing columns with flexural, shear, and torsional damage, and excellent performance in repairing compression damaged columns. The results of tests available in literature show that RC jackets are capable of enhancing the strength, ductility, and stiffness of damaged columns without fractured reinforcing bars (i.e., damage states DS-1 to DS-5). The results of columns with fractured reinforcing bars (i.e., damage state DS-6) repaired with RC jackets are inconsistent, but nevertheless inferior (e.g., Lehman et al. 2001). Since the implementation of this method is quite laborious and requires a minimum jacket thickness, other methods are more appropriate for slightly damaged columns (i.e., damage states DS-1 and DS-2).

Steel Jackets. Steel jackets, since they are adaptable to all conditions, can be effectively designed to withstand flexural, shear, and torsional actions. The high strength of the material typically results in a relatively small thickness required but makes longitudinal elements susceptible to local buckling if compressed. Increases in the column compressive strength, however, can be achieved by confinement effect. Results of tests reported in Appendix A show that steel jackets can enhance the strength, ductility, and stiffness of damaged columns without fractured reinforcing bars (i.e., damage states DS-1 to DS-5). No results have been reported for DS-6 damaged columns. Application of steel jackets is labor intensive, therefore it may not be the best solution for slightly damaged columns (i.e., damage states DS-1 and DS-2). Columns that have failed (i.e., damage state DS-6) may require considerable use of steel to restore the original strength, therefore the use of lighter material may be preferred.

NSM Rebar. The use of NSM (steel) rebar is usually focused on restoring the flexural capacity of the RC column. Since longitudinal steel bars are inserted into the column, the shear, torsional, and compression capacity can also be improved, although improvements are generally minimal. Cyclic lateral loading tests conducted by Hasan et al. (2016) showed that NSM rebar can be very effective to enhance the flexural strength, ductility, and stiffness of a damaged column without fractured reinforcing bars (i.e., damage states DS-1 to DS-5). No results have been reported for DS-6 damaged columns. Since cutting the grooves in the concrete surface is labor intensive, the method is recommended for columns with moderate damage (i.e., damage states DS-3 to DS-5). Columns that have already failed (i.e., damage state DS-6) may require a considerable amount of reinforcing bars to restore their original strength, and therefore alternative methods are preferred.

NSM FRP Bars. NSM FRP bars are effective in restoring the flexural capacity of RC columns. Since FRP bars are inserted in the column, the shear, torsional, and compression capacity can also be improved, although improvements are generally minimal. Since cutting the grooves in the concrete is labor intensive, this method is recommended for columns with moderate damage (i.e., damage states DS-3 to DS-5). Considering that FRP bars have a higher strength than conventional steel rebar, the number of bars (and grooves required) can be reduced by using NSM FRP. No results have been reported for DS-6 damaged columns; however such columns may require a considerable number of bars to restore their original strength, and therefore alternative systems are preferred.

EB Longitudinal FRP. EB longitudinal FRP reinforcement can be designed to withstand bending actions. Their contribution to shear and torsional strength is minor unless applied onto the appropriate faces and properly anchored. This method is not considered to contribute to the compressive strength since the fibers act in tension only. In experimental studies, this method is typically used in combination with other techniques, such as EB transverse FRP reinforcement (jackets) installed outside the EB-FRP longitudinal reinforcement, it is difficult to evaluate its effectiveness alone. Anchorage of the reinforcement remains one of the major limitations of this method. In fact, it is ineffective near the extremities of the column, where plastic hinges are usually formed, unless adequately anchored. Different types of anchoring schemes have been attempted, but it is difficult to evaluate their effectiveness. On the other hand, the high strength of the material and ease of use make this technique suitable for all levels of damage (i.e., damage states DS-1 to DS-6).

EB Transverse FRP. EB transverse FRP reinforcement can effectively enhance the shear, torsional, and compression strength of damaged RC bridge columns. The contribution to the bending strength is minimal and is generally due to confinement effect, thereby increasing the ductility of the element. Many studies have been conducted on use of this method to repair RC columns without fractured bars with good results: strength, ductility, and stiffness are typically restored, and in many cases they are also enhanced. The effectiveness of the method for columns with fractured bars is more difficult to evaluate, since in this case the system has been used in combination with other methods. The results of tests in Appendix A are inconsistent, and indicate that the strength, ductility, and stiffness of columns repaired with this method can be lower or higher than the original value. The high strength of material and ease of use makes this technique suitable for all levels of damage (i.e., damage states DS-1 to DS-6).

SMA Wires. SMA wires have been proven to be a valid solution to enhance the shear, torsional, and compression strength of RC bridge columns. Test conducted on RC damaged columns without fractured bars (i.e., damage states DS-1 to DS-5) show that this method is capable of enhancing the strength, ductility, and stiffness of the element. Tests on RC damaged columns with fractured bars (i.e., damage state DS-6) showed that this method is capable of restoring the strength of the element and enhancing ductility and stiffness. The high cost of the raw material limits the use of this technique to columns with a high degree of damage (i.e., DS-5 to DS-6).

Finally, the methods described above can be combined to optimize the performance of the repair.

Table 6.1 Selection of rapid repair system

	Type and severity of damage	RC jacket	Steel jacket	NSM steel rebar	NSM FRP bar	EB-FRP longitudinal composite	EB-FRP transverse composite	SMA spiral
Damage type	Flexural	Very effective; Time-consuming; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-consuming; Cost-intensive	Very effective; Time-consuming; Cost-intensive	Very effective; Time-saving; Cost-effective	Effective; Time-saving; Cost-intensive	Effective; Time-saving; Cost-intensive
	Shear	Very effective; Time-consuming; Cost-effective	Very effective; Time-saving; Cost-effective	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-saving; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	Torsion	Very effective; Time-consuming; Cost-effective	Very effective; Time-saving; Cost-effective	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-saving; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	Compression	Very effective; Time-consuming; Cost-effective	Effective; Time-saving; Cost-effective	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-saving; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
Damage severity	DS-1	Very effective; Time-consuming; Cost-intensive	Effective; Time-saving; Cost-effective	Effective; Time-consuming; Cost-intensive	Effective; Time-consuming; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	DS-2	Very effective; Time-consuming; Cost-intensive	Effective; Time-saving; Cost-effective	Effective; Time-consuming; Cost-intensive	Effective; Time-consuming; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	DS-3	Very effective; Time-consuming; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-consuming; Cost-intensive	Very effective; Time-consuming; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	DS-4	Very effective; Time-consuming; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-consuming; Cost-intensive	Very effective; Time-consuming; Cost-intensive	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-intensive
	DS-5	Very effective; Time-consuming; Cost-effective	Effective; Time-saving; Cost-effective	Effective; Time-consuming; Cost-intensive	Very effective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Slightly effective or ineffective; Time-saving; Cost-intensive
	DS-6	Slightly effective or ineffective; Time-consuming; Cost-effective	Effective; Time-saving; Cost-effective	Effective; Time-consuming; Cost-intensive	Very effective; Time-consuming; Cost-intensive	Slightly effective or ineffective; Time-saving; Cost-effective	Very effective; Time-saving; Cost-effective	Slightly effective or ineffective; Time-saving; Cost-intensive

Legend

Effectiveness of the system	Time	Cost
Very effective	Time-saving	Cost-effective
Effective		
Slightly effective or ineffective	Time-consuming	Cost-intensive

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Appendix A Summary of Studies Reported in Literature

Table A.1 Summary of studies on repair of RC bridge columns without fractured longitudinal bars

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Loading Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
Bett et al. (1988)	2/3	Square (Sub-Standard)	7%	Cyclic lateral loading	Badly damaged with brittle shear failure	Installed RC jacket with closely-spaced ties and cross-ties connected to mid-face longitudinal bars	Enhanced	Not reported	Enhanced
Chai et al. (1991)	2/5	Circular (Sub-Standard)	17%	Cyclic lateral loading	Bond failure of the spliced reinforcement in plastic hinge region	Removed loose concrete; installed steel jacket; installed external pre-stressing on footing	Restored	Enhanced	Not reported
Priestley et al. (1993)	2/5	Circular (Sub-Standard)	18%	Cyclic lateral loading	Open diagonal cracks; spalled concrete cover	Removed loose concrete; patched with mortar; applied full height GFRP jacket; injected epoxy through the jacket	Restored	Enhanced	Restored
Saadatmanesh et al. (1997)	1/5	Circular & Rectangular (Sub-Standard)	-	Cyclic lateral loading	Debonded starter bars; spalled and crushed concrete; buckled longitudinal bars; separation of the main bars from core concrete	Replaced spalled concrete; installed GFRP strap around failure zone; pressurized gap between GFRP and column with epoxy grout	Restored	Restored	Lower
Fukuyama et al. (2000)	1/2	Square	30%	Cyclic lateral loading	Heavily damaged with crushed core concrete; buckled longitudinal bars	Installed RC jacket with welded wire shear reinforcement	Enhanced	Enhanced	Enhanced
						Installed steel plates around column; grouted between steel plates and concrete with added longitudinal bars	Enhanced	Enhanced	Enhanced
Sheikh & Yau (2002)	-	Circular	54%	Cyclic lateral loading	Flexural cracks; spalled cover concrete; yielded longitudinal and spiral reinforcement	Removed loose concrete; patched concrete; installed EB transverse FRP (either CFRP or GFRP)	Enhanced	Enhanced	Not reported
Li & Sung (2003)	2/5	Circular	15%	Cyclic lateral loading	Shear failure at low displacement ductility	Replaced damaged concrete with non-shrinkage mortar; injected epoxy into cracks; installed EB transverse CFRP	Enhanced	Enhanced	Not reported
Chang et al. (2004)	2/5	Rectangular	-	Cyclic lateral loading	Flexural failure in the plastic hinge zone	Removed damaged concrete cover; placed non-shrink mortar; installed EB transverse CFRP	Restored	Restored	Lower

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Loading Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
Nesheli & Meguro (2006)	1/2	Square	20%	Cyclic lateral loading	Brittle shear failure with large diagonal cracks	Repaired damaged concrete; wrapped EB transverse carbon fiber belts; pretensioned fiber belts	Lower	1 Lower, 1 Not reported	Lower
Belarbi et al. (2008)	1/2	Circular	7%	Combined cyclic lateral loading and torsion	Spalled cover concrete; crushed core concrete; buckled longitudinal reinforcing bars	Removed damaged concrete; placed low viscosity grout; applied EB longitudinal CFRP with mechanical anchorage, applied EB transverse CFRP	Enhanced	Not reported	Not reported
Vosooghi et al. (2008)	1/4	Circular	-	Shake table testing and additional static loading	Visible bars; initial buckling in longitudinal bars; initial concrete core damage	Removed loose concrete; injected epoxy into cracks; patched concrete with quickset grout; wrapped with EB CFRP	Restored	Restored	Lower
Vosooghi & Saiidi (2009)	1/3	Circular	-	Shake table testing	Visible spirals and longitudinal bars; buckled longitudinal bars; concrete core damage	Replaced loose concrete with non-shrink mortar; injected epoxy into cracks; wrapped with EB CFRP	Restored	Restored	Lower
Elsouri and Harajli (2011)	Full	Rectangular (Sub-Standard)	-	Cyclic lateral loading	Bond failure of the starter bars; concrete damaged in the splice zone	Replaced concrete; installed steel ties and/or FRP wraps	Enhanced	Enhanced	Not reported
He et al. (2013a)	1/2	Square	7%	Cyclic lateral loading and torsion	Spalled cover concrete; crushed core concrete; buckled longitudinal bars; yielded and/or opened ties	Removed and replaced loose concrete; applied EB longitudinal CFRP sheets with anchorage system; installed EB transverse CFRP	Restored	Restored	Lower
Rutledge et al. (2013)	-	Circular	6%	*Cyclic lateral loading	Buckled longitudinal bars	Relocated the plastic hinge by using EB CFRP in longitudinal direction with CFRP anchors; installed EB transverse CFRP	Enhanced	Enhanced	Restored
Shin & Andrawes (2011)	1/3	Circular	5%	Cyclic lateral loading	Crushed and cracked concrete; buckled longitudinal bars	Removed loose concrete; straightened, cut, and coupled buckled bars; injected epoxy into cracks; applied mortar; wrapped pre-strained SMA	Enhanced (in one direction)	Enhanced (in one direction)	Enhanced (in one direction)

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Loading Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
He et al. (2014)	1/2	Square	7%	Cyclic torsional moment	Spalled cover concrete; crushed core concrete; buckled longitudinal reinforcing bars	Replaced damaged concrete with repair mortar; applied CFRP sheets in longitudinal and transverse directions	Restored	Enhanced	Restored
Fakharifar et al. (2015b)	Full	Circular	Not reported	Cyclic lateral loading	Crushed core concrete; lap splice failure of longitudinal bars	Replaced damaged concrete with grout; applied hybrid repair jacket (cold-formed steel sheet with prestressing steel strands)	Enhanced	Enhanced	Lower
Ma & Li (2015)	-	Square	30% & 40%	Cyclic lateral loading	Flexural failure in the plastic hinge zone	Removed damaged concrete cover; injected epoxy; cast early strength mortar; wrapped with BFRP	Lower	Enhanced	Lower
Rodrigues et al. (2015a)	-	Rectangular	10%	Biaxial cyclic lateral loading	Cracked concrete; yielded and buckled longitudinal bars	Removed damaged concrete; aligned and replaced longitudinal reinforcement bars; added additional welded bars to ensure lap splice; replaced and increased transverse reinforcement; applied a pre-mixed microconcrete; added CFRP sheet jacket	Enhanced	Lower	Lower
						Removed damaged concrete; aligned and replaced longitudinal reinforcement bars; added additional welded bars to ensure lap splice; replaced and increased transverse reinforcement; applied a pre-mixed microconcrete; added CFRP plate jacket	Enhanced	Lower	Lower
						Removed damaged concrete; aligned and replaced longitudinal reinforcement bars; added additional welded bars to ensure lap splice; replaced and increased transverse reinforcement; applied a pre-mixed microconcrete; added steel plate jacket	Enhanced	Lower	Lower

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Loading Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
Hasan et al. (2016)	1/2	Rectangular	-	Cyclic lateral loading	Cracked concrete in the flexural zone	Cut grooves in face of column, installed NSM reinforcing bar	Enhanced	Enhanced	Enhanced
						Installed EB longitudinal CFRP laminate with CFRP laminate wrap at ends	Restored	Enhanced	Enhanced
Jiang et al. (2016)	1/4	Circular	12%	Cyclic lateral loading	Cracked and spalled cover concrete; yielded and buckled longitudinal bars	Removed loose concrete; drilled holes in footing and chiseled grooves along column; injected holes and grooves with epoxy; installed NSM-BFRP bars in holes and grooves; placed repair concrete in plastic hinge region; installed BFRP sheets	Restored	Restored	Restored
Li et al. (2017)	-	Square	10%	Cyclic lateral loading	Cracked and spalled cover concrete; flexural failure	Removed damaged concrete in column and footing; cast high-performance fiber-reinforced cementitious composite (HPFRCC) to restore original dimensions	Enhanced	Enhanced	Restored
He et al. (2018)	-	Square	23%	Cyclic lateral loading	Crushed concrete; yielded longitudinal bars	Installed steel jacket	Enhanced	Enhanced	Enhanced
Jung et al. (2018)	1/6	Circular	5%	Shake table testing	Severe concrete cover spalling	Removed loose concrete from the damaged region; applied rapid set mortar grout; wrapped SMA spirals around the plastic hinge zone	Enhanced	Enhanced	Not reported
Chen et al. (2018)	1/8	Rectangular	1.4%	Cyclic lateral loading	Flexural failure at pier-footing region	Cleared and glued the interface; wrapped CFRP (longitudinal and transverse); drilled and assembled the anchored steel bar; concrete casting	Enhanced	Enhanced	Not reported

Table A.2 Summary of studies on repair of RC bridge columns with fractured longitudinal bars

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Load Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
Lehman et al. (2001)	1/3	Circular	7%	Cyclic lateral loading	Buckled longitudinal bars; fractured longitudinal and spiral bars	Severed damaged region; spliced new longitudinal bars connected to the footing and column with mechanical couplers; placed new spirals; cast new concrete	Enhanced	Enhanced	Restored
						Installed RC jacket reinforced with headed longitudinal bars (relocation of the plastic hinge)	Restored	Lower	Restored
						Severed all existing bars in the plastic hinge to maintain plastic hinge location; provided RC jacket with replacement bars	Lower	Lower	Not reported
Cheng et al. (2003)	Full	Hollow circular	10%	Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Repaired concrete; repaired fractured longitudinal bars with dog-bone welded steel plate; replaced transverse bar; installed EB transverse FRP	Lower	Lower	Not reported
Saiidi & Cheng (2004)	2/5	Flared	16%	Cyclic lateral loading	Fractured longitudinal bars; crushed concrete	Repaired concrete; installed EB longitudinal CFRP and GFRP; installed EB transverse GFRP	Restored or enhanced	Lower	Not reported
Shin and Andrawes (2011)	1/3	circular	5%	Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Repaired concrete; reconnected longitudinal bars with mechanical couplers; installed SMA wrap	Restored or enhanced	Enhanced	Enhanced
He et al. (2013a&b)	1/2	Square	7%	Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Repaired concrete; installed EB longitudinal CFRP with anchorage system; installed EB transverse CFRP	Lower	Lower	Lower
Rutledge et al. (2013)	-	Circular	6%	*Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Repaired concrete; relocated the plastic hinge using EB longitudinal CFRP with CFRP anchors, installed EB transverse CFRP	Enhanced	Restored	Restored

Reference	Scale	Cross-Section Shape	Axial Load Index	Lateral Load Type	Description of Apparent Damage/Failure	Repair Summary	Strength	Displacement Ductility	Stiffness
Yang et al. (2015a)	1/2	Oval	7%	Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Removed concrete; severed longitudinal bars in plastic hinge region; coupled longitudinal bar segments onto existing bars; replaced concrete; installed EB transverse CFRP	Restored	1 Restored, 1 Not determined	Lower
Yang et al. (2015b)	1/2	Oval	7%	Cyclic lateral loading	Buckled and fractured longitudinal bars; crushed concrete	Repaired concrete; installed EB longitudinal CFRP laminate strips embedded into footing; installed transverse CFRP laminate embedded into footing	Restored	Restored	Restored
Parks et al. (2016)	1/2	Octagonal	6%	Cyclic lateral loading	Pulled-out and fractured longitudinal bars; crushed concrete	Drilled holes into footing; installed headed bars into holes; applied prefabricated CFRP shell around plasti hinge region; filled CFRP shell with nonshrink or expansive concrete	Restored	Restored	Restored
Wu & Pantelides (2017)	-	Octagonal	6%	Cyclic lateral loading	Buckled or fractured longitudinal bars; crushed concrete	Drilled holes into footing; installed headed bars into holes;; applied prefabricated CFRP shell around plastic hinge region; filled CFRP shell with nonshrink concrete with expansive cement, sealed the CFRP shell	Restored	Restored	Enhanced