Chapter 7: Emergency Repairs

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7-1 Introduction

After completion of bridge construction, bridge repair is required not only as maintenance work for wear and tear associated with aging and normal usage, but also as emergency work. In accordance with Caltrans Emergency Work Guidance[1] (found within Division of Construction – Emergency Contracting[1]), California Public Contract Code (PCC), Section 1102, defines an emergency as follows:

> "'Emergency,' as used in this code, means a sudden, unexpected occurrence that poses a clear and imminent danger, requiring immediate action to prevent or mitigate the loss or impairment of life, health, property, or essential public services."

It should be noted that emergency work is not always due to accidents and natural disasters such as earthquakes. Emergency repairs could also be needed when normal maintenance work is not performed properly or in a timely manner (typically due to delayed discovery of issues that affect the structure's integrity). For example, if a problem with a bearing pad is not detected and repaired in a timely fashion, this could lead to complete failure of the bearing; to avoid the potential of a bridge collapse, the bearing pads might be repaired as emergency work. This chapter aims to provide a basic understanding of emergency work to repair common bridge damage and offer references for more detailed information. It is important to realize that while the bridge work discussed in this section is focused on emergency repairs, the techniques and methods discussed in this section may also be used for other types of bridge rehabilitation, including maintenance, strengthening, and widening.

7-1.01 Background

Bridges may be damaged by high-load hits, fire, or earthquakes. In a research paper titled *Overheight Vehicle Collisions with Highway Bridges*, Fu, Burhouse, and Chang (2004) reported that, based on a nationwide survey, 62 percent of all responding states considered overheight collisions to be a significant problem. The paper further stated that in a study in Virginia (Hilton 1973), overheight vehicles were listed as the leading cause of damage (81 percent) to prestressed concrete bridges, and in a similar report (Shanafelt & Horn, 1984) they accounted for 94 percent of damage to steel bridges. Similarly, in National Cooperative Highway Research Program (NCHRP) Report 226 (NCHRP, 1980), an average incident rate of 0.72 percent per year was reported for damage due to overhead bridge impacts and fire damage. It also indicated that collisions with bridges are often not reported at the time of the accident; as a result, bridges are often susceptible to additional damage beyond the initial impact due to various elements such as rusting or reduction of load carrying capacity. While a bridge damaged in an accident or natural disaster may require complete or partial structure

[1] Caltrans internal use only

replacement, this approach is very costly and may have major traffic impacts. Repair or retrofit of bridge damage is often the superior alternative that substantially mitigates the cost and traffic impacts to the bridge. In this chapter, bridge damage assessment and repair methods are discussed for both concrete bridges and steel bridges. The material is presented in two sections. The first section covers repair methods for concrete bridges, while the second section covers steel bridges.

7-1.02 Structure Construction's Role in Emergency Response

As stated in the Structure Construction (SC) *Emergency Operations Plan Supplement*[1]:

> "Our role as SC engineers is to assist Structure Maintenance & Investigations (SM&I) engineers perform preliminary damage assessment. Per the Caltrans *DES Emergency Operations Plan Supplement*[1]and Deputy Directive 109[1], in the case of an emergency involving structures, the Division of Maintenance, SM&I, is the lead coordinator for DES support. At such times, DES functional units will provide support as requested by the District Emergency Response Manager and SM&I."

While SC staff assist in the initial assessment of a bridge, the Office of Structure Maintenance & Investigations (SM&I)[1] and the Office of Bridge Design (BD) provide plans and specifications to repair the assessed-damage. SC's primary responsibility will be to administer the emergency contract created by the Director's Order. A Director's Order is a formal document signed by the Caltrans director or a delegated deputy director that allocates funding and grants authority to a district to accelerate a project by setting aside the State Contract Act requirements for project advertising, bidding and award processes for public works contracts. Director's orders are critical to Caltrans' ability to respond quickly and effectively to emergencies on the State Highway System.

Approval authority to set aside normal advertising, bidding, and awarding procedures has been delegated by the Caltrans director to district directors for district directors' orders up to the State Highway Operations Protection Program (SHOPP) Minor B project cost limit. More information about the Director's Order can be obtained at the Maintenance Division's Major Damage Restoration[1] website.

The information presented in this chapter is focused on providing an understanding of common repair methods to aid SC personnel in performing their role in administering emergency construction contracts. As such, design topics such as design analysis, detailed bridge assessment method, and maintenance topics are not presented.

7-1.03 Damage Prevention Repair Work

There is an expression that an ounce of prevention is worth a pound of cure. Similarly, in addition to emergency repairs after a vehicular collision or fire damage to a bridge,

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preventive repair work is often required to improve conditions which can prevent or lower the chances of a future collision, and/or to construct bridge improvements to minimize the potential for future damage. To minimize the chances of a collision, some of the repair work in the past has included improving lighting at bridge tunnels, increasing the bridge vertical clearance by lowering the roadway surface below the bridge or raising the bridge superstructure, rerouting of truck traffic, and improved vertical clearance signage or a warning system. Furthermore, the installation of additional full-height intermediate diaphragms can aid in helping to minimize damage due to collision (NCHRP, 2012).

7-1.04 Field Investigation, Damage Assessment, and Repair Plans

Per Caltrans *SM&I Emergency Response Plan*[1], by the time the Area Bridge Maintenance Engineer (ABME) arrives, maintenance crews or SC personnel may already be on site performing damage assessment. The initial inspection is to assess the safety and operational status of a bridge. After the inspection, SC staff needs to prepare a damage inspection report. SC has developed an *SC Emergency Operations Plan Supplement*[1] that provides inspection guidelines and instructions for preparing damage inspection reports. After the initial safety/capacity inspection, in-depth inspections and reports are performed by the ABME, which may be used in developing the repair project. Depending on the size and complexity of the repair project, the design of the repairs may be handled by SM&I field personnel, by the SM&I design section, or by the appropriate Division of Engineering Services (DES) Bridge Design section. Note that in this chapter, the design professional responsible for the repair plans will be referred to as the Designer. Repairs will be done by maintenance forces, emergency contracts, regular contracts, or change orders for bridges within the limits of ongoing construction contracts. Bridge repairs that are performed under contracts administered by SC will also be looked at. For further details on field investigation, damage assessment, inspection reporting, and creation of the repair plans, please refer to the *SM&I Emergency Response Plan*.

SC employees need to be familiar with the *SC Emergency Operations Plan Supplement* (EOP). Note that in the past, Appendices C and D of this supplement constituted the now obsolete *SC Emergency Response Handbook*. The SC EOP outlines SC personnel responsibilities, damage assessment guidelines, and resource information such as SC priorities, Roles and Responsibilities, Bridge Inspection Guidelines, Communication Options, etc. The SC EOP can be downloaded from the SC website, under the "Safety[1]" tab. It is also recommended to be familiar with the *SM&I Emergency Response Plan*.

[1] Caltrans internal use only

7-2 Part One: Repair Methods for Concrete Bridges

7-2.01 Development of Guidelines for Repair Methods of Concrete Bridge Members

In discussing the repair method of concrete structures after vehicular impact, fire, or other emergency events, the National Cooperative Highway Research Program (NCHRP) Report 226, titled *Damage Evaluation and Repair Methods for Prestressed Concrete Bridge Members,* and NCHRP Report 280, *Guidelines for Evaluation and Repair of Prestressed Concrete Bridge Members,* are the main sources of information in this section. This section simply aims to provide a brief introduction to repairs discussed in these papers. For detailed information, readers are referred to the above reports; although dated 1980 and 1985 respectively, these reports can prove to be a valuable resource and may be located through an online search.

7-2.02 Classification of Bridge Damage

NCHRP Report 226 (NCHRP, 1980) classifies bridge damage by severity and provides suitable repair methods. Note that although the report is focused primarily on repairs to longitudinal girders due to collision, the intent of the information will be extrapolated to include substructure elements and seismic events. Damage is classified as follows:

1. **Minor Damage**- Damage only to concrete portions of bridge elements such as girders, barriers, or columns. This damage may consist of extensive spalled areas on the girder, barrier, or column, but there shall be no exposed reinforcing bars or prestressing strands. Minor damage cracks are too small for epoxy injection. Cracks emanating from spalled areas shall be less than 3 mils in width. Caltrans *Standard Specifications* Section 60-3.05C(3), *Existing Structures – Structure Rehabilitation – Repairing Structures – Epoxy Crack Injection – Construction*, uses a minimum width of 8 mils for epoxy injection.

   Minor concrete damage and its repair were discussed in Chapter 5, *Concrete Structure Repair and Rehabilitation*, of this manual.

2. **Moderate Damage**- Damage to concrete portions of bridge elements such as girders or columns. This damage may consist of extensive spalled areas, exposing prestressing strands. Cracks emanating from spalled areas may be wider than 8 mils, but they shall be closed below the surface damage. There shall be no severed or visibly deformed prestressing strands or main reinforcing bars.

   Moderate concrete damage and its repair were discussed in Chapter 5, *Concrete Structure Repair and Rehabilitation*, of this manual.

3. **Severe Damage**- Severe damage is when the load-carrying capacity of the bridge element has been reduced. This damage may consist of one or more of the following:
   a. Cracks extending across the width of the bottom flange of a precast (PC) prestressed (PS) girder, but closed below the surface damage.
   b. Major or total loss of concrete section in the bottom flange of a girder
   c. Major loss of concrete section in the web of a girder, but not occurring at the same location as loss of concrete section in the bottom flange.
   d. Major loss (concrete loss extending into the core of a column beyond spiral, hoops and/or main reinforcement) of concrete section in a column.
   e. Severed reinforcing steel or prestressing tendons that are visibly deformed.
   f. In beams, horizontal misalignment of the bottom flange in excess of the allowed standard tolerance, and vertical misalignment (i.e., “tilt” or “off plumb”) not exceeding the normal allowable.

   Severe concrete damage and its repair were also discussed in Chapter 5, *Concrete Structure Repair and Rehabilitation*, of this manual. However, in that chapter, the discussion was limited to repairing the damage to the concrete portion only. As stated above, in severe damage, the main reinforcing steel and prestressing tendon could also be damaged. In this chapter, severe damage will be further discussed to explain the work needed for repairing any severed reinforcing steel or prestressing tendons.

4. **Critical Damage**- Critical damage is when the bridge or bridge components (such as a girder or column) need to be replaced instead of repaired. This damage consists of one or more of the following:
   a. In a PC girder, cracks extend across the bottom flange and/or in the web directly above the damaged bottom flange, that are not closed below the surface damage (this indicates that the prestressing strands have exceeded their yield strength).
   b. In beams, abrupt lateral offset as measured along the bottom flange or lateral distortion of exposed prestressing strands or reinforcement. (This also indicates that the prestressing strands or reinforcement have exceeded their yield strength.)
   c. The loss of prestressing force or reinforcement in the beam is so extensive that repairs cannot be made based on the load rating analysis.
   d. Vertical misalignment in excess of the normal allowable.
   e. Longitudinal cracks at the interface of the web and the top flange that are not substantially closed below the surface damage. (This indicates permanent deformation of stirrups)
   f. Buckling or collapse of bridge column rebar. Note that although this was not in the referenced report, SM&I and Bridge Design reviewed and provided concurrence on this item.

7-2.03 Rationale/Criteria Used for Selection of Repair Methods

Bridge damage is repaired per plans developed by BD or SM&I Design when the repair work is performed under a contract administered by SC. To develop the plans, the rationale/criteria used by Design for the repair method selected include the following items:

1. Restoration of load capacity
2. Durability of repair
3. Cost of repair
4. Time required for repairs /Inconvenience to the public
5. Aesthetics.

Repair methods often don’t perform equally well for all criteria and a decision needs to be made to prioritize and weigh competing criteria before a repair method is selected. For example, in repairing a broken prestressing strand, one repair method might be cost-efficient and quick to perform but aesthetically not very pleasing; in comparison, another method might provide very good aesthetics but be very costly. As a result, a decision needs to be made to prioritize and weigh the criteria and select the best repair method. In this chapter, concrete repair methods commonly used in contract plans for each class of bridge damage will be described, and field activities that SC staff perform for the delivery of the repair project will be explained. However, this discussion will be provided in two separate sections. The first section will provide the conventional concrete repair methods that have been utilized traditionally for many decades. The second section will provide fiber-reinforced polymer concrete repair and retrofitting that has been in use for roughly 30 years, emerging in the early to mid-1990s on Caltrans projects.

7-2.04 Conventional Concrete Repair

In this section, conventional concrete repair methods employed in Caltrans projects will be discussed, aligning with the damage classifications in NCHRP Report 226.

7-2.04A Minor and Moderate Damage Repair

Minor and moderate damage repair methods were discussed in detail in Chapter 5, *Concrete Structure Repair and Rehabilitation.*

7-2.04B Severe Damage Repair

Severe damage repair was also discussed in Chapter 5 of this manual. However, in that chapter severe damage repair was only limited to concrete repair. In this section, severe damage repair that includes reinforcing or prestressing steel damage will also be discussed.

Severe bridge damage requires the repair of concrete as well as reinforcing steel and/or prestressing tendons. Severe bridge damage repair methods include conventional methods along with non-conventional methods using advanced fiber-reinforced polymer (FRP) materials. These repair methods predominantly differ in how they restore bridge member load capacity lost due to reinforcing steel or prestressing tendons damage. The conventional repair methods are:

- Metal sleeve/casing strengthening for columns
- Internal splicing of reinforcement and/or prestressing.

Each repair method has strengths and weaknesses that the designer must consider before a method is selected for the contract plans.

Repair methods discussed above include several construction activities that are common among most methods. Each repair method will be revisited individually, and the construction sequence and activities specific to each method will be discussed. The common construction activities for most of the repair methods include the following:

1. Removal of unsound concrete- All damaged and unsound concrete must be removed, as illustrated in Figure 7-1 (the removal of unsound concrete was discussed in Chapter 5, *Concrete Structure Repair and Rehabilitation*).

Figure 7-1. Removal of Unsound Concrete

2. Cleaning and corrosion repair of reinforcing and prestressing strands- Exposed reinforcing steel strands must be cleaned of heavy rust deposits by abrasive blasting. As shown in the photo below, prestressing strand can be significantly corroded at the time of the repair because substantial time may have elapsed

before damage to a bridge is discovered. Prestressing strands damaged by corrosion pitting must be cut out as shown in Figure 7-2 below.

Figure 7-2. Exposing, Cleaning, and Repairing Prestressing Steel

Additionally, to prevent future corrosion damage, anodic protection might be called out on the plans; see Figure 7-3 below.

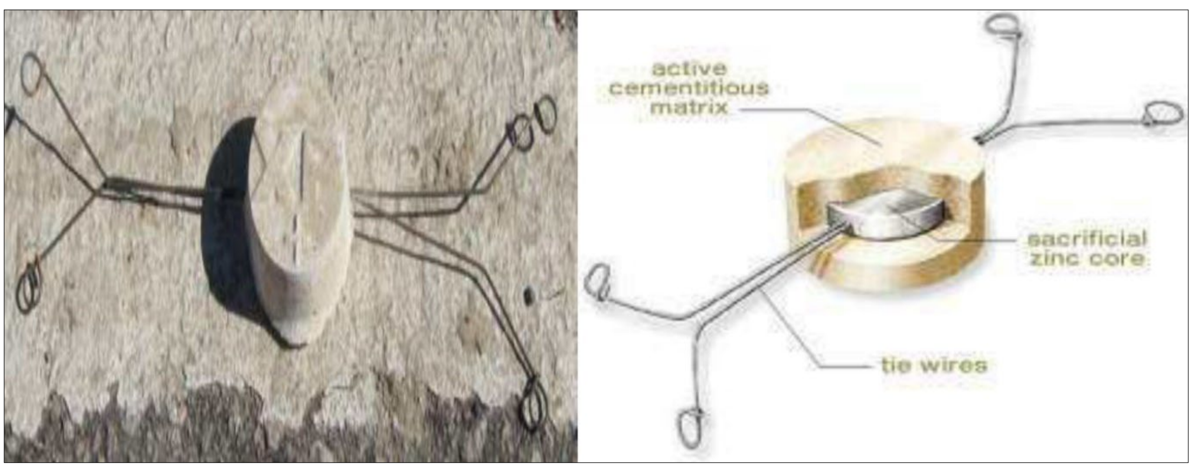


Figure 7-3.Galvanic Anode

3. Forming, patching, and/or pouring concrete- After existing concrete surfaces are cleaned, patching may be applied as described in *Standard Specifications* Section 60-3.05B, *Existing Structures – Structure Rehabilitation – Repairing Structures – Repairing Spalled Surface Areas*. However, depending on the volume of unsound concrete that has been removed, placement of new concrete using formwork might be required, as shown in Figure 7-4 below.

Figure 7-4. Forming for Recasting of Concrete

At this point, construction activities that are common to all severe damage repair methods have been discussed. Next, each repair method will be evaluated separately, and construction activities and sequences that are specific to each method will be discussed. As a reminder, while the repair methods are significantly different in the construction process and the aesthetics of the final product, they share a common purpose of restoring load-carrying capacity lost due to the damage.

7-2.04B(1) Metal Sleeves/Casing Strengthening

The construction of metal sleeves/casings around concrete members is a common method to repair and retrofit elements of concrete structures. In the examples below, the metal sleeve is used for retrofitting bridge columns for earthquakes.

Construction Procedure:

1. Place temporary support and apply any jacking shown on the contract plans to unload the column.
2. Remove unsound concrete.
3. Repair concrete damage.
4. Install metal sleeve.
5. Grout the gap between the column and sleeve.

An example of plan details of metal sleeve/casing for a bridge column is provided below in Figure 7-5 and Figure 7-6.

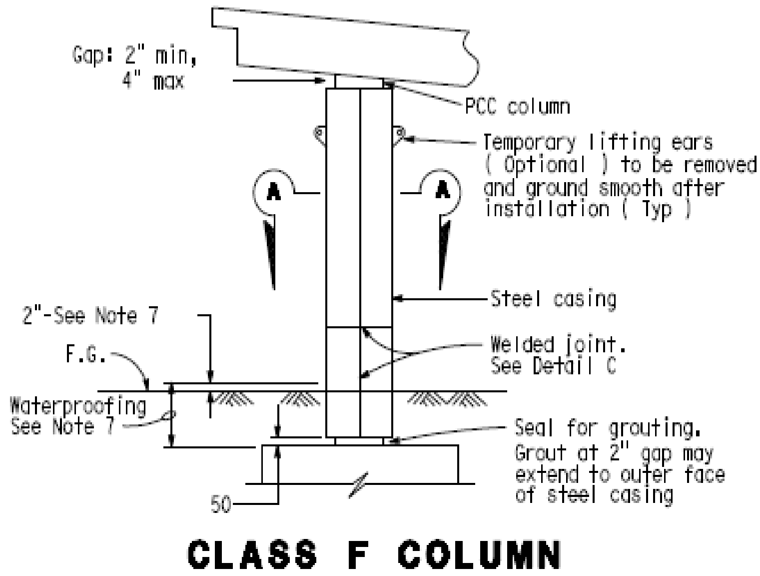


Figure 7-5. Steel Column Casing

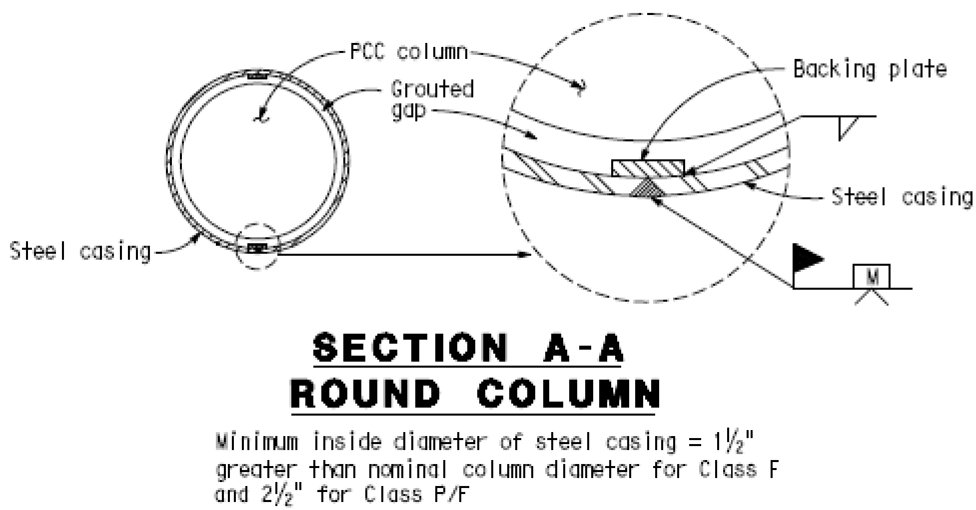


Figure 7-6. Steel Column Casing Detail

When constructing steel casing or sleeves, the existing concrete surfaces need to be closely examined for imperfections such as bulges or uneven lines, since the imperfections can interfere with the installation of the metal sleeve/casing. SC field staff should discuss with the Contractor and the Designer the potential for surface imperfections. Similarly, it is important that the Contractor field verify the existing dimensions of the concrete member before fabricating and cutting the plates. Field welding will require a Welding Quality Control Plan (WQCP) submission and testing.

Since this work will require field painting after welding is performed, an approved Painting Quality Work Plan (PQWP) will also be required.

If the plans call for the drilling of holes into existing members to anchor the metal sleeve, damage to existing strands or reinforcement must be avoided by checking for unusual or sudden changes in the movement of the drill. Fabricated pieces delivered to the field need to be properly identified in the shop plans to verify that the pieces are installed in the correct sequence and orientation. Installation locations of metal sleeves or casing grout ports are typically identified on the shop drawings. The elevation and distance between the grout ports are important to completely fill the casing without excess pressure that might cause bulging or deformation of the casing.

7-2.04B(2) Internal Splicing of Existing Prestressing Strands

Splicing of damaged reinforcing bars (rebar) or prestressing strands is another method of restoring member load-carrying capacity. When post-tensioning is required after splicing, there are two methods of tensioning. One method involves using rapid heating of strands to develop tension. The other method uses a turnbuckle nut to create tension. While the heating method will be briefly discussed, it needs to be pointed out that this method is not frequently used. The second method will be discussed in more detail. An overview of the construction sequence used in repairing a beam with strand splicing and heat to create tensioning, followed by a plan detail and construction photos are provided below.

7-2.04B(2)(a) Internal Strand Splicing with Heating to Create Tension

Construction procedure:

1. Remove unsound concrete
2. Splice strands as described below
    a. Cut frayed ends of severed strands
    b. Slip ordinary splicing strand chucks over ends of broken strands.
    c. Allow space between ends for thermal expansion.
    d. Heat the exposed length of the strand to approximately 400 F.
    e. Use “temperature sticks” to ensure that no portion of the strand is being excessively heated. Tighten strand grips with a wrench and then repair damaged concrete.

For additional details, see Splice 6 in NCHRP Report 226 (NCHRP, 1980).

7-2.04B(2)(b) Construction Procedure- Internal Strand Splicing Using Turnbuckle Nut

Construction procedure:

1. Remove unsound concrete
2. Assemble splice, locating splice sleeves and strand grips to allow seating of the strand grips and sufficient thread length in the splice sleeves (see photo below in Figure 7-8 for assembly details)
3. Torque lubricated splice sleeve to obtain the required tension. The strand grips must be prevented from rotating during torquing.
4. A suitable means of measuring stress or load in the splice must be provided.
5. Repeat steps 2 and 3 for other severed strands.
6. Repair concrete.

For additional details, see Splice 4 in NCHRP Report 280 (NCHRP, 1985). See Figure 7-7 for an example of a contract plan that utilized this method of a prestress strand splice, and Figure 7-8 for a photo illustration.

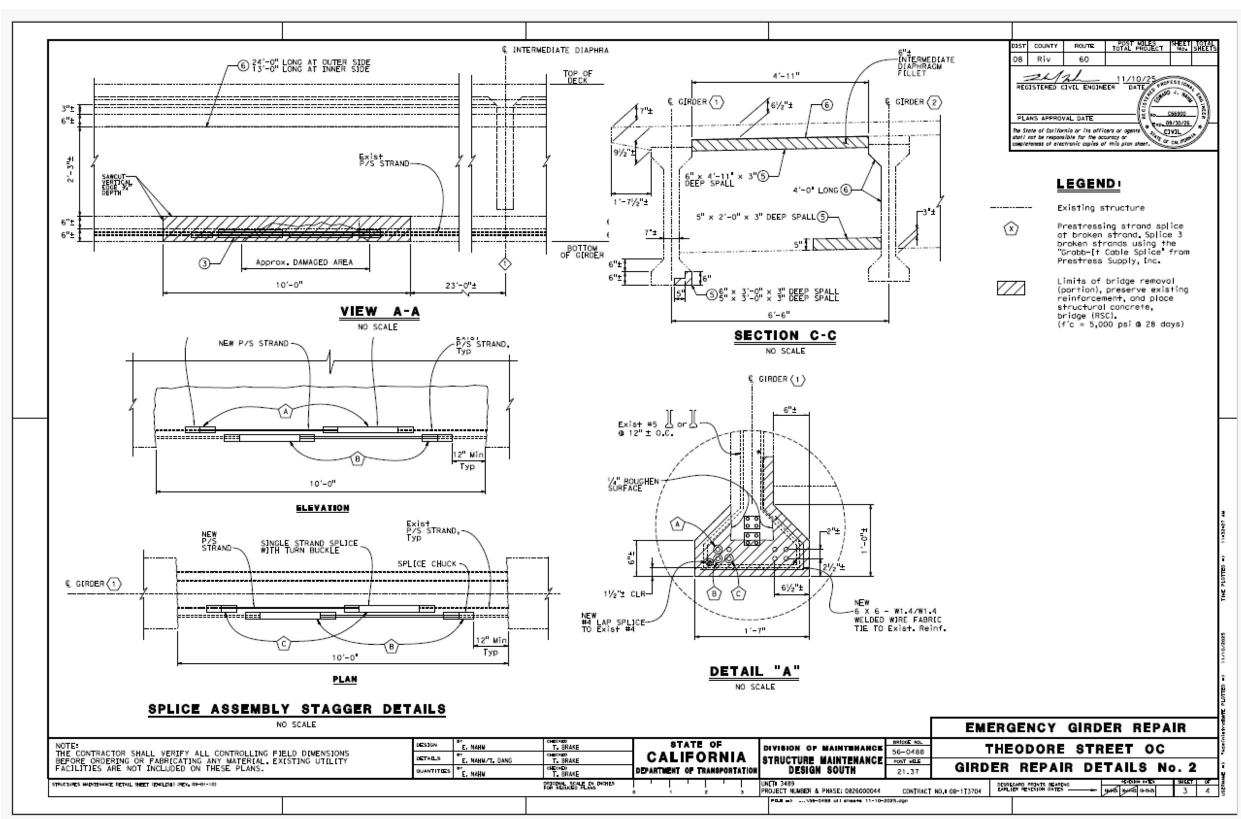


Figure 7-7. Strand Splice for Bridge No. 56-0488 (EA: 08-1T3704)

Figure 7-8. Single Strand Splice

Before installation of the strand splicing, the method used to measure the amount of post-tensioning needs to be determined. The post-tensioning force may be measured using turn-of-nut methods, or by measuring the torque on the wrench, or both. When using the torque method, a calibration chart needs to be created to correlate torque and tensile force. The condition in the field needs to match the condition used during calibration testing, including the use of any lubricant, the presence of any rust or surface imperfections, etc. Note that a calibrated torque wrench was specified by the manufacturer for the splice system in Figure 7-8.

When using the turn-of-nut method, the turn of the nut and the thread spacing is the basis of measuring the induced strain in the post-tension strands and ultimately calculating the post-tensioning force. However, in this method, a determination needs to be made of the point of no slack and the start of zero strain. Also, the length of the prestressing strand that will be post-tensioned needs to be accurately determined to calculate the strand strain. Lastly, another method for measuring the strain is by using the Alberta Infrastructure and Transportation Department (ABITD) gauge. The advantage of this gauge over the turn-of-nut method is that when using the ABITD gauge, the length of the tendon being used for measurement of the strain can be determined very accurately. See Figure 7-9 for a schematic and photo of the ABITD gauge.

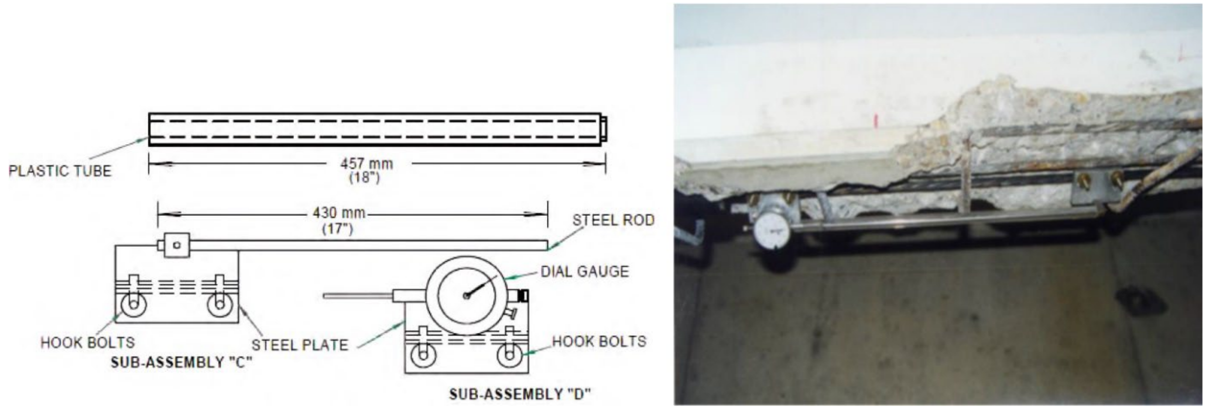


Figure 7-9. ABITB Stressing Gauge (NCHRP20-07(307), 2012)

In addition to determining the method of measuring post-tensioning force in the strand, the equipment, personnel, and splicing material intended for use may also require prequalification and testing if required by the contract documents. Figure 7-10 is a photo of the setup, calibration, and prequalification testing for a strand splice.

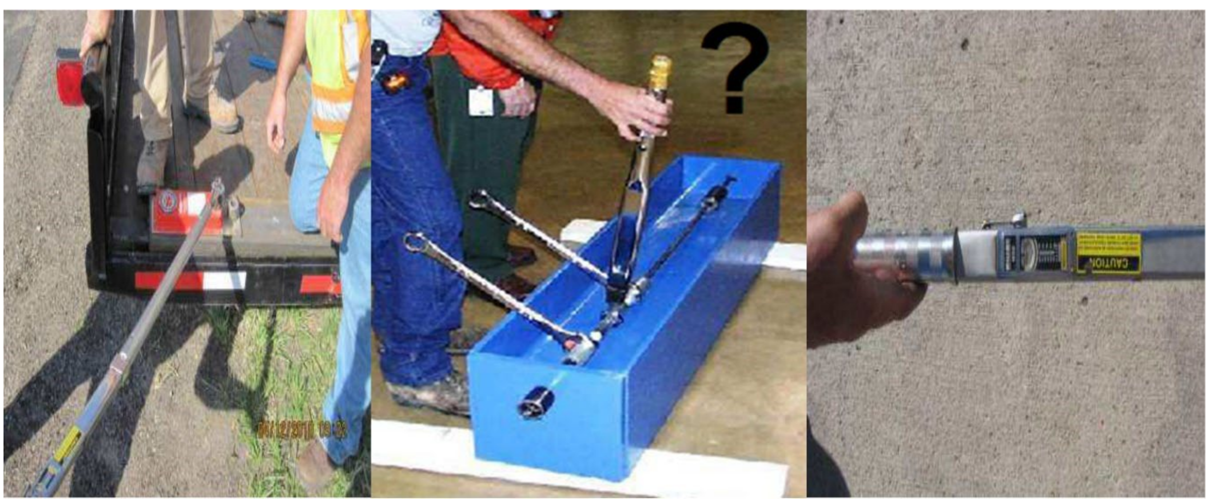


Figure 7-10. Calibration Testing of Strand Splice

After successful qualification testing of the mechanical splice system and setup, the system may be installed in the field per the construction procedure described above. Figure 7-11 shows installation of the mechanical splice system. It is important to note that when there is more than one strand to be repaired, the splices need to be staggered. Figure 7-12 shows the installation of multiple staggered strand splices.

Figure 7-11. Installation of Splicing System

Figure 7-12. Strand Splices Are Staggered

As seen in Figures 7-11 and 7-12, due to the size of the couplers and turnbuckles used for the splice, there would likely be reduced clearance between the coupler and the concrete final finished surface (i.e., surface of the plywood formwork). As such, when concrete is used to repair the girder, the size of the aggregate must be limited to allow for the proper flow of concrete around the coupler. Alternatively, grout may be used instead of concrete when there is limited clearance.

7-2.04B(3) Applicability of Repair Methods

When discussing conventional repair methods for severe bridge damage, predominantly precast concrete I-girders have been used for our examples and photos. It should be pointed out that the repair methods discussed above can also be applied to other types of concrete bridges or members. See Figure 7-13 for an example of contract plans used for splicing main reinforcement in a cast-in-place (CIP) reinforced concrete box girder bridge.

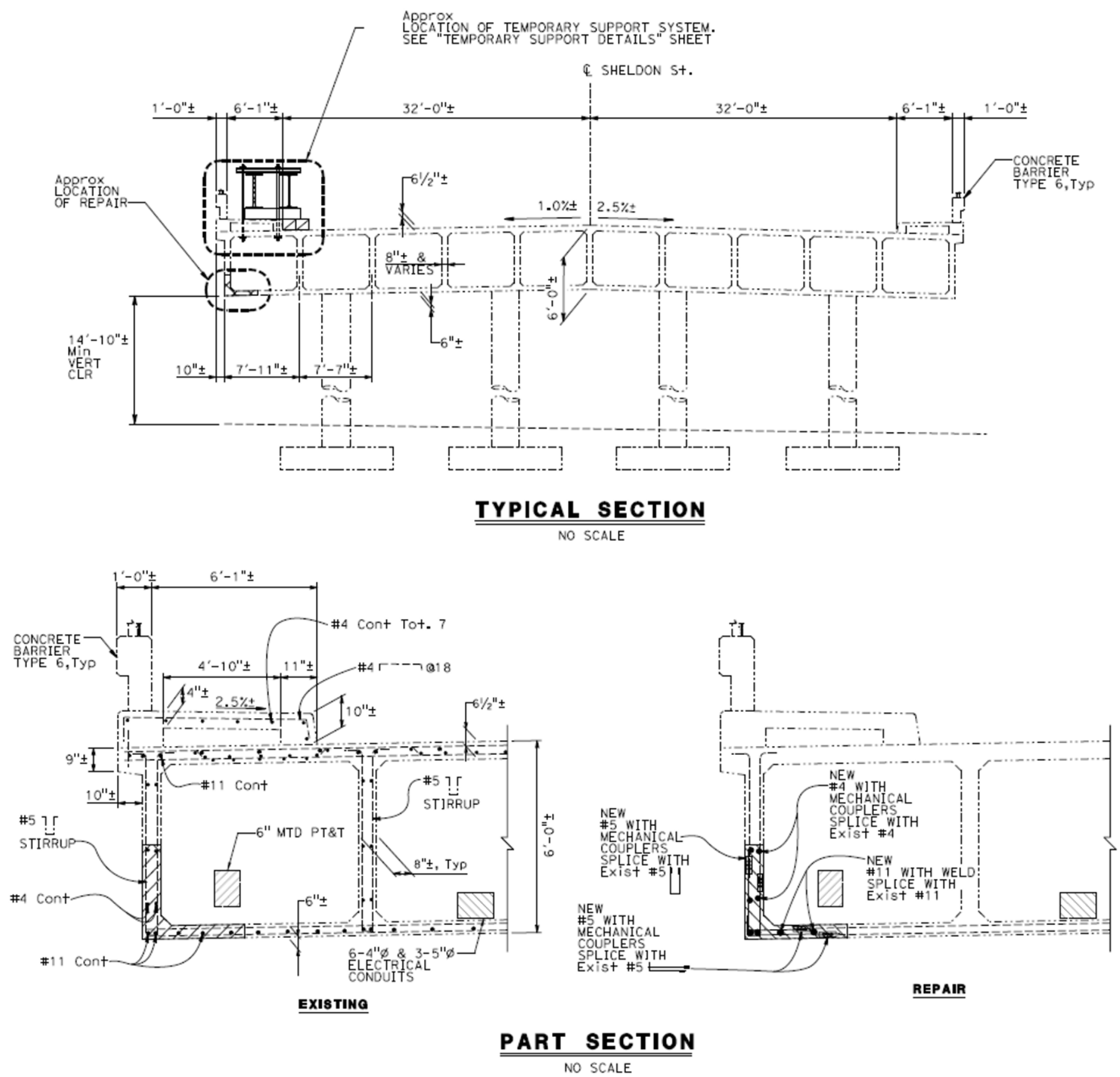


Figure 7-13. CIP Reinforced Concrete Box Girder Repairs (Bridge No. 53-1120)

7-2.05 Concrete Repair and Bridge Retrofit Using Fiber-Reinforced Polymers

So far, conventional bridge repair has been looked at. However, with the population and economic growth, larger stresses are put on our aging and deteriorating infrastructure. The aging transportation system also needs to be upgraded to support the increase in demand. The Department is always looking for more efficient and economical methods to both repair bridges and increase live load capacity. Fiber-reinforced polymers are one of the advanced materials that have the potential to provide efficient and economical repair and upgrade.

The material presented in this section is from the Federal Highway Administration (FHWA) publication, FHWA-HIF-18-041, *Report on Techniques for Bridge Strengthening*: *Main Report* (FHWA, 2019). This section is intended to be a very brief introduction to FRP. For more detailed information, the reader is referred to the original FHWA-HIF-18-041 publication.

7-2.05A Composite Material Overview

A composite material consists of two or more constituent materials that have distinct physical and/or chemical properties. For instance, two-phase metal alloys are particulate composites in terms of different atomic structures. The combination of the selected constituent materials creates a material with enhanced properties and targeted performance goals.

7-2.05A(1) What is a FRP Composite Material?

Fiber-reinforced polymers (FRP, also called fiber-reinforced plastics) are composite materials. FRPs consist of a thermosetting or thermoplastic polymer matrix and embedded reinforcing fibers. The fibers are fabricated filaments with diameters in micron scale and can be in the form of short, long, continuous, and discontinuous fibers. For instance, a composite material might have unidirectional long and continuous fibers distributed homogeneously along the longitudinal direction (i.e., long fiber direction) and randomly throughout the cross-section of the composite.

7-2.05A(2) Different Types of FRP Materials and Current Industry Specifications

According to NCHRP 20-07 (Task 307), *Updated Research for Collision Damage and Repair of Prestressed Concrete Beams,* FRP systems are made of a polymer binder that is strengthened with high-performance fibers (NCHRP, 2008). These reinforcing fibers may include aramid-based FRP (AFRP, which is rarely used in North America), carbon-based FRP (CFRP), glass-based FRP (GFRP), high-performance steel-based FRP (SFRP), or combinations of these materials.

Additionally, NCHRP 20-07 (Task 307) provides a list of applicable national specifications and guidance manuals related to the use and design of FRP composite repairs for strengthening, repair, and rehabilitation, which include the following US Standards:

1. National Cooperative Highway Research Program (NCHRP) - *Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Using Bonded FRP Composites* – Report 609.
2. National Cooperative Highway Research Program (NCHRP) - *Bonded Repair and Retrofit of Concrete Structures Using FRP Composites: Recommended Construction Specifications and Process Control Manual* – Report 514.
3. American Concrete Institute (ACI) Committee 440 - *ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*.
4. *Concrete Repair Manual*, 3rd Ed. - published jointly by the American Concrete Institute (ACI) and International Concrete Repair Institute (ICRI).

7-2.05A(3) Benefits and Drawbacks of FRP

FRP provides numerous benefits and advantages over traditional construction materials. Below is a list of some of the advantages of FRP:

1. When compared to steel, FRP has a much higher tensile strength (90-160 ksi) vs traditional steel rebar (60-80 ksi). FRP is also significantly lighter than steel; as a result, it can have a strength-to-weight ratio between three to five times that of steel.
2. FRP is a durable material and extremely low-maintenance. It is corrosion-resistant and does not rust like steel, rot, or degrade in high-moisture environments. FRP generally does not require painting, sealing, or frequent repairs, leading to reduced long-term maintenance costs and a longer lifespan, often exceeding 75 years.
3. Depending on the bridge and the member location, FRP can generally be installed quickly, lowering labor costs and reducing any traffic impacts.
4. FRP offers great design flexibility and versatility because FRP fabrics can easily be cut into desired shapes and applied on or molded into complex shapes.

However, FRP has some drawbacks too. Below are some of the disadvantages of FRP:

1. Bonded FRP reinforcement could be susceptible to potentially damaging environmental and mechanical effects. According to ACI 440.2R-08, these include exposure to ultraviolet light, fire exposure, vandalism, impact, abrasion, and wear.

2. As a relatively newer material, there is a smaller pool of qualified professionals and less long-term performance history compared to traditional materials like steel or concrete.
3. FRP has limited ability to hold screws and fasteners, creating challenges for connections and overall structural integrity, often requiring adhesives or specialized techniques.
4. FRP panels and materials are often more expensive upfront than traditional construction materials like wood or low-carbon steel.

7-2.05A(4) Use of FRP to Repair Concrete Elements

FRP can be used as a repair method to strengthen a bridge member and restore load-carrying capacity lost due to severe damage. The following items from the FHWA-HIF-18-041, Section 7.2.1, *Laboratory Research and Key Findings,* provide findings regarding flexural strengthening using composites:

1. Before strengthening, the concrete substrate should be repaired, and spalling and chloride ions removed to prevent further deterioration from these problems after strengthening.
2. U-wraps can be used to provide additional anchorage, increase member stiffness, increase cracking moment, and allow the FRP to reach rupture without debonding.
3. Externally Bonded (EB) FRP can increase the ultimate capacity of concrete girders significantly without sacrificing the member’s ductility.
4. EB FRP can be used to strengthen one-way and two-way concrete slabs, by applying the FRP to the slab soffit in the form of strips and grid patterns, respectively.
5. EB FRP can be used in conjunction with prestressed steel rods to produce a better result than one strengthening method alone, yielding a higher ultimate capacity while maintaining ductility and also improving serviceability.
6. Prestressing can be directly applied to CFRP laminates, which can then be used to strengthen concrete girders or deck slabs while improving serviceability.

The following is a summary of key findings regarding shear strengthening using composites that have come from both laboratory work and field installations; from FHWA-HIF-18-041, Section 7.3.2, *Field Implementations* (FHWA, 2019):

1. CFRP grid sections can be installed vertically in concrete deck slabs to change the failure mode from shear to flexure.
2. CFRP plates can be bonded to slab soffits to increase shear capacity.

3. FRP double-headed shear bars provide excellent shear reinforcement, good fatigue performance, and are easy to install in shallow concrete members.
4. EB FRP stirrups can be used to strengthen bridges that were designed without internal shear reinforcement, but implanting shear bars is a more effective strengthening method.
5. U-wraps can increase shear capacity and deformation capacity of a beam, but the new governing failure mode is debonding of the U-wrap.
6. The application of vertical strips with a horizontal anchoring strip was found to be the most effective shear-strengthening system orientation for RC girders.
7. When using a full wrap to strengthen a girder in shear, it is recommended that the wrap be left unbonded on the sides of the beam, because it will yield a greater increase in shear strength, than if it were fully bonded.
8. Dynamic debonding and deformation from the movement of a composite strengthening system on either side of a shear crack can cause the composite to fail at lower strains than the failure strain of tensile coupons.
9. Partial or full embedment of L-shaped CFRP stirrups is more effective than EB FRP in shear strengthening.
10. Load testing of a bridge should be conducted prior to strengthening because capacity calculations based on strengthening codes can vary from the actual capacity.

7-2.05A(5) FRP Application Methods

In this section, strengthening methods developed using FRP will be discussed; these methods can be used for the repair of damaged concrete bridge elements. Also, the strengths and weaknesses of each method will be discussed. The information presented in this section is from the NCHRP 20-07 (Task 307) report Section 1.5.3, *Emerging Repair Materials and Methods*. The reader is encouraged to read the referenced report for additional details.

7-2.05A(5)(a) Externally Bonded Non-Post-Tensioned CFRP Retrofit (EB-CFRP)

Carbon fiber-reinforced polymer (CFRP) is adhesively bonded to the external face of a bridge element. CFRP can be used to restore or increase the flexural capacity of damaged girders, control cracking if it is present and reduce deflections under subsequent load. The use of externally bonded (EB) CFRP strips to restore the flexural capacity of damaged girders is well documented. There are two ways that CFRP material can be bonded to bridge elements, as described below:

- **Wet-layed up fabrics**

  In wet-layed up method, the CFRP fabric is saturated with epoxy resin at the bridge site. Typically, a layer of epoxy resin is placed on the prepared concrete substrate as a ‘primer’ layer and the dry CFRP fabrics are overlayed onto this; an additional layer of saturant is applied and the material is worked to ensure complete epoxy wet-out of the fiber. Additional layers are applied in the same fashion. Wet layed-up applications are suitable for column wrapping and U-wrap applications.

- **Preformed strips/plate**

  The terms “preformed strips” and “preformed plates” are interchangeable. In this method, a pre-cured rigid composite strip or plate is delivered to the job site. The strip or plate is then bonded to the prepared concrete substrate using conventional structural adhesives. The strips are preferred over wet layed-up method for beam flexural strengthening for the following reasons:

  1. Preformed strips have exceptional quality control in their fabrication whereas wet lay-up is accomplished overhead in situ.
  2. Preformed strips are considerably more durable under typical exterior environments (Cromwell et al., 2011).
  3. The bond performance of preformed strips has been observed to be twice as good as wet layed-up materials; that is, CFRP strain at debonding failure – typically the dominant limit state – is twice as high for strips. (Harries and Shahrooz 2011).
  4. ‘Sag’ of CFRP strips is not observed during bonding with conventional adhesive materials, compared to sag which is often observed in large wet layed-up applications.
  5. Adhesive bonding is a regularly conducted construction task and has minimal requirements for containment. Wet lay-up is a specialized skill usually requiring special clothing along with containment in cases where the resin may enter a water course.
  6. Bonding preformed strips is reported to be significantly less expensive – requiring less surface preparation, labor, and time than wet lay-up methods.
  7. Only preformed strips are practical if the CFRP is to be prestressed or post-tensioned.

7-2.05A(5)(b) External Prestressed (P-CFRP) and Post-Tensioned (PT-CFRP) CFRP Retrofit

NCHRP 20-07 (Task 307) report states that a parallel can be drawn between prestressed and nonprestressed CFRP retrofits and prestressed and conventionally reinforced concrete beams (note the difference from the traditional abbreviation for prestressed (PS), used in this section). In the latter case, prestressing the reinforcing steel places the concrete in the girder’s tension zone under precompression. As the member is subsequently loaded, it must first overcome this induced compressive stress before entering tension, which contributes to a stiffer and more durable concrete section. The advantages of applying stress to CFRP strips before installation are comparable to those achieved by using prestressed strands in concrete beams. The main advantages of using a stressed CFRP repair are (Nordin and Taljsten 2006):

1. Better utilization of the strengthening material.
2. Smaller and better distributed cracks in concrete.
3. Unloading (stress relief) of the steel reinforcement resulting in higher steel yielding loads.

Conventionally used CFRP materials have roughly 1.5 times the tensile capacity of 270-ksi steel prestressing strand and a Young’s modulus about 75 percent that of steel, allowing for higher strain capacity. Stressing the CFRP during repair can restore prestressing force lost through damage or strand failure, improving load redistribution and reducing stresses in both the remaining strands and the concrete (Kim et al. 2008b). As a result, when the beam is reloaded, the remaining strands experience lower stresses than in an unrepaired member. Prestressed CFRP systems, therefore, provide an active load-carrying mechanism in which part of the dead load is resisted by the CFRP, whereas non-prestressed CFRP can only carry loads applied after installation (Wight et al. 2001; El-Hacha et al. 2003; Kim et al. 2008a, 2008c). Loading after installation of prestressed CFRP leads to higher CFRP strains, indicating that the material is used more efficiently, and the CFRP contributes immediately to increased flexural capacity.

NCHRP 20-07 (Task 307) report outlines three methods to prestressing or post-tensioning and uses the following terminology to define the various types of prestressed CFRP systems.

- **Prestressed CFRP (P-CFRP)**

  The CFRP is drawn into tension using external reaction hardware and is adhesively bonded to the concrete substrate while under stress. The stress is maintained using the external reaction until the bonding adhesive is cured. The reacting stress is released and the ‘prestress’ is transferred to the substrate concrete. This method of prestressing is susceptible to large losses at stress transfer and long-term losses due to the creep of the adhesive system. As a result, only relatively low levels of prestress may be achieved. Additionally, details (such as FRP U-wraps) must be provided to mitigate debonding of the CFRP strips. P-CFRP systems are analogous to prestressed concrete systems where the stress is transferred by bond to the structural member.

- **Unbonded post-tensioned CFRP (UPT-CFRP)**

  The CFRP is drawn into tension using the member being repaired to provide the reaction. The stress is transferred to the member by mechanical anchorage only. Typically a hydraulic or mechanical stressing system will be used to apply the tension after which it will be ‘locked off’ at the stressing anchorage. This method of post-tensioning is susceptible to losses during the ‘locking off’ procedure. Depending on the anchorage method, long-term losses due to creep in the anchorage are a consideration. Such systems must be designed with sufficient clearance between the CFRP and substrate concrete to mitigate the potential for fretting. UPT-CFRP systems are analogous to conventional unbonded steel post-tensioning systems.

- **Bonded post-tensioned CFRP (BPT-CFRP)**

  The CFRP is stressed and anchored in the same fashion as the unbonded systems. Following anchorage, however, the CFRP is bonded to the concrete substrate, resulting in a composite system with respect to loads applied following CFRP anchorage. Since the adhesive system is not under stress due to the post-tensioned force, adhesive creep is not as significant a consideration with this system (Wang et al. 2012b). The bonding of the CFRP may also help to mitigate creep losses associated with the anchorage (Wang et al 2012b). BPT-CFRP systems are analogous to conventional bonded steel post-tensioning systems.

The externally bonded CFRP application methods discussed above are summarized in Figure 7-14.

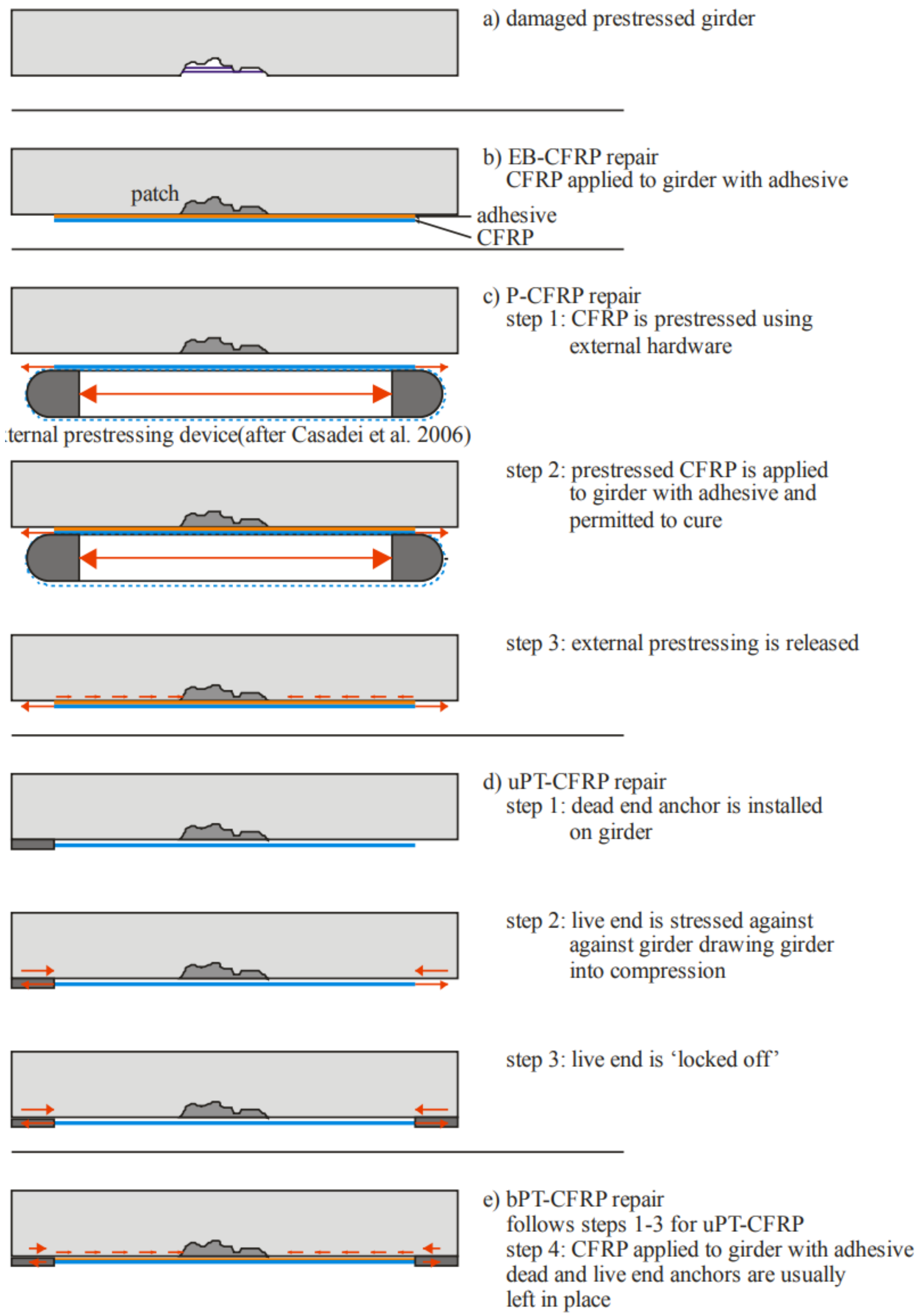


Figure 7-14. Schematic Representations of CFRP Applications (NCHRP, 2012)

7-2.05A(5)(c) Near Surface Mounted CFRP Reinforcement

The NCHRP 20-07 (Task 307) report explains that near-surface mounted (NSM) CFRP repairs provide an alternative to externally bonded repair systems. In the NSM method, the CFRP is placed within the concrete cover, offering the material improved protection against impact and environmental exposure (Nordin et al. 2002). As with external CFRP repairs, NSM systems may be prestressed when serviceability improvements are desired, or left unprestressed when only ultimate strength is targeted. However, prestressing NSM applications has proven difficult and has only been achieved under laboratory conditions using procedures not feasible for field applications (Nordin et al. 2002; Casadei et al. 2006).

Because NSM CFRP is fully embedded in epoxy, it can develop higher bond strength than externally bonded strips due to the greater bonded surface area. NSM systems also mobilize a larger portion of the cover concrete, enabling higher stress transfer to the substrate (Quattlebaum et al. 2005). Since externally bonded systems are commonly governed by bond capacity, NSM applications generally require less CFRP material due to their improved bond performance. NSM repairs are sensitive to the available concrete cover, and insufficient cover makes the method unsuitable. ACI 440 (2008) specifies that NSM slots must have a clear spacing of at least twice the slot depth and an edge distance of at least four times the slot depth. Laboratory studies have shown that both prestressed and non-prestressed NSM repairs can successfully restore girder ultimate capacity (Nordin et al. 2002; Casadei et al. 2006).

NSM bonded CFRP requirements described above are summarized in Figure 7-15 below.

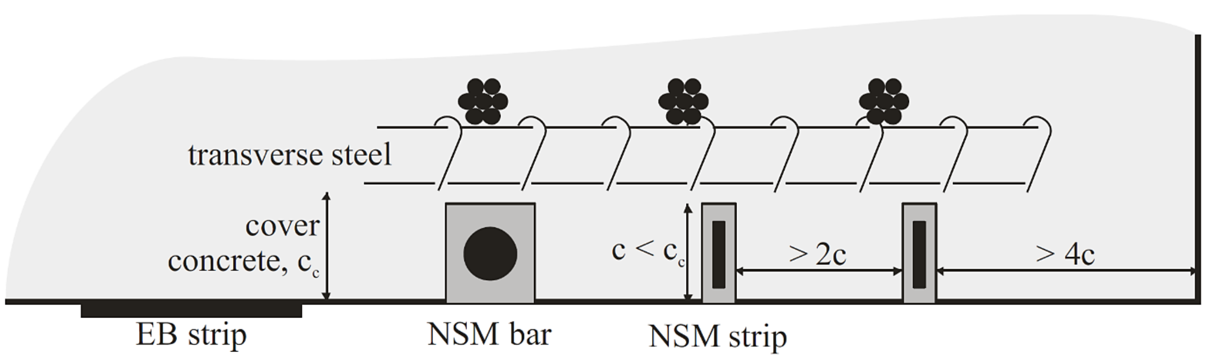


Figure 7-15. Schematic of Externally Bonded and NSM CFRP Techniques (NCHRP, 2012)

7-2.05A(6) Construction Guidelines for Using FRP

As outlined in FHWA-HIF-18-041 (Section 6.2, *Typical Content of Guidelines*), when repairing bridge members using the FRP strengthening method, the following items need to be considered:

1. Materials proposed to be used including material data (dimensions, shelf life, strength/stiffness, strain to failure, fiber volume fraction, thermal resistance, etc.)
2. Concrete repair: repair of defective reinforcement, restoration of concrete cross-section, and cleaning and preparation of all concrete surfaces before installing the FRP system.
3. Surface preparation: surface grinding, chamfering corners, grooves for near-surface mounted FRP system, surface profiling, and surface cleaning.
4. Installation of FRP system: shoring of repaired members, examining environmental conditions before and after installation of the FRP system.
5. Application of different FRP systems:
    a. Application of wet lay-up FRP systems: mixing of resin components, primer, and putty saturant; applying fiber sheet and saturant, multi-ply fiber plies installation, overlapping, alignment of FRP materials, and anchoring of FRP sheets.
    b. Application of PreCured FRP systems: application of adhesive, placement of procured system, grouting of procured shells.
    c. Application of Prestressed or Post-Tensioned FRP systems.
    d. Application of Near-Surface-Mounted FRP systems: application of embedding paste and placing FRP reinforcement.
    e. Application of column wrap FRP systems in non-seismic application: FRP composite jacket or sleeves and continuous filament woven fabric.
6. Curing:
    a. Methods to achieving proper cure (ambient temperature or rapid cure under elevated temperature).
    b. Time for full cure.
    c. Temperature limits (minimum application temperature).
7. Protective coating and finishing:
    a. Temporary protection: install temporary protection if needed.

   b. Permanent protection: to protect the fibers from the elements, especially UV radiation, and to give the final aesthetic effect.

8. Inspection and quality assurance: inspection for debonding, inspection for adhesion, inspection for cured thickness, and auxiliary tests.
9. Repair of defective work: repair of protective coating, epoxy injection of small defects, patching of minor defects, placement.

7-2.05A(7) Bridge Damage Repair and Retrofit Using FRP at Caltrans

Fiber Reinforced Polymer (FRP) concrete repair and retrofitting in Caltrans (California Department of Transportation) projects has been in use for roughly 30 years, emerging in the early-to-mid 1990s. The technology saw early development and testing in California around the time of the 1994 Northridge earthquake, focusing on seismic retrofitting of columns. Early FRP liners for infrastructure repairs were designed based on "lessons learned through the Caltrans study" and laboratory tests in the mid-1990s.

Since then, FRP has been extensively used for structural rehabilitation, particularly for strengthening concrete bridge columns and girders (often using carbon fiber, or CFRP).

While early implementations were experimental, FRP repair methods have evolved through the 2000s and 2010s, with technical reports on the integrity of these repairs dating back to at least 2008. Currently, FRP repair and retrofit methods are a well-established option complete with AASHTO guidance and Caltrans non-standard special provisions (NSSP). The application of FRP for repair is a rapid and very cost-effective procedure capable of restoring the strength or supplementing the existing strength of damaged structures such as columns, girders, bent caps, pier walls, bridge deck overhangs, etc. In most cases, FRP strengthening does not change the appearance of the structure, and is painted to blend in with the existing concrete surface.

In section 7-2.04, conventional repairs for several types of bridge damage were discussed. In this section, we will look at the FRP repair~~s~~ options for the same type of bridge damage discussed earlier. In general, FRP repair methods can be effective in repairing minor, moderate, and even severe damage. It is important to note here that while the benefits and drawbacks of using FRP were discussed earlier in section 7-2.05A(3), the decision to use FRP vs conventional repair is made by the Office of SM&I Design or the Office of Bridge Design. They provide plans and specifications to repair the assessed damage; SC staff are simply responsible for administering the contract and for delivering construction projects per plan.

7-2.05A(7)(a) FRP Composite Column Casing

FRP composite column casing is a proven rapid repair or strengthening process. No heavy lifting equipment is required. This method can be performed adjacent to existing structures or very close to a traffic barrier. This method can restore a severely damaged column to its original strength. Figure 7-16 shows the Caltrans bridge standard detail (Sheet XS7-020, *Column Casing – FRP Composite System*) used to install EB-CFRP on bridge columns.

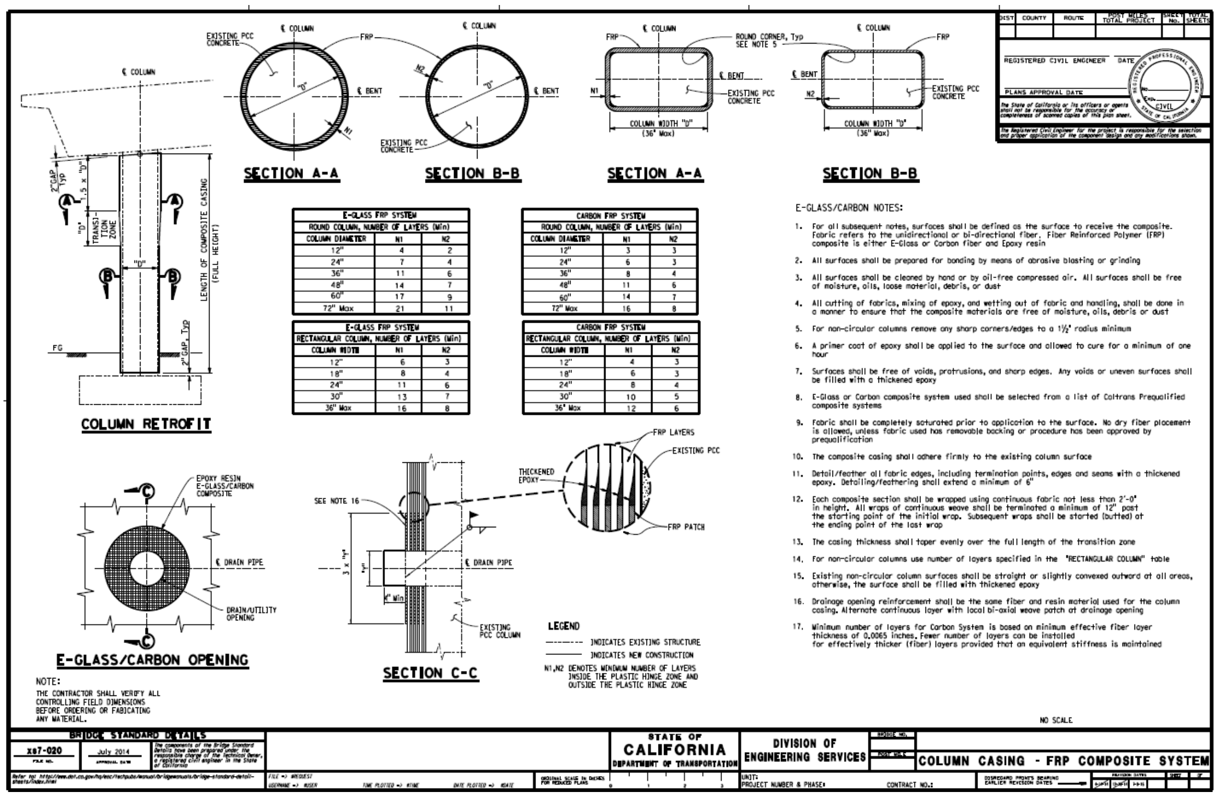


Figure 7-16. Bridge Standard Plan Sheet (XS7-020) for Bridge Column Retrofit using FRP

When installing FRP composite column casing, *Special Provisions* section "Carbon Fiber Reinforced Polymer Sheets" (CFRP sheets) describes the requirements that must be complied with. Before starting the FRP, the Contractor must provide:

1. Shop Drawings- some of the requirements for the shop drawing are listed below (for complete details, please refer to your contract special provisions):
    a. Details of the materials to be used, including the supplier's name, technical data, commercial designation of materials, and a few other items.
    b. Details of ends of fiber and splices.

c. Details of transition in composite section.

d. Process Specification Manual reference.

e. Name of the authorized laboratory.

f. Measures for protecting workers and public from hazardous materials.

g. Measures to permit application and curing during inclement weather.

h. Measures for preventing materials from falling from overhead structures.

2. Certificate of Compliance- for each material used and for each shipment.
3. Experience Qualifications- documentation is to be submitted for each supervisor to show:

   a. Manufacturer Training Certification

   b. Three successfully completed wet lay-up operations in the last 3 years.

<u>7-2.05A(7)(b)</u> <u>Construction Procedure for CFRP Sheet Installation</u>

1. Remove and patch unsound concrete. The Engineer determines the soundness of the concrete. This work is change order work. See Figure 7-17 for the removal of unsound concrete, on a bridge column.

Figure 7-17. Removal of Unsound Concrete (Column Crack Visible)

2. Next, the concrete needs to be prepared by performing the following:
   a. Epoxy inject cracks if damage has caused column cracking. See Figure 7-18 for epoxy injection to fill cracks.

Figure 7-18. Epoxy Injection to Fill Cracks

   b. Fill voids larger than 1/2 inch in diameter.
   c. Roughen the surface per the International Concrete Repair Institute (ICRI) surface profile of CSP 3 for bonding critical applications.
   d. Corners of rectangular members need to be rounded.
   e. At the time of installation, the surface must be:
      i. Clean and free of efflorescence, oils, loose materials, and dust
      ii. Temperature must be 5 degrees above the dew point
      iii. No moisture present on the concrete surface
      iv. Humidity must be less than 90 percent.

See Figure 7-19 for a photo of a concrete column surface patched and prepared for CFRP sheet installation.

Figure 7-19. Prepared Concrete Column Surface

3. After completion of concrete surface preparation, the CFRP sheets may be installed. To install the CRFP, the Contractor must:
   a. Mix the components per the manufacturer's recommendations
   b. Apply resin within 1 hour of mixing
   c. Apply primer and allow it to cure for at least 1 hour before application of the fiber sheet
   d. Apply resin and fiber at a uniform authorized rate
   e. Completely saturate the fabric before applying to the surface
   f. Feather all fabric edges
   g. Squeeze out any entrapped air
   h. Place successive layers before the complete cure of the previous layer
   i. Coat the exterior surface with the final coat of resin.

See Figure 7-20 for a photo of CFRP sheet installation on a concrete column.

Figure 7-20. Partial CFRP Wrap of a Column

It is important to note that for performing the CFRP installation, the Contractor must comply with the following:

1. Provide a daily installation log. The log must provide material traceability and process records for each installation during a shift.
2. Perform job control testing in the presence of the Engineer.

<u>7-2.05A(7)(c)</u> <u>FRP Flexural and Shear Strengthening</u>

There are several applications utilizing FRP for strengthening and repairing concrete bridge elements for flexural and shear at Caltrans, including high load impact, fire damage, and retrofitting bridge overhangs.

1. **High load impact repair**

   A bridge girder damaged by a high load impact can rapidly be restored to its original capacity by using FRP materials. This repair method has been utilized on Caltrans bridges (see Br: 33-0236, Tennyson Road OC EA: 04-

3Y6104), where the internal reinforcement, including the tension steel and shear stirrups, was damaged, and some of the prestressing strands were severed. It should be noted that capacity was restored without replacing the damaged prestressing strand. Figures 7-21 through 7-23 show the typical detailing for this type of FRP repair.

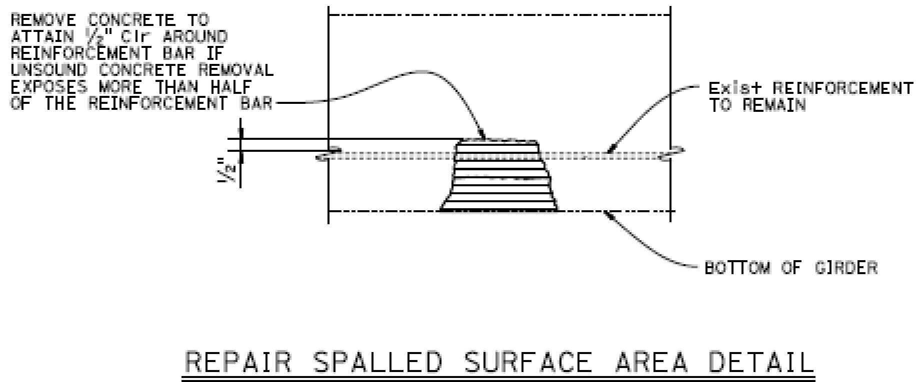


Figure 7-21. Typical FRP Detailing for Spall Repair

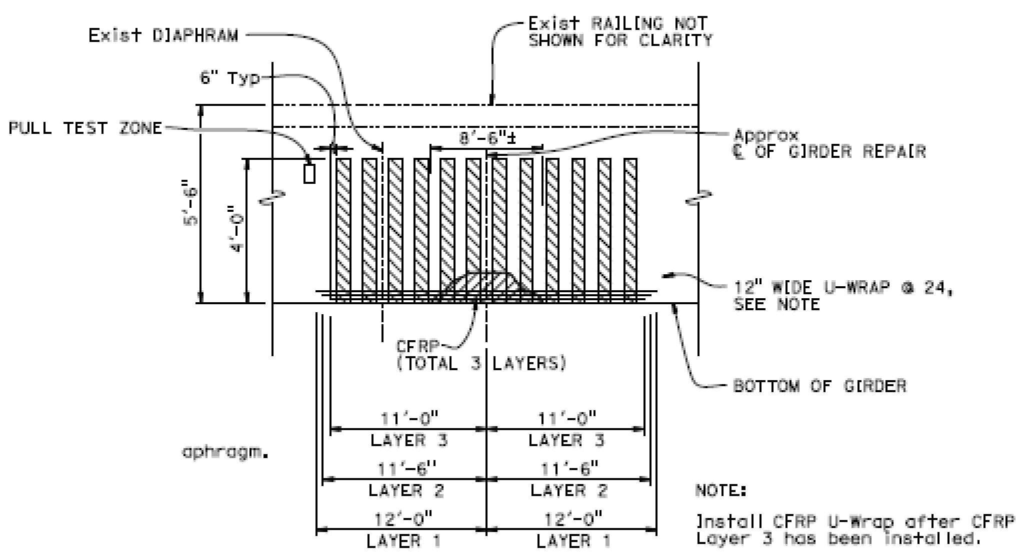


Figure 7-22. Typical FRP Detailing for Installing CFRP U-Wrap

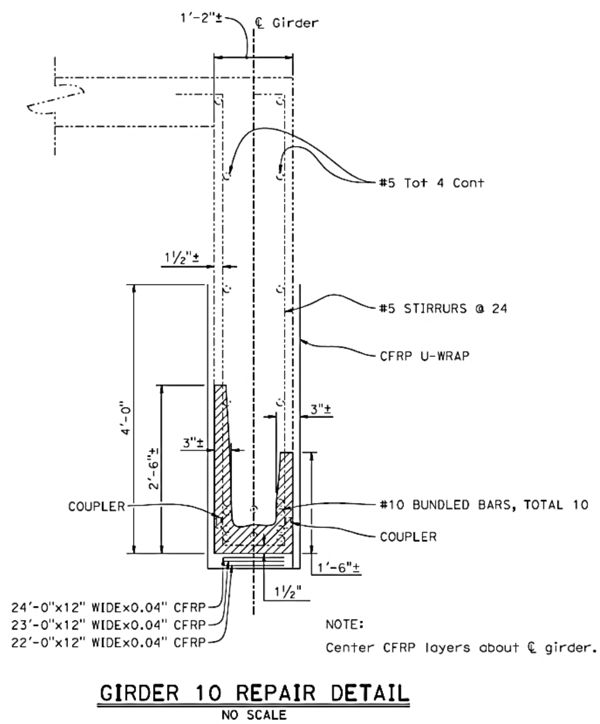


Figure 7-23. Typical FRP Detailing for Girder Repair

The construction contract requirements for FRP flexural and shear strengthening are provided in the project *Special Provisions* as discussed earlier in Section 7-2.05A(7)(a), *FRP Composite Column Casing*.

2. **Fire damage repair**

   In 2013, the SR-2/I-5 connector tunnel bridges (Br. No. 53-0577 and Br. No. 53-0527 L/R) were damaged due to a tanker truck fire. Figure 7-24 shows the damage to the bridges due to fire.

Figure 7-24. Fire Damage to SR-2/I-5 Connector Tunnel

The damage to the bridge outriggers were repaired (EA 07-4X1004) to restore shear capacity of the outriggers using EB-CFRP as shown in Figure 7-25.

Figure 7-25. Repair of Fire Damage Using FRP

3. **Repair or retrofit of a bridge overhang using NSM-bonded CFRP**

   When repairing or upgrading bridge barriers, the overhang supporting the barrier often needs to be retrofitted, too. Near-surface mounted NSM-bonded CFRP (i.e., CFRP strips) have been used on several bridges to retrofit the overhang. For example, Figure 7-26 illustrates the contract plan for retrofitting a bridge deck using CFRP Strips (Br. No. 23-0147, Meridian Rd. OC, EA: 04-4G5104)

   Construction of CFRP strips is relatively simple, as shown in Figure 7-27. However, before the actual construction begins, significant work needs to be done by SC staff for the following tasks:

   a. Submittal Review- For CFRP strip installation projects, the contract specifications will require the Contractor to provide a number of submittals. These submittals typically include:

i. Certificate of compliance and test results for each shipment of material
ii. Shop drawings specifying methods, equipment, and materials to be used; the properties of epoxy adhesive; and step-by-step installation procedures.
iii. Experience qualifications, including manufacturer's training certifications for each supervisor and documentation of prior projects
iv. Test results for each test performed as part of the preconstruction field NSM bond strength test (as described below).

b. Verification of preconstruction field NSM Bond Strength Test-The contract documents require bond and testing of preconstruction CFRP strips before starting production of CFRP strip work. SC staff need to verify that the Contractor performs the testing in compliance with contract requirements. The testing requirements include the type, frequency, and equipment calibration for testing.
c. Verification of unsound concrete removal and concrete repair work-Before the actual installation of the CFRP, SC staff need to verify that all unsound concrete is removed and all necessary concrete repairs have been performed.

During the CFRP strip work production, SC staff need to verify that the concrete temperature is within the allowed installation temperature specified in the contract documents. SC staff also need to verify that the Contractor saw cuts grooves for CFRP strips to the proper width and depth, and to the alignment and locations shown on contract plans. After saw cutting, SC staff need to verify that the Contractor removes the concrete from the interior of the groove, producing a substrate that is clean, sound, and dry. Finally, when placing the CFRP strip, the SC staff need to verify that the Contractor centers the strip within the groove and that the adhesive is present on both sides and has filled the groove.

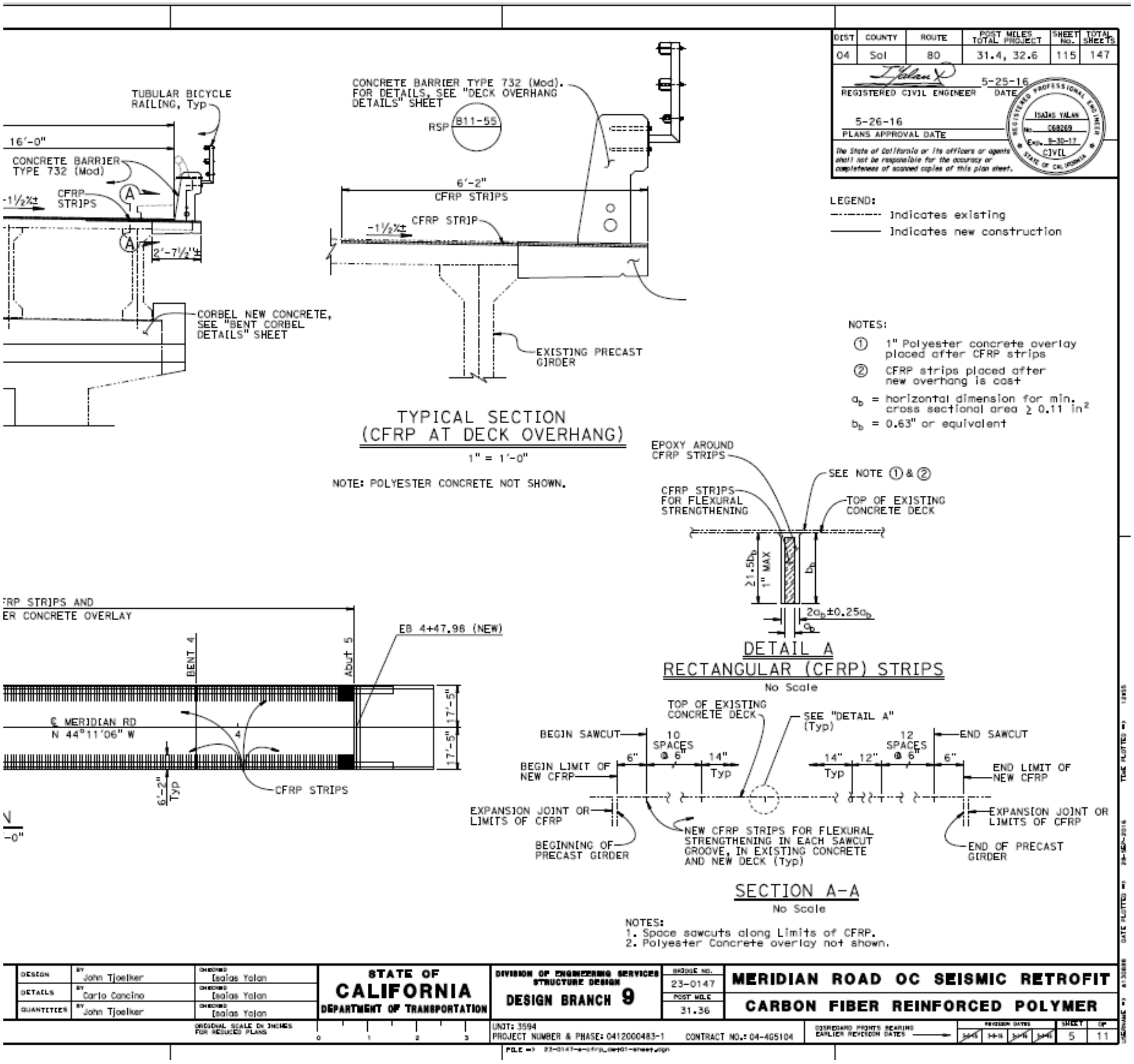


Figure 7-26. Contract Plan for Overhang Retrofit using FRP (Br No 23-0147)

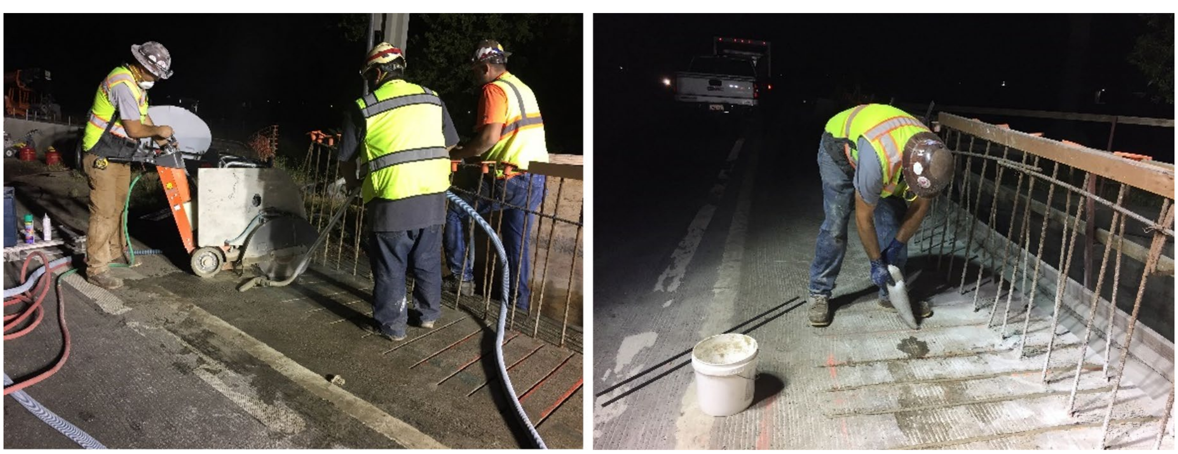


Figure 7-27. Construction of Overhang Retrofit Using FRP

7-3 Part Two: Repair Methods for Steel Bridges

There are multiple repair methods for steel bridges, but in this section, the heat-straightening repair method will be discussed.

7-3.01 Heat-Straightening Repair Method for Steel Bridge Members

The information presented in this section is from Report No. FHWA-IF-08-999, *Guide for Heat-Straightening of Damaged Steel Bridge Members: Final Draft of the AASHTO Guidelines* (FHWA, 2008). This section is intended to be a brief introduction to the heat-straightening method and simply summarizes the aforementioned report. The readers are referred to the original paper for further details. Specification requirements for this topic are found in *Contract Specifications* Section 60-3.05D, *Existing Structures – Structure Rehabilitation – Repairing Structures – Heat-Straighten Steel Girders;* although the section is reserved in the standard specifications, the project-specific *Special Provisions* will likely govern. SC staff must also reference corresponding BCM 60-3.05D, *Existing Structures – Heat-Straighten Steel Girders,* to understand their responsibilities and procedures for administering contracts involving heat-straightening existing steel girders.

7-3.02 What Is Heat-Straightening?

Heat-straightening is a procedure in which controlled heat is applied in specific patterns to regions of steel members in repetitive heating and cooling cycles to gradually straighten a steel member. The process relies on internal and external restraints that produce thickening (or upsetting) during the heating phase and in-plane contraction during the cooling phase. Heat-straightening is distinguished from other methods in that force is not used as the primary instrument of straightening. Rather, the thermal expansion/contraction is an unsymmetrical process in which each cycle leads to a gradual straightening trend. The process is characterized by the following conditions which must be maintained:

1. The temperature of the steel does not exceed either:
   a. The lower critical temperature (the lowest temperature at which molecular changes occur), or
   b. The tempering limit for quenched and tempered steels.
2. The stresses produced by applied external forces do not exceed the yield stress of the steel in its heated condition.
3. Only the regions in the vicinity of the plastically deformed zones are heated.

When these conditions are met, the material properties undergo relatively small changes, and the performance of the steel remains essentially unchanged after heat-straightening is complete. Properly conducted, heat-straightening is a safe and economical procedure for repairing damaged steel.

7-3.03 History of Heat-Straightening

The origins of heat-straightening can be traced to the early days of welding. Steel fabricators observed how the heat from welding distorted regular patterns. Some of these individuals began to experiment with ways to reverse this distortion by heating the steel in specific patterns to counteract the initial distortion. With experience, some of these technicians developed skills at not only removing weld distortion but repairing other damage as well. These heating procedures developed as an art form passed from one practitioner to the next.

The earliest written information found was traced to Joseph Holt who defined some of the basic concepts of heat-straightening in an unpublished manuscript in 1938. Over the years since, more publications began to appear which tended to be more qualitative than quantitative.

Well into the 1980s, so little was understood about the use of heat-straightening that one-half of the States did not allow heat-straightening repair of bridges (Shanafelt and Horn, 1984). At that time, there were reasons why heat-straightening repair had not been widely accepted. First, the basic mechanism of heat-straightening was not well understood in that the effects of both external restraints (jacking) and internal restraints (redundancy) were thought of as minor concern rather than fundamental to the broad application of the process. Second, as a result of not identifying the importance of these parameters, there had been little documentation of the behavior of vee heated plates subjected to varying degrees of constraint and even less on rolled shapes. Third, while a fair amount of research indicated that most material properties are relatively unaffected by heat-straightening, two important aspects had been overlooked: the influence of strain aging on ductility; and residual stress distribution. Finally, the research information available was predicated almost entirely on laboratory studies of simple elements. The reported field investigations were qualitative rather than quantitative and thus could not serve as a building block for validating heat-straightening.

In August 2008, the aforementioned technical report was published (FHWA-IF-08-999), which presented a comprehensive evaluation of the heat-straightening process. This report provided a scientific basis to enable an engineering evaluation of heat-straightening repairs and provided the methodology for conducting actual repairs.

In the past, heat-straightening has been more of an art than a science. While the fundamental principles and basic methodology are now developed as presented in the

FHWA-IF-08-999 report, heat-straightening is still a skill requiring practice and experience. The proper placement and sequencing of heat combined with control of the heating temperature and jacking forces distinguishes the expert practitioner.

7-3.04 How Heat-Straightening Works

Heat-straightening works based on the following properties of steel:

1. Steel will permanently deform and will not assume its original shape (referred to as plastic deformation) if it is compressed or pulled beyond a certain stress limit (referred to as yield point).
2. Heating between 700 to 1300 degrees F will cause steel to expand at a predictable rate.
3. Heating will lower the stress yield point of steel.

How the above three properties of the steel are used for heat-straightening can be illustrated using an undeformed steel bar clamped snug-tight in the longitudinal direction in a vice. When the undeformed bar is heated in the middle, the heating will lower the stress yield point of the steel at the heated zone. As the steel is heated, it also causes the steel to expand in three dimensions. However, since the steel is restrained from expanding in the longitudinal direction, stresses begin to develop in the steel bar. Eventually, the bar will begin to deform permanently at the locations where the stresses in the bar exceed the yield stress. In this example, the bar will deform and bulge in the middle since the heating zone has been the middle of the bar and the heating has lowered the yield stress limit in the middle. The bar will contract when the heating is removed and the cooling starts. Since the vice does not restrain the bar in contraction, the bar will start to shorten during the cooling process. The net effect of this heating and cooling will be the shortening of the bar and a permanent bulge (commonly referred to as “upsetting”) in the middle of the bar where heat was applied (The redistribution of material is referred to as “plastic deformation” or “plastic flow”). This process is depicted in Figure 7-28.

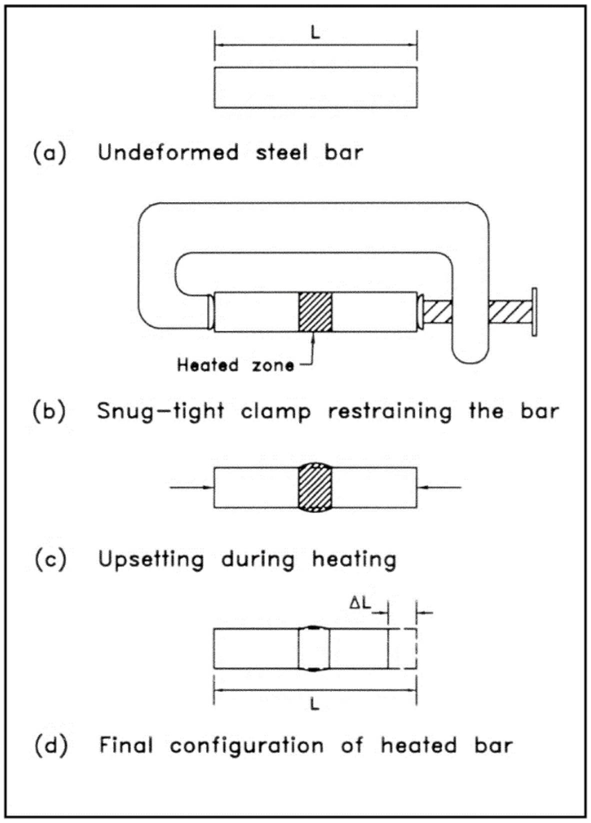


Figure 7-28. Conceptual Example of Shortening a Steel Bar (FHWA, 2008)

The heat-straightening utilizes this "shortening" effect during a heating and cooling cycle of a restrained steel member to repair portions of the member that have been damaged.

7-3.05 Damage Types and Fundamental Heating Patterns

To help understand the heat-straightening process for steel damage repair, two classifications have been developed. The two classifications are:

- Fundamental Damage Patterns
- Fundamental Heat Patterns.

This section will begin by first explaining the purpose of each classification, followed by an explanation of how the two classifications are used to provide a heat-straightening repair plan.

Damage to steel members is uncontrolled distortions, and the deformation in the members can be any shape or pattern. When using heat-straightening to repair the distortion, it is often not evident at first what part of the steel member must be "shortened". To help determine the repair need, fundamental damage patterns have been defined, and for each fundamental damage pattern, the corresponding damaged zone has been identified (commonly referred to as "yield zone"). Accordingly, damage to steel members is then classified into one or more fundamental damage patterns to help determine the repair need. Below is a list of the four fundamental damage patterns and a short explanation for each pattern:

1. **Category/Pattern S**

   This type refers to damage as a result of bending about the "**S**trong" or major axis.

2. **Category/Pattern W**

   This type refers to damage as a result of bending about the "**W**eak" or minor axis.

3. **Category/Pattern T**

   This type refers to damage as a result of **T**orsion or twisting about the longitudinal axis of a member.

4. **Category/Pattern L**

   This category includes damage that is **L**ocalized in nature. Local flange or web buckles, web crippling and damage at bracing locations, as well as bends or crimps in plate elements of a cross-section, typify this behavior.

See Figures 7-29 to 7-32 for an example of each damage pattern.

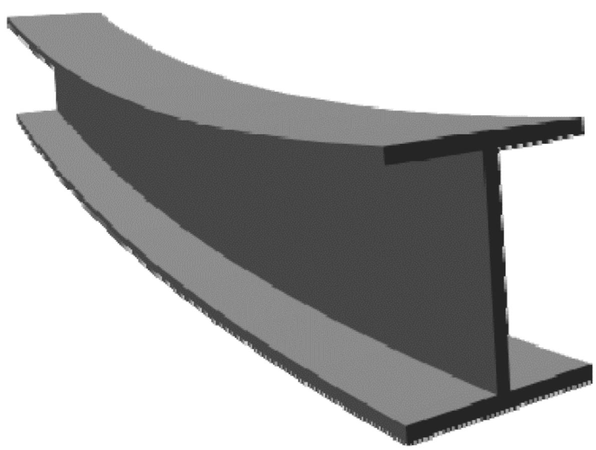


Figure 7-29. Category S-Damage (FHWA, 2008)

Figure 7-30. Category W-Damage (FHWA, 2008)

Figure 7-31. Category T-Damage (FHWA, 2008)

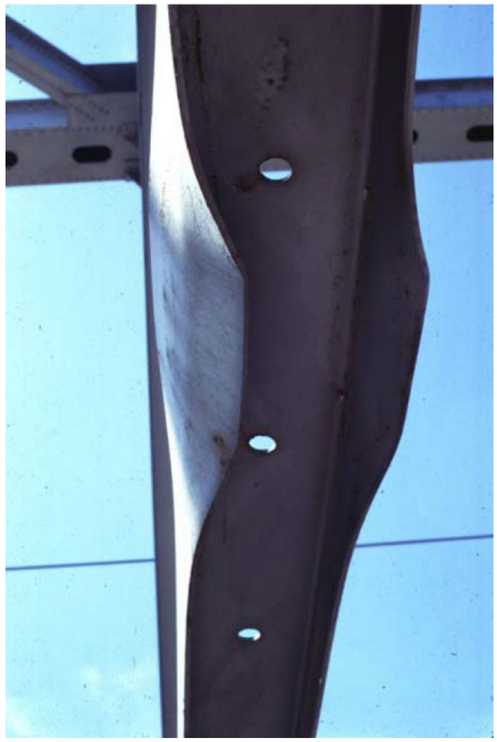


Figure 7-32. Category L-Damage (FHWA, 2008)

After identifying the repair need of a damaged steel member using fundamental damage patterns, the next step is to determine the location/pattern of the heating (as well as the location of the movement restraint) that must be applied to create the required “shortening”/repair. In the simple bar example discussed earlier, the heating was applied uniformly in the middle of the bar while it was restrained longitudinally; this heating pattern created a uniform shortening in the longitudinal direction of the bar. However, heating could have been applied anywhere to the bar and the bar movement could have also been restrained in other directions to create a different “shortening” effect. To help determine how to achieve a required “shortening”, fundamental heating patterns have been developed. Fundamental heat patterns define the location/pattern of heating of steel members (along with any needed restraint) that will result in a specific “shortening” effect. Below is a list of the fundamental heating patterns and a short explanation for each pattern:

1. **Vee heat**:

   The vee heat is the most fundamental pattern. A typical vee heat starts with a very small spot heat applied at the apex of the vee-shaped area using an oxy-fuel torch. When the desired temperature is reached (usually around 1200 degrees F for mild carbon steel), the torch is advanced progressively in a serpentine motion toward the base of the vee; see Figure 7-33 for an example.

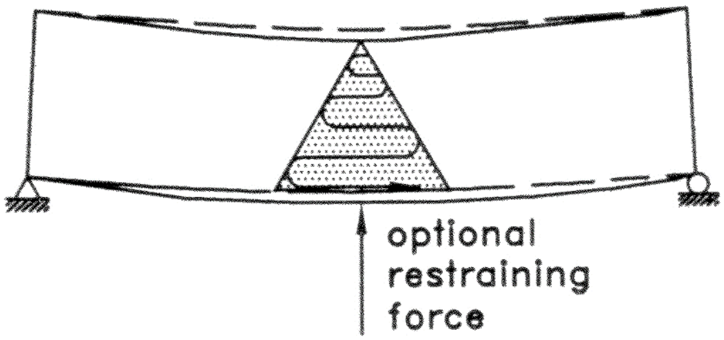


Figure 7-33. Vee Heat Pattern (FHWA, 2008)

2. **Edge heat**:

   If a smooth gentle bend is desired, a line near the edge of the member is heated. The line may be continuous or intermittent, depending on the degree of curvature desired; see Figure 7-34 for an example.

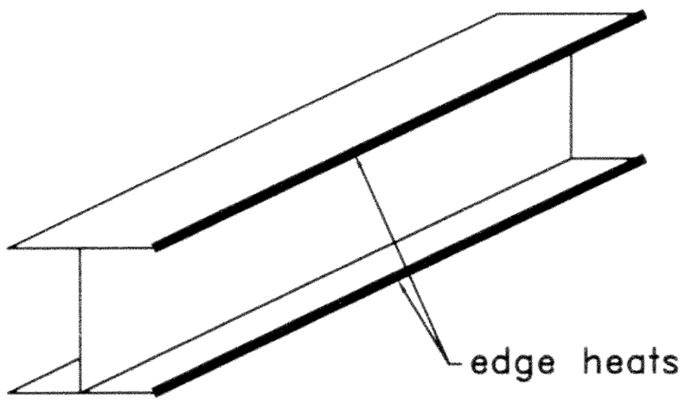


Figure 7-34. Edge Heat Pattern (FHWA, 2008)

3. **Line heat**:

   A line heat consists of a single straight pass of the torch. The restraint in this case is often provided by an external force although some movement will occur without external constraints; see Figure 7-35 for an example.

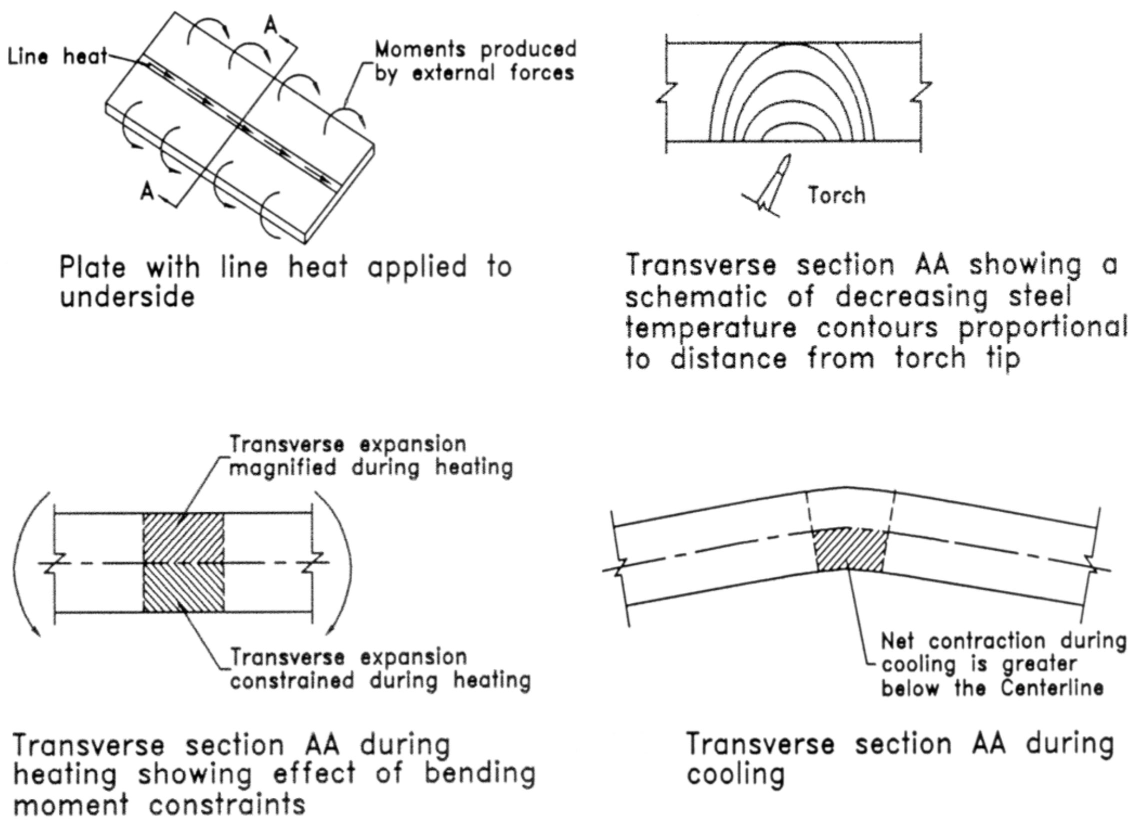


Figure 7-35. Schematic of Line Heat Mechanism (FHWA, 2008)

4. **Spot heats**:

   For spot heat, a small round area of the metal is heated by moving the torch in a slow circular motion increasing the diameter until the entire area of the metal is heated. Spot heat causes upsetting of the metal through the thickness due to the restraint provided by the cool surrounding material. On cooling, a spot heat leaves tensile stresses in all the radial directions across the heated area. During a spot heat, the torch should not be held at a point for too long, as the spot may get too hot and buckling may occur due to excessive thermal expansion on the heated side of the member.

5. **Strip heats:**

   Strip heats, also called rectangular heats, are used to remove a bulge in a plate element or to complement a vee heat. Strip heats are similar to vee heats and are accomplished in like manner. Beginning at the initiation point, the torch is moved back and forth in a serpentine fashion across a strip for a desired length. This pattern sequentially brings the entire strip to the desired temperature. The orientation can be an important consideration. The strip heat may be initiated at the midpoint and moved toward both edges simultaneously using two torches. This approach would minimize the weak axis bending of the beam. A second alternative with a similar effect is using a single torch and starting from one side. Depending on the structural configuration, the strip may also be started at a free edge. See Figure 7-36 for an example of strip heat.

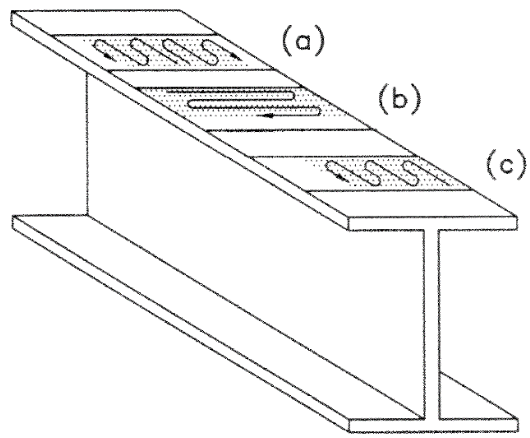


Figure 7-36. Strip Heat Pattern (FHWA, 2008)

To understand the heat-straightening process, correlations are made between each damage pattern to one or more heating patterns. In other words, damage patterns will help identify the repair need. In addition to correlating a heat pattern or a group of heat patterns, the sequence of heat application is also important for repairing damage. The process of applying a group of heating patterns in each sequence followed by cooling down of material afterward is commonly known as a heating cycle. To repair steel damage, a heating cycle must frequently be repeated several times before the repair is complete. See Figures 7-37 to 7-40 below for a description and illustration of the heating cycle needed for each type of bridge damage (in other words, the figures below correlate bridge damage patterns to a group of heating patterns applied in a sequence).

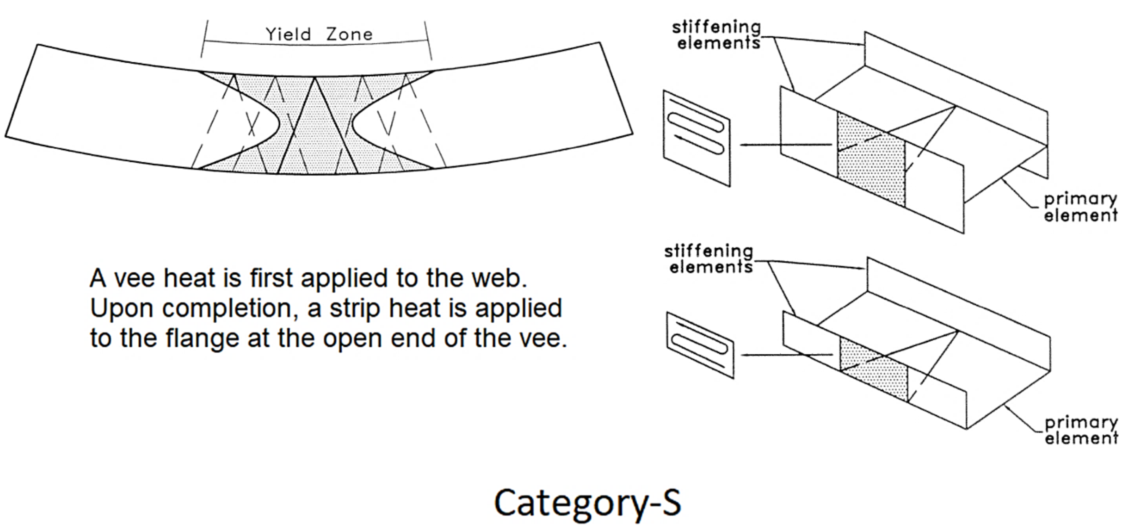
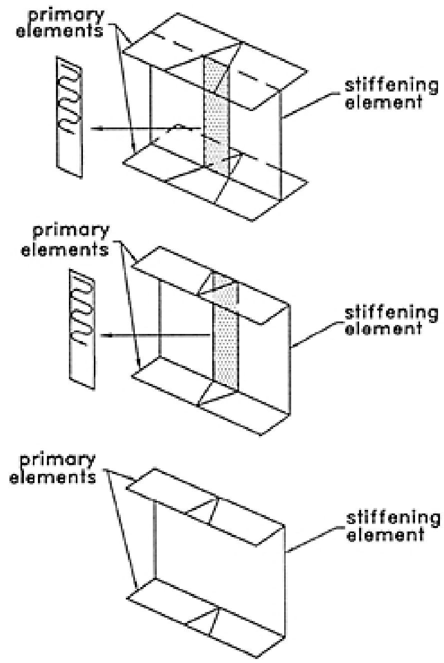


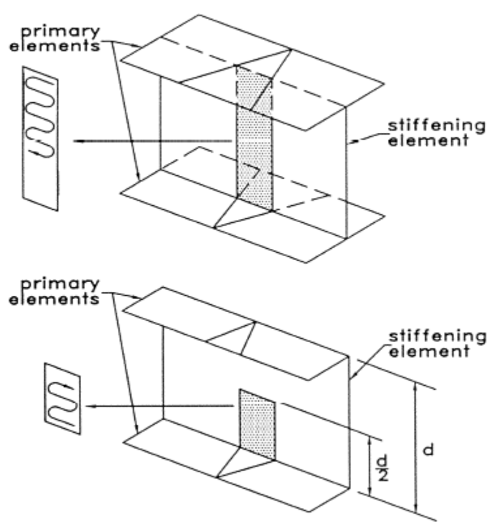
Figure 7-37. Category-S Damage & Heating Pattern (FHWA, 2008)



The vee heat is first applied to both flanges (either simultaneously or one at a time) After heating these primary elements, a strip heat is applied to the web.

Category-W

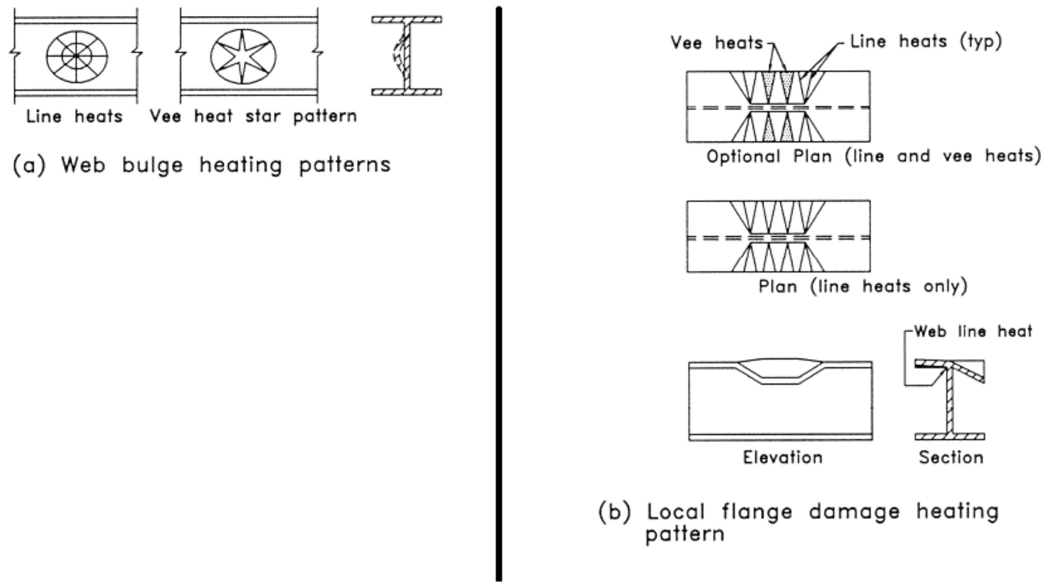
Figure 7-38. Category W Damage & Heating Pattern (FHWA, 2008)



The vees on the top and bottom flange are reversed to reflect the different directions of curvature of the opposite flanges. The vee heats are applied first and then the strip heat is applied. Note that for the channel, the strip heat need only be applied to half depth. This half depth strip allows the lower flange vee to close with minimal restraint from the web.

Category-T

Figure 7-39. Category T Damage & Heating Pattern (FHWA, 2008)



A local buckle or bulge requires the bulging area to be shortened. A series of vee or line heats can be used. These vees are heated sequentially across the buckle or around the bulge. For web bulges either lines or vees may be used. If vees are used, they are spaced so that the open ends of the vees touch.

Category-L

Figure 7-40. Category L Damage & Heating Pattern (FHWA, 2008)

To summarize this section, the heat-straightening process is simplified as follows:

Step 1- Classify any steel member damage into one or more damage pattern.

Step 2- For each of the damage patterns identify the required heating pattern.

Step 3- Repeat the heating pattern with the number of cycles necessary to repair damage.

7-3.06 Challenges of Heat-Straightening Process and Required Qualification of Contractor

While the understanding of the heat-straightening process can be made simple, the actual practice of heat-straightening is challenging and requires significant experience and skill for its proper application. Some challenges and considerations are discussed below:

1. Complexity of damage- Most damage is a combination of the basic types and the repair patterns can be complex. It is often challenging to properly identify the damage category and to plan the heat cycles.

2. Selection of equipment and its use- Even though the primary tool for heat-straightening is a simple heat torch, it requires the selection of an appropriate setting, including an appropriate ratio of gas mixture, gas pressure, and correctly sized tip orifice. Additionally, considerable skill is required to quickly determine how long to apply enough heat without overheating; the timing is dependent on the thickness of steel material and the ambient temperature. The operator must have sufficient experience to be able to quickly decide how to determine and adjust the appropriate flame temperature and to apply it for the proper length of time.
3. Location of restraints- The Contractor performing the work needs to properly locate and size the required restraints.
4. If the beam is a simple span and non-composite, some form of temporary support will likely be required.
5. Often, the intermediate diaphragms and bolted angle attachments will need to be replaced.
6. At times, a high load hit will result in tearing of the girder web and/or bottom flange that will require repairs after the heat-straightening is done.
7. Safety items:
    a. Gases used for heat-straightening are extremely volatile. Correct handling, storage of tanks, and hose management are very important.
    b. Heat-straightening is often applied to an elevated bridge surface. Fall protection is very important. Experience in operating the equipment safely is required to perform the repairs on elevated surfaces.
    c. High temperature of heated surfaces requires constant attention to avoid getting burned.

As a result, contracts often specify requirements for contractors to demonstrate qualification and expertise in performing heat-straightening operations.

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