JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Synthesis Study: Repair and Durability of Fire-Damaged Prestressed Concrete Bridge Girders

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16. Abstract
Recent research results from INDOT research project SPR-4221 indicate that the damage to prestressed concrete bridge girders from an intense hydrocarbon fire is limited to concrete material degradation up to a depth of 1 inch from the surface. Additionally, concrete cracking and spalling occur in the fire-damaged region, but the structural strength (flexure and shear) of fire-exposed prestressed concrete bridge girders is not compromised. The findings open the possibility for repairing damaged bridge girders and answers questions regarding the durability of damaged-unrepaired and damaged-repaired girders.

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EXECUTIVE SUMMARY

Introduction

This project focused on investigating current knowledge of assessments and repair/retrofit methods for prestressed concrete bridge girders subjected to fire. A synthesis study was conducted to gather and organize research-based, practical information, which included a survey of practice, and review existing documents. The knowledge obtained from the survey study and detailed literature review was analyzed and synthesized to form more insight into the plausible treatments for fire-damaged bridges. The primary topics for this study were (1) repair/retrofit methods for prestressed concrete bridge girders, (2) assessing the structural performance (serviceability and strength) of repaired girders, and (3) assessing the durability of damaged, unrepaired, and repaired prestressed girders. With the aid of this study, bridge inspectors and engineers will have a proper reference to develop a rational post-fire assessment/repair plan for the concrete bridge girders with various levels of fire damage.

Findings

The research team prepared a survey form (online and paper-based) and distributed it to transportation representatives from all 50 states. The questionnaire assessed current practices for post-fire assessment and listed commonly used repair/retrofit methods for prestressed concrete bridge girders that sustain different levels of fire damage. Afterward, responses were received from 19 states. In general, not many cases regarding fire-damaged concrete bridges can be studied, and the damage level of available cases is mainly minor (concrete cracks and shallow spalls which do not affect tendons) or moderate (large concrete cracks and spalls and exposed, undamaged tendons). Based on the survey results, most respondents will choose not to repair the damaged bridges for concrete bridges with minor fire damage. On the other hand, bridges with moderate fire damage are usually repaired using various methods (e.g., patch concrete, concrete replacement, and steel/FRP jacketing). Lastly, most agencies prefer to replace the entire damaged structure when a concrete girder bridge undergoes significant fire damage (exposed and damaged tendons; loss of a portion of cross-section), although it rarely happens.

Two case studies about prestressed concrete bridges that experienced serious fire incidents were reviewed. These studies reported the distribution and severity of fire-induced damage to the target bridges. Moreover, different potential repair strategies were also investigated and implemented to restore the damaged bridges. These studies suggest that concrete bridge girders mostly have superficial concrete damage after severe fire scenarios (e.g., 5 hours of burning, which raised the concrete surface temperature to 1,112°F (600°C)). On the contrary, the degradation of the steel strands' mechanical properties and prestressing force may be localized and insignificant, which agrees with the findings obtained from the survey study and previous INDOT research project SPR-4221.

Next, the research team reviewed the documents and standard specifications about the damage level classification and repair methods of fire-damaged concrete bridges. Features and limitations of different retrofit strategies are discussed and presented, and they mainly include (1) concrete surface repair, (2) patch concrete, (3) pressure-injection of epoxy resins, (4) concrete removal/cast-in-place concrete, (5) tendon cleaning/coating, (6) steel encasement, (7) Fiber Reinforced Polymer (FRP) wrapping, and (8) replacing the damaged structure. After comparison, the Carbon Fiber Reinforced Polymer (CFRP)-based repair techniques was found to be more advantageous than other alternatives for restoring fire-damaged concrete bridges. However, the fire resistance of FRP-based repair may be a concern since the commonly used epoxy adhesive system is fragile at high temperatures (with a suggested maximum service temperature range of 140°F to 180°F (60°C to 82°C)). Therefore, in some fire-critical cases, cement-based adhesive or fireproofing systems may be necessary.

Implementation

Based on the survey study and the literature review results, the damage levels for concrete girders subject to fire incidents are primarily minor or moderate (without significant section loss and damaged tendons). Different repair techniques can be considered to restore these damaged bridge girders. The repair methods recommended in the literature are similar to the retrofit approaches adopted by survey respondents. It is worth noting that most survey respondents claimed that there are no perceived issues with the durability and serviceability of the repaired bridge if the repair is performed successfully. Nevertheless, due to the limited cases and lack of existing studies on unrepaired or repaired fire-damaged concrete girders, their long-term performance and durability may be questionable. Hence, additional research is needed to address these concerns. Finally, for the extreme and unusual case that the concrete bridge experienced significant fire damage, it is recommended to replace the entire bridge structure due to the uncertain structural performance that will result from repairing such a high level of damage.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Recent research results from INDOT research project SPR-4221 (Varma et al., 2021) indicate that the damage to prestressed concrete bridge girders from an intense hydrocarbon fire is limited to concrete material degradation up to a depth of one inch from the surface. In addition, concrete cracking and spalling occurs in the fire-damaged region, but the structural strength (flexure and shear) of fire exposed prestressed concrete bridge girders is not compromised. The findings open the possibility of repairing damaged bridge girders and questions regarding the durability of damaged-unrepaired and damaged-repaired girders.

There is limited experience in Indiana in repairing damaged prestressed concrete bridge girders and testing for evaluating the durability of repaired girders. Additionally, there is little to no experience in the repair of fire-damaged prestressed concrete bridge girders, as most of them have been replaced in the past. The results from SPR-4221 (Varma et al., 2021) have challenged this conventional wisdom but raised questions regarding the feasibility, economy, and legality of repairing fire-damaged girders and their long-term durability. Therefore, a synthesis study is needed to gather the current state of knowledge from various research literature and transportation agencies to learn about the techniques and practices employed to evaluate/restore the prestressed concrete bridge girders that have experienced elevated temperatures.

1.2 Project Objectives

The goals of this project are to conduct a synthesis study for (1) repair/retrofit methods for prestressed concrete bridge girders, (2) assessing the structural performance (serviceability and strength) of repaired girders, and (3) assessing the durability of damaged, unrepaired, and repaired prestressed girders.

A survey of state transportation representatives was performed to investigate the following.

- What are conditions, reasons, justifications, legal implications, and decision-making processes when the repair is recommended in lieu of replacement of a damaged prestressed girder?
- What parameters/techniques are employed to evaluate the severity of the fire-induced damage and determine the possibility of repairing the damaged bridge girder?
- What methods/approaches are usually used to properly restore the structural performance and serviceability of the concrete bridge that sustained fire impact?
- How is the structural performance assessed, including serviceability, longevity, and strength of the repaired prestressed bridge girder when the girder is repaired?

Subsequently, a detailed literature review, synthesis, and analysis of the survey results were conducted and focused on (1) repair methods, decision-making processes, (2) structural performance assessment of damaged/damaged-repaired girders, (3) assessment methods to determine "acceptable performance" including long-term durability, and (4) post-repair inspection methods, plans, and frequency. The study presented in this report aims to assist bridge inspectors and engineers in developing an appropriate plan to restore the fire-damaged bridge to its expected strength and serviceability performance, concerning the safety and efficiency issues of different probable schemes.

2. SURVEY STUDY

2.1 Overview of Survey Study

The research team prepared a survey form (online and paper-based version), and INDOT distributed it to transportation agencies from other states. The survey form is developed based on the survey study proposed by Harries et al. (2009) (primarily addressing the vehicular impact damage) to gather the current practices about the post-fire assessment and typically adopted repair/retrofit methods for prestressed concrete bridge girders impacted by the fire exposure. The questionnaire aims to answer the following questions: (1) What organizations usually develop and implement the repair plan for fire-damaged bridge girders. (2) What parameters affect the determination of the repair/retrofit strategies. (3) How many prestressed concrete bridges have experienced fire damage (with various degrees of damage), and what techniques/tools are usually used to determine the extent of fire-induced damage. (4) What methods are employed to repair prestressed concrete girders sustained different levels of fire damage. (5) How is the structural performance evaluated, including serviceability, longevity, and strength of the repaired/unpaired prestressed bridge girder. In summary, there are 22 questions in the questionnaire, and the degree of fire-induced damage in the survey form is classified into three levels: minor damage, moderate damage, and significant damage. The definition for each damage level is developed according to the descriptions in Table 4.1 and showed as follows.

- *Minor damage:* concrete cracks and shallow spalls which do not affect tendons.
- *Moderate damage:* large concrete cracks and spalls; exposed, undamaged tendons.
- *Significant damage:* exposed and damaged tendons; loss of portion of cross section.

A copy of the survey form is provided in Appendix A, and it was delivered to transportation agencies in the other 50 states. Responses were received from representatives of 19 states. It is worth noting that the survey was conducted anonymously to increase the rate and quality of the responses. Therefore, this survey study did not collect personally identifiable information from respondents. Moreover, although 19 agencies responded to the survey and provided their experience with concrete bridge girders subjected to fire, most of the agencies indicated that they do not have much experience with the bridge girders with *significant* fire damage. Some respondents even mentioned that no concrete bridge sustained fire incidents in their jurisdictional areas over the last 5 years. Hence, some of the responses were based on respondents' knowledgeable judgments assuming that fire scenarios happen and damage concrete bridge girders.

The responses and feedback from survey respondents are presented and discussed in the following sections, and the provided comments have not been edited except for several typographical errors. The results are demonstrated by the number of respondents who select each answer. Moreover, charts are provided to present the distribution of different responses more clearly for some questions.

2.2 Survey Results

Respondents were asked to indicate who usually prepares the plans for repair/retrofit of fire-damaged prestressed girders in Q1 (from the provided options, see Table 2.1) and provide their comments in Q2 (Table 2.2) if they select "Other" in Q1. It should be noted that respondents were allowed to select one or more answer choices in Q1. "DOT/district design/bridge engineer" (74% of respondents) and "Private consultant" (42% of respondents) are two more popular choices. Four respondents claimed to let DOT/district maintenance engineer develop the related repair/retrofit plan for fire-damaged girders. At last, three respondents selected "Other" in the first question and provided their comments in Q2.

In Q3 (Table 2.3), respondents were asked to answer who usually performs the constructions for repair/retrofit of fire-damaged prestressed girders and provide their comments in Q4 (Table 2.4) if they select "Other" in Q3. In this question, respondents could choose one or more answer choices in Q3 "Private contractor" was checked by most respondents (84%), and eight respondents indicated that they may have DOT/district/agency personnel perform the construction activities. Furthermore, one respondent (Respondent 14) said the low bid contractors usually perform the repair/retrofit constructions for the transportation agency.

In Q5 (Table 2.5), respondents were asked to rate the importance of different factors that may affect their development of repair plans for the fire-damaged prestressed concrete bridges. The respondents who selected the answer choice "Other" could provide their comments in Q6 (Table 2.6). Figure 2.1 summarizes the survey results for the Q5. As shown in the figure, the bridge's load capacity has the top priority in determining the repair strategies, and all respondents claimed this factor is highly important. Moreover, the expected service life of repair (68% of respondents) and interruption of service (53% of respondents) were also selected by most respondents as highly important factors in their decision-making processes. Finally, two respondents chose the "Other" answer option and provided their additional comments in Q6.

TABLE 2.1
Q1. Plans for the repair/retrofit of fire-damaged prestressed girders are usually prepared by (select all that apply)

14	DOT/district design/bridge engineer
4	DOT/district maintenance engineer
8	Private consultant
3	Other (please describe in Question 2)

TABLE 2.2
Q2. Please provide your answer if you select "Other" in Question 1. You can skip this question if not applicable

Respondent 1	Maryland does not build prestressed girder bridges over roadways, so the chances of a fire are extremely rare. If we did have a situation, we would not repair, but replace.
Respondent 5	We perform about 50% of our design work in-house and 50% with consultants. Depending on the size and scope of the repairs, we could assign this work to either.
Respondent 9	Director, Division of Maintenance, KYTC

TABLE 2.3
Q3. Construction of repair/retrofit is usually performed by (select all that apply)

8	DOT/district/agency personnel
16	Private contractor
1	Other (please describe in Question 4)

TABLE 2.4
Q4. Please provide your answer if you select "Other" in Question 3. You can skip this question if not applicable

Respondent 14	Low bid contractor

TABLE 2.5
Q5. Rate the following factors by importance in the determination of the method of repair

	Low	Moderate	High	Not Considered
Cost of repair	3	9	7	0
Time required to make repair	0	10	9	0
Aesthetics of repair	11	7	1	0
Interruption of service	0	9	10	0
Load capacity	0	0	19	0
Expected service life of repair	0	6	13	0
Maintenance required	1	10	7	1
Other (please specify in Question 6)	0	0	2	17

TABLE 2.6
Q6. Please provide your answer if you select "Other" in Question 5. You can skip this question if not applicable

Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 14	Repair constructability, insurance claim limitations

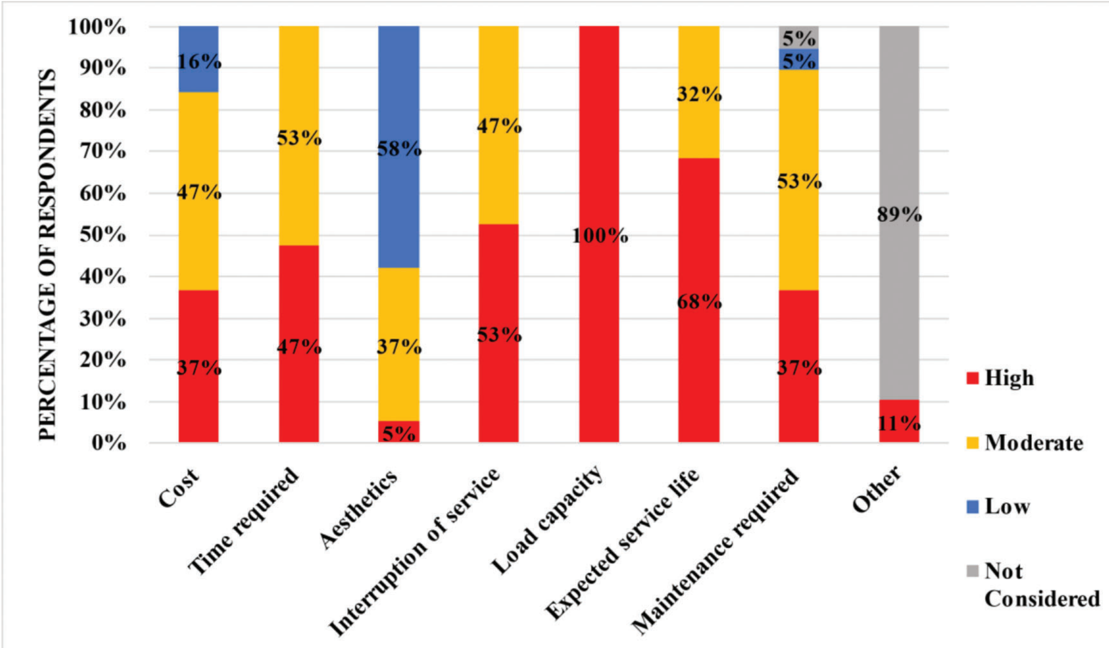

Figure 2.1 Results of Question 5.

TABLE 2.7
Q7. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degree of damage (write N/A if there was no bridge being damaged by fire in this level based on your judgement). *Minor damage:* concrete cracks and shallow spalls which do not affect tendons

Respondent 1	Zero
Respondent 2	One incident in the past 5 years with only minimal surface damage and no visible cracking or exposed reinforcing or pre-stressing steel
Respondent 3	few
Respondent 4	N/A
Respondent 5	0
Respondent 6	N/A
Respondent 7	2 in the last 5 years
Respondent 8	2
Respondent 9	0
Respondent 10	N/A
Respondent 11	2
Respondent 12	One
Respondent 13	N/A
Respondent 14	N/A
Respondent 15	1
Respondent 16	N/A–none known
Respondent 17	NA
Respondent 18	1
Respondent 19	5

In Q7 (Table 2.7), respondents were asked to estimate the number of fire-damaged (with minor damage) prestressed concrete bridges in their judgments over the last 5 years. Only Respondent 19 stated that five concrete bridges sustained minor fire damage in their district. On the contrary, eight respondents reported that only a few concrete bridges had sustained minor fire-induced damage in their jurisdictional areas; and a total of ten respondents pointed out that they do not have the related experience.

TABLE 2.8
Q8. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degree of damage (write N/A if there was no bridge being damaged by fire in this level based on your judgement). *Moderate damage:* large concrete cracks and spalls; exposed, undamaged tendons

Respondent 1	Zero
Respondent 2	None
Respondent 3	2
Respondent 4	N/A
Respondent 5	0
Respondent 6	N/A
Respondent 7	1 in the last 5 years
Respondent 8	0
Respondent 9	2
Respondent 10	N/A
Respondent 11	0
Respondent 12	None
Respondent 13	N/A
Respondent 14	1
Respondent 15	0
Respondent 16	N/A–none known
Respondent 17	2 bridges
Respondent 18	N/A
Respondent 19	8

In Q8 (Table 2.8), respondents were asked to estimate the number of fire-damaged (with moderate damage) prestressed concrete bridges in their judgments over the last 5 years. Only Respondent 19 stated that eight concrete bridges experienced that degree of fire damage in their region. However, five respondents reported that less than two concrete bridges had sustained moderate fire damage in their areas; and a total of 13 respondents stated that they do not have the related experience.

Results in Q9 (Table 2.9) indicate that most transportation agencies lack experience in dealing with concrete bridge girders with significant fire damage (e.g., the prestressing strands are exposed and damaged by fire). For example, only four agencies declared that they had few cases in the last 5 years, whereas the rest stated that they do not have concrete bridges in their regions that sustained significant fire-caused damage.

In Q10 (Table 2.10), respondents reported their typical actions to repair/retrofit the prestressed concrete bridges subjected to various degrees of fire damage, and the results are presented in Figure 2.2. It is worth noting that respondents could select one or more answer choices in this question. It can be observed that 13 respondents (68%) stated that they would perform a non-structural repair to the concrete bridge with minor fire-caused damage. On the other hand, 14 respondents (74%) indicated that the load-carrying repair is their preferred choice for the bridges with moderate fire damage. Lastly, 16 respondents (84%) mentioned that the concrete bridge that experienced significant fire damage would be replaced by the new structure based on their judgments.

TABLE 2.9
Q9. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degrees of damage (enter N/A if there was no bridge being damaged by fire in this level based on your judgement). ***Significant damage:*** **exposed and damaged tendons; loss of portion of cross section**

Respondent 1	Zero
Respondent 2	None
Respondent 3	2
Respondent 4	N/A
Respondent 5	0
Respondent 6	N/A
Respondent 7	N/A–none in the last 5 years
Respondent 8	0
Respondent 9	0
Respondent 10	N/A
Respondent 11	0
Respondent 12	One
Respondent 13	N/A
Respondent 14	N/A
Respondent 15	0
Respondent 16	N/A–none known
Respondent 17	1 bridge
Respondent 18	N/A
Respondent 19	3

In Q11 (Table 2.11), respondents were asked to indicate the typically adopted procedures for evaluating the extent of the damage if they determine to repair the fire-damaged concrete bridges. Moreover, respondents could provide their additional comments in Q12 (Table 2.12). Figure 2.3 summarizes the survey results for the Q11. Based on the survey result, most respondents selected visual inspection (89%) as their commonly used process to assess the damage condition. In contrast, non-destructive (37%) and destructive (11%) evaluation processes were checked by fewer respondents. In addition, based on the provided comments in Q12, concrete sounding seems to be a favored non-destructive technique to evaluate the extent of fire damage, which seven respondents suggested. However, respondents also stated that the sounding process might further damage the bridge element according to the area of fire damage.

In Q13 (Table 2.13), respondents were asked to answer the typically used analytical procedures to assess the fire-induced damage and the need to repair prestressed concrete bridges, and respondents could provide their additional comments in Q14 (Table 2.14). Figure 2.4 shows the survey results of this question. As shown, bridge/structure analysis software (47%) and hand calculation (37%) are two procedures commonly employed by the respondents. Moreover, the comments in Q14 demonstrate that different respondents typically use various types of analysis software (e.g., BrR, PGSuper, and Conspan). For the hand calculation, *AASHTO LRFD Bridge Design Specifications* and ACI 440.2R-08 are two design specifications that respondents mentioned.

Respondents provided their opinions/experiences regarding repairing prestressed concrete bridges with minor fire damage in Q15 (Table 2.15), and their additional comments are presented in Q16 (Table 2.16). The results are organized and shown in Figure 2.5. It is noticeable that the option "do nothing" is the most commonly used strategy in this case (74%). Moreover, more than half of respondents chose the patch concrete method (58%) and concrete surface repair method (53%) as preferred methods. On the other hand, pressure injection of epoxy resins is a relatively unpopular choice, and it was selected by 26% of respondents as a

TABLE 2.10
Q10. What actions are typically taken for the following degrees of damage (use definitions for the damage levels in Questions 7 to 9)?

	No Repair Made	Non-Structural Repair	Load-Carrying Repair	Replace Member or Structure
Minor	6	13	0	1
Moderate	2	3	14	1
Significant	2	0	1	16

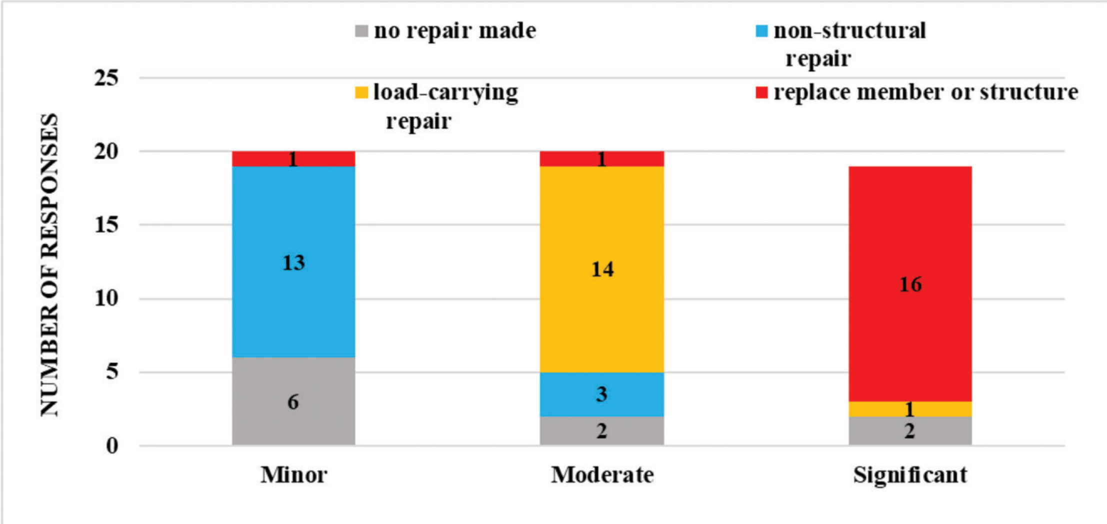

Figure 2.2 Results of Question 10.

TABLE 2.11
Q11. For cases where repair action is finally taken, what procedures are used to determine the extent of the damage?

	Commonly	Rarely	Never	n/a
Visual inspection	17	0	0	2
Non-destructive evaluation (NDE/NDT). Which methods are typically used? (please describe in Question 12)	7	8	0	4
Destructive evaluation. Which methods are typically used? (please describe in Question 12)	2	7	4	6
Other (please describe in Question 12)	1	1	0	17

TABLE 2.12
Q12. Please provide the supplementary answer for your responses in Question 11. You can skip this question if not applicable

Respondent 1	As mentioned in Question 2, Maryland SHA does not build these types of bridges over roadways and have never had fire damage to a prestressed girder bridge. If we did have fire damage, the bridge would likely be replaced.
Respondent 2	Surface cleaning and visual inspection, hammer sounding and Schmidt Hammer measurements
Respondent 5	Pachometer, GPR
Respondent 6	Soundings and core samples for lab testing
Respondent 7	Sounding of concrete coring of beams
Respondent 9	Sounding of concrete members
Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 14	Sounding with hammer core samples taken from beams and/or substructure for petrographic analysis
Respondent 15	Would hire a consultant to determine the correct NDT methods for assessing the damage
Respondent 16	Visual, hand-on inspection is very common for all types of damages, not just fire damage of PC bridges. Nondestructive testing may be used to get a better insight of the extent of damage, if damage is not too severe and a decision is made to preserve the structure.
Respondent 17	Typically, the damaged area is sounded. Depending on the extent of the fire damage, the element could be damaged further during the sounding process.
Respondent 19	Hammer sounding is standard to determine extent of delamination. Removing delaminated concrete is also part of the inspection process.

common method to repair minor fire damage. Lastly, Respondent 12 and Respondent 17 also mentioned that they often employ FRP (or CFRP) material to wrap and confine the damaged/patched areas.

In Q17 (Table 2.17), respondents were asked to provide their judgments for repairing prestressed concrete bridges with moderate fire damage and give their additional comments in Q18 (Table 2.18). The survey results

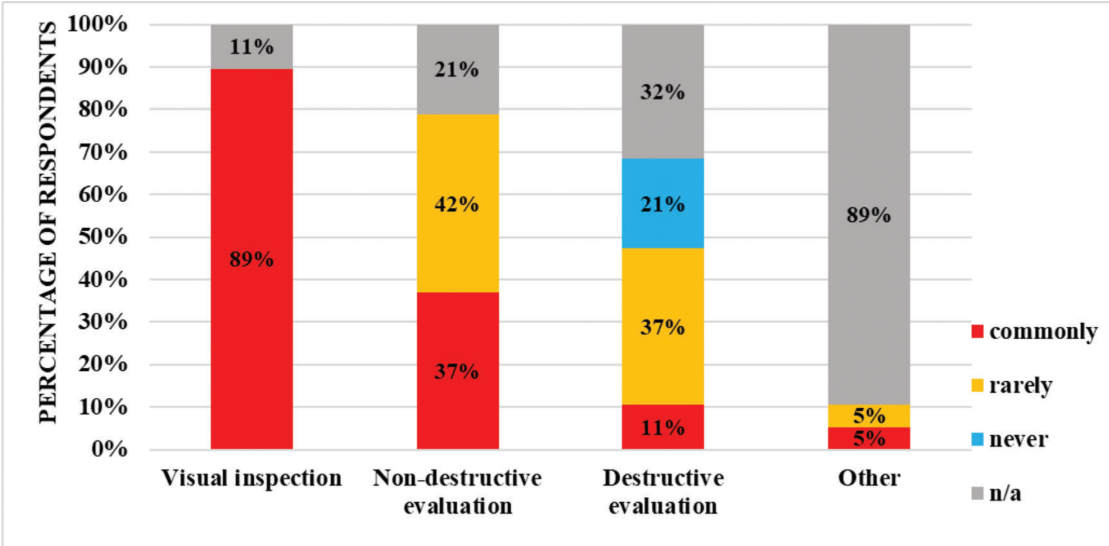

Figure 2.3 Results of Question 11.

TABLE 2.13
Q13. What analytical procedures are used to assess the fire-induced damage and the need for repair of prestressed concrete bridges?

	Commonly	Rarely	Never	N/A
Hand calculation. Which codes/specifications are typically used? (please describe in Question 14)	7	4	1	7
Bridge/structure analysis software. Which software is typically used? (please describe in Question 14)	9	5	0	5
Finite element analysis software. Which software is typically used? (please describe in Question 14)	1	8	2	8
Other (please describe in Question 14)	1	0	0	18

TABLE 2.14
Q14. Please provide the supplementary answer for your responses in Question 13

Respondent 2	Reduced f′c based upon assumed fire temperature and duration then recalculated girder load rating
Respondent 5	LRFD design specs
Respondent 6	FDOT developed beam design software, supplemented by a proprietary software, such as CONSPAN
Respondent 7	Codes: *AASHTO LRFD Bridge Design Specifications* structural analysis: In house load rating software FEA: typically performed by a consultant, thus the consultant selects the software
Respondent 9	LARS
Respondent 11	Use current design specifications if possible, or match the ones used at the time of construction. Goal is to have no change in the load rating or decrease in load carrying capacity
Respondent 12	Bridge rating software typically such as BrR or PC-LARS. Possibly beam analysis software such as PGSuper
Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question
Respondent 14	AASHTOWare load rating software, in-house bridge design software
Respondent 15	Typical prestressed girder design software such as Bentley Conspan or Conspan
Respondent 16	Basic hand computations backed up with the commercially available design software may be used in the repair design. All new designs and repair designs are done in accordance with AASHTO LRFD, state specifications, supplemental specifications and job specific special provisions.
Respondent 17	Hand calculations—ACI 440.2R-08 Analysis software from Bentley and Midas
Respondent 18	Current codes if possible or the code when the bridge was built
Respondent 19	Beam analysis is common to account for the loss of prestressing strands because assumed loss of bond of strands related to longitudinal cracking (PG Super, PSTRS14).

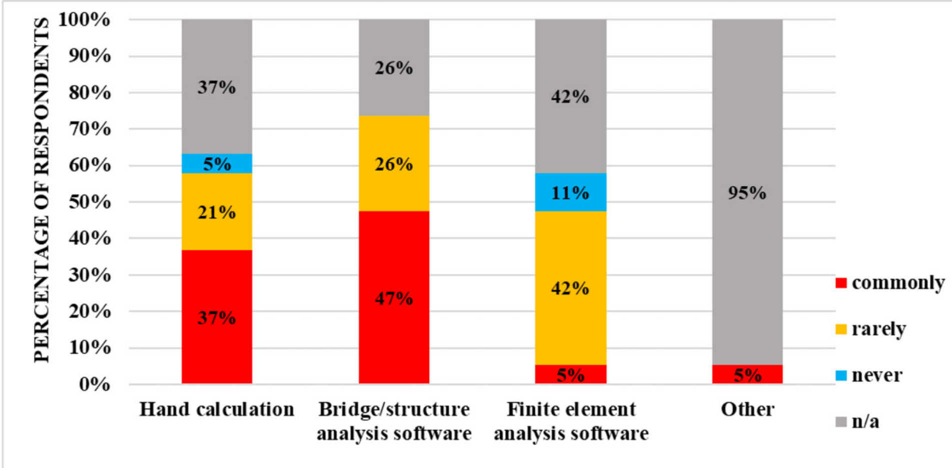

Figure 2.4 Results of Question 13.

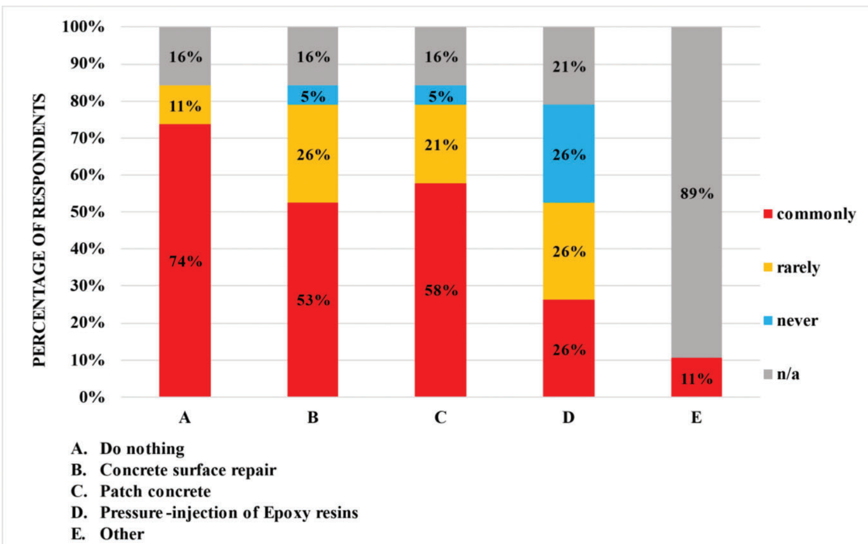

Figure 2.5 Results of Question 15.

TABLE 2.15
Q15. What methods are used to repair prestressed concrete bridges with minor damage (concrete cracks and nicks; shallow spalls and scrapes not affecting tendons)?

	Commonly	Rarely	Never	N/A
Do nothing	14	2	0	3
Concrete surface repair	10	5	1	3
Patch concrete	11	4	1	3
Pressure-injection of epoxy resins	5	5	5	4
Other (please describe in Question 16)	2	0	0	17

TABLE 2.16
Q16. Please provide your answer if you select "Other" In Question 15. You can skip this question if not applicable

Respondent 2	Surface cleaning and removing debris from below bridge
Respondent 12	FRP wrap to contain/confine patch is typical
Respondent 13	We do not have very many fire-damaged prestressed girders, so it is difficult to answer this question.
Respondent 17	Wrapping the damaged area with CFRP

TABLE 2.17
Q17. What methods are used to repair prestressed concrete bridges with moderate damage (large concrete cracks and spalls; exposed, undamaged tendons)?

	Commonly	Rarely	Never	N/A
No bridge being damaged by fire in this level based on your judgement	5	0	0	14
Do nothing	1	5	4	9
Patch concrete	12	0	0	7
Shotcrete	1	7	1	10
Pressure-injection of epoxy resins	7	4	1	7
Concrete removal/Cast-in-place concrete	12	0	0	7
Steel/FRP jacketing	4	8	0	7
Tendon cleaning/coating	5	6	0	8
Installation of active or passive corrosion control measures	3	1	6	9
Replace individual girder	3	4	4	8
Replace bridge	1	1	8	9
Other (please describe in Question 18)	1	0	0	18

TABLE 2.18
Q18. Please provide your answer if you select "Other" in Question 17. You can skip this question if not applicable

Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 17	Entire span may be replaced
Respondent 19	CFRP

of Q17 are displayed in Figure 2.6. Based on the received responses, the patch concrete method and concrete removal/cast-in-place concrete are suggested by most respondents (63%). Besides, pressure injection of epoxy resins (37%), tendon cleaning/coating (26%), and steel/FRP jacketing (21%) are three methods that were selected by more than 20% of respondents as their preferable repair methods in this scenario. It should be noted that, in this damage level, three respondents (Respondents 3, 10, and 17) claimed that they might replace the damaged bridge girders, and Respondent 3 indicated that the entire bridge might be replaced depending on the extent of the damage.

In this question, 26% of respondents stated that the concrete bridge experienced moderate fire damage rarely happens in their areas, and 74% of respondents answered "n/a" for this option, which produces the difficulty to judge the real fire-damaged cases that each respondent had experienced. Therefore, the survey results of Q8 should be more representative in reflecting the experience of different respondents.

In Q19 (Table 2.19), respondents indicated their decisions to deal with a prestressed concrete bridge sustained significant fire damage, and they could provide additional comments in Q20 (Table 2.20). The results of Q19 are demonstrated in Figure 2.7. In this case, 47% of respondents claimed that they would replace the fire-impacted bridge girder, and 26% of respondents pointed out that the whole bridge might need to be entirely reconstructed. Except for these two options, steel/FRP jacketing (32%), concrete removal/cast-in-place concrete (26%), and patch concrete method (21%) are suggested by more than 20% of respondents. It is worth noting that, similar to Q17, even though 32% of respondents stated that the significant fire damage on the concrete bridge is a rare situation in their areas, which does not imply that the other respondents often experience significant fire damage. In this case, the results of Q9 should be more representative in reflecting each respondent's experience.

In Q21 (Table 2.21), respondents were asked to share their judgments on the performance of fire-damaged and unrepaired prestressed concrete bridges based on their experience. Based on the responses, most respondents do not have the corresponding experience that fits the problem's description, and only Respondents 3, 7, 11, 17, and 18 stated that the performance of unrepaired bridges might be unaffected and acceptable if the fire-induced damage is minor. However, Respondent 9 mentioned that, due to the salt intrusion, even the minor damage could degrade the service life of the bridge.

In Q22 (Table 2.22), respondents shared their experience with the performance of fire-damaged and repaired prestressed concrete bridges. Although nine respondents replied that they do not have related experience, eight respondents (Respondents 3, 5, 7, 11, 12, 15, 17, and 19) stated that the durability and serviceability of the repaired bridge are appropriate and acceptable if the repair is performed successfully. Moreover, Respondent 9 indicated that the fixed bridge could have even better serviceability and more long-term durability than the original bridge structure. Lastly, Respondent 10 mentioned that they had replaced

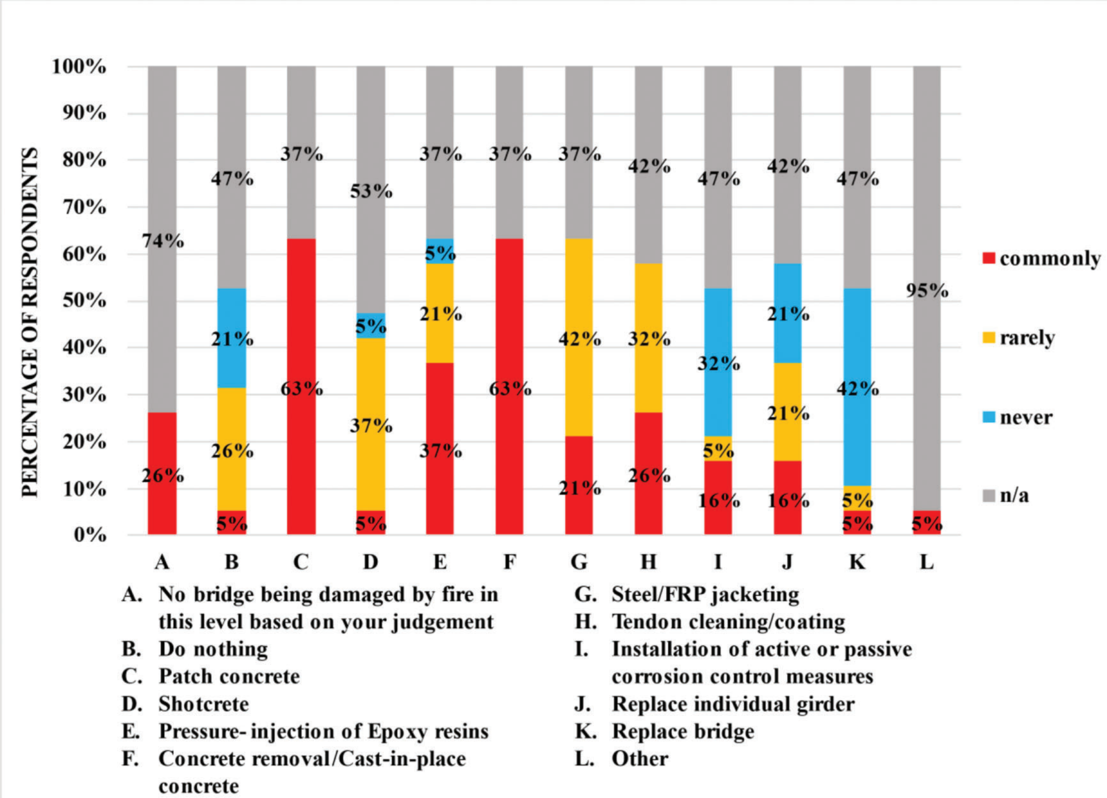

Figure 2.6 Results of Question 17.

TABLE 2.19
Q19. What methods are used to repair prestressed concrete bridges with significant damage (exposed and damaged tendons, loss of portion of cross section)?

	Commonly	Rarely	Never	N/A
No bridge being damaged by fire in this level based on your judgement	6	0	0	13
Patch concrete	4	3	1	11
Shotcrete	1	3	3	12
Pressure-injection of epoxy resins	3	4	1	11
Concrete removal/Cast-in-place concrete	5	3	1	10
Steel/FRP jacketing	6	2	1	10
Cut tendons with damaged section (no repairment)	2	4	3	10
External post-tensioning (please describe the employed method Question 20)	0	4	4	11
Internal splices (please describe the employed method and answer if the repair is re-stressed in Question 20)	1	3	5	10
Metal sleeve splice (please describe the employed method below and answer if the repair is re-stressed in Question 20)	0	2	5	12
Externally applied reinforcing material (FRP, etc.) (please describe the employed method in Question 20)	3	4	2	10
Installation of active or passive corrosion control measures (please describe the employed method in Question 20)	1	2	6	10
Replace individual girder	9	2	0	8
Replace bridge	5	4	1	9
Other (please describe in Question 20)	1	0	0	18

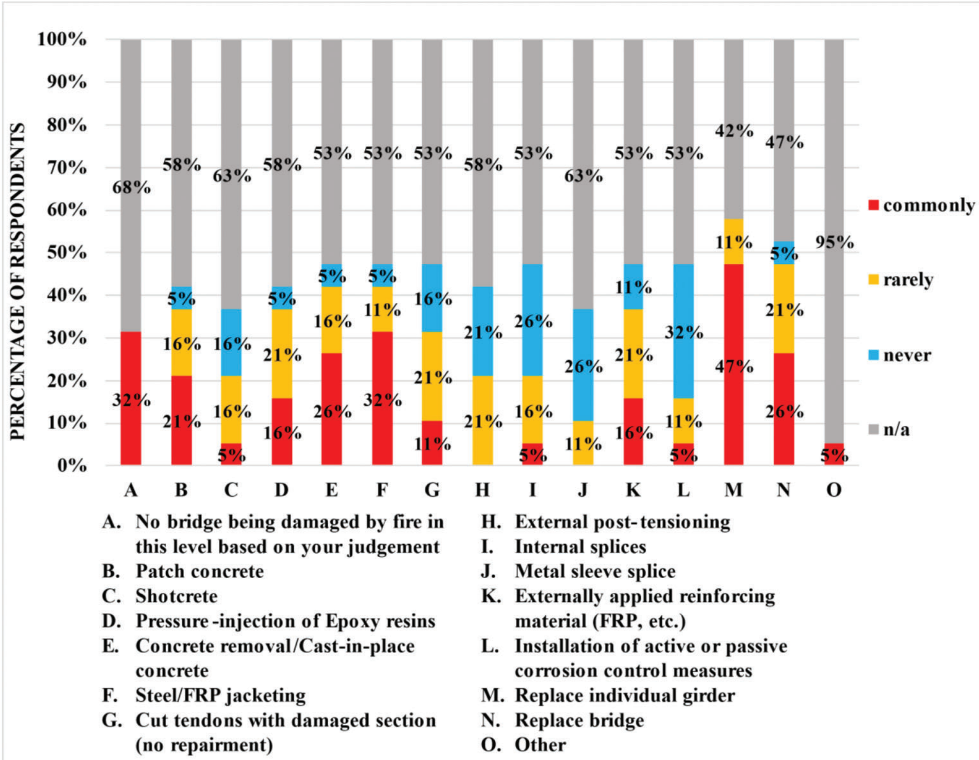

Figure 2.7 Results of Question 19.

TABLE 2.20
Q20. Please provide the supplementary answer for your responses in Question 19. You can skip this question if not applicable

Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 17	Internal splices are installed according to the manufacturer's recommendations. FRP is installed according to the Bridge Engineer's directions and the manufacturer's recommendations. An entire span has been replaced.
Respondent 19	CFRP. Internal splices for impact damage but not for fire damage

TABLE 2.21
Q21. How do the fire-damaged/unrepaired prestressed concrete bridges perform in your experience (e.g., long-term durability and serviceability)? Please indicate if there are any problems

Respondent 1	No comment. No experience in this area.
Respondent 2	No significant experience to share.
Respondent 3	Adequate
Respondent 4	N/A
Respondent 5	N/A
Respondent 6	We don't have any bridges that fit this description in our inventory.
Respondent 7	No problems
Respondent 8	N/A
Respondent 9	Minor and moderate damage do have less service life due to salt intrusion.
Respondent 10	We haven't had many fire-damaged girders in the relatively recent past. The last one, to my knowledge, was well over a decade ago and that location required the damaged girder to be replaced fully.
Respondent 11	For the minor damage experienced, all have performed acceptably.
Respondent 12	Typically, we do something if there is fire damage, so I think this question is N/A.
Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 14	NA, no unrepaired fire damaged concrete bridges in recent memory.
Respondent 15	No known issues or problems
Respondent 16	No data available on this. No fire damaged PC bridges encountered in the near past.
Respondent 17	Bridges with minor damage and gone unrepaired have had no serviceability issues that we are aware of.
Respondent 18	We've only had minor damage due to fires, therefore performance has not been affected.
Respondent 19	N/A

TABLE 2.22
Q22. How do the fire-damaged/repaired prestressed concrete bridges perform in your experience (e.g., long-term durability and serviceability)? Please indicate if there are any problems

Respondent 1	No comment. No experience in this area
Respondent 2	No significant experience to share
Respondent 3	Adequate
Respondent 4	We luckily have not had any fires of any type under or adjacent to any PS Girder bridges, so we don't have much to offer. But will be interested to see the results so when or if we get in this situation—we can learn from this survey.
Respondent 5	If repaired properly, they will perform well.
Respondent 6	We don't have any bridges that fit this description in our inventory.
Respondent 7	No problems
Respondent 8	N/A
Respondent 9	Better serviceability and more long-term durability
Respondent 10	Given that we replaced the existing girder that sustained fire damage, the remaining bridge is performing similarly to any other bridge that is within our inventory.
Respondent 11	For the minor damage experienced, repairs if undertaken are surficial (patching concrete spalls). All have performed acceptably.
Respondent 12	Beams with minor damage have been repaired successfully with no significant concerns for long term durability.
Respondent 13	We do not have very many fire-damaged prestressed girders so it is difficult to answer this question.
Respondent 14	We have very few examples of these bridges in our inventory.
Respondent 15	No known issues or problems
Respondent 16	No data available on this. No fire damaged PC bridges encountered in the near past
Respondent 17	They have performed well.
Respondent 18	N/A
Respondent 19	We have not seen anything to be concerned with related to the repaired prestressed concrete beams. Generally, these are redundant structures and is load shedding is needed as a result of some loss of capacity, that occurs without noticing anything. Related to long term durability, if that is a concern, we wrap the damaged portions of the beam with CFRP wrap.

a bridge girder that sustained fire damage and the remaining bridge performed similarly to other bridges in their jurisdictional area.

2.3 Discussion of Survey Results

Nineteen respondents from different domestic transportation agencies provided their professional and experiential knowledge about the fire-damaged prestressed concrete bridge girders. Based on the survey results, not many cases related to fire-damaged concrete bridges can be studied. Only several respondents stated that they had few available cases, and more than half (ten) respondents mentioned that they do not have any prestressed concrete bridges that sustained fire damage in the last 5 years. Besides, the damage levels of the reported fire-damaged bridges were mainly minor or moderate (damage levels as defined in Section 2.1), which indicates that the fire exposure may primarily impact the surficial concrete components, and the influence on prestressing strands will be insignificant. This conclusion also shows reasonable agreement with the findings of the INDOT research project SPR-4221 (Varma et al., 2021).

Subsequently, more details were inquired about in the questionnaire. Of the factors that influence the potential repair plans, the load capacity is the most dominant, and most respondents also consider the expected service life and interruption of service. Moreover, according to the received feedback, non-structural repair, load-carrying repair, and bridge replacement is suggested by most respondents to deal with concrete bridges with minor, moderate, and significant fire damage, respectively. In general, most respondents typically employ visual inspection and non-destructive evaluation methods (e.g., concrete sounding) to evaluate the extent of the fire damage and check the damaged bridge's performance using a bridge/structure analysis software and provisions from design specifications. It should be noted that the selected analysis software seems to vary depending on the assessment performed by the different agencies.

As mentioned previously, most respondents prefer to replace the bridge structure if the fire damage is significant (exposed and damaged prestressing strands or loss of a portion of cross-section). However, when the fire damage is less severe (minor or moderate), most respondents may repair the damaged bridge with different techniques. Based on the survey responses, the commonly used repair methods for minor damage include (1) patch concrete method, (2) concrete surface repair method, and (3) pressure injection of epoxy resins. FRP (CFRP) material may also be used to confine the repaired regions and increase their durability. When the damage level rises to moderate, the favored solutions are (1) patch concrete method, (2) concrete removal/cast-in-place concrete, (3) pressure injection of epoxy resins, (4) tendon cleaning/coating, and (5) steel/FRP jacketing. Most respondents believe that when these repair methods are implemented effectively, then the durability and serviceability of the repaired bridge will be restored (to pre-fire conditions).

3. CASE STUDY FOR FIRE-DAMAGED PRESTRESSED CONCRETE BRIDGE GIRDERS

3.1 Overview of Case Study

This chapter reviews two case studies (de Melo, 2014; Stoddard, 2004). Both studies documented experiences from existing prestressed concrete bridges that experienced severe fire exposure. The inspection of the extent of fire damage and the evaluation of residual capacities of damaged bridges were conducted in both these studies. Different repair approaches were evaluated and recommended/implemented to restore damaged bridges. By reviewing the existing cases, more practical information can be gathered, and it can be further synthesized with the conducted survey study, which is helpful to get more insight into the repair of fire-damaged prestressed concrete bridges.

The first fire incident that was reviewed happened in 2002. A railroad tanker collision caused a fire under a prestressed concrete girder bridge. The incident was inspected by the Washington State Department of Transportation (WSDOT) and reported by Stoddard (2004). The bridge was constructed in 1997 with a span length of 146 ft. About 30,000 gallons of methanol was consumed during the fire. The fire engulfed one of the bridge spans for approximately 1 hour, as shown in Figure 3.1. After the fire, inspection and evaluation were performed to determine the damaged bridge's structural capacity. The author then investigated several potential repair strategies and provided a preferable solution for restoring the target bridge.

The second case was reported in April 2011 for the Dean's Brook Viaduct on the M1 motorway in the Greater London area, UK. The south span of a prestressed concrete bridge was damaged by fire in a scrap yard underneath the bridge, as shown in Figure 3.2. Since the priority was to cool the gas cylinders near the fire instance, the fire under the bridge was kept burning for a prolonged period (approximately 5 hours) until it was extinguished. The maximum flame temperature was estimated to be about 1,472°F (800°C) by the London Fire Brigade. Concrete spalling was observed

Figure 3.1 Railroad tanker bridge fire in Washington State (Stoddard, 2004).

Figure 3.2 End of bridge fire in London, UK (de Melo, 2014).

at about 3 hours from the beginning of the fire. The process for inspecting, evaluating, and repairing concrete bridges subjected to the described fire incident was reviewed and documented by de Melo et al. (2014). The evaluation processes and recommended repair strategies for both cases are presented in the following subsections.

3.2 Prestressed Bridge Under Fire in Washington State (Stoddard, 2004)

3.2.1 Damage Inspection and Assessment

After the fire incident, a visual inspection was performed, indicating that the girders in the burned span were damaged by fire. The color of the bottom flange became whitish-gray and was able to be easily removed to expose the prestressing strands. The depth of the fire-damaged concrete in the top flange and web is approximately 0.5 inches. Based on the estimation, the maximum flame temperature of the fire was around 3,000°F (1,649°C). According to the fire temperature curve recommended by PCI design provisions (Gustaferro & Martin, 1989), it is likely that the methanol tanker fire could raise the air temperature near the bottom of the bridge girders to almost 2,700°F (1,482°C) after only 30 minutes. However, after 2 hours, the temperature at the same location could decrease to less than 1,000°F (538°C).

An estimated through-depth temperature contour (Figure 3.3) was produced by considering the visual observation of the concrete color, ease of concrete removal, and the concrete temperature profile under fire exposure suggested by PCI design provisions. The surface temperature on prestressed girders soffit was estimated around 1,700°F (927°C), with the internal temperature in the bottom flanges and webs ranging from 500°F to 1,100°F (260°C to 593°C). Furthermore, compression tests were carried out on the core samples removed from the bottom flange of the girder, as presented in Figure 3.4. It should be noted that concrete with a 28-day concrete compressive strength of 7,000

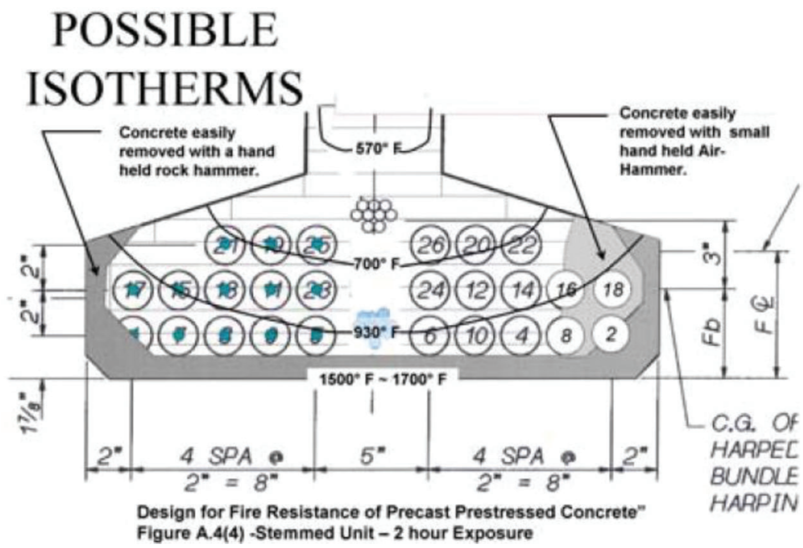

Figure 3.3 Estimated temperature profile in bottom flanges (Stoddard, 2004).

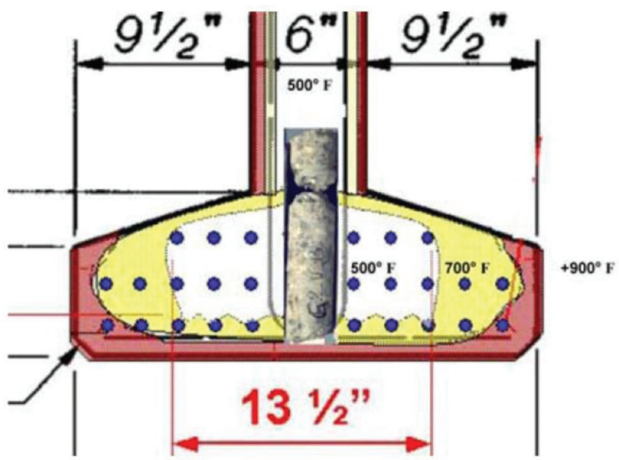

Figure 3.4 Core sample taken from extreme-white color region (Stoddard, 2004).

psi and Grade 270 steel strand with a diameter of 0.5 inches were used to construct the bridge girders. Moreover, the bridge columns and decks were built using 5,000 psi concrete and 60 ksi mild steel.

According to the conducted material tests, although the outer part of the concrete spalled and fell off (about 0.75 inches thick), the compressive strengths of the remaining concrete still exceeded 9,000 psi, which indicates the residual strengths for the remaining concrete are still adequate. The damage to the superficial concrete in the girders and columns was caused by the rapid heating and cooling rates. Furthermore, the microscopy analysis was performed on the cored samples from the girder webs and bottom flanges to determine the extent of the fire-induced damage to the concrete microstructure. The results indicate severe fire damage (with extensive microcracks in cement paste) primarily existed on the concrete with a depth of 2 inches from the exposed surface.

Based on the estimated temperature distribution shown in Figures 3.3 and 3.4, the exterior row of strands for the bottom flange might experience an elevated temperature higher than 900°F (482°C). To determine the steel strands' post-fire structural capability and serviceability, the concrete around the bottom straight strands was removed using a handheld impact hammer, and a deflection test was conducted to examine the residual prestressing force in the exposed strands preliminarily. It should be mentioned that the concrete surrounding the bottom strands (up to a depth of one inch) in the bottom flange could be removed by a rock hammer easily. However, the concrete at the deeper location was hard to be removed by the rock hammer but could still be removed using an impact hammer, showing that the most extensive fire damage might exist at one inch of concrete from the exposed surface.

The test was performed before the exposed strands were cut off, a dead load was applied to the strand directly, and the deflection at the load point was measured to estimate the existing prestressing force. The setup of the deflection test is demonstrated in Figure 3.5. The calculated prestressing force suggests that the strands retained almost 100% of the original design force even surrounded by the hot concrete, indicating that the fire-induced reduction in the yield strength was not significant for the steel strands. After the deflection test, samples of steel strands in the burned region were removed to perform the material test in the laboratory. The samples were obtained from areas with different severities of the fire damage (the region away from the hot zone, the region directly above the fire, and the intermediate region). The tested samples' ultimate tensile strength and elastic modulus are greater than 280 ksi and 26,190 ksi, respectively. The results show that the steel strand's mechanical properties (strength and modulus of elasticity) were not affected significantly by the fire and can still meet the

Figure 3.5 Deflection test on exposed strand (Stoddard, 2004).

ASTM requirements for the seven-wire prestressing strands.

In summary, during the 1-hour tank fire incident, the maximum flame temperature was 3,000°F (1,649°C), and the concrete surface temperature reached 1,700°F (927°C). According to a series of inspections and evaluations, even though the maximum experienced temperature for the surrounded concrete was estimated to be 900°F (482°C) during the fire instance, degradation of prestressing steel strands was not noticeable. The prestressing force, tensile strength, and elastic modulus did not change much compared to its original design values. On the other hand, the high temperature apparently altered the concrete properties and integrity. When removing the concrete from the bottom flange, it was found that 0.75–1.0 inches of concrete from the exposed surface was severely spalling and easy to be removed by a rock hammer. Nevertheless, the remaining concrete was unaffected by the fire exposure and kept an adequate compressive strength (more than 9,000 psi), even though the microscopy analysis indicates that the concrete microcracking can extend to a depth of 2 inches from the heated surface.

3.2.2 Repair Strategy

Strategies for repairing and replacing fire-damaged bridge girders were investigated and evaluated. The primary objectives for the repair or replacement options are to (1) restore the pre-fire structural capacity/serviceability, (2) ensure the accessibility for typical bridge inspection and maintenance, and (3) reduce the impact to the relating traffic service. Since the tensile cracks may cause the corrosion issue of the steel strands, WSDOT requires the prestressed bridge girders to remain fully compressed for the whole section under the service load (meaning that tension in the concrete of the bottom flange should not occur). Therefore, an appropriate repair strategy must re-establish the precompression for the replaced concrete. Additional force shall be applied during the repair procedure to precompress the new concrete. Based on the damage conditions, the author proposed and compared three potential repair strategies, including (1) encasement, (2) hydro-blast/preload/pour-back, and (3) hydro-blast/prestress/pour-back. Details for different repair methods are summarized in the following sections.

As discussed previously, the tank fire damaged the concrete in the girder's bottom flange and web, which may expose the prestressing strands and lead to a subsequent deterioration. Therefore, the encasement strategy can be adopted to protect the girder by effectively confining the fire-damaged bridge girders. A typical encasement repair is performed using steel forms, wire mesh, shotcrete, and pressurized epoxy grout to surround the damaged area. Although this option can provide endurable confinement for the damaged girder, there are still some disadvantages that may be noticeable. The first drawback of the encasement repair is the introduction of additional weight. Since the steel forms will stay in place after the repair is finished, the live load capacity may be reduced because of the extra imposed dead load. The second disadvantage is the difficulty of inspecting the repaired girders. Because the stay-in-place steel forms can hide the fixed region, it may be hard to maintain and visually inspect the damaged girder. Therefore, some non-destructive technologies may be necessary to monitor the long-term durability of the retrofitted bridge girders.

The next proposed repair method is hydro-blast/preload/pour-back. In this method, the damaged concrete is removed using hydro blasting machines and replaced by the new concrete. Before pouring back the new concrete, a vertical load should be applied since the precompression needs to be introduced to the replaced concrete in the bottom flange (to keep the whole section in compression under the maximum service load). In addition, preloading can also mitigate shrinkage issues for the replaced concrete. Epoxy grout is injected into the cold joint between the original and new concrete during the repair to provide more bonding strength in the interface. After the new concrete is poured back and cured, the repair can be completed by taking off the temporary forms and removing the external vertical load (to compress the concrete for the repaired area). Figure 3.6 illustrates the procedure of this repair method.

Figure 3.7 shows the last repair alternative, similar to the second repair option. The main difference is that the precompression to the bottom flange concrete is introduced by additional prestressing strands rather than the vertical applied load. Firstly, the damaged concrete is removed using the hydro blasting equipment. The prestressing strands will then be installed above and below the bottom flange; moreover, an anchoring point and a jacking point need to be

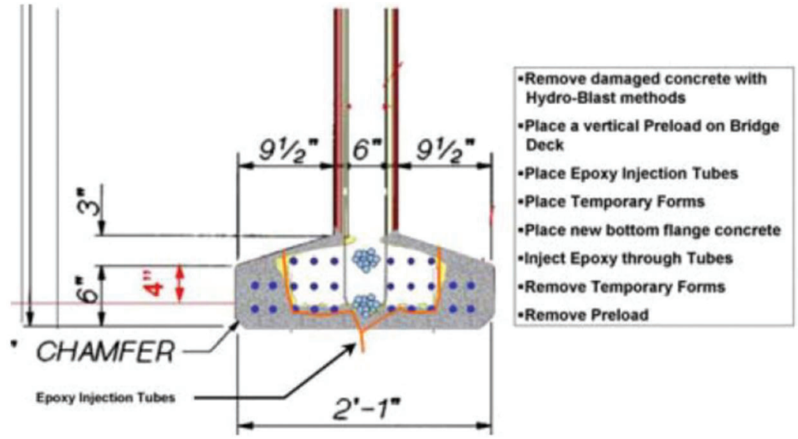

Figure 3.6 Hydro-blast, preload, and pour-back repair (Stoddard, 2004).

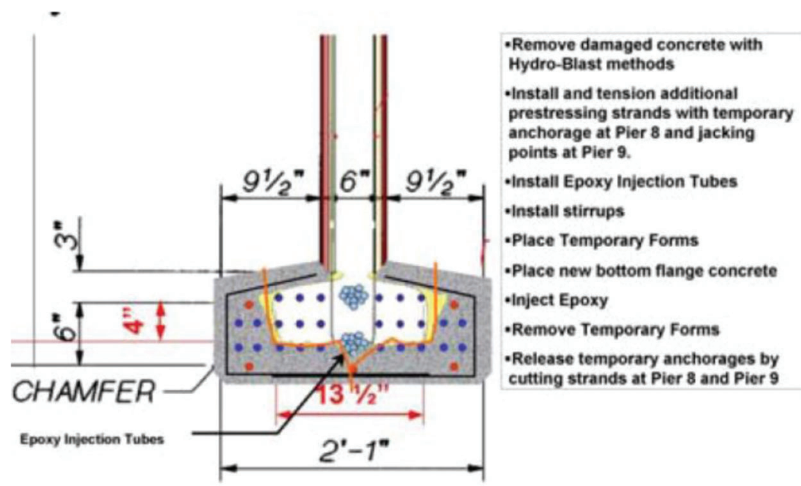

Figure 3.7 Hydro-blast, prestress, and pour-back repair (Stoddard, 2004).

established on the far-sided and near-sided bridge piers. Next, steel stirrups and epoxy grout tubes will be put around the existing concrete components before placing the new concrete. Lastly, after pouring back and setting the new concrete, the temporary forms can be removed, and the newly installed prestressing strands will be cut to apply the additional precompression to the repaired girder section.

Replacing fire-damaged bridge girders is also a potential solution to restore the prestressed concrete bridges. The report also conducted a study to assess the cost of demolishing the damaged bridge girders and constructing the new ones. Based on the cost analysis, replacing the fire-damaged bridge girders has a similar cost to the repair option (assuming that the hydro-blast/prestress/pour-back is adopted). Moreover, the long-term serviceability and performance of the repaired bridge girders are typically more questionable than the new precast girders. Therefore, the WSDOT Bridge Office finally decided to replace the damaged concrete girders.

This assessing/inspecting study indicates that the damage caused by the fire exposure (1-hour duration with a maximum flame temperature of 3,000°F) was mainly to the surface concrete of the bridge girder's web and bottom flanges. In contrast, the degradation of the steel strand mechanical properties and prestressing force was insignificant. In general, the observation of this study is identical to the conclusions stated by the conducted INDOT research project (Varma et al., 2021). Subsequently, varying strategies (repair and replacement) were investigated and evaluated to restore the damaged bridge girders. The replacement alternative was eventually adopted because of its lower uncertainty in the long-term service life and similar cost compared to the selected repair option (which was unfavorable since its long-term performance was questionable).

This case study also reveals the lack of knowledge regarding the repair methods of fire-damaged prestressed concrete girders, especially for the construction procedures and long-term performance/durability issues. Therefore, additional research addressing the related repair approaches needs to be conducted and will be beneficial. With rational research-based guidance, bridge engineers can make a more feasible and accurate judgment regarding the rehabilitation of bridges exposed to fire.

3.3 Prestressed Bridge Under Fire in the United Kingdom (de Melo et al., 2014)

3.3.1 Damage Inspection and Assessment

Based on the visual inspection after the fire, typical damage for the target bridge was the concrete spalling at the girder flange's corners (see Figure 3.8(a)) and the bottom surfaces (see Figure 3.8(b)). In addition, the steel reinforcement and prestressed strands were exposed in some regions that sustained severe fire-caused damage.

Schmidt Hammer testing was conducted to identify the damaged region for the concrete exposed to elevated temperature. The results revealed that the actual fire-damaged area was more extensive than what was visually observed. Detailed material testing was performed later at the locations with more extensive damage. Cylinder samples with a length of 7.87 inches (200 mm) and a diameter of 1.97 inches (50 mm) were extracted vertically from girder bottom flanges to webs, and several 0.276 inches-diameter (7 mm-diameter) prestressing strands were cut to remove the concrete cores successively. Figure 3.9 shows the coring plan at the damaged prestressed concrete girder. The material test results (petrographic examination) indicated that the maximum concrete surface temperature might have reached 1,112°F (600°C) and the internal concrete temperature near the exposed surfaces mostly ranged from 572°F to 1,112°F (300°C to 600°C). Figure 3.10 presents the result of the material tests from concrete samples taken from the two different fire-damaged girders. It can be observed that the severe concrete damages (experienced temperature higher than 572°F (300°C)) occurred from the exposed surfaces to the depth of approximately 1.26 inches (32 mm) for the prestressed girders. Furthermore, the material test results also stated that the experienced temperatures for most prestressing strands were not higher than 572°F (300°C) since the bottom strands were located at a depth of 1.97 inches (50 mm) from the bridge girder's bottom. Most of the steel components were still encased by concrete heated to less than 572°F (300°C) (although parts of the strands and reinforcements were exposed after the fire).

The steel reinforcement and prestressing strand samples were also removed from the damaged girders and tested for the residual tensile strength. The results showed that the prestressing strands did not undergo significant reductions in ultimate tensile strength and strain, suggesting that the maximum temperature which

(a) Concrete Spalling of Flange Corners

(b) Exposed Reinforcements on Bottom Surfaces

Figure 3.8 Damage conditions for bridge exposed to fire (de Melo et al., 2014).

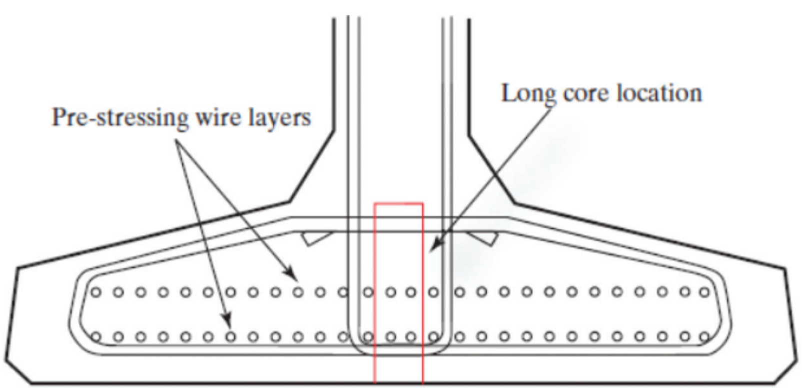

Figure 3.9 Location of concrete cores at girder bottom flange (de Melo et al., 2014).

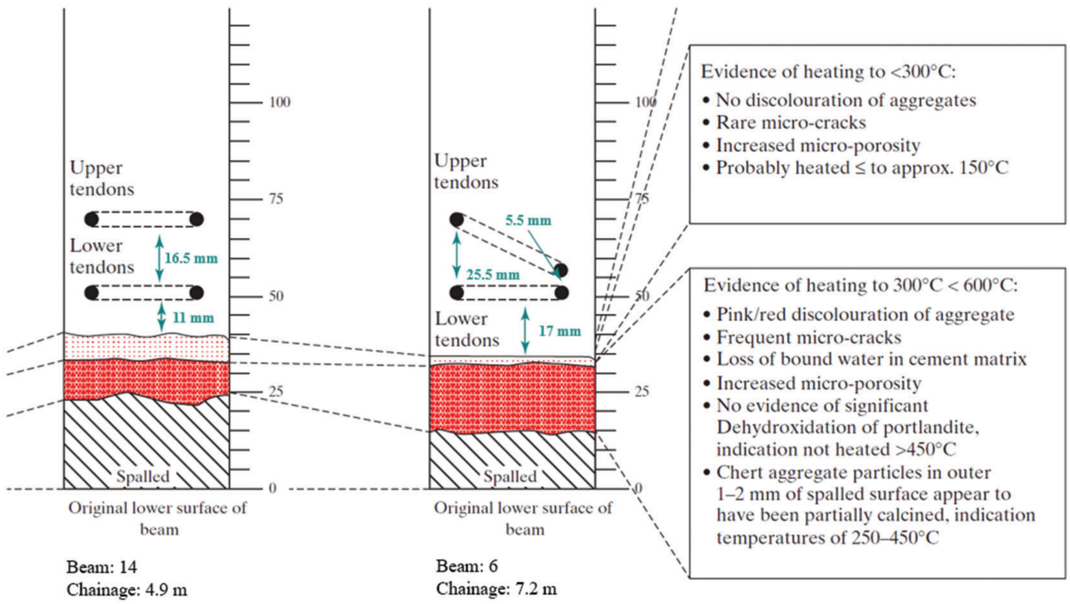

Figure 3.10 Petrographic examination results (de Melo et al., 2014).

the strands experienced did not exceed 572°F (300°C) (Schneider, 1990). Subsequently, the residual prestressing force in the steel strands was evaluated by two different (destructive and non-destructive) methods, including measuring the strand deformation after cutting the strands (relaxation test) and the natural vibration frequency test. Although these test methods are not standardized and have several inherent assumptions, they were used to provide preliminary predictions. Results from two different testing methods were comparable, pointing out that the prestressing force in strands directly exposed to fire (only two locations of the entire bridge) was reduced to 40% of the original design value. Nevertheless, the prestress losses were negligible for the strand samples with sound concrete cover, and these intact strands were merely located at 39.37 inches (1 meter) away from the exposed strands. Therefore, the author stated that the fire-caused prestress reductions only locally existed in the regions with serious concrete spalling and did not affect the entire girder section.

3.3.2 Repair Strategy

Finally, repair strategies were developed to restore the fire-damaged bridge girders. Since the bridge girders did not sustain noticeable prestress losses and still had sufficient load-carrying capacity after 5-hour fire exposure, the restoration for the prestressing force was not needed. And the rehabilitation was aimed to restore the long-term serviceability/durability of the prestressed concrete bridge. Figure 3.11 demonstrates the repair strategy for a typical girder section. First, the damaged concrete was removed utilizing the hydro-demolition method. Next, sprayed concrete and steel wire meshes were used to restore the damaged area. In addition, extra steel reinforcements were also installed to tie the new steel meshes and old steel stirrups. Therefore, additional concrete covers were constructed to provide adequate protection to the extra steel refinements (the darker gray area in the plot). Figures 3.12(a) and (b) illustrate the bridge soffit before and after the restoration. It can be seen that, during the repair process, temporary supports are necessary to be used because the removal of the damaged concrete could decrease the bridge's structural capacity and lead to severe safety concerns.

In summary, the results from the performed inspection and assessment on the fire-damaged concrete bridge show that, even for a prestressed concrete bridge girder subjected to an extreme fire incident (with a 5-hour burning duration), the concrete damage may be superficial (about 1-inch depth). Besides, the prestressing strands (tensile strength and prestressing force) will not be affected significantly if the remaining concrete cover is relatively sound. Although the prestress losses may be significant at limited locations with exposed steel strands, the fire-induced reduction in prestressing force seems to be localized and without influencing the entire girder section. These observations generally agree well with the survey results presented in Chapter 2 and findings obtained from the previous INDOT project (Varma et al., 2021), which shows that a desirable repair strategy for the prestressed concrete bridge exposed to fire may not need an extensive restoration for the prestressing strands (force). Instead, the developed repair plan should focus on fixing the integrity and durability of the damaged concrete and preventing the structure's long-term degradation.

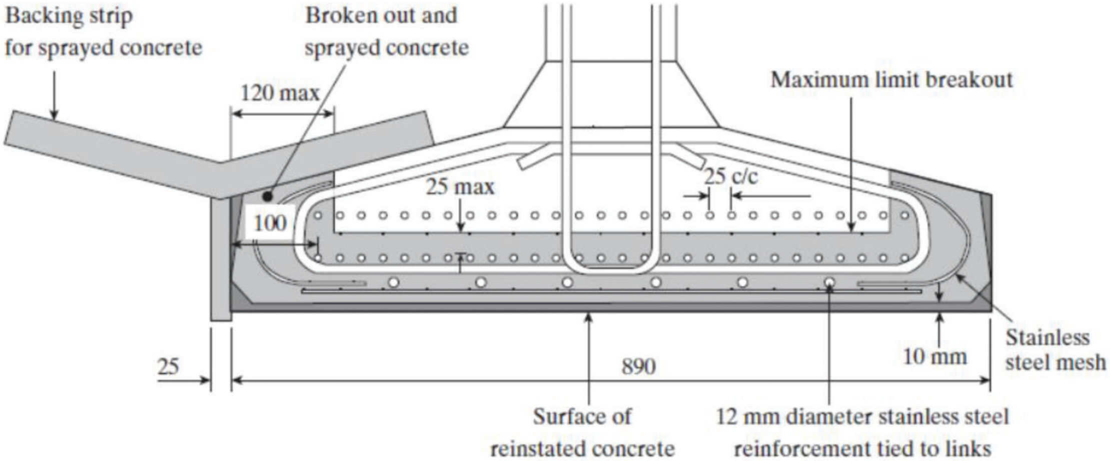

Figure 3.11 Typical repaired section (de Melo et al., 2014).

Figure 3.12 Restoration of bridge soffit (de Melo et al., 2014).

4. RECOMMENDED REPAIR METHODS FOR FIRE-DAMAGED PRESTRESSED CONCRETE BRIDGE GIRDERS

4.1 Overview of Repair Methods

According to the survey study and case studies discussed in Chapter 2 and Chapter 3, respectively, the primary factor affecting the necessities of repair and/or replacement is the severity of the fire-induced damage. As discussed previously, the level of fire damage in the concrete bridge is most likely to be minor or moderate (as defined in Section 2.1). For this level of damage, the concrete girder will not experience severe section loss or damage to prestressing tendons. Multiple repair methods can be considered to retrofit the damaged bridge. However, when the concrete bridge sustains significant fire damage (which may be rare) and the girder sections are severely compromised, the target bridge shall be replaced with a new structure due to the uncertainty of the repair's structural performance.

Since minor and moderate fire damage occur most frequently in practical scenarios, it is important to consider and evaluate different repair techniques. In general, the guidelines for repairing fire-damaged prestressed concrete bridge girders are limited. However, repair strategies for vehicular impact-damaged prestressed bridge girders have been well investigated and documented (Ghaffary & Moustafa, 2020; Harries et al., 2009; Morcous et al., 2020) due to the relatively higher probability of occurrence of the impact damage. Although the proposed documents focus on the structural repair methods for restoring impact-damaged concrete bridge girders, some of the techniques discussed in these documents may be useful to repair the fire-damaged prestressed concrete bridge girders. It is worth mentioning that the damage caused by the vehicular impact may be more substantial than the fire damage (especially for the short-term damage). The impact incident caused by over-height vehicles (typically with side impact) can produce shear cracking on the exterior girder, leading to severe section loss and strand damage. In some cases, the prestressing strands near the impacted region may lose the prestressing force and compromise the structural capacity significantly. However, based on the research conducted by Stoddard (2004), de Melo et al. (2014) and INDOT project SPR-4221 (Varma et al., 2021), even a severe fire exposure can merely damage the concrete within a depth less than

2 inches, and the impact on the prestressing strands should be inconsequential. The classification of damage levels for prestressed concrete bridge girders is suggested by Harries et al. (2012) and shown in Table 4.1. According to the recommended damage classification, most fire-induced damage can probably be classified as minor or moderate damage since significant strand losses are rarely seen for the bridge girders that experienced fire exposure. Therefore, the repair methods discussed in this chapter focus on that restoring the surficial concrete damage, and some repair techniques described in the literature for repairing the prestressing strands (e.g., post-tensioning steel and strand-splicing) may not be applicable for the bridge girders exposed to fire and are excluded in this synthesis study.

4.2 Patching Repair

Concrete patching repair methods are usually used for retrofitting the spalls or section losses for damaged concrete structures. The objective of patching repair is to restore an unsound concrete section to its original cross-section. Therefore, this technique is applicable for repairing the fire-damaged concrete girder without severe damage on steel strands and reinforcements. Details for implementing different patching methods are provided and published by Precast/Prestressed Concrete Institute (PCI, 2006), *FHWA Bridge Maintenance Reference Manual* (FHWA, 2015), and Section 710 of *INDOT Standard Specifications* (INDOT, 2022). The first step of the patching repair is removing the damaged concrete portions, and the methods of concrete removal are provided by International Concrete Repair Institute (ICRI) guidelines (ICRI, 2013). The concrete removal methods may comprise (1) acid etching and surface retarder, (2) abrasion, (3) high-pressure water erosion, (4) impact, and (5) pulverization. Since the high-pressure water erosion method (hydro-demolition method) can remove the unsound concrete efficiently and reduce the dust levels during the concrete removal process, it is usually adopted as a potential option for restoring damaged concrete bridge girders. Moreover, it is often recommended to remove slightly more concrete (exceeding the damaged region) to ensure the repairing quality, unless it affects the prestressed strands or steel reinforcements.

Concrete patching can generally serve as a stand-along repair method for the concrete bridge girders without significant damage (minor or moderate damage in Table 4.1). However, the FRP sheets are often used to wrap (U-wrap) the patched regions to confine patches, preventing them from detaching from the repaired bridge girders (and it may also provide additional shear strength to the bridge girders). Besides, a proper patching application is also essential. It can serve as a substrate for other repair techniques, such as Externally Bonded FRP systems (EB-FRP) for bridge girders that sustain more significant damage and need a more extensive repair.

Formwork may be needed for patching repair when concrete spalls are deeper than 2 inches (Morcous, 2020). Moreover, as discussed previously, preloading is usually introduced to compress patches if no additional pre-stress is applied during the bridge repair. An adequately designed preloading can reduce the shrinkage and keep the whole repaired section in compression

TABLE 4.1
Damage classification (Harries et al., 2009)

	Description	Strand Loss	Camber
Minor	Concrete with shallow spalls, nicks, cracks, scrapes, and some efflorescence, rust, or water stain. Damage does not affect member capacity. Repairs are for aesthetic and preventative purposes only.	No exposed strands	No effect
Moderate	Larger cracks and sufficient spalling or loss of concrete to expose strands. Damage does not affect member capacity. Repairs are intended to prevent further deterioration.	Exposed strands but no severed strands	No effect
Severe I	Damage affects member capacity but may not be critical—being sufficiently minor or not located at a critical section along the span. Repairs to prevent further deterioration are warranted although structural repair is typically not required.	Less than 5% strand loss	Partial loss of camber
Severe II	Damage requires structural repair that can be affected using a non-prestressed/post-tensioned method. This may be considered as repair to affect the STRENGTH (or ultimate) limit state.	Strand loss greater than 5%	Complete loss of camber
Severe III	Decompression of the tensile soffit has resulted. Damage requires structural repair involving replacement of prestressing force through new prestress or post-tensioning. This may be considered as repair to affect the SERVICE limit state in addition to the STRENGTH limit state.	Strand loss exceeding 20%. In longer and heavily loaded sections, decompression may not occur until close to 30% strand loss	Vertical deflection less than 0.5%
Severe IV	Damage is too extensive. Repair is not practical, and the element must be replaced.	Strand loss greater than 35%	Vertical deflection greater than 0.5%

under the maximum service load. In practice, preloading the damaged girder is accomplished by placing loaded vehicles (or loading apparatus) on top of the bridge before putting the patching material, and the external load will be removed after the curing of the patching material.

Several patching methods may be suitable for restoring fire-damaged concrete bridge girders. The descriptions of these patching methods are discussed and demonstrated. (1) The mortar patching method is used for concrete members with shallow defects and requires a relatively thin layer (e.g., 0.5 inches to 2.0 inches-deep spalls) of repair. Trowels are usually used to apply and finish the patching mortar. (2) The concrete replacement method replaces the damaged concrete with machine-mixed new concrete that will be integral to the original concrete. Plywood formwork is usually used to cast new concrete, and a bonding agent (usually a cement grout) is applied to the original concrete interface before placing the new concrete. The concrete replacement method is preferred when the damaged region is extensive and beyond the reinforcement layer. In addition, concrete replacement can provide the best substrate for other repairs, such as the Fiber Reinforced Polymer (FRP)-based repairs. (3) Synthetic patching—this patching method can be applied using epoxy or latex-based products. This method is adequate when the cement patches are difficult to apply, including patching at freezing temperature or very shallow surface defects. (4) The prepackaged patching method: commercially available patching products can also be employed to repair the damaged concrete girders. This method is similar to the concrete replacement, but the prepackaged dry mixed products (Portland cement and aggregates) are utilized instead of the ordinary concrete. It is convenient and preferable to use prepackaged products. However, some compounds may generate excessive heat and cause issues regarding shrinkage and durability, so selecting prepackaged products and their construction process should be cautious. Moreover, Section 901.08 of *INDOT Standard Specifications* (INDOT, 2022) provides some requirements for prepackaged patching products, which shall be followed when developing the related repair plans. (5) The shotcrete method is desirable for vertical and overhead repairs since the formwork is unnecessary. The mortar can be applied pneumatically and repair large areas rapidly. However, the compressive strength of shotcrete may be challenging to achieve the original concrete's compressive strength (typically higher than 8,000 psi for prestressed concrete bridge girders). More requirements about the shotcrete method are documented in Section 708 of *INDOT Standard Specifications* (INDOT, 2022).

The selection of patching techniques and materials should be determined according to their limitations, compatibility with the original concrete, long-term durability, and the surrounding environment. For example, the compressive strength of the patching material should be equal to the original concrete. In addition, the elastic modulus of the patching material should be close to that for the original concrete since the difference in elastic modulus will lead to an unevenly distributed stress for the whole repaired section under the service load. Lastly, the patching material with high early strength is often used to reduce the overall construction time to return the traffic service more quickly. However, the shrinkage may occur if the patching material gains strength rapidly, resulting in significant stresses at the interface and eventually cracking/debonding issues. Therefore, special patching material (e.g., low-shrinkage grout) may be helpful to mitigate the shrinkage issues.

4.3 Fiber Reinforced Polymer (FRP)-Based Repair

Harries et al. (2012) developed guidance to recommend repair methods for damaged prestressed concrete girders. As mentioned previously, since most fire exposures can only lead to superficial concrete damage for bridge girders and without significant prestressing damage, several steel-based techniques discussed in the document may not be applicable and will be excluded in this study. Moreover, the guide also provides several repair techniques similar to what was discussed in Section 3.2, including steel jackets (encasement) and preloading structural repair. The related details of these repair approaches are not presented here since they have already been described previously. However, the guide indicates several disadvantages of these techniques worthy of mentioning. For example, when applying the repair method with the steel jackets, as mentioned before, the dead load demand (from the extra weight of the stay-in-place steel forms) will be increased. Besides, field welding jobs to fix the steel forms may also be necessary, and the welding work can be complex to enclose the steel jackets entirely. Furthermore, since the girder section's dimension may vary along the span, the steel forms may need to be grouted to accommodate the dimensional change of the bridge girder.

On the other hand, there are drawbacks to preloading and concrete patching repair. Although this strategy is convenient to implement by directly applying a vertical load with the jacking system or loaded vehicles, the preloading repair is only available to restore the small bridge girders. Once the dimension of the bridge girder becomes more extensive, the needed vertical load may be significant and impractical to be applied. In addition, the guide also points out that the preloading repair may not be applicable for restoring the severe degradation of the prestressing force since it can only pre-compress the repaired regions (patched regions). However, considering that the severe prestressing force damage is typically unexpected for the concrete bridge exposed to fire, the preloading and concrete patching repair should still apply to some fire-damaged bridge girders.

Because of their excellent performance and practicability, the repair techniques recommended and emphasized by the guide are the methods using Fiber Reinforced Polymer (FRP) materials. The FRP-based repair methods are appropriate to restore the damaged bridge sections because of the high strength and flexibility of FRP materials. The favorable fiber materials for the highway bridge repair are generally Carbon Fiber Reinforced Polymer (CFRP) materials. They are readily available in the industry and manufacturers with various sizes and grades. Moreover, CFRP is also an endurable material against fatigue loads, exhibiting a significantly lower material degrading rate than steel (the tensile S-N curve slope for CFRP is approximately half of that for steel). Commonly adopted types of CFRP materials for bridge repair include High Strength (HS), High Modulus (HM), and Ultra-High Modulus (UHM). Table 4.2 provides the material properties of these types of CFRP materials. The UHM-CFRP has the highest value of modulus of elasticity (about 44,000 ksi) and may be beneficial for the efficiency of bridge repairing. However, its high elastic modulus comes with lower strength and ductility compared to the other CFRP materials, which may lead to a higher possibility for the rupture failure of the repairing system. Therefore, the selection of the potential repair materials should be determined by a thorough evaluation and assessment of varying cases.

Several Externally Bonded (EB) CFRP repair alternatives are recommended by Harries et al. (2012), considering the severity of the fire-induced damage on prestressed concrete bridges, the available repair techniques include (1) externally bonded non-post-tensioned CFRP (EB-CFRP), (2) Prestressed CFRP (P-CFRP), (3) unbonded Post-Tension CFRP (uPT-CFRP), and (4) bonded Post-Tension CFRP (bPT-CFRP). The details for each CFRP-based repair method are described in the following subsections.

TABLE 4.2
Mechanical properties of available CFRP materials (Harries et al., 2009)

	HS-CFRP	HM-CFRP	UHM-CFRP
Tensile elastic modulus (ksi)	23,200	30,000	44,000
Ultimate tensile strength (ksi)	406	420	210
Tensile rupture strain	0.017	0.014	0.005

4.3.1 Externally Bonded Non-Post-Tensioned CFRP (EB-CFRP)

The external prestressing force would not be considered during the repairing process for the EB-CFRP system. Therefore, it is recommended to repair the damaged prestressed concrete girders without a severe deterioration on the prestressing force. The objective of the EB-CFRP is to externally bond the damaged sections with CFRP strips, which can mitigate the concrete cracking of the damaged region and increase/repair the bridge girder's flexural capacity and structural stiffness. Figure 4.1 demonstrates the procedure of the EB-CFRP system. Firstly, the concrete located in the damaged region needs to be removed before restoration, and the concrete which slightly exceeds the unsound area can also be removed for conservatism. Then, concrete patching can be employed to repair the damaged region. The selection of the patching methods (e.g., mortar patching or concrete replacement) should be determined according to the level of concrete damage. Subsequently, the EB-CFRP repair can be implemented once the patched material is cured. The CFRP systems can be constructed using high-strength carbon fabrics (typically unidirectional dry fiber sheets) with a wet lay-up process. Epoxy adhesive is usually employed to impregnate the carbon fibers and provide bonding strength to the prepared concrete surface. After the epoxy adhesive is properly cured, the fully composite action can be established. The EB-CFRP system can perform as an integral part of the repaired girder section, strengthening the structural capacity of the girder section.

The EP-CFRP system is primarily constructed based on the bonding strength between the carbon fabrics and concrete substrate. Therefore, the strength provided by the bonding agent (e.g., epoxy resin) between the carbon fabrics and the concrete substrate is crucial for EB-CFRP repair. For a bridge girder repaired using the EB-CFRP system, the critical limit state is usually the debonding of the repaired region (between CFRP, epoxy adhesive, and concrete), including the delamination of concrete cover and/or attached carbon fiber sheets. This type of failure may be induced by the occurrence of shear/flexural concrete cracking (as shown in Figure 4.2), which can compromise the load-carrying capacity of the repaired girders due to a

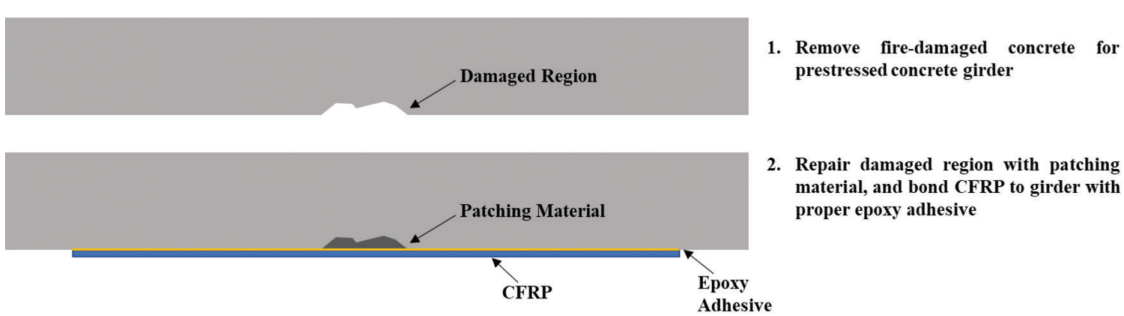

Figure 4.1 EB-CFRP repair (Harries et al., 2009).

decrease in the EB-CFRP system's strengthening effects. To prevent the debonding failure, Equation 10.1.1 of the ACI 440.2R-17 (ACI Committee 440, 2017) provides a recommended value to limit the allowable effective strain of the FRP reinforcement. It is worth mentioning that, as investigated by Pevey et al. (2021), the spike anchor (also known as the fan anchor) can provide appropriate compatibility with the FRP strengthening system. This is beneficial for reducing the possibility of debonding, and the spike anchor method is recommended for anchoring FRP sheets to the system.

Additional details and guidance about applying FRP composite materials in concrete structure repair are well documented and can be found in ACI 440.2R-17 (ACI Committee 440, 2017). The EB-CFRP system is usually adopted to repair damaged concrete columns. However, since CFRP strips are not stressed in the EB-CFRP system, this strategy may not be appropriate to restore the fire-damaged prestressed girder if the precompression in the concrete section needs to be re-established.

4.3.2 Prestressed CFRP (P-CFRP)

In order to improve the structural performance of the EB-CFRP system, a modified CFRP-based technique can be considered when repairing the prestressed concrete bridge girders subject to fire. The Prestressed CFRP method (P-CFRP) allows the CFRP strips to be prestressed using proprietary reaction equipment. Therefore, the prestressing force can be introduced to the repaired girder and increase its load-carrying capability. Figure 4.3 presents the scheme for the P-CFRP method. Firstly, the damaged concrete should be removed and replaced with patching material (and cured sufficiently). The CFRP strips are then tensioned and attached with an appropriate bonding agent to the damaged area. Next, the externally applied force is retained until the adhesive is cured; afterward, the external reaction equipment is released, and the precompression is transferred to the concrete section.

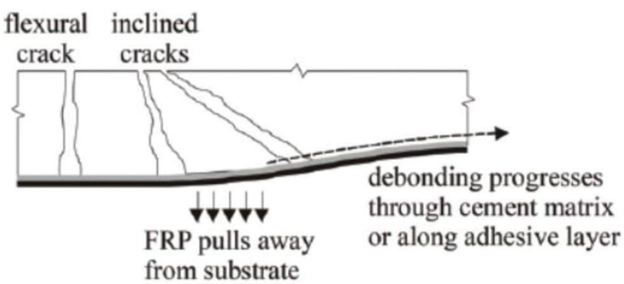

Figure 4.2 Debonding of EB-FRP system initialed by flexural and/or shear cracks (ACI Committee 440, 2017).

There are some drawbacks to the P-CFRP method. The losses of prestressing force may not be neglectable since the prestress transferring is primarily based on the epoxy adhesive between the CFRP strips and concrete surface. Suppose epoxy material's deformation (short term and long term) is significant after releasing the external force. In that case, the performance of the repaired bridge girder will be impaired since the introduced prestressing force is lower than the expected value. Moreover, the debonding at the end of CFRP is a possible failure mode for the P-CFRP repair method. Thus, more details (special wrapping strategies) need to be considered at the repair ends to reduce the failure possibility.

4.3.3 Unbonded Post-Tension CFRP (uPT-CFRP)

Unlike the P-CFRP system, which transfers prestress to the concrete section by the bonding agent (e.g., epoxy adhesive), the prestressing force for the uPT-CFRP system is transferred to the repaired girder by the special anchorages installed at bridge girder ends. Figure 4.4 shows the schematic drawing for the uPT-CFRP system. The significant difference between the uPT-CFRP and P-CFRP is that the former needs

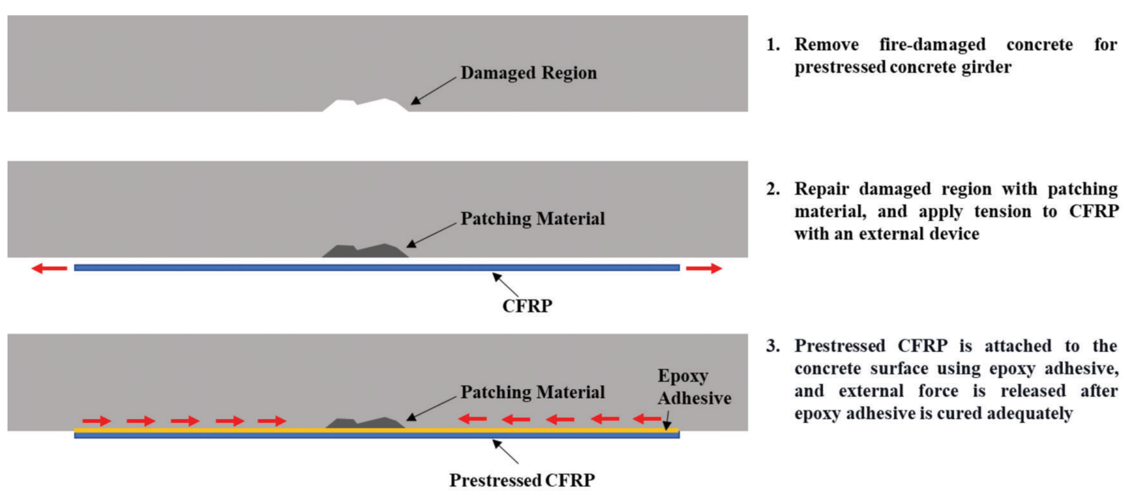

Figure 4.3 P-CFRP repair (Harries et al., 2009).

anchor devices installed at one end (called dead end) and stress the CFRP strips at the other end (called the live end or jacking end) to transfer the external force. The stressing system for loading CFRP strip is usually commercially available proprietary hardware and provided by specific manufacturers. The repairing system generally consists of a dead-end steel anchorage fixed on the concrete surface (as shown in Figure 4.5(a)) and a live-end jacking system (as shown in Figure 4.5(b)). The movable frame and hydraulic jack are equipped in the jacking system to tension CFRP strips to a target stress level. After the design tensile stress is achieved, the jacking system can be removed. And the CFRP strips can be fixed in the jacking end by proprietary anchorage hardware. Figure 4.5(c) illustrates a completed repair work with multiple anchored points in the jacking end.

Fretting damage is the most suspectable issue for the uPT-CFRP repaired girder, which is caused by the unexpected contact between the installed CFRP strips and the concrete substrate. It may adversely influence the serviceability of the repaired bridge girder. Therefore, the clearance between CFRP and concrete must be designed and considered cautiously to reduce the possibility of fretting damage. In addition, since the prestressing force for the uPT-CFRP repair is mainly transferred by the anchorage system, potential prestress losses of this system should be taken care of when developing the associated repair plan. One of the most common types of prestress losses is the short-term loss which occurs when locking CFRP strips to the anchorage at the jacking end. Moreover, a long-term prestress loss may also exist due to the creep deformation of the anchorage system. Therefore, the uPT-CFRP system is not recommended to repair the damaged prestressed concrete girders.

4.3.4 Bonded Post-Tension CFRP (bPT-CFRP)

In order to overcome the disadvantages mentioned above of the P-CFRP and uPT-CFRP systems, an improved post-tension CFRP-based method is proposed, which is the so-called bonded Post-Tension CFRP (bPT-CFRP) system. This system is developed based on the uPT-CFRP system; therefore, the application procedures for these two repair approaches are

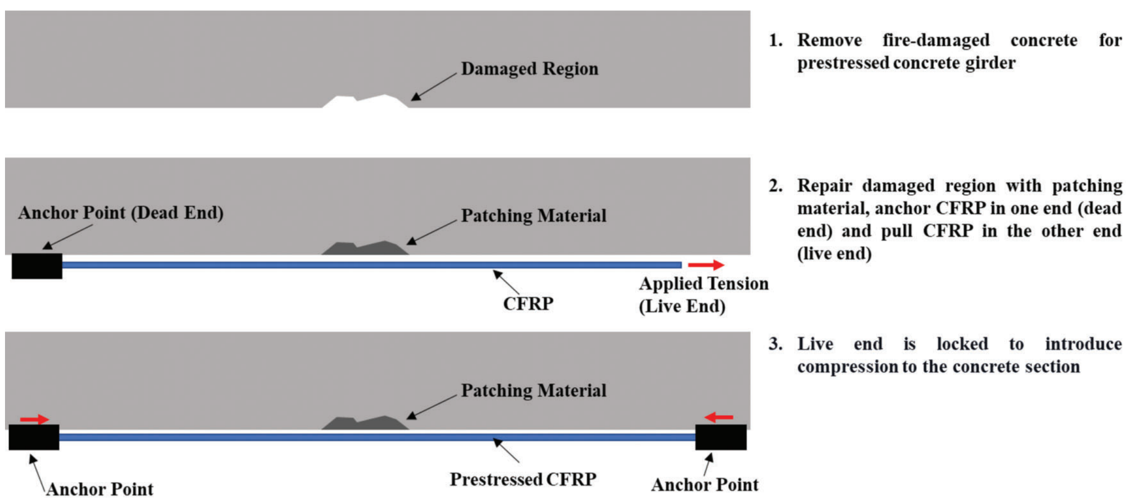

Figure 4.4 uPT-CFRP repair (Harries et al., 2009).

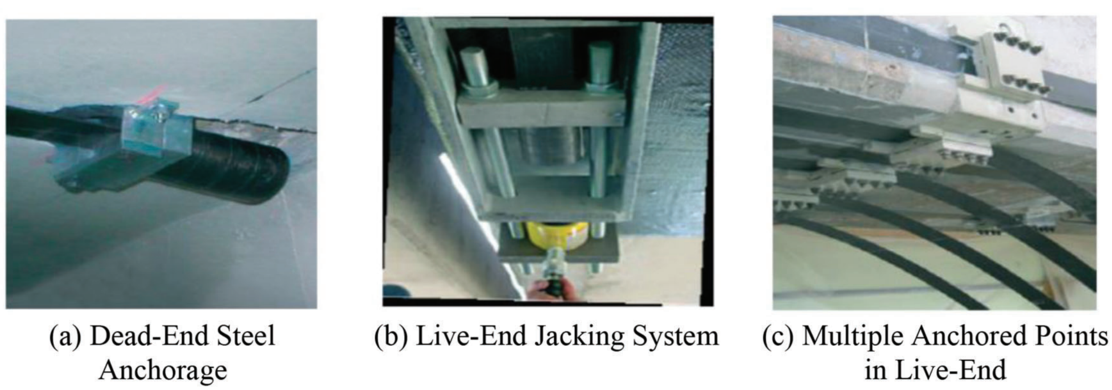

Figure 4.5 Commercially available PT-CFRP system (Harries et al., 2009).

similar. The summarized process for implementing bPT-CFRP repair is displayed in Figure 4.6. It can be seen that the significant modification for this improved system is employing epoxy adhesive to provide additional bonding strength between prestressed CFRP strips and concrete substrate. Furthermore, the bonding agent in the bPT-CFRP method is not stressed since it is applied after locking off the live end anchorage. Hence, the prestress losses contributed from the deformation of epoxy adhesive (which may be significant in the P-CFRP system) can be mitigated. Moreover, the additional bond between CFRP and concrete provided by the adhesive system can also reduce anchorages' creep and decrease the related prestress losses. Since its advantages are apparent and the additional cost is marginal compared to the P-CFRP and uPT-CFRP, the bPT-CFRP method is recommended to repair the prestressed concrete girder that needs restoration for a certain level of prestressing force.

4.3.5 Concerns for Fiber Reinforced Polymer (FRP) Material-Based Repair

Although the FRP material is commonly used to repair damaged prestressed concrete girders because of its outstanding performance, durability, and commercial accessibility, there are still concerns that need to be addressed when employing FRP to repair the fire-damage concrete girders. As discussed previously, the bonding strength between the FRP sheets/strips and concrete surfaces is substantial for the FRP-based repair methods since it significantly influences the composite action for the FRP system. However, Ghaffary and Moustafa (2020) pointed out that the epoxy adhesive (resin), which is typically used for FRP-based repair, could degrade notably at elevated temperatures. When the experienced temperature for the epoxy adhesive reaches its glass-transition temperature, the epoxy resin would transform from the glassy state to the viscoelastic state and lose its mechanical capacity. ACI 440.2R-17 (ACI Committee 440, 2017) suggests that the maximum service temperature for the typically available FRP systems ranges from 140°F to 180°F (60°C to 82°C). Once the allowable temperature is reached, the externally bonded FRP system's mechanical capacity should be considered wholly lost unless other special techniques are employed to improve the fire resistance of the FRP system.

Therefore, if the fire load is a crucial factor for the serviceability of repaired prestressed concrete bridges, the fire resistance of the adopted repair strategy needs to be considered and designed specifically. Plausible solutions for improving the FRP system's fire resistance include but are not limited to the application of (1) cement-based adhesive instead of epoxy adhesive and (2) cementitious or special epoxy fireproofing materials. According to the related research (Al-Safy, 2020; Hashemi & Al-Mahaidi, 2008), the developed cement-based bonding material (which consists of cement mortar with the mineral additives or polymeric material) can be used when the working temperature may be higher than the maximum service temperature of epoxy adhesive. Alternatively, the performed studies (Beneberu & Yazdani, 2018; Bisby et al., 2005) revealed that, with the application of an approximately 1.57-inches-thick (40-mm-thick) cementitious insulation system, the fire resistance of the FRP system could be significantly improved by reducing the temperature of the CFRP-concrete interface. The concrete structures strengthened by CFRP materials with the proper fire protection systems can maintain their full mechanical capacities after being subjected to severe fire instances (e.g., 1-hour hydrocarbon fire).

Even though several methods for enhancing the FRP system's fire resistance have been studied and developed, the proposed fireproofing techniques might still be questionable (e.g., economic issues and related long-term durability issues). Therefore, more experimental and analytical studies are required to develop rational design recommendations for applying the fireproofing

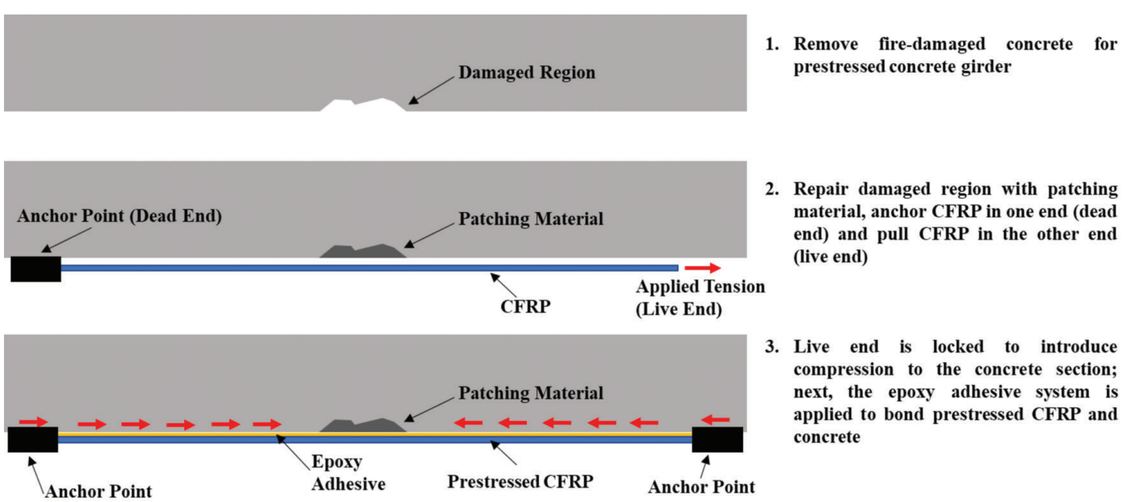

Figure 4.6 bPT-CFRP repair (Harries et al., 2009).

FRP systems. However, fire hazards may not be the most significant factor for bridge design in most cases due to their lower possibility of occurrence. Hence, if the repaired bridges are not fire-critical, the conventional CFRP system with epoxy adhesive should still be adequate. On the other hand, in fire-critical cases, the fire-resistant capacity of the CFRP-repaired bridge girders should be considered and designed carefully due to the fragility of the epoxy adhesive system at high temperatures.

5. CONCLUSIONS

Based on the investigations conducted as part of this project, including a survey study of state transportation agencies and detailed literature review. The following conclusions have been drawn.

1. Based on the case studies, prestressed concrete bridge girders impacted by intense fire instances (e.g., 5 hours with 1,112°F (600°C) maximum concrete surface temperature) may only experience superficial concrete material damage, and degradation of the steel strands (mechanical properties and prestressing force) may be insignificant. This finding generally agrees well with the conclusions obtained from the INDOT research project SPR-4221 (Varma et al., 2021). Moreover, the survey results also suggest that the concrete bridge with damaged prestressing strands (significant fire damage) is rarely observed.
2. Both literature review and survey study suggest similar repair methods for fire-damaged concrete bridges, and they include (1) concrete surface repair, (2) patch concrete, (3) pressure-injection of epoxy resins, (4) concrete removal/cast-in-place concrete, (5) tendon cleaning/coating, (6) steel encasement, (7) FRP wrapping, and (8) replace the damaged structure. Features and limitations of different repair approaches are discussed in Chapters 3 and 4.
3. In general, most respondents use visual inspection and non-destructive evaluation methods (e.g., concrete sounding) to determine the extent of the fire damage and evaluate the bridge's mechanical capacity using a bridge/structure analysis software and structural design specifications.
4. For bridges that sustain minor fire damage (concrete cracks and shallow spalls which do not affect tendons), most survey respondents (74%) will choose not to repair the damaged bridges. If the restoration is performed, the preferred repair methods may include (1) concrete surface repair, (2) patch concrete, and (3) pressure injection of epoxy resins, and bridge engineers commonly adopt them in different transportation agencies. Moreover, CFRP material can be employed to wrap and confine the damaged/patched area, which can improve its long-term durability.
5. Bridges with moderate fire damage (large concrete cracks and spalls; exposed, undamaged tendons) are often repaired using various methods, including (1) patch concrete method, (2) concrete removal/cast-in-place concrete, (3) pressure injection of epoxy resins, (4) tendon cleaning/coating and (5) steel/FRP jacketing. Pre-compression can be applied to restore the prestressing force in the repaired areas. Moreover, most survey respondents believe that the durability and serviceability of the repaired bridge can be restored to pre-fire conditions if the repair is conducted effectively.
6. According to the literature review, CFRP-based repair techniques generally show more advantages than other alternatives and could be a favorable option to retrofit fire-damaged concrete bridges. However, the fire resistance of FRP-based repair may be questionable due to the fragility of the epoxy adhesive system at high temperatures. Therefore, in fire-critical cases, fireproofing systems may be necessary.
7. Once a concrete girder bridge sustains significant fire damage (exposed and damaged tendons; loss of a portion of cross-section), although it is rare, most transportation agencies will prefer to replace the damaged structure rather than repair/retrofit it.

This synthesis study consists of reviewing related research documents and the survey of practice. Therefore, both research-based and experiential knowledge about the repair/retrofit for the fire-damaged prestressed concrete bridge girders is provided in this report. In conclusion, for most accessible cases, the typical damage level for prestressed concrete bridge girders exposed to fire is either minor or moderate (without significant section loss and damaged tendons). Different repair techniques are available to restore concrete girders with this level of fire damage. For the most extreme case with concrete girders subjected to significant section loss and damaged tendons, it is recommended to replace the damaged girders since repair and retrofit may not be a practical strategy due to the uncertainties associated with the structural performance of the repaired system without detailed experimental investigation.

With the assistance of this study, bridge inspectors and engineers can have a reference for developing a proper assessment/repair plan for the target bridge in different levels of fire damage. However, although this report includes various approaches in dealing with the fire-damaged concrete bridges, the final decision should still be made by the representative after considering all the conditions and limitations (e.g., economy and constructability issues) of the actual scenario.

6. RECOMMENDATIONS FOR FUTURE WORK

The results of this research report focused on (1) probable repair/retrofit methods for prestressed concrete bridge girders exposed to fire, (2) methods for inspecting and assessing the performance of repaired/unrepaired girders, and (3) performance and long-term durability of the repaired/unrepaired girders. The research results can be employed to develop assessment and repair plans for fire-damaged prestressed bridges. However, there are still several concerns that need to be investigated by additional research.

1. The long-term durability of unrepaired fire-damaged bridge girders needs to be studied. For the unrepaired

girder with minor damage, most survey respondents claimed that the option "do nothing" may be a favored decision. However, the durability of the unrepaired bridge may be problematic due to superficial concrete cracking of the exposed surface, and it should be evaluated more cautiously. More research-based knowledge regarding this issue is needed to support the decision not to repair the concrete bridges with minor fire damage.

2. Most survey respondents indicated that the performance and durability of repaired fire-damaged concrete girder may be adequate if the repair is "properly conducted." However, this statement is questionable since most respondents stated that they had only a few available cases in recent years. Furthermore, there is little research investigating the long-term serviceability and durability of repaired fire-damaged bridges (most of the existing studies are for impact-damaged bridges). Hence, the long-term performance and durability of fire-damaged and repaired bridge girders need to be assessed.
3. For repairing a fire-damaged concrete bridge, CFRP-based methods seem to be a more appropriate solution. However, as discussed in Section 4.3.5, in some rare cases the repaired bridge may be fire-critical, and the fire-resisting capability of the repair may be limited since the epoxy bonding agent of the repair system has poor fire resistance. Therefore, alternative cement-based bonding agents or fireproofing techniques may be needed to protect the repaired areas. Although some research articles addressing this topic have been published, the economic and long-term serviceability issues of using cement-based adhesives or fireproofing techniques are still relatively unexplored, and additional investigations are needed.

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APPENDICES

Appendix A. Survey Questions

APPENDIX A. SURVEY QUESTIONS

1. Plans for repair/retrofit of fire-damaged prestressed girders are usually prepared by (select all that apply):

	DOT/District design/bridge engineer
	DOT/District maintenance engineer
	Private consultant
	Other (please describe in Question 2)

2. Please provide your answer if you select “Other” In Question 1. You can skip this question if not applicable.

3. Construction of repair/retrofit is usually performed by (select all that apply):

	DOT/district/agency personnel
	Private contractor
	Other (please describe in Question 4)

4. Please provide your answer if you select “Other” In Question 3. You can skip this question if not applicable.

5. Rate the following factors by importance in the determination of the method of repair.

	Low	Moderate	High	Not Considered
Cost of repair				
Time required to make repair				
Aesthetics of repair				
Interruption of service				
Load capacity				
Expected service life of repair				
Maintenance required				
Other (please specify in Question 6)				

6. Please provide your answer if you select “Other” In Question 5. You can skip this question if not applicable.

7. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degree of damage (write N/A if there was no bridge being damaged by fire in this level based on your judgement):

MINOR damage: (concrete cracks and shallow spalls which do not affect tendons**)**

8. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degree of damage (write N/A if there was no bridge being damaged by fire in this level based on your judgement):

MODERATE damage: (large concrete cracks and spalls; exposed, undamaged tendons**)**

9. Estimate the number of fire-damaged prestressed concrete bridges in your judgement over the last 5 years for the following degrees of damage (enter N/A if there was no bridge being damaged by fire in this level based on your judgement):

SIGNIFICANT damage: (exposed and damaged tendons; loss of portion of cross section**)**

10. What actions are typically taken for the following degrees of damage (use definitions for the damage levels in Questions 7 to 9)?

	No Repair Made	Non-Structural Repair	Load-Carrying Repair	Replace Member Or Structure
Minor				
Moderate				
Significant				

11. For cases where repair action is finally taken, what procedures are used to determine the extent of the damage?

	Commonly	Rarely	Never	N/A
Visual inspection				
Non-destructive evaluation (NDE/NDT). Which methods are typically used? (please describe in Question 12)				
Destructive evaluation. Which methods are typically used? (please describe in Question 12)				
Other (please describe in Question 12)				

12. Please provide the supplementary answer for your responses in Question 11. You can skip this question if not applicable.

13. What analytical Procedures are used to assess the fire-induced damage and the need for repair of prestressed concrete bridges?

	commonly	rarely	never	n/a
Hand calculation. Which codes/specifications are typically used? (please describe in Question 14)				
Bridge/structure analysis software. Which software is typically used? (please describe in Question 14)				
Finite element analysis software. Which software is typically used? (please describe in Question 14)				
Other (please describe in Question 14)				

14.Please provide the supplementary answer for your responses in Question 13.

15.What methods are used to repair prestressed concrete bridges with **MINOR** damage (concrete cracks and nicks; shallow spalls and scrapes not affecting tendons)?

	commonly	rarely	never	n/a
Do nothing				
Concrete surface repair				
Patch concrete				
Pressure-injection of epoxy resins				
Other (please describe in Question 16)				

16. Please provide your answer if you select "Other" In Question 15. You can skip this question if not applicable.

17. What methods are used to repair prestressed concrete bridges with **MODERATE** damage (large concrete cracks and spalls; exposed, undamaged tendons)?

	commonly	rarely	never	n/a
No bridge being damaged by fire in this level based on your judgement				
Do nothing				
Patch concrete				
Shotcrete				
Pressure-injection of epoxy resins				
Concrete removal/ Cast-in-place concrete				
Steel/FRP jacketing				
Tendon cleaning/coating				
Installation of active or passive corrosion control measures				
Replace individual girder				
Replace bridge				
Other (please describe in Question 18)				

18. Please provide your answer if you select "Other" In Question 17. You can skip this question if not applicable.

19.What methods are used to repair prestressed concrete bridges with **SIGNIFICANT** damage (exposed and damaged tendons; loss of portion of cross section)?

	commonly	rarely	never	n/a
No bridge being damaged by fire in this level based on your judgement				
Patch concrete				
Shotcrete				
Pressure-injection of epoxy resins				
Concrete removal/ Cast-in-place concrete				
Steel/FRP jacketing				
Cut tendons with damaged section (no repairment)				
External post-tensioning (please describe the employed method Question 20)				
Internal splices (please describe the employed method and answer if the repair is re-stressed in Question 20)				
Metal sleeve splice (please describe the employed method below and answer if the repair is re-stressed in Question 20)				
Externally applied reinforcing material (FRP, etc.) (please describe the employed method in Question 20)				
Installation of active or passive corrosion control measures (please describe the employed method in Question 20)				
Replace individual girder				
Replace bridge				
Other (please describe in Question 20)				

20. Please provide the supplementary answer for your responses in Question 19. You can skip this question if not applicable.

21. How do the fire-damaged/unrepaired prestressed concrete bridges perform in your experience (e.g., long-term durability and serviceability)? Please indicate if there are any problems.

22. How do the fire-damaged/unrepaired prestressed concrete bridges perform in your experience (e.g., long-term durability and serviceability)? Please indicate if there are any problems.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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