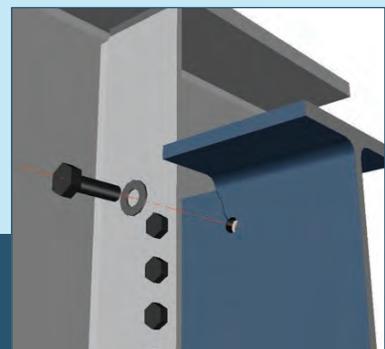


MAINTENANCE GUIDELINES FOR STEEL BRIDGES

Addressing Fatigue Cracking and Details
at Risk of Constraint-Induced Fracture

G14.I-2021



AMERICAN ASSOCIATION
OF STATE HIGHWAY AND
TRANSPORTATION OFFICIALS
AASHTO



AASHTO/NSBA STEEL BRIDGE COLLABORATION

American Association of State Highway
and Transportation Officials

National Steel Bridge Alliance

Preface

This document presents guidelines developed by the AASHTO/NSBA Steel Bridge Collaboration. The primary goal of the Collaboration is to achieve steel bridge design and construction of the highest quality and value through standardization of the design, fabrication, and erection processes. Each document represents the consensus of a diverse group of professionals.

It is desired that Owners adopt and support Collaboration guidelines in their entirety to facilitate the achievement of standardization. It is understood, however, that local statutes or preferences may prevent full adoption of the guidelines recommended herein. In such cases, Owners may adopt these guidelines with the exceptions they feel are necessary.

Disclaimer

The information presented in this publication has been prepared in accordance with recognized engineering principles and is for general information only. While it is believed to be accurate, this information should not be used or relied upon for any specific application without competent professional examination and verification of its accuracy, suitability, and applicability by a licensed professional engineer, designer, or architect.

The publication of the material contained herein is not intended as a representation or warranty on the part of the American Association of State Highway and Transportation Officials (AASHTO) or the National Steel Bridge Alliance (NSBA) or of any other person named herein, that this information is suitable for any general or particular use or of freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability arising from such use.

Caution must be exercised when relying upon other specifications and codes developed by other bodies and incorporated by reference herein since such material may be modified or amended from time to time subsequent to the printing of this edition. The authors and publishers bear no responsibility for such material other than to refer to it and incorporate it by reference at the time of the initial publication of this edition.

Copyright © 2022 by the AASHTO/NSBA Steel Bridge Collaboration

AASHTO Publication No: NSBAMGFC-1

Acknowledgements

This document was originally prepared for the AASHTO Committee on Bridges and Structures, with funding provided through the National Cooperative Highway Research Program (NCHRP) Project 20-07 Task 387, *Maintenance Actions to Address Fatigue Cracking in Steel Bridge Structures*. The NCHRP is supported by annual voluntary contributions from the state departments of transportation. Project 20-07 is intended to fund quick response studies on behalf of the AASHTO Subcommittee on Bridges and Structures (SCOBS). The report was prepared by Dr. Robert J. Connor, P.E., Professor of Civil Engineering at Purdue University and Dr. Jason B. Lloyd, P.E., former Research Engineer at Purdue University, with computer drafting support provided by Mr. Jonathan Hui, former Graduate Research Assistant at Purdue University. The work was guided by a technical working group. The project was managed by Dr. Waseem Dekelbab, NCHRP Senior Program Officer.

Table of Contents

PREFACE	ii
AASHTO EXECUTIVE COMMITTEE 2021–2022	iii
AASHTO/NSBA COLLABORATION TASK FORCE	vi
ACKNOWLEDGEMENTS	vii
EXECUTIVE SUMMARY	xx
CHAPTER 1: INTRODUCTION	1
CHAPTER 2: FATIGUE AND FRACTURE FUNDAMENTALS	3
2.1—Historical Steel Bridge Issues	3
2.2—Fundamentals of Fracture	4
2.2.1—Introduction to Fracture Mechanics	4
2.2.2—Constraint	5
2.2.3—Strain Rate	5
2.2.4—Temperature	5
2.2.5—Stress	6
2.2.6—Discontinuity	6
2.2.7—Material Toughness	6
2.3—Fundamentals of Fatigue	9
2.3.1—Nominal Stress Approach of Fatigue Design and Evaluation	10
2.4—Considerations for Fatigue Detail Classification	13
2.5—Considerations for Evaluating Existing Steel Bridges	14
2.5.1—Fatigue Evaluation of Existing Steel Bridges	14
2.5.2—Fracture Evaluation of Existing Steel Bridges	15
2.6—Considerations for Urgency of Repair and Retrofit	16
CHAPTER 3: FUNDAMENTAL TECHNIQUES FOR FATIGUE REPAIR AND RETROFIT OF STEEL BRIDGES	19
3.1—Basic Inspection Techniques	19
3.2—Paint Coating Techniques for Local Repairs	19
3.3—Hole Drilling Techniques for Crack Arrest	20
3.3.1—General Considerations for Hole Drilling to Arrest Cracks	22
3.3.2—Procedural Guidelines for Hole Drilling to Arrest Cracks	26
3.4—Surface Grinding Techniques	28
3.4.1—General Considerations for Surface Grinding	28
3.4.2—Procedural Guidelines for Surface Grinding	29
3.5—Weld Toe Improvement Techniques	29
3.5.1—Weld Toe Grinding	29

3.5.2—Procedural Guidelines for Weld Toe Grinding	30
3.5.3—Hammer Peening.....	31
3.5.4—Procedural Guidelines for Weld Toe Hammer Peening	31
3.5.5—Ultrasonic Impact Treatment	32
3.5.6—Procedural Guidelines for Ultrasonic Impact Treatment	33
3.6—Fundamentals of Performance Testing	35
3.6.1—Considerations for Repair and Retrofit Performance Tests.....	35
3.6.2—Considerations for NDT Inspector Performance Tests	36
3.7—Considerations for Prototyping.....	38
CHAPTER 4: MAINTENANCE ACTIONS FOR LOAD-INDUCED FATIGUE.....	41
4.1—Welded Cover Plate Terminations.....	41
4.1.1—Description of Problem	41
4.1.2—Repair or Retrofit Guidelines	44
4.1.2.1—Weld Toe Treatment.....	44
4.1.2.2—Bolted Splice Retrofit.....	44
4.2—Re-entrant Corners at Coped or Blocked Stringers and Floorbeams.....	47
4.2.1—Description of Problem	47
4.2.2—Repair or Retrofit Guidelines	48
4.2.2.1—Increase Cope/Block Transition Radius	49
4.2.2.2—Drilled Hole for Crack Arrest.....	51
4.2.2.3—Bolted Doubler Plate Retrofit.....	52
4.2.2.4—Fastener Removal Retrofit	53
4.3—Notches and Gouges	54
4.3.1—Description of Problem	54
4.3.2—Repair or Retrofit Guidelines	54
4.4—Longitudinal Stiffener and Gusset Plate Weld Terminations	55
4.4.1—Description of Problem	55
4.4.2—Repair or Retrofit Guidelines	57
4.4.2.1—Weld Termination Removal.....	57
4.4.2.2—Weld Toe Treatment.....	59
4.4.2.3—Web Plate Isolation Holes	60
4.5—Riveted Connections	62
4.5.1—Description of Problem	62
4.5.2—Repair or Retrofit Guidelines	64
4.6—Transverse Butt Welds	66
4.6.1—Description of Problem	66
4.6.2—Repair or Retrofit Guidelines	67
4.6.2.1—Grind Weld Reinforcement Smooth	67
4.6.2.2—Weld Toe Treatment.....	68
4.6.2.3—Bolted Splice Retrofit	68
4.7—Flame-Cut Holes, Weld Access Holes, and Other Open Holes	70
4.7.1—Description of Problem	70

4.7.2—Repair or Retrofit Guidelines	70
4.8—Tack Welds and Extraneous Welds	72
4.8.1—Description of Problem	72
4.8.2—Repair or Retrofit Guidelines	73
4.9—Plug Welds	73
4.9.1—Description of Problem	73
4.9.2—Repair or Retrofit Guidelines	75
4.10—Gusset Plates Welded to Flanges	75
4.10.1—Description of Problem	75
4.10.2—Repair or Retrofit Guidelines	76
4.10.2.1—Weld Toe Treatment.....	76
4.10.2.2—Conversion to Bolted Connection	77
4.11—Discontinuous Backing Bars.....	78
4.11.1—Description of Problem	78
4.11.2—Repair or Retrofit Guidelines	79
4.12—Impact-Damaged Zones.....	81
4.12.1—Description of Problem	81
4.12.2—Repair or Retrofit Guidelines	83
 CHAPTER 5: MAINTENANCE ACTIONS FOR DISTORTION-INDUCED FATIGUE.....	85
5.1—Connection Plate Web Gaps on Girder, Girder-Floorbeam, and Box Girder Bridges.....	86
5.1.1—Description of Problem	86
5.1.2—Repair or Retrofit Guidelines	88
5.1.2.1—Drilled Hole for Crack Arrest.....	88
5.1.2.2—Web Gap Stiffening: Welded Splice Retrofit.....	88
5.1.2.3—Web Gap Stiffening: Bolted Splice Retrofit	90
5.1.2.4—Web Gap Softening: Large-Hole Retrofit.....	94
5.1.2.5—Web Gap Softening: Connection Plate Cutback Retrofit	95
5.1.2.6—Diaphragm or Cross-Frame Removal Retrofit	97
5.1.2.7—Bolt Loosening Retrofit.....	98
5.2—Floorbeam Web Gaps on Tied-Arch Bridges, Trusses, and Plate Girder Bridges	99
5.2.1—Description of Problem	99
5.2.2—Repair or Retrofit Guidelines	101
5.2.2.1—Drilled Hole for Crack Arrest.....	101
5.2.2.2—Floorbeam Cutback Retrofit	102
5.3—Cantilever Bracket Connections	104
5.3.1—Description of Problem	104
5.3.2—Repair or Retrofit Guidelines.....	105
5.4—Cantilever Bracket Tie Plates.....	106
5.4.1—Description of Problem	106
5.4.2—Repair or Retrofit Guidelines	108
5.5—Riveted and Bolted Connections Using Angles.....	110
5.5.1—Description of Problem	110

5.5.2—Repair or Retrofit Guidelines	112
5.5.2.1—Bearing Seats Retrofit.....	112
5.5.2.2—Diaphragm Removal Retrofit	112
5.5.2.3—Connection Angle Replacement Retrofit.....	113
5.5.2.4—Fastener Removal Retrofit	114
5.6—Web Penetrations in Cross Girders	114
5.6.1—Description of Problem	114
5.6.2—Repair or Retrofit Guidelines	116
CHAPTER 6: MAINTENANCE ACTIONS FOR DETAILS AT RISK OF CONSTRAINT-INDUCED FRACTURE	119
6.1—Intersecting Welds at Gusset Plates (Hoan Details).....	122
6.1.1—Description of Problem	122
6.1.2—Retrofit Guidelines	124
6.1.2.1—Gusset Plate Cope Retrofit	124
6.1.2.2—Web Plate Isolation Holes Retrofit	126
6.1.2.3—Ball End Mill Retrofit.....	129
6.2—Intersecting Welds at Longitudinal Stiffener Plates.....	131
6.2.1—Description of Problem	131
6.2.2—Retrofit Guidelines	133
6.3—Poor Quality Longitudinal Stiffener Splices.....	135
6.3.1—Description of Problem	135
6.3.2—Retrofit Guidelines	138
6.3.2.1—Longitudinal Stiffener Core Retrofit	138
6.3.2.2—Web Plate Core Retrofit.....	140
6.4—Web Gaps at Bearing Stiffeners in Negative Moment Regions	144
6.4.1—Description of Problem	144
6.4.2—Retrofit Guidelines	145
CHAPTER 7: VARIOUS METHODS WITH UNDETERMINED PERFORMANCE.....	147
7.1—Doubler Plate-Angle Retrofit for Web Gap Stiffening.....	147
7.2—Fusion-Welded Threaded Stud for Web Gap Stiffening	148
7.3—Carbon Fiber Reinforced Polymer (CFRP)	150
7.4—Drilled Hole with Cold Expansion Sleeve	152
REFERENCES	155
APPENDIX A: QUICK REFERENCE TABLES.....	161
A.1—Load-Induced Fatigue Quick Reference Tables.....	162
A.2—Distortion-Induced Fatigue Quick Reference Tables.....	166
A.3—Constraint-Induced Fracture Quick Reference Table.....	169

List of Figures

Figure 2-1.	Stress Concentration at a Finite Element Model Flange Thickness Transition	6
Figure 2-2.	Material Toughness Curves	7
Figure 2-3.	Charpy Impact Test Machine	8
Figure 2-4.	Sample of Charpy Impact Test Data Showing Transitions.....	8
Figure 2-5.	Modern <i>S-N</i> Curve Showing All AASHTO Fatigue Categories	11
Figure 2-6.	Sample Variable Amplitude Load Spectrum from Field Monitoring.....	11
Figure 2-7.	Category C <i>S-N</i> Curve Illustrating the Regions of the Plot	12
Figure 2-8.	FEM Illustrating Differing Stress Concentrations for Length and Thickness Effects	13
Figure 3-1.	(Left) Example of Magnetic-Based Drill, (Right) Annular Cutter Used for Hole Drilling	21
Figure 3-2.	Crack Tip Tunneling Contributing to a Missed Crack Tip That Later Fractured.....	22
Figure 3-3.	Crack Length Appears Different on Each Side of a Plate as it Transitions to Through-Thickness .	23
Figure 3-4.	Improper and Proper Drilled Hole Placements for Crack Arrest	24
Figure 3-5.	Example of Chasing the Crack Tip with Repeated Drilling.....	25
Figure 3-6.	Drilled Hole Showing Rough Edges and Burrs	25
Figure 3-7.	Magnetic Particle Test Performed Before Drilling Crack Arrest Hole in Order to Locate the Crack Tip.....	26
Figure 3-8.	Shows an Annular Cutter Breaking the Surface on the Opposite Side of the Plate, Positioned Correctly to Intercept the Crack Tip.....	27
Figure 3-9.	Example of Finished Crack Arrest Hole Prior to Painting.....	27
Figure 3-10.	Typical Angle Grinder with Flap Wheel	28
Figure 3-11.	Typical Die Grinder with Burr Bit	28
Figure 3-12.	Correct Tool Position for Angle Grinding of Weld Toe	30
Figure 3-13.	Correct Tool Position for Die Grinding with Burr Bit at Weld Toe	30
Figure 3-14.	Typical Peening Bits.....	32
Figure 3-15.	Examples of UIT Tools	33
Figure 3-16.	Sketch Demonstrating the Path of the Handheld Tool During Unp Application	34
Figure 3-17.	Appearance of Properly Treated Weld Toe Using Unp Method.....	34
Figure 3-18.	Recommended Peening Locations for Cover Plate Details with (Left) and without (Right) the Transverse Weld	35
Figure 3-19.	(Left) Example of Used Mockup, (Right) Performance Testing of a Contractor Prior to Implementation of a Repair Project	36
Figure 3-20.	(Left) Welded Steel Test Specimen Hung on a Bridge, (Right) Performance Testing of an Inspector Prior to Beginning NDT on Bridge Welds	36
Figure 3-21.	Sample of UT Performance Testing Results	37
Figure 3-22.	Distortion-Induced Fatigue Crack Growing out of the Throat of the Weld	39

Figure 3-23. Example of Prototype “Two-Hole” Retrofit Installed	39
Figure 4-1. Example of Load-Induced Fatigue Crack Located on a Railroad Through-Truss Hanger	41
Figure 4-2. 16-inch-long Fracture Resulting from Fatigue Crack at Cover Plate Weld Toe.....	42
Figure 4-3. Example of a Cover Plate Fatigue Crack at Detail without Transverse Weld.....	43
Figure 4-4. Example of a Fatigue Crack at a Cover Plate with Transverse Weld.....	43
Figure 4-5. Crack Arrest Hole Preventing Crack from Propagating into the Web Plate.....	44
Figure 4-6. Rendering of Full Flange Splice at Cover Plate Detail	45
Figure 4-7. Rendering of Partial Flange Splice at a Bottom Flange Cover Plate Detail with Weld Toe Peening.....	45
Figure 4-8. Sample Re-Entrant Corner Details with No Transition Radius	47
Figure 4-9. Example of Load-Induced Crack at Floorbeam Cope.....	48
Figure 4-10. Example of Floorbeam Cope Crack.....	49
Figure 4-11. Examples of Typical Acceptable Copes	49
Figure 4-12. Drilled Hole Used to Increase Cope Transition and Reduce Stress Concentration	50
Figure 4-13. Before (A) and after (B) Pictures of Cope Transition Retrofit.....	51
Figure 4-14. Drilled Hole Retrofit for Cracked Cope Details Using High-Strength Bolt Assembly.....	52
Figure 4-15. Bolted Doubler Plate Retrofit with Drilled Hole for Crack Arrest.....	53
Figure 4-16. Example of 5:1 Taper Ratio Marking.....	55
Figure 4-17. Example of Edge Flaw Removed with 5:1 Fairing Ratio, Shown Prior to Repainting.....	55
Figure 4-18. Example of Fatigue Crack at a Gusset Plate Weld Termination	56
Figure 4-19. Example of Fatigue Crack at a Longitudinal Stiffener Weld Termination.....	56
Figure 4-20. Example of Longitudinal Stiffeners Located in Tension and Compression Zones.....	57
Figure 4-21. Weld Termination Removal Using Burr Bit and Die Grinder.....	58
Figure 4-22. Retrofit for Plate Termination Using Drill and Annular Cutter.....	59
Figure 4-23. Weld Toe Peening at Gusset Plate Termination	60
Figure 4-24. Example of Dog-Bone Retrofit (Left) and Web Isolation Holes (Right)	61
Figure 4-25. Example of Web Isolation Hole Placement at Weld Termination of a Gusset Plate	61
Figure 4-26. Example of Punched and Drilled Hole Quality	63
Figure 4-27. Perspective with Rivet Removed Revealing Appearance of Punched (a) vs. Drilled (b) Hole.....	63
Figure 4-28. Test Specimen Showing Fractured Cover Plate with Fatigue Crack Propagating from Rivet Hole in the Flange Angle	64
Figure 4-29. Rivet Removal Using a Blunt Tip and Pneumatic Rivet Buster Hammer.....	65
Figure 4-30. Transverse Groove Weld with Reinforcement Left in Place (Category C).....	66
Figure 4-31. Category C Transverse Groove Weld	67
Figure 4-32. Example of Bolted Splice Installed on a Tie Girder	68
Figure 4-33. Top View Showing Dog-Bone Retrofit on a Tie Girder Butt Weld	69
Figure 4-34. Poor Quality Flame-Cut Hole That is Prone to Fatigue and Fracture.....	70

Figure 4-35. Repair of a Cracked Weld Access Hole Showing before (Left) and after (Right) (Photographs courtesy of Kansas DOT)	71
Figure 4-36. Examples of Tack Welds Used in Fabrication.....	72
Figure 4-37. Common Crack Location at Tack Weld	73
Figure 4-38. I-57 Farina Overpass Fracture at Plug Weld	74
Figure 4-39. Magnetic Particle Test Results at a Plug Weld Showing Lack of Fusion Defects	74
Figure 4-40. Example of Gusset Plate Welded to the Flange with only Transverse Welds	76
Figure 4-41. Weld Toe Peening for Gusset Plates Attached to Flanges.....	77
Figure 4-42. Completed Retrofit Showing Removal of Welds and Bolted Connection.....	78
Figure 4-43. Example of Backing Bar Discontinuity Found in Fort Duquesne Approach Spans	79
Figure 4-44. Example of Backing Bar Termination Removed Inside the Tie Girder of the Hoan Bridge	80
Figure 4-45. Discontinuous Backing Bar Retrofit Showing Fairing of Weld Terminations	81
Figure 4-46. (a) Example of Microcrack Resulting from Impact (b) Example of Brittle Fracture Resulting from Impact at Another Location	82
Figure 4-47. Fractures on the Same Girder Resulting from a Single Impact Event	82
Figure 5-1. Example of Floorbeam Web Gap Cracking	85
Figure 5-2. Exaggerated Illustration Depicting Bending in a Web Gap Caused by Uneven Loading of the Plate Girders.....	87
Figure 5-3. Example of Web Gap Cracking Resulting from Distortion	87
Figure 5-4. Welded Splice at Connection Plate and Top Flange.....	89
Figure 5-5. Completed Welded Splice Retrofit Showing Filler Plate Option to Close Gap	90
Figure 5-6. Insufficiently Stiff Splice Angle Shown Installed on Gusset–Connection Plate Web Gap	91
Figure 5-7. Completed Bolted Splice Retrofit Showing Double Angle Stiffening Elements	92
Figure 5-8. Completed Bolted Splice Retrofit Showing WT Stiffening Element.....	93
Figure 5-9. WT Stiffening Retrofit Implemented on the Hoan Bridge.....	93
Figure 5-10. Drilled Hole Prototype Installed at Bearing Stiffeners	94
Figure 5-11. Large-Hole Retrofit—Note Interception of Horizontal and Vertical Weld Toes.....	95
Figure 5-12. Lexington Ave Bridge Cutback Retrofit.....	96
Figure 5-13. Cutback Retrofit Installed on Polk County Bridge	97
Figure 5-14. Illustration Highlighting in Red the Area of a Floorbeam Web Prone to Web Gap Cracks.....	99
Figure 5-15. Cross Section Illustrating Driving Stresses for the Floorbeam Web Gap Cracking.....	100
Figure 5-16. Example of Distortion-Induced Cracking in Web Gab of Floorbeam Connected to Tie Girder....	100
Figure 5-17. Floorbeam Web Gap Crack	101
Figure 5-18. Results of PT Revealing Extent of Crack.....	101
Figure 5-19. Drilled Hole Prior to Sanding Edges.....	102
Figure 5-20. Finished Repair with Zinc-Rich Paint.....	102
Figure 5-21. Birmingham Bridge before Retrofit Showing Web Gap Cracking.....	103

Figure 5-22. Birmingham Bridge Softening Retrofit That Cut Back the Floorbeam	103
Figure 5-23. Sketch Illustrating Mechanism Driving Fatigue Cracking of Bracket Connection Plates	104
Figure 5-24. Cantilever Floorbeam Web Gap and Connection Plate Cracks	104
Figure 5-25. Softening Retrofit on Floor Bracket Connection Plates Showing Removal of Bolts and Plate	105
Figure 5-26. Close Up Showing Softening Detail with Crack Arrest Hole	106
Figure 5-27. Illustration of Cantilever Tie Plate Distortion	106
Figure 5-28. Fatigue Crack Emanating from Tack Weld on a Tie Plate	107
Figure 5-29. Typical Tie Plate Detail Prior to Retrofit with Common Crack Location Highlighted.....	109
Figure 5-30. Tie Plate Retrofit Showing Reduced Plate Width and Decoupling from Girder.....	109
Figure 5-31. Common Locations for Fatigue Cracks in Connection Angles.....	110
Figure 5-32. Cracked Connection Angle Fillet	111
Figure 5-33. Example of Fatigue Crack Located at the Bend of a Connection Angle	111
Figure 5-34. Rendering of Connection Angles Used by Cousins et al. (1998).....	114
Figure 5-35. Dan Ryan Expressway with Fractured Cross Girder	115
Figure 5-36. Fatigue crack Enhanced with PT at Girder Flange Tip and Cross Girder Web.....	116
Figure 5-37. Cross Girder Structure with Dog-Bone Retrofit at the Web Penetration	117
Figure 5-38. Completed Dog-Bone Retrofit on a Web Penetration Detail	117
Figure 6-1. U.S. 422 Bridge Fracture Discovered in 2003 During Retrofitting	119
Figure 6-2. U.S. 422 Bridge Fracture That Arrested in the Web	120
Figure 6-3. Defining Characteristics of CIF Details	120
Figure 6-4. Illustration of Effect of Web Gap Size and Constraint on the Stress Condition at the Weld Termination with the Web Gap	121
Figure 6-5. Illustration of Effect of a Sufficient Web Gap That Removes Constraint at the Weld Termination	122
Figure 6-6. Hoan Bridge Fracture Showing the Gusset Detail of the Interior Girder.....	123
Figure 6-7. CIF Detail Located at the Intersection of Transverse and Horizontal Welds on the Hoan Bridge	123
Figure 6-8. Gusset Plate Cope Retrofit	124
Figure 6-9. Burr Grinder Being Used to Remove Leftover Gusset Plate and Weld	125
Figure 6-10. Completed Gusset Plate Cope Retrofit with $\frac{3}{4}$ Inch Web Gap.....	126
Figure 6-11. CIF Arrested in One of the Hoan Bridge Web Isolation Holes Shortly after Installation.....	127
Figure 6-12. Web Plate Isolation Holes Retrofit for CIF Details.....	128
Figure 6-13. Web Isolation Holes Retrofit on the Hoan Bridge (A) beneath the Gusset, (B) Opposite Side of Gusset.....	128
Figure 6-14. Diefenbaker Bridge Fracture Originated at CIF Detail.....	130
Figure 6-15. Ball End Mill Retrofit on Diefenbaker Bridge.....	131
Figure 6-16. Matthew E. Welsh Bridge CIF Ball End Mill Retrofit.....	131

Figure 6-17. CIF at a Longitudinal Stiffener	132
Figure 6-18. Example of CIF Retrofit on Longitudinal Stiffener Providing the Necessary 1/4-Inch Web Gap ..	133
Figure 6-19. Hoan Bridge Longitudinal Stiffener CIF Retrofit	133
Figure 6-20. CIF Retrofit at a Longitudinal Stiffener	134
Figure 6-21. Example of a Poor-Quality Longitudinal Stiffener Butt Splice Weld	136
Figure 6-22. Poor-Quality Longitudinal Stiffener Splice	136
Figure 6-23. I-95 Bridge over Brandywine River in Delaware with a Fracture Initiated at the Longitudinal Stiffener Butt Splice	137
Figure 6-24. Illustration of the Longitudinal Stiffener Core Retrofit	139
Figure 6-25. Alternate Version of the Longitudinal Stiffener Core Retrofit with the Stiffener Plates Cut Back in Addition to the Drilled Hole	139
Figure 6-26. Longitudinal Stiffener Core Retrofit Showing Drilled Holes in the Web Plate for Crack Arrest ..	140
Figure 6-27. Hole Drilled in Web for Web Core Retrofit.....	141
Figure 6-28. Removal of Butt Weld and Drilled Core for Web Core Retrofit	142
Figure 6-29. Finished Retrofit with Drilled Holes for Optional Bolted Splice.....	142
Figure 6-30. Illustration of the Web Plate Core Retrofit for Longitudinal Stiffener Splices	143
Figure 6-31. Alternate Version of the Web Plate Core Retrofit.....	144
Figure 6-32. Fracture Initiated at Stiffener in Negative Moment Region.....	145
Figure 6-33. Illustration of Large-Hole Retrofit at Bearing Stiffener.....	146
Figure 7-1. Example Details of Doubler Plate Stiffening for Distortion-Induced Fatigue.....	147
Figure 7-2. Stiffened-Angles-with-Plate Retrofit.....	148
Figure 7-3. Example of Fusion-Welded Threaded Stud Retrofit Shown Blast Cleaned in Preparation for Painting.....	149
Figure 7-4. Torque Testing Arrangement	150
Figure 7-5. Components of the PUR System.....	151
Figure 7-6. Strengthened Floorbeam Using PUR System	152
Figure 7-7. Cold Expansion of Crack Arrest Holes (a) Floorbeam Cope Cracking, (b) Drilled Hole at the Crack Tip, (c) & (d) Finished Repairs with Expansion Sleeve	153

List of Tables

Table 1-1. Description of Ideograms Used in Repair and Retrofit Tables for Success of Performance	1
Table 1-2. Description of Ideograms Used in Repair and Retrofit Tables for Ease of Installation.....	2
Table 1-1. Description of Ideograms Used in Repair and Retrofit Tables for Success of Performance	161
Table 1-2. Description of Ideograms Used in Repair and Retrofit Tables for Ease of Installation.....	161
Table A.1-1. Strategies for Welded Attachments Subject to Primary Stresses	162
Table A.1-2. Strategies for Miscellaneous Details Subjected to Primary Stresses	163
Table A.1-3. Strategies for Riveted and Damaged Details	165
Table A.2-1. Strategies for Web Gaps on Primary Members Subject to Secondary Stresses.....	166
Table A.2-2. Strategies for Web Gaps on Secondary Members Subject to Secondary Stresses.....	167
Table A.2-3. Strategies for Connections Using Angles Subjected to Secondary Stresses.....	168
Table A.3-1. Strategies for Constraint-Induced Fracture (CIF) Details.....	169

Executive Summary

Nearly thirty percent of the U.S. national bridge inventory (highway bridges) is made up of bridges having steel superstructures with an average age of about 48 years at the time of this writing. Fortunately, steel bridge superstructures lend themselves well to repair and retrofit methods that can improve and even eliminate fatigue and constraint-induced fracture (CIF) concerns, extending the service life for many years or even decades. Unfortunately, fatigue and fracture tend to be the least understood by engineers of the limit states affecting steel bridges. In some cases, this has led to repair or retrofit strategies that rendered a worse condition than existed prior to the attempted fix.

This document provides simple-to-follow guidelines for the maintenance actions to address fatigue cracking as well as details at risk of constraint-induced fracture (CIF) in steel bridges. It is a synthesis of best practices from published literature, project reports, and past and ongoing research projects, as well as input from industry professionals. Intended to be a very practical reference text, it is written with everyone in mind, from a maintenance contractor to an asset manager or design engineer, providing detailed descriptions of the driving causes of fatigue cracking and CIF in steel bridges and accepted methods for repair or retrofit. A number of case studies are discussed, giving context for the different detail susceptibilities and utilizing a mixture of real-world and rendered images to illustrate the problems and solutions. For each case, a suggested sequence of steps is also provided as a “how-to.”

Appendix A contains quick reference tables with Harvey Ball ideograms that help users qualitatively identify appropriate repair or retrofit approaches for a type of detail. Some steel bridge details have multiple strategies that can be implemented and the tables are intended to give the reader a snapshot view of the benefits of each one, the degree of success it has had historically, and the level of ease (which translates to cost) with which the strategies can be implemented. Chapter 1 explains the ideogram tables in more detail.

Chapter 2 reviews several important general topics such as a brief history of steel bridge issues, the basics of fracture mechanics, and the basics of fatigue and fatigue evaluation. In addition, Chapter 2 also includes a section on the urgency of repairs, helping to ensure the reader considers factors that contribute to how urgently a repair or retrofit should be treated. Chapter 3 delves into some fundamental repair and retrofit techniques, such as grinding and hole drilling. These techniques are referred to many times throughout the rest of the guidelines. Chapter 4 introduces details commonly susceptible to load-induced fatigue, giving repair and retrofit strategies specific to those details. Load-induced fatigue is that caused by primary stresses and includes many of the details contained in the fatigue detail tables in the *AASHTO LRFD Bridge Design Specifications* (referred to as LRFD Design hereafter) (AASHTO, 2017). Chapter 5 transitions into distortion-induced fatigue caused by secondary stresses in steel structures. These are the most common types of fatigue cracks found in the steel bridge inventory. Chapter 6 covers the mechanics of constraint-induced fracture and details a number of effective retrofits that can be implemented to reduce or eliminate risk of fracture. And finally, Chapter 7 discusses several retrofit or repair concepts that may be in use, or being considered for use, that need additional research and development before being recommended.

CHAPTER 1

INTRODUCTION

The following is a synthesis of best practices from published literature, ongoing research activities, and input from industry professionals with the objective to provide guidelines for maintenance actions to address fatigue cracking in steel bridges. These Guidelines cover repair procedures, detailing techniques, maintenance recommendations, inspection recommendations, and preservation actions to repair and retrofit steel bridges in order to mitigate initiation of fatigue cracks on details known to have low fatigue resistance, control further growth of existing fatigue cracks, and reduce or eliminate the risk of CIF in steel bridges. The findings are primarily intended for highway bridges but are conceptually equally applicable to railroad bridges. In addition to fatigue, preemptive maintenance actions related to constraint-induced fracture (CIF) are also presented.

Fatigue and fracture tend to be the two limit states of steel bridges least understood when it comes to design, inspection, and especially for repair and retrofit. Although a wealth of research and case studies of fatigue damage and other failures related to steel bridge cracking exist in the literature, few university civil engineering programs offer courses on these topics. Only a limited number of professional short courses are offered which specialize in these topics, and even fewer reference manuals are available to practitioners. As a result, bridge owners and their consultants are often left to develop their own strategies. Unfortunately, experience has shown that some implemented repairs or retrofits have actually made the conditions worse due to the lack of understanding of what drives the development of fatigue cracks and how best to address it.

Detailed discussion is included regarding the cause or driving force behind various fatigue cracks observed in the field. As expected, the mitigation approaches have widely varied throughout the inventory, with some being more effective than others. During the literature review, which included a survey and conversations with industry leaders, the most effective retrofit strategies were identified for a given type of cracking. While the reader is encouraged to study these Guidelines to become fully familiar with the associated recommended retrofit strategy, ideograms were developed to assist the user in quickly selecting the most effective retrofit(s) for a given type of cracking. The approach follows that which is often used in publications that are used for rating and comparing cars or appliances. The concept is illustrated and explained in Table 1-1.

It is noted that there are often several “acceptable” retrofit strategies for a given type of cracking. Thus, assuming multiple approaches are known to be effective, other criteria, such as the required skills of the workforce or ease of installation, which generally translate into cost, should also be considered. Hence, the ideogram shown in Table 1-2 was prepared to provide a simple summary of these other factors which should be considered with each approach. While these tables explain the meaning of the ideograms, Appendix A contains the quick reference tables that help users qualitatively identify appropriate repair or retrofit approaches for a type of detail. Some steel bridge details have multiple strategies that can be implemented, and the tables are intended to provide a snapshot view of the benefits of each one, the degree of success it has had historically, and the level of ease with which the strategies can be implemented.

While the quick reference tables provided in Appendix A should not be used without reviewing the content of these Guidelines, they do provide a useful quick reference guide. Further, it is noted that some retrofits are inherently more challenging to install than others. For example, simple grinding is useful in removing a shallow nick or gouge, while retrofit and repair of a detail susceptible to CIF will require considerably more effort and possibly engineering analysis.

Table 1-1. Description of Ideograms Used in Repair and Retrofit Tables for Success of Performance

Success of Repair	
	Well-documented successful performance in the laboratory and in the field. Significant increase in fatigue resistance or significant reduction of risk of fracture.
	Documented successful performance in the laboratory or in the field showing moderate fatigue resistance enhancement or reduction of risk of fracture.
	Unknown or unproven long-term success or documented poor performance

Table 1-2. Description of Ideograms Used in Repair and Retrofit Tables for Ease of Installation

Ease of Installation	
	Relatively easy to install with common hand tools (e.g., grinder, mag-drill) and minimal experience with iron work required.
	Decreased ease of installation, but still manageable with most common hand tools and beginner skill level in iron work.
	Some ease, requiring average working knowledge of repairing steel and/or specialized tools or training (e.g., ultrasonic impact machine, turn-of-nut wrench).
	Moderate effort required. Specialized training and tools required. Sound engineering judgement needed.
	Significant effort required. Difficult to install, generally requiring expert knowledge. May also require engineering analysis.