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That's Not Fracture Critical:
Classifying System Redundant Members
August 11, 2020

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Course Description

That's Not Fracture Critical: Classifying System Redundant Members
August 11, 2020

The Federal Highway Administration (FHWA) began recognizing system-redundant members (SRMs) in a 2012 memorandum clarifying the requirements on fracture-critical members (FCMs). The FHWA memorandum defines an SRM as a member that receives fabrication according to the Fracture Control Plan but is not considered an FCM for in-service inspection, allowing owners to more efficiently manage resources for bridge inspections. This webinar is a great way for owners and consulting engineers to learn the ins and outs of the FHWA process for classifying SRMs and how the Texas DOT and Wisconsin DOT have implemented this practice.

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Learning Objectives

- Define fracture critical member and system redundant member.
- Explain the processes by which system redundant members may be identified.
- Describe the approximate structural analysis and refined structural analysis approaches developed by TxDOT for designing for the event of member failure.
- Identify the details and bridge characteristics that corresponded to members being classified as system redundant, as found by a study of existing Wisconsin bridges.

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That's Not Fracture Critical: Classifying System Redundant Members

Dayi Wang, PhD, PE

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Andrew Smith, PE

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Part 1: Fracture Control and System Redundant Member (SRM) Provisions

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August 11, 2020

U.S. Department of Transportation
Federal Highway Administration

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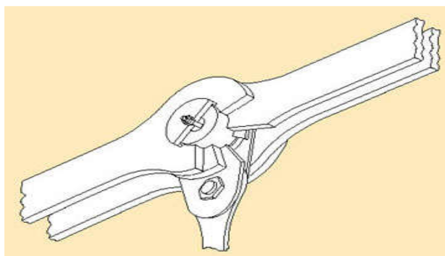
Fracture Failures in Steel Bridges

Point Pleasant Bridge Collapse (1967)

- **46 fatalities**
- **Fracture Critical Members (FCM) provisions/1978 AASHTO Guide Spec**
- **National Bridge Inspection Standards (NBIS) Creation**



FHWA is the source for all images in this presentation.

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Fracture Failures in Steel Bridges

Mianus River Bridge Collapse (1983)

- **Two girder bridge, pin-and-hanger failure**
- **NBIS added "Hands-on" Inspection**

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Fracture Failures in Steel Bridges

Hoan Bridge Failure (2000)

- **All three girders fractured due to constraint-induced-fracture (CIF) details. Bridge dismantled.**
- **Similar CIF details - evaluate/retrofit existing; avoid in new designs.**

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Fracture Control Practice for Steel Bridges

1. Fabrication FCP – higher standard:
   - Steel toughness and fine-grain
   - Shop fabrication, welding and inspection

   Per AASHTO/AWS D1.5 clause 12 (23 CFR 625.4(b)(5))
2. In-Service Inspection – in-depth and more frequent:
   - "Hands-on" FCM inspection
   - 24 month interval

   Per NBIS (23 CFR part 650 Subpart C)
3. Design – more than 1 and 2 above:
   - Continuity/composite
   - Details – accessible, no CIF

   Per AASHTO LRFD (23 CFR 625.4(b)(3))

Keep these valuable assets!!!
Question: the application range, especially item 2.

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Fracture Critical Member (FCM)

Definition per CFR and NBIS:

A steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse.

(National Bridge Inspection Standards, 23 CFR 650.305)

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System Redundant Member (SRM)

Definition per FHWA 2012 FCM Memo:

A non-load-path-redundant member that gains its redundancy by system behavior.

U.S. Department of Transportation
Federal Highway Administration

MEMORANDUM

Subject: **Action:** Clarification of Requirements for Fracture Critical Members

Date: June 20, 2012

From: /s/ Original Signed by
M. Myint Lwin, P.E., S.E.
Director, Office of Bridge Technology

In Reply Refer To: HIBT-10

To: Directors of Field Services
Federal Lands Highway Division Engineers
Division Administrators

The purpose of this memo is to provide clarification of the FHWA policy for the classification of Fracture Critical Members. For design and fabrication, only Load Path Redundancy may be considered. For in-service inspection

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System Redundant Member (SRM)

Definition per FHWA 2012 FCM Memo:

A non-load-path-redundant member that gains its redundancy by system behavior.

SRMs are not FCMs, do not need FCM inspection.

(the failure of an SRM would not cause a collapse.)

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System Redundant Member (SRM)

Also per FHWA 2012 Memo:

"To demonstrate that a structure has adequate strength and stability sufficient to avoid partial or total collapse and carry traffic in the presence of a totally fractured FCM, a State must submit through the Division Office to the FHWA Office of Bridge Technology for review the detailed analysis and evaluation criteria that will be used to conduct the study. Once reviewed, these criteria can then be employed by the State systematically on their inventory."

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System Redundant Member (SRM)

Also per FHWA 2012 Memo:

"To demonstrate that a structure has adequate strength and stability sufficient to avoid partial or total collapse and carry traffic in the presence of a totally fractured FCM, a State must submit through the Division Office to the FHWA Office of Bridge Technology for review the detailed analysis and evaluation criteria that will be used to conduct the study. Once reviewed, these criteria can then be employed by the State systematically on their inventory."

"must" => "should" (good guidance)

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SRM determination

Should follow an FHWA accepted procedure, which may be done:

- **through analyses, or**
- **without analyses, by satisfying a list of conditions, or**
- **by comparison with previously determined SRMs**

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Procedures Acceptable to FHWA Include:

- **AASHTO SRM Guide Specifications, acceptable to FHWA.**
  Requiring forensic refined analyses. Applications:
  - **WisDOT, *FC analysis Phase I&II*. Twin-tub girder SRMs accepted by FHWA.**
- **Procedures based on experimental and analytical research and accepted by FHWA.**
  Using linear elastic engineering analyses. Examples:
  - **TXDOT, *"TXDOT engineering criteria and procedure for the evaluation of system redundancy in steel twin tub girder bridges".* Accepted by FHWA in November 2019.**
  - **Purdue University, "*AASHTO Twin Tub Simplified SRM Procedures" (draft)*, proposed to AASHTO T-14 in December 2019. The final may be accepted by FHWA once submitted.**

Note: **(a) "Accept" does not mean requiring the procedure, nor all its details.**
(b) Good engineering still must be exercised.

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FHWA Review of Major Bridge SRMs:

SRMs in major projects may be handled individually, through refined analysis with bridge-specific criteria. FHWA has done so for:

- **The Tappan Zee Bridge**
- **The Gordie Howe International Bridge**
- **The Lewis and Clark Bridge (East End Crossing)**

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Part 2:
Navigating SRM Approval in Texas

Jamie F. Farris, P.E.
Bridge Division Deputy Director
Texas Department of Transportation

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August 11, 2020

Table of Contents

- Background
- Research
- Designing for Redundancy
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- FHWA Approval
- Moving Forward

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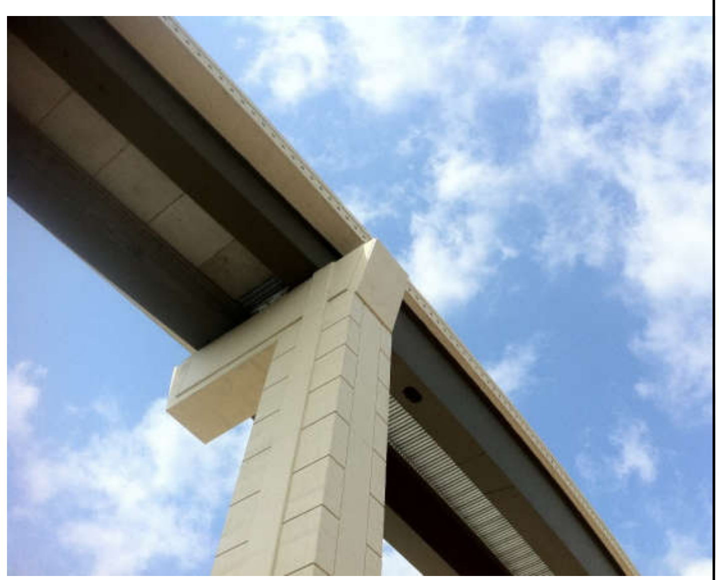
Background

Steel Twin Tub Girders

- Consist of two steel box girders
- Composite with a concrete deck
- Bottom flanges and webs are considered Fracture Critical in +Moment region
- Require hands-on inspection every two years



Steel Twin Tub Girders

- Effective for curved ramps and connectors in multi-level interchanges

Steel Twin Tub Girders

- Common type of fracture critical (FC) classified bridge
- Texas has over 480 existing twin tub girder spans
- $2.3M spent every 2 years on inspection *(this figure doesn't include traffic control)*

Research

UT Twin Tub Research

- *Modeling and Response of Fracture Critical Steel Box-Girder Bridges* - TxDOT Project 9-5498 (2010)
- University of Texas at Austin
- Characterize the redundancy that exists in twin tub girder bridges
- Developed guidelines for modeling behavior in the event of a fracture of the tension flange and web in tension
- Research included combination of laboratory testing, full-scale tests of a twin tub girder bridge, and detailed structural analysis

UT Twin Tub Research

- Full Scale bridge test represented the worst case:
  - Simply supported
  - No external intermediate diaphragms
  - Bridge rails had expansion joints
  - Horizontally curved

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UT Twin Tub Research

Test #1:

- Linear shape charge explosive rapidly cut bottom flange
- Simulated HS-20 Truck positioned above fracture – most severe location
- The bridge deflected less than 1 inch

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UT Twin Tub Research

Test #2:
- Exterior girder – full depth fracture
- Induced and applied loads suddenly
- Fractured girder deflected only 7 inches

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UT Twin Tub Research


Incremental loading


Collapsed bridge

Test #3:
- Conducted under statically applied loads
- Bridge was able to carry 363,000 lbs
- More than 4 times than a legal truck load

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UT Twin Tub Research

- Clearly demonstrated system redundancy for a span that was not designed specifically to have system redundancy
- Highlighted the importance of the deck and shear connectors and their contribution to system performance
- Barrier railing was also observed to contribute structurally

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Designing for Redundancy

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2012 FHWA Memo

- Memorandum, *Clarification of Requirements for Fracture Critical Members*
- Introduced new member classification of System Redundancy Member (SRM)
- Provides a path to design new steel twin tub girder spans that can be shown to possess adequate redundancy such that the bridge will not collapse and safely support live load


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Load Rating | NBIS | NBI

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U.S. Department of Transportation
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Director, Office of Bridge Technology
In Reply Refer To: HIBT-10

To: Directors of Field Services
Federal Lands Highway Division Engineers
Division Administrators

The purpose of this memo is to provide clarification of the FHWA policy for the classification of Fracture Critical Members. For design and fabrication, only Load Path Redundancy may be considered. For in-service inspection protocol, Structural Redundancy demonstrated by refined analysis is now formally recognized and may also be considered. Internal member redundancy is currently not recognized in the classification of Fracture Critical Members for either design and fabrication or in-service inspection. Finally, this memo introduces a new member classification, a System Redundant Member (SRM), which is a non-load-path-redundant member that gains its redundancy by system behavior.

Several States and FHWA Division Bridge Engineers have requested that we clarify our policy regarding the classification of Fracture Critical Members (FCMs). There are two primary implications related to identifying FCMs in bridges: 1) specification of proper materials and testing for design and fabrication, and 2) establishment of proper in-service inspection protocol. Clarification of our current policy and future direction is provided herein.

Definitions

The current National Bridge Inspection Standards (NBIS) definition for a FCM is **"a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse."**

The AASHTO *Manual for Bridge Evaluation* (MBE), 2nd Edition, defines a FCM as "**steel tension members or steel tension components of members whose failure would be expected to result in a partial or full collapse of the bridge.**"

The AASHTO *LRFD Bridge Design Specifications* (LRFD), 6th Edition, defines a FCM as a "**component in tension whose failure is expected to result in the collapse of the bridge or the inability of the bridge to perform its function.**"

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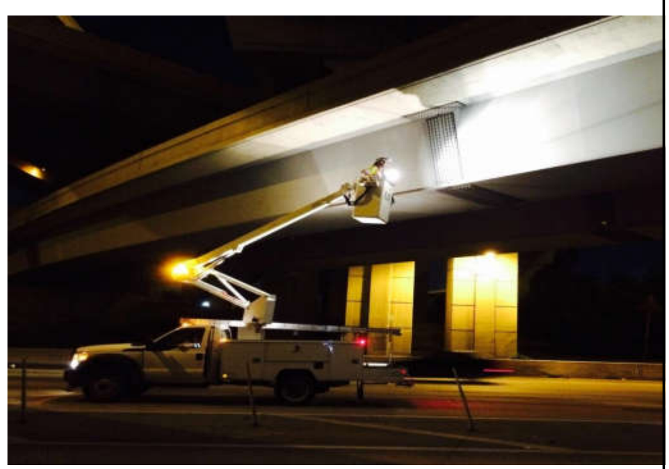
2012 FHWA Memo

- What if we can <u>design new twin tub girder bridges</u> to be system redundant?
  - Eliminate the requirement for hands-on inspection every 2 years for the life of the structure
  - Inspections:
    - Often take place at night
    - High traffic volume
    - Costly traffic control



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Redundancy Case Studies

- After the 2012 FHWA Memo, TxDOT met with FHWA to discuss a path forward
- Starting point – use proposed analytical modeling methods from the 9-5498 research project
- 9-5498 developed a simple method – assumes a simulated full-depth fracture in one of the girders
- TxDOT bridge engineers analyzed 3 example existing steel twin tub bridges using the simplified modeling procedure

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Redundancy Case Studies

Case studies represent typical flyover steel twin tub bridge configurations

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Redundancy Case Studies – Results of Intact Girder Using Approximate Analysis

- Bending capacity ✓
- Deck shear strength ✓
- Shear stud tensile capacity ✓
- Combined torsion and shear at supports ✗

	Year Designed	Span Lengths (ft.)	Overall Deck Width (ft.)	Girder Depth (ft.)	Centerline Structure Radius (ft.)
Case 1	1998	148 – 265 – 190	30	6.5	716
Case 2	2007	199 – 243 – 179	28	6	1033
Case 3	2008	163 - 163	28	5	895

Redundancy Case Studies – Results of Intact Girder Using Approximate Analysis

- Compared to the 9-5498 experimental bridge, the three TxDOT study cases had longer span lengths and a sharper horizontal curvature, which lead to greater dead load, larger eccentricity, and higher torsion and shear at supports
- All three cases did not pass the simplified method criteria at the support girder section shear capacity check due to large torque and shear forces.
- None of the cases failed due to lack of shear stud tensile capacity.

Texas Steel Quality Council - Task Group

- 2016 instituted a Twin Tub Task Group
- Task Group members reflected the overall structure of TSQC
- Develop LRFD-based design specifications
- Would govern the analysis and design of non-fracture critical steel twin tubs

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Texas Steel Quality Council - Task Group

- AASHTO Ballot Item was developed and presented at several industry and AASHTO meetings
- In the end, AASHTO was not ready to put language in the specifications specifically for twin tub girder bridges.
- TxDOT was encouraged by FHWA to submit for approval as a state
- Led TxDOT to develop language for its own bridge design policy manual

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TxDOT SRM Design Methodology

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TxDOT Design Methodology

- The *TxDOT Bridge Design Manual-LRFD* presents a LRFD based methodology to design spans with two tub girders in cross section such that the span will not collapse after the fracture of one of the girders.

Bridge Design Manual - LRFD

Texas Department of Transportation

Revised January 2020

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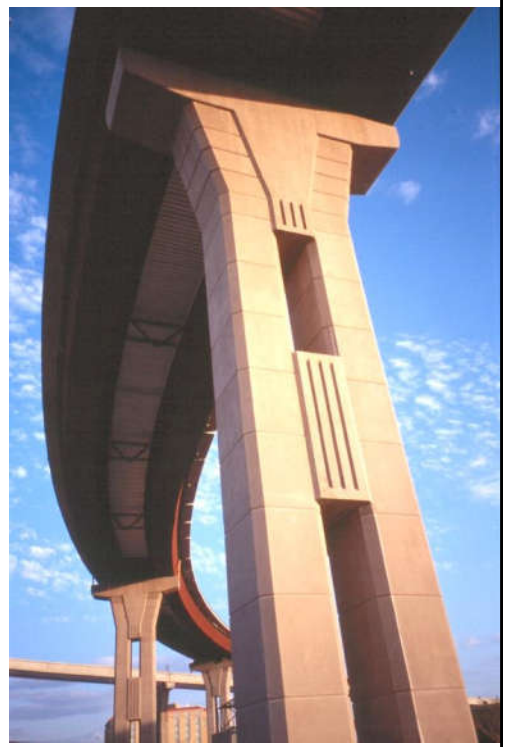
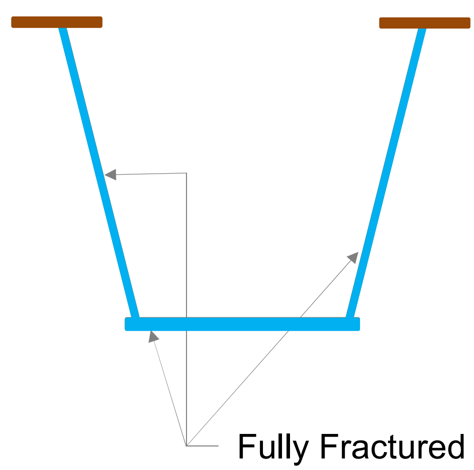
TxDOT Design Methodology

1. The bridge is designed as it normally would, using the following limit states and exceptions:
   - Design for Strength Limit State using a Redundancy Factor, $\eta_R = 1.05$
   - Design for Service Limit State
   - Design for Infinite Fatigue life for Fatigue and Fracture Limit State
2. Next, the bridge is designed for <u>member failure</u>



TxDOT Design Methodology – Designing for Member Failure

- **Bottom flange in tension and webs attached to that flange** of the critical girder are assumed to be fully fractured at the location of the max factored tensile stress in the bottom flange determined using Strength I load combination



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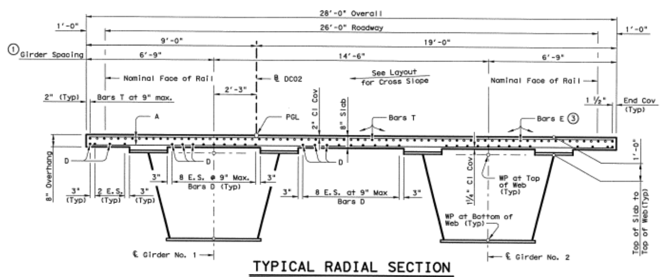
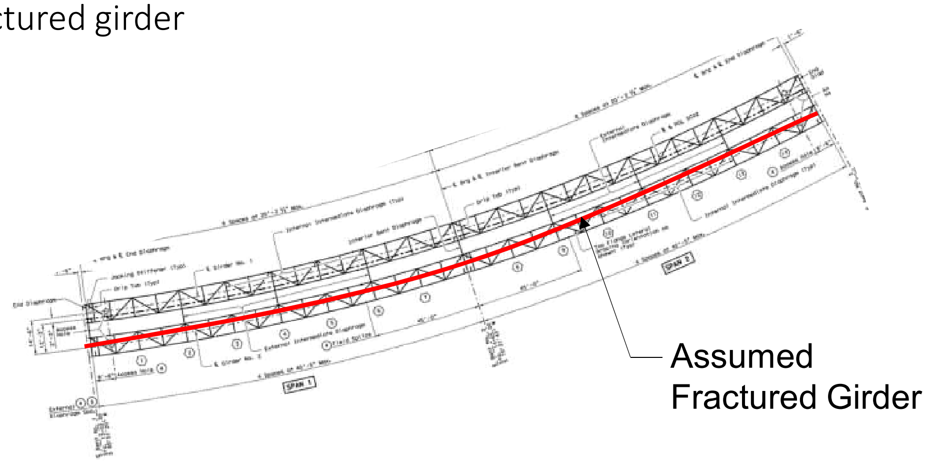
TxDOT Design Methodology – Designing for Member Failure

- To result in the worst case loading scenario, the assumed fractured girder is chosen based on its position in the cross-section relative to traffic lanes and its eccentricity to the deck and railing



TxDOT Design Methodology – Designing for Member Failure

- Points the designer to check simple spans and end spans of continuous units
- If the span is horizontally curved, the girder with largest radius is assumed to be the fractured girder



TxDOT Design Methodology – Designing for Member Failure

- Probability of such a fracture for tub girders designed for infinite fatigue life is considered exceedingly small in comparison to the bridge’s design life
- TxDOT method addresses the design of simulated fracture with the Extreme Event Limit State
- TxDOT revised the AASHTO definition of Extreme Event Limit State to include structural member or component failure

TxDOT Design Methodology – Designing for Member Failure

New Load Combination - Extreme Event III

Supplements AASHTO Tables 3.4.4-1 and 3.4.4-2

Load Combination Limit State	DC DD DW EH EV ES PS CR SH	LL IM CE BR PL LS	WA	WS	WL	FR	TU	TG	SE	Use One of These at a Time: EQ	BL	IC	CT	CV
Extreme Event III	γ_p	1.10	1.00	--	--	1.00	--	--	--	--	1.00	1.00	1.00	1.00

Type of Load, Foundation Type, and Method Used to Calculate Downdrag	Load Factor	
	Maximum	Minimum
DC: Components and Attachments for the evaluation of system redundancy as specified in the *TxDOT Bridge Design Manual-LRFD*, for Extreme Event III only	1.10	0.90

TxDOT Design Methodology – Designing for Member Failure

New Load Combination - Extreme Event III:

- All load effects during assumed fractured event are amplified by a factor of 1.20 to simulate the dynamic effects of a fracture on the twin tub girder spans

Minimum	Maximum
(1+0.2)(0.9 DC + 0.9 DW + 1.10 LL)	(1+0.2)(1.1 DC + 1.1 DW + 1.10 LL)

TxDOT Design Methodology – Designing for Member Failure

Live Load

- Live load includes both truck and lane load
- Truck is positioned on the bridge deck directly above the presumed fracture location
- Number and width of design lanes = the actual number and width of striped traffic lanes on the bridge

TxDOT Design Methodology – Designing for Member Failure

Internal and External Diaphragms

- Internal and external diaphragms – must provide at all supports

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TxDOT Design Methodology – Designing for Member Failure

Internal and External Diaphragms

- Diaphragms and connections must be designed:
  - To resist the torsional moment in the assumed intact girder
  - To transmit vertical and lateral forces to the bearings during and after an assumed fracture event
  - To act compositely with the slab with the shear connectors

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TxDOT Design Methodology – Designing for Member Failure

Permanent Intermediate External Diaphragms

- At least two permanent external intermediate diaphragms must be provided on each side of the location of the maximum factored tensile stress in the bottom flange

Intended to enhance system redundancy by providing additional load paths on each side of an assumed fracture location

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TxDOT Design Methodology – Designing for Member Failure

Check intact tub girder and portions of the fractured girder that can still resist load

Flexure

- Adequate flexural resistance after the assumed fracture event
- Extreme Event III
- Article 6.11.7, 6.11.8 - Flexural Resistance – Sections in Positive & Negative Flexure

Shear

- Adequate shear resistance after the assumed fracture event
- Extreme Event III
- Article 6.11.9 - Shear Resistance

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TxDOT Design Methodology – Designing for Member Failure

Shear

- Concrete deck
- End Diaphragms
- Shear Connectors
- Top flange lateral bracing

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TxDOT Design Methodology – Designing for Member Failure

Shear – Concrete Deck

- Check for adequate shear resistance to resist shear due to torsion after the assumed fracture event
- Use Extreme Event III load combination according to the provisions of AASHTO Article 5.7.3.3
- The use of empirical deck design is prohibited

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TxDOT Design Methodology – Designing for Member Failure

Shear – End Diaphragms

- Check end diaphragms and their connection to both tub girders to ensure adequate shear resistance to the torque applied to the intact girder after the assumed fracture event
- Use Extreme Event III load combination

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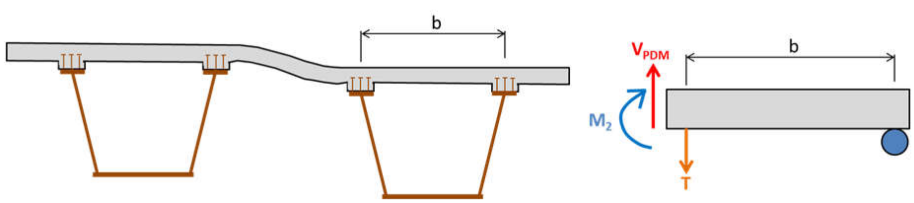
TxDOT Design Methodology – Designing for Member Failure

Shear – Shear Connectors

- Check that the stud shear connectors connecting the deck to the assumed fractured girder have sufficient tension capacity to develop the plastic beam mechanism in the bridge deck after the assumed fracture event



(a) Plastic Deck Mechanism

(b) Shear Stud Pull-out Capacity

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TxDOT Design Methodology – Designing for Member Failure

Shear – Shear Connectors – Design Alternatives

- Design shear connectors and the shear connectors on all support diaphragms for combined shear and axial force according to the provisions of Provisions for Seismic Design Article 6.16.4.3 – Shear Connectors
- Analysis method for shear connectors from *Modeling the Response of Fracture Critical Steel Box-Girder Bridges, Barnard et al., Research Report 5498-1, 2010* is permissible. This approach neglects shear on the studs in the fractured girder due to the assumption that the fractured girder is not carrying any load.

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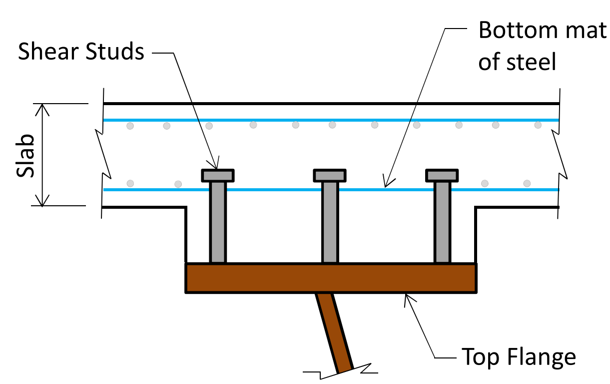
TxDOT Design Methodology – Designing for Member Failure

Shear – Shear Connectors – Detailing

- Detail to extend above the bottom mat of deck reinforcement



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TxDOT Design Methodology – Designing for Member Failure

Shear – Top Flange Lateral Bracing

- Can be considered part of the resisting section for St. Venant torsional shears in addition to the concrete deck
- The contributions of the deck and top lateral bracing are additive

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TxDOT Design Methodology – Designing for Member Failure

- Two types of analysis can be used to evaluate Extreme Event III:

1. Approximate structural analysis
2. Refined structural analysis

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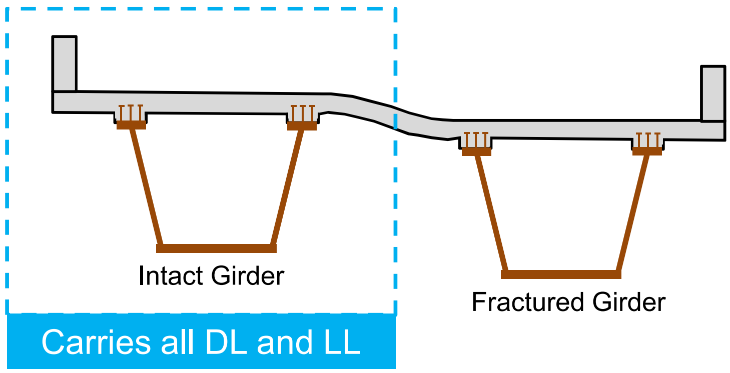
TxDOT Design Methodology – Designing for Member Failure

Approximate Structural Analysis

- After fracture event - the entire self-weight of the span under consideration and the entire live load is assumed to be carried by the intact girder after the assumed fracture event.



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TxDOT Design Methodology – Designing for Member Failure

Approximate Structural Analysis

- The Simplified Method (Approximate structural analysis) can be used if:
  - Spans do not exceed 250 ft.
  - Supports are skewed no more than 20 degrees
  - Horizontal curvature greater than 700 ft.
  - Engineer ascertains that the use of an approximate analysis method is adequate.

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TxDOT Design Methodology – Designing for Member Failure

Approximate Structural Analysis

- To use the simplified method, the bridge must satisfy three conditions:
  1. Intact girder has adequate shear and moment capacity
  2. Deck has adequate shear capacity
  3. Shear studs have adequate tension capacity.
- If the bridge satisfies the first two conditions but doesn't satisfy 3), then a more refined analysis can be used to evaluate the ability of the deck to transmit load to the intact girder without the shear studs connecting the deck to the fractured girder.

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Design Guide - Appendix C

Appendix C — Steel Twin Tub Girder System Redundancy Simplified Method Guide | *Section 2 — Simplified Method Procedure Outline*

Section 2

Simplified Method Procedure Outline

Step 1 Design the bridge as normally done with the following exceptions:

- Design for Strength Limit State using a Redundancy Factor, $\eta_R = 1.05$
- Design for Infinite Fatigue life for Fatigue and Fracture Limit State

Step 2 Design the bridge for member failure under Extreme Event III according to the TxDOT Bridge Design Manual-LRFD

1. Assume one girder is fractured, within the span under consideration.
   - Fracture the girder at the bottom flange in tension and webs attached to that flange. Assume the other girder in the span under consideration is intact. For continuous units, assume that both girders are still intact in adjacent spans.
   - The location of the fracture within the span is assumed to be at the maximum factored tensile stress in the bottom flange determined using Strength I load combination.
   - The fractured girder should be the girder that would result in the worst loading scenario.
2. **Calculate the transmitted load to the intact girder.** It is assumed that just prior to the fracture event, the girder that will fracture is carrying 50% of the total dead load of the bridge and all of the live load, due to the position of the live load. Once the fracture occurs, the slab must transfer the entire load the fractured girder was carrying to the intact girder via the bridge slab. Therefore, the intact girder will now be carrying 100% of the dead load of the bridge and the entire live load.

$$F = (L)(W_{girder} + W_{deck}/2 + W_{railings}/2) + W_{LL}$$

Where:

F = Transmitted load to intact girder (kips)
W_{girder} = Weight of one steel tub girder plus weight of diaphragms and stiffeners, etc. (kips)
W_{deck} = Concrete deck and haunches weight (kips)
$W_{railings}$ = Total Railing weight (kips)
W_{LL} = Live Load (kips)

Bridge Design Guide | *C-3* | *TxDOT January 2020*

Appendix C — Steel Twin Tub Girder System Redundancy Simplified Method Guide | *Section 2 — Simplified Method Procedure Outline*

3. **Calculate the maximum moment on the bridge.**

   Maximum moment due to dead load:

$$M_{DL} = (L^2/8)(2W_{girder} + W_{deck} + W_{railings})$$

   Maximum moment due to live load:

   Position the HL-93 live load, including truck and lane load on the bridge deck directly above the fracture location.
   - The number, width, and location of design lanes is taken as the number, width, and location of striped traffic lanes on the bridge.
   - The live load is notional and meant to capture an envelope.
   - The impact factor, IM, is zeroed out for the fracture event
4. **Calculate the bending capacity demand on the intact girder under Extreme Event III**, according to the TxDOT Bridge Design Manual - LRFD, Chapter 2, Section 1:

   I. Φ, Resistance Factor = 1.0
   II. DL Load Factor = 1.10
   III. LL Load Factor = 1.10
   IV. DIF, Dynamic Increase Factor = 1.2

$$M_{EEIII} = (1.2)(1.10M_{DL} + 1.10M_{LL})$$

   Where:

   M_{EEIII} = Moment of member at failure under Extreme Event III
5. **Calculate the plastic moment capacity, M_P, of the intact girder** to determine if it has sufficient capacity to sustain the total live load and total dead load on the bridge.

$$M_P \geq M_{EEIII}$$

6. **Check the bending and shear capacity of the concrete deck** to ensure adequacy to resist the moment and shear produced by the unsupported load of the fractured girder.

   <u>Positive Moment Capacity, M_n^+ of Concrete Deck</u>

   The assumed strain and stress gradients at positive moment regions are shown in Figure C-1.

Bridge Design Guide | *C-4* | *TxDOT January 2020*

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Design Guide - Appendix C

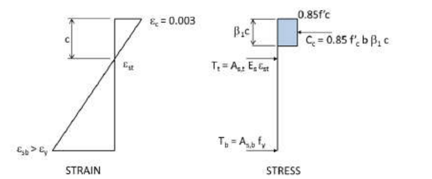


Figure C-1: Strain and stress gradients at positive moment regions

Take the moments about the neutral axis to solve for the nominal moment capacity.

Negative Moment Capacity, M_n^- of Concrete Deck

The assumed strain and stress gradients at negative moment regions are shown in Figure C-2.

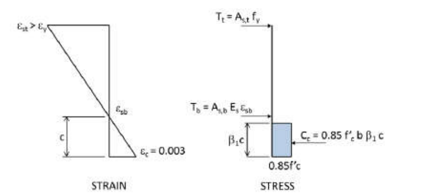


Figure C-2: Strain and stress gradients for negative moment regions

Take the moments about the neutral axis to solve for the nominal moment capacity.

Bending and Shear Capacity Check of Concrete Deck:

The deflected shape of the concrete deck and the bending moment diagram, assuming that the shear studs have adequate tensile capacity, is shown below:

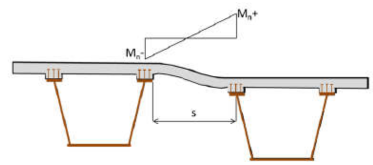


Figure C-3: Deflected shape and moment diagram before any failure of shear studs

The shear associated with the plastic deck mechanism is:

$$V_{PDM} = (M_n^+ + M_n^-) / s$$

Where:

M_n^+ = Positive Moment Capacity of Concrete Deck (k-ft)

M_n^- = Negative Moment Capacity of Concrete Deck (k-ft)

s = Distance between the mid-width of the fractured girder's interior top flange and edge of the interior top flange of the intact girder (ft)

The shear capacity, V_c, is calculated using the ACI equation below and based on a 12 inch wide transverse deck section.

$$V_c = 2\sqrt{f'_c}\, b\, d$$

Where:

f'_c = Compressive strength of concrete for use in design (psi)

b = Width of compression face of member (in)

d = Effective depth of member, distance from extreme compression fiber to centroid of longitudinal tension reinforcement (in)

Design Guide - Appendix C

$\psi_{ed,N}$ = Edge distance modification factor

= 1.0 for $c_{a,min} \geq 1.5\, h_h$

= $0.7 + 0.3 \dfrac{c_{a,min}}{1.5\, h_h}$ for $c_{a,min} < 1.5\, h_h$

$c_{a,min}$ = smallest edge distance measured from center of stud to the edge of concrete (in)

$\psi_{c,N}$ = Cracked concrete modification factor

= 1.0, Cracked or no haunch

= 1.25, Uncracked or with haunch

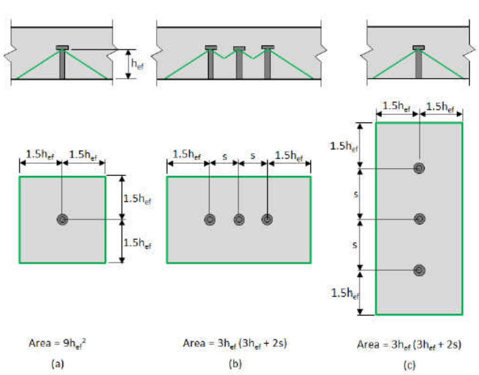


Figure C-4: Dimensioned Projected Concrete Cone Failure Areas for (a) 1 Stud (b) 3 studs Spaced Transversely (c) 3 Studs Spaced Longitudinally, all without a Haunch

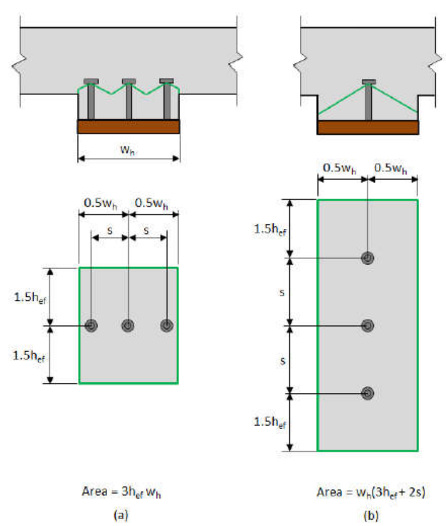


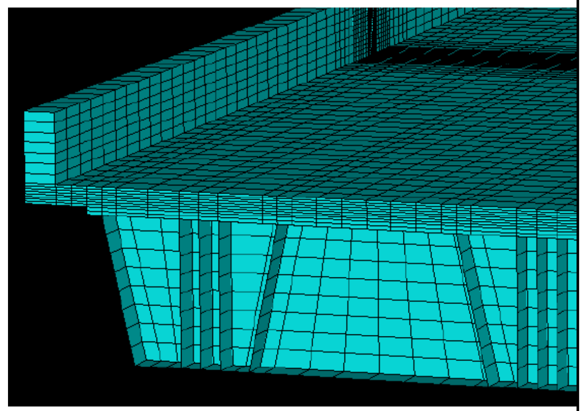
Figure C-5: Dimensioned Projected Concrete Cone Failure Areas for (a) 3 Studs spaced Transversely and (b) 3 Studs Spaced Longitudinally, both in a Haunch

The shear studs connecting the deck to the fractured girder must have sufficient tension capacity to develop the plastic beam mechanism in the bridge deck. The required shear stud tensile capacity is estimated by using the model of the bridge deck shown in Figure C-6 below.

TxDOT Design Methodology – Designing for Member Failure

Refined Structural Analysis

- Accounts for the capacity of the intact girder as well as portions of the fractured girder that can still provide structural resistance
- Load distribution between the intact girder and the fractured girder are realistically modeled



TxDOT Design Methodology – Designing for Member Failure

Refined Structural Analysis

- Modeled with the approach found in TxDOT research project 9-5498
- Non-linear material properties
- Girders modeled as shell elements
- Deck modeled as solid elements
- Deck reinforcing as 2-node truss elements

TxDOT Design Methodology – More Information

- 2020 TxDOT Bridge Design Manual – LRFD
  - Chapter 3, Section 17
  - http://onlinemanuals.txdot.gov/txdotmanuals/lrf/index.htm

POLICY

- 2020 TxDOT Bridge Design Guide
  - Chapter 3, Section 12
  - Appendix C
  - http://ftp.dot.state.tx.us/pub/txdot-info/brg/design/bridge-design-guide.pdf

COMMENTARY

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FHWA Approval

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FHWA Approval Process

- 2012 Memo allows Owners to demonstrate that a structure has adequate redundancy and be classified as System Redundant
- Under this Memo, Owners must submit each bridge for approval
- TxDOT's goal was to be automatically approved by FHWA if the bridge was designed using TxDOT's SRM methodology for twin tub girder bridges

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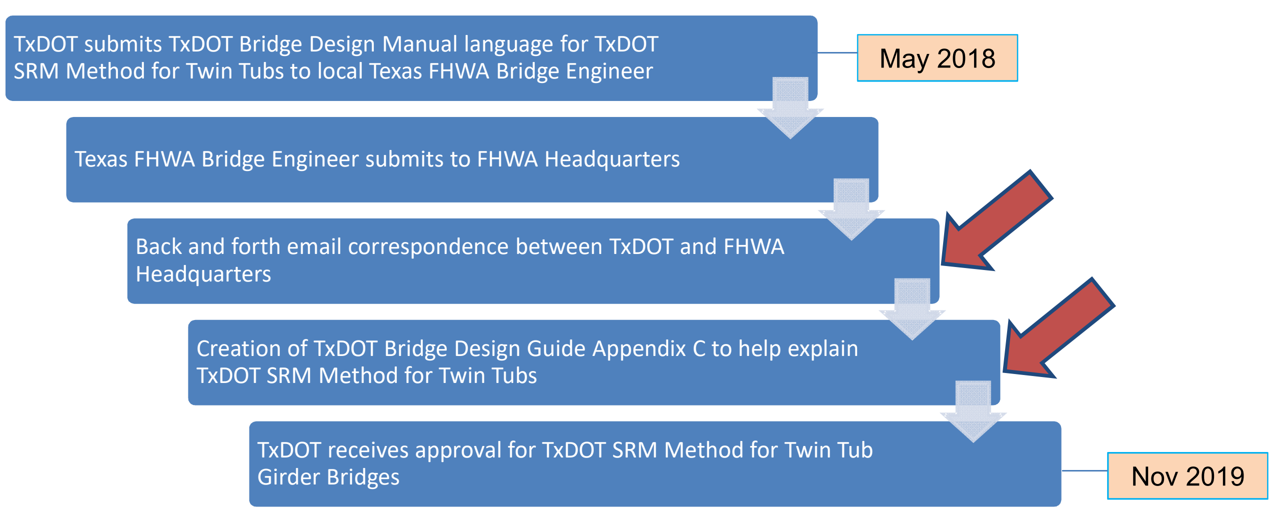
FHWA Approval Process



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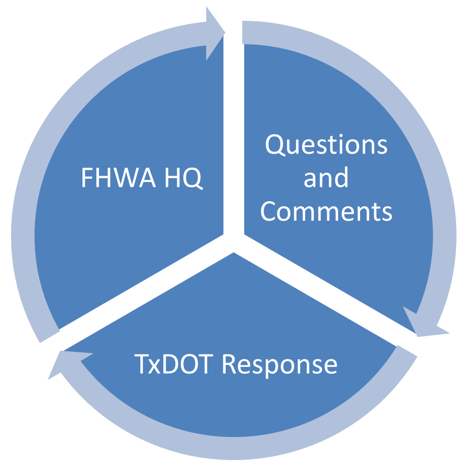
Back and Forth Correspondence

- FHWA Headquarters discussed the TxDOT SRM Methodology and sent questions and comments back to TxDOT
- TxDOT responded with answers and if needed revised the manual language to be more clear
- This occurred in several iterations



TxDOT Bridge Design Guide

- Guide is used in companion with the policy manual
- Commentary
- To make the SRM Method more clear, TxDOT wrote a procedure that outlines each step
- Appendix C – 9 clear steps

Appendix C — Steel Twin Tub Girder System Redundancy Simplified Method Guide — *Section 2 — Simplified Method Procedure Outline*

Section 2

Simplified Method Procedure Outline

Step 1: Design the bridge as normally done with the following exceptions:

- Design for Strength Limit State using a Redundancy Factor, $\eta_R = 1.05$
- Design for Infinite Fatigue life for Fatigue and Fracture Limit State

Step 2: Design the bridge for member failure under Extreme Event III according to the TxDOT Bridge Design Manual-LRFD

1. Assume one girder is fractured, within the span under consideration.
   - Fracture the girder at the bottom flange in tension and webs attached to that flange. Assume the other girder in the span under consideration is intact. For continuous units, assume that both girders are still intact in adjacent spans.
   - The location of the fracture within the span is assumed to be at the maximum factored tensile stress in the bottom flange determined using Strength I load combination.
   - The fractured girder should be the girder that would result in the worst loading scenario.
2. **Calculate the transmitted load to the intact girder.** It is assumed that just prior to the fracture event, the girder that will fracture is carrying 50% of the total dead load of the bridge and all of the live load, due to the position of the live load. Once the fracture occurs, the slab must transfer the entire load the fractured girder was carrying to the intact girder via the bridge slab. Therefore, the intact girder will now be carrying 100% of the dead load of the bridge and the entire live load.

$$F = (L)(W_{girder} + W_{deck}/2 + W_{railings}/2) + W_{LL}$$

Where:

F = Transmitted load to intact girder (kips)

W_{girder} = Weight of one steel tub girder plus weight of diaphragms and stiffeners, etc. (kips)

W_{deck} = Concrete deck and haunches weight (kips)

$W_{railings}$ = Total Railing weight (kips)

W_{LL} = Live Load (kips)

Bridge Design Guide — C-3 — *TxDOT January 2020*

Key to Success

- The key to the success was the extensive collaboration

http://www.picserver.org

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Moving Forward

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Moving Forward

- Future twin tub spans will be designed using the TxDOT methodology and be classified as SRM
- TxDOT is currently developing in-house spreadsheet tools to allow for simple application of the approximate analysis method
- Prototype refined models are under development to provide guidance for future redundancy evaluations
- Future goal is to have all existing twin tub girder spans evaluated for redundancy
- Current research project on Steel Box Straddle Caps

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Part 3: Redundancy of Twin Steel Tub Girder Bridges in Wisconsin

Andrew Smith, P.E.
Bridge Load Rating Engineer
Wisconsin Department of Transportation

BUREAU OF STRUCTURES

Smarter. Stronger. Steel.

Outline

- **Overview of Steel Tubs in Wisconsin**
- **Cost, User Delay, Safety**
- **System Redundant Member (SRM) Evaluation and FHWA Review**
  - **Overview**
  - **Pilot Phase**
  - **Phase I**
  - **Pilot Parametric Evaluation**
  - **Phase II**
- **Simplified Approach to SRM Classification**

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Overview of Steel Tubs in Wisconsin

- Most steel tubs < 15yrs old
- Predominantly in Milwaukee and Green Bay
- Brought into service having Fracture Critical Members (FCMs) – *not load path redundant*

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Key Feature: External Diaphragms

- Full Depth
- Solid Plate
- Composite with Deck
- Located at 1/3 span

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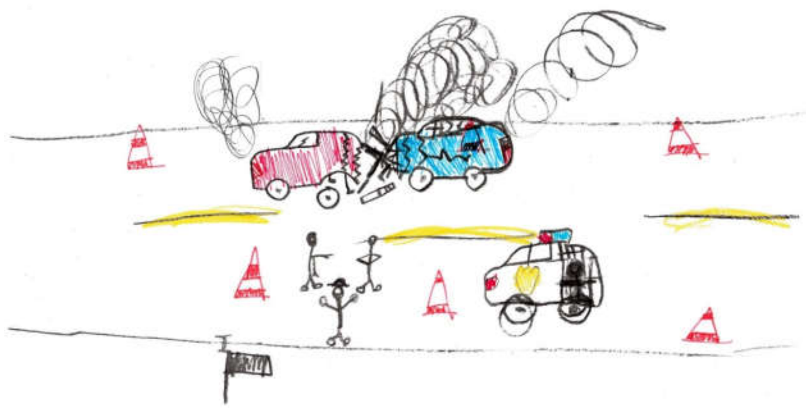
Cost, User Delay, Safety

Fracture critical, hands-on inspection has considerable cost, as well as safety risks to the inspectors, traffic control personnel, as well as the traveling public during lane closures.



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Resources for Inspections

Fracture critical inspection of twin tub girders

- 10 to 24 hours over several days/nights
  - Depends on size of structure, equipment needs and availability of qualified inspectors
- Two under-deck access vehicles (Snoopers)
- Four operators, and up to six inspectors
- Traffic control, law enforcement, etc.

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Cost

- Fracture Critical hands-on inspection per cycle (every two years)
  - $36,000 to $66,000 per bridge (depends on if in-house staff or consultants used)
  - $700k to $1.2mil per cycle for inventory
  - Includes traffic control cost

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Access Vehicle (Snooper) in Action

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Night Work

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Work over a RR

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SRM Classification

U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: **ACTION:** Clarification of Requirements for Fracture Critical Members
Date: June 20, 2012

/s/ original Signed by
From: M. Myint Lwin, P.E., S.E.
Director, Office of Bridge Technology
In Reply Refer To: HIBT-10

To: Directors of Field Services
Federal Lands Highway Division E
Division Administrators

The purpose of this memo is to provide clarification of the FHWA policy for the classification of Fracture Critical Members. For design and fabrication, only Load Path Redundancy may be considered. For in-service inspection protocol, Structural Redundancy demonstrated by refined analysis is now formally recognized and may also be considered. Internal member redundancy is currently not recognized in the classification of Fracture Critical Members for either design and fabrication or in-service inspection. Finally, this memo introduces a new member classification, a System Redundant Member (SRM), which is a non-load-path-redundant member that gains its redundancy by system behavior.

[FHWA 2012]

What does it get you?

Identification of FCMs for In-service Inspection Protocol
Currently available refined analysis techniques have provided a means to more accurately define FCMs for new designs and to re-evaluate existing bridge members that were previously classified as fracture critical on the record design documents. If refined analysis demonstrates that a structure has adequate strength and stability sufficient to avoid partial or total collapse and carry traffic in the presence of a totally fractured member (by structural redundancy), the member does not need to be considered fracture critical for in-service inspection protocol. The assumptions and analyses conducted to support this determination need to become part of the permanent inspection records or bridge file so that it can be revisited and adjusted as necessary to reflect changes in bridge conditions or loadings. However, non-load path redundant tension members in existing bridges that were not fabricated to meet the modern FCP introduced in 1978 are not

[FHWA 2012]

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How do you go about it?

“The criteria for a refined analysis used to demonstrate that part of a structure is not fracture-critical has not yet been codified. Therefore, the loading cases to be studied, location of potential cracks, degree to which the dynamic effects associated with a fracture are included in the analysis, and fineness of models and choice of element type should all be agreed upon by the Owner and the Engineer. The ability of a particular software product to adequately capture the complexity of the problem should also be considered and the choice of software should be mutually agreed upon by the Owner and the Engineer.”

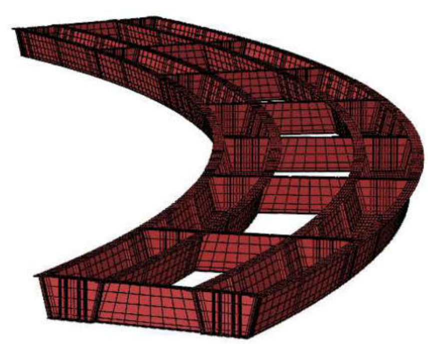
But since 2012 →

Modern analytical techniques have provided a means for engineers to more accurately assess bridge redundancy and identify fracture critical members, with full consideration of 3-D system behavior in damage scenarios. It is no longer necessary to identify FCMs by simple checking for load path redundancy alone, unless the State chooses to maintain such criteria. To demonstrate that a structure has adequate strength and stability sufficient to avoid partial or total collapse and carry traffic in the presence of a totally fractured FCM, a State must submit through the Division Office to the FHWA Office of Bridge Technology for review the detailed analysis and evaluation criteria that will be used to conduct the study. Once reviewed, these criteria can then be employed by the State systematically on their inventory.

[FHWA 2012]

Structural Redundancy Analysis

- Evaluation of WisDOT twin steel tubs based on methodology developed in NCHRP Report 883
- Worked with the S-BRITE Center at Purdue University
- Uses 3-D non-linear detailed, calibrated finite element analysis
  - Using Abaqus FEA software
- Modeling benchmarked to full-scale testing at University of Texas, Austin



Structural Redundancy Analysis

- Detailed models that included:
  - Shell elements for the deck (reinforcement as part of shell section)
  - Parapets included as solid elements
  - Internal and lateral braces as Timoshenko beam elements with connector elements
  - Shear studs as connector elements
    - Properties based on parametric study, calibrated to full-scale testing

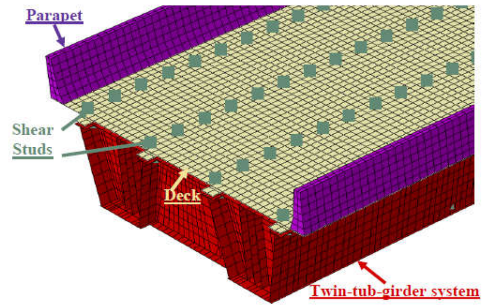
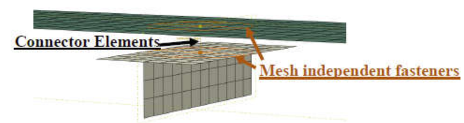


Figure 3-8 Shear studs and connector elements



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Structural Redundancy Analysis

- Two load combinations used in analysis
- *Redundancy I*: Describes loading condition at instant of failure (striped lanes)
- *Redundancy II*: Describes loading between failure and detection (design lanes)

0.2

$$Redundancy\ I: (1 + DA_R)[1.05(DC) + 1.05(DW) + 0.85(\mathrm{LL})]$$

$$Redundancy\ II: 1.05(DC) + 1.05(DW) + 1.30(1+\mathrm{IM})(\mathrm{LL})$$

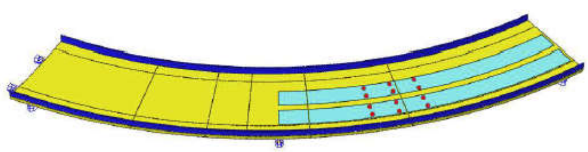

Figure 3-18 Redundancy I – Analysis II (two lane analysis) of B40-868

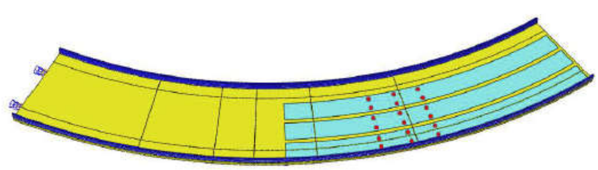

Figure 3-21 Redundancy II – Analysis III (three lane analysis) of B40-868

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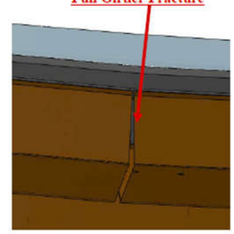
Structural Redundancy Analysis

- Fracture is full-depth of one of the two girders
- Multiple analyses indicated the critical fracture was:
  - End Span
  - Outside girder (of radius)
  - Just before first exterior diaphragm or near midspan



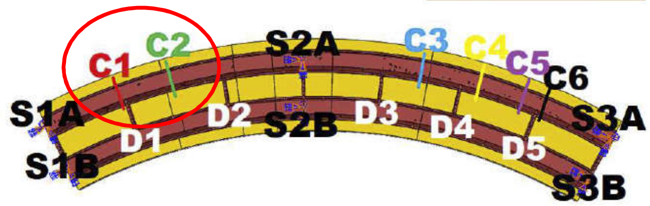


Figure 5-2 B40-868 Crack Locations

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Structural Redundancy Analysis

Assessment Criteria

- $\varepsilon_{ave} < \min(5*\varepsilon_y, 0.01)$
- $\varepsilon_{max} < \varepsilon_u = 0.05$
- $\sigma_{comp} < \sigma_{cr}$
- 15% reserve margin
- $\varepsilon_C < 0.003$

Commentary

- Limits redistribution of forces
- Conservative
- Not explicitly checked
- Ensures load-displacement curve ascending
- Deck (not parapets). Insignificant concrete crushing allowed

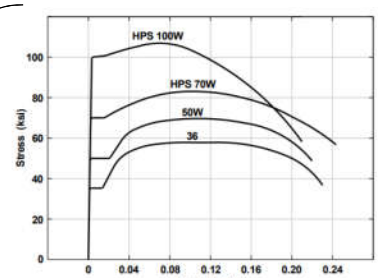

Figure 5 Typical engineering stress-strain curves for structural bridge steels.

[FHWA Steel Bridge Design Handbook]

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Project Timeline

Existing Structure Evaluation	Initiate Project	2015 - *March*
	Pilot Phase Report Submitted to FHWA	2016 - *May*
	B-40-837 Approved as SRM	2016 - *May*
	Phase I Report Submitted to FHWA	2018 - *February*
	Phase I Structures Approved as SRM	2018 - *September*
	B-5-671 Parametric Eval to FHWA	2018 - *October*
	B-5-671 Approved as SRM	2019 - *January*
	Phase II Report Submitted to FHWA	2019 - *December*
	Phase II Structure Approved as SRM	2020 - *January*
Future Designs	**Systematic Classification of SRM**	**In Progress…**

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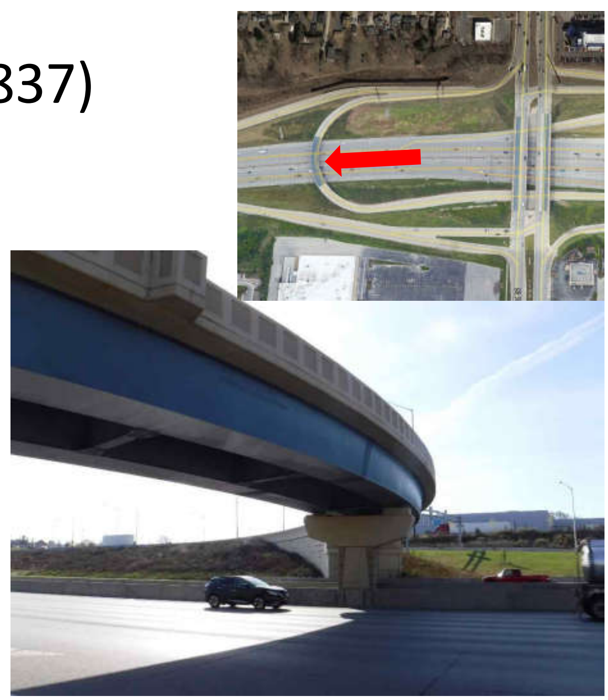
Pilot Analysis (B-40-837)

- Funded by NSBA-WisDOT
- Analysis based on information being developed under NCHRP 12-87a → NCHRP Report 883
- Determined to be Redundant!!!
- Report submitted to FHWA and approved for reclassification as SRM in 2016



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Report Submitted to FHWA

- Modeling requirements and assumptions
- Loading scenarios
- Fracture locations
- Evaluation Criteria

FHWA very supportive. Provided quality review and feedback in a timely manner

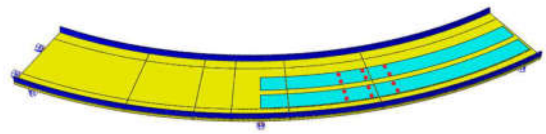
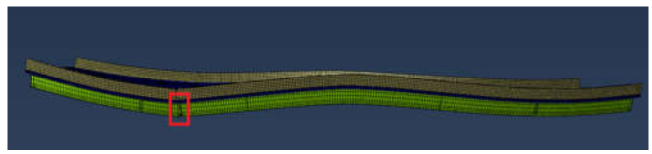


Figure 3-18 Redundancy I – Analysis II (two lane analysis) of B40-868



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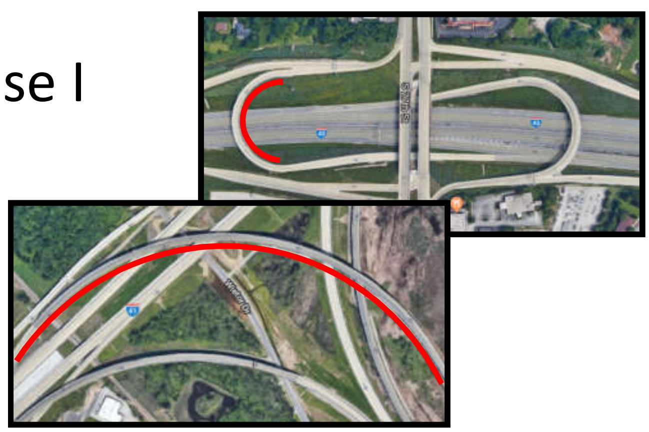
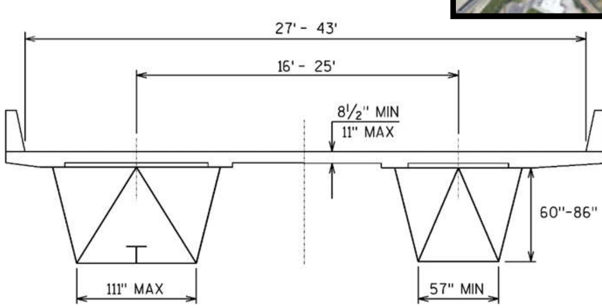
Phase I

- 12 additional bridges analyzed
- Wisconsin works with the S-BRITE Center at Purdue University
- Report January, 2018 – All determined redundant!





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“Change of Inspection Type Saves Millions While Ensuring Safety”

The Wisconsin Department of Transportation worked with Purdue University to analyze 13 twin tub girder bridges statewide. The study helped to identify structural system redundancies that maintain safety, allowing the department to gain Federal support to streamline inspection efforts. An “arm’s length” inspection method with associated costs, user delays and safety issues, will be replaced by the standard visual inspection used for all other bridges.

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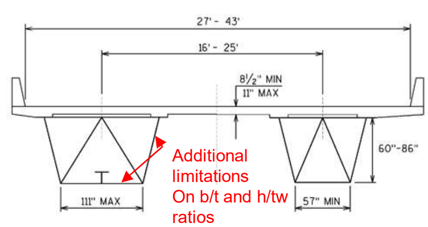
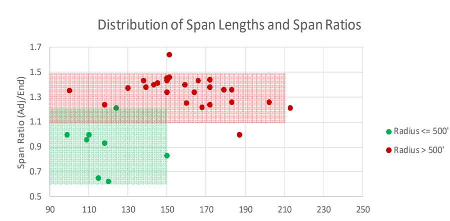
Parametric Evaluation

Parametric Evaluations (defining the “sandbox”) by which existing or future twin steel tub girders achieve SRM classification without the need for rigorous FEA.

- Design per LRFD
- Multi-span and continuous
- Utilize solid, full-depth intermediate and end external diaphragms
- Composite throughout
- Section and System limitations





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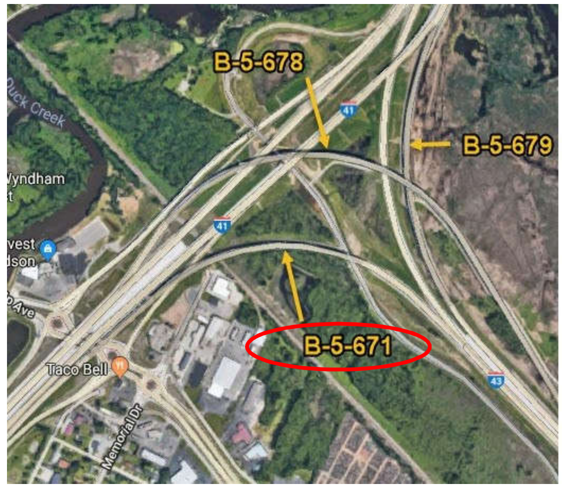
Piloted Parametric SRM Evaluation: B-5-671



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Piloted Parametric Evaluation: Bridge B-5-671

- Five similar bridges evaluated as part of original 13 in study
- Met parametric limitations for SRM
- Accepted by FHWA, so fracture critical inspection is not required
- SRM approval remains case-by-case

	SRM Parametric Evaluation Checklist *Structure B-05-0671*	*Unit 1(a)*	*Unit 1(b)*	*Unit 2*	*Unit 3*	Limit
Initial Conditions	Structure is designed per LRFD Code	X	X	X	X	
	Structure is Continuous, Multispan	X	X	X	X	
	Structure is Composite	X	X	X	X	
	Solid Full Depth Intermediate External Diaphragms	X	X	X	X	
System Parameters	Number of Design Lanes	3	3	3	3	2 or 3
	Radius, *R* (to outside girder C/L), [ft]	99999	99999	1500	1500	
	Length End Span, *L* [ft]	177	168	183	180	~~150 max (for R ≤ 500)~~ 210 max (for R > 500)
	Span Ratio (adjacent span length / end span length)	1.30	1.37	1.44	1.42	~~0.6 min, 1.25 max (R ≤ 500)~~ 1.1 min, 1.5 max (R > 500)
Section Parameters	Structure Clear Width [ft]	42				27 min, 43 max
	Girder Spacing [ft]	25				16 min, 25 max
	Deck Thickness [in]	10				8.5 min, 11 max
	Web Depth (measured plumb) [in]	86				60 min, 86 max
	Bottom Flange Width [in]	111				57 min, 111 max
	Grade of Steel	HPS 50W				Grade HPS 50W or HPS 70W only
	Bottom Flange Longintudinally Stiffened?	YES	YES	YES	YES	
	Bottom Flange width-thickness ratio (b/t)	89	89	68	74	60 max (unstiffened), 120 max (stiffened)
	Web width-thickness ratio (h/t)	98	98	98	98	135 max
External Diaphragms	Initial External Diaphragm Spacing, Si [ft]	36	34	33	33	42 max
	Max External Diaphragm Spacing, Smax [ft]	53	50	66	66	~~52 max (R ≤ 500)~~, 84 max (R > 500)
	Shear Stud Density (studs per row / row spacing [in])	0.33	0.33	0.33	0.33	0.33 min
	Flange Width [in]	20				16 min
	Flange Thickness [in]	1				~~3/4 min (L ≤ 160)~~, 1 min (L > 160)
	Web Thickness [in]	0.75				~~1/2 min (L ≤ 160)~~, 5/8 min (L > 160)
	Meets All SRM Qualification Checks?	YES	YES	YES	YES	

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Phase II

- 7 additional bridges analyzed
- All contain unique characteristics
- Analyzed based on *"AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members"* and prior work
- 3 bridges reclassified as SRMs, remaining bridges retained FCM status

Analysis doesn't guarantee SRM…

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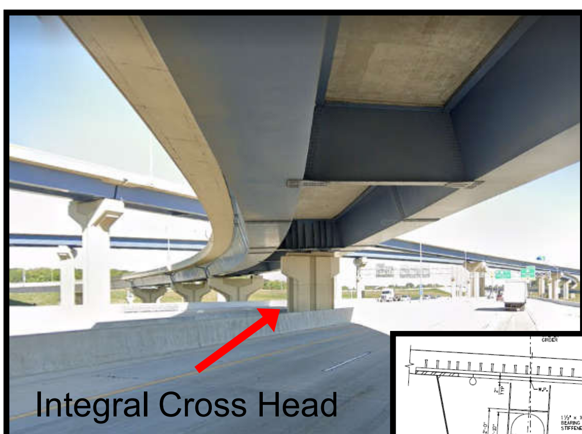
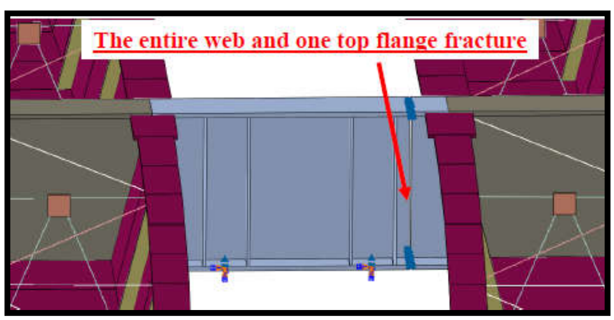
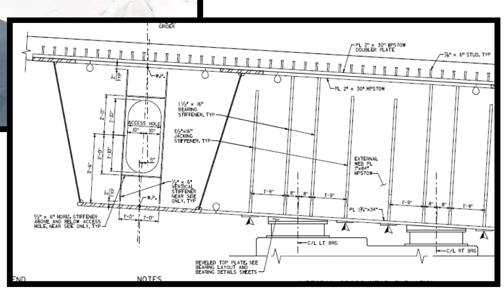
B-40-855



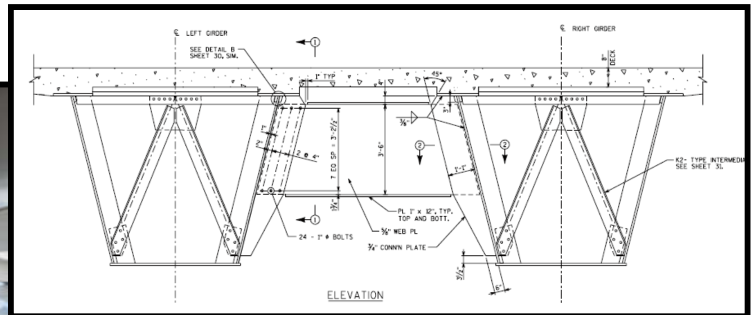




✓ Pass

110

B-37-360 and 362



✓ Pass

111

B-30-30

No shear studs over piers

X-frame intermediate diaphragms

✗ Remain FCM

Bottom flange buckling

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B-32-202

Remain FCM

Failure of cross-frame at pier followed by buckling of bottom flange

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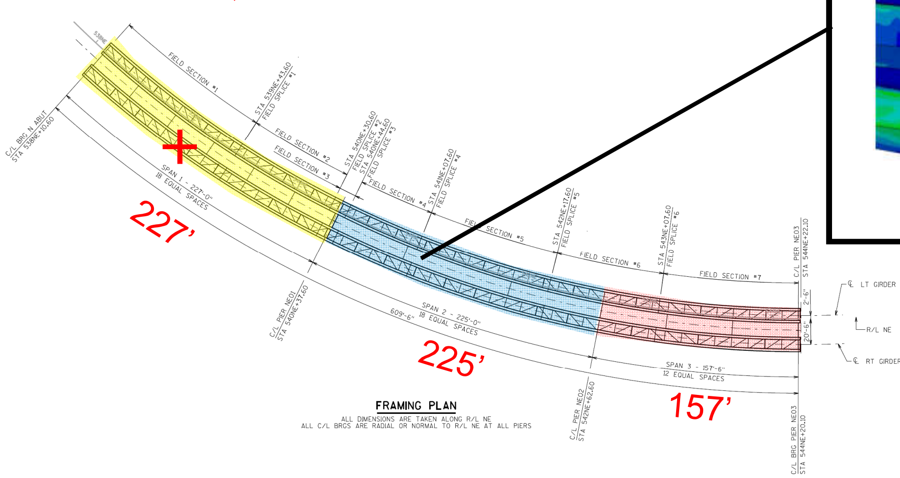
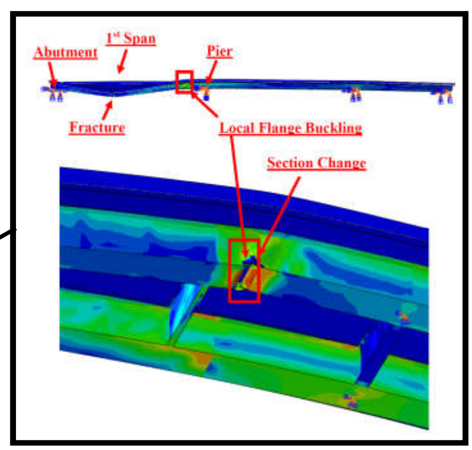
B-40-853

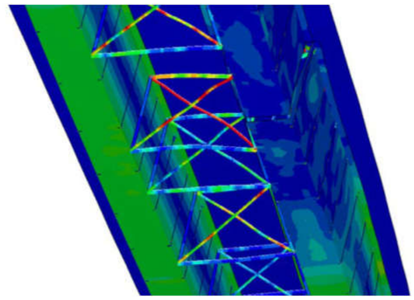
Remain FCM





114

B-62-187



❌ Remain FCM

Failure of cross-frames near mid-span with extensive shear stud failure

Key Feature: External Diaphragms

- Analysis demonstrates the benefit of relatively stiff external diaphragms
  - Insufficient redundancy found in select twin steel tubs without external diaphragms
  - Analysis of representative bridge without external diaphragms

Next Steps…

- Wisconsin removed 17 existing structures from the FC list
- Possible retrofits to address those structures deemed not sufficiently redundant
- Statewide policy for new designs that *automatically* achieve SRM classification

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A Simplified Approach for Designing SRMs

- Purdue has developed a simplified approach to SRM classification for AASHTO consideration
  - Intended to complement AASHTO SRM Guide Spec
  - Can be used for both *new* and *existing* designs
  - Subject to geometric limitations with additional design details and checks
  - No FEA Required!!!

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A Simplified Approach for Designing SRMs

- Geometric Limitations and "Screening" Process
  - Continuous and Composite
  - Limits on deck width, span lengths, skew, etc…
  - Limit on dead load deflection to span ratio (unfaulted state)
    - Avoids applying SRM classification to more flexible systems which could result in significant inelastic behavior
    - Deflections based on typical engineering analysis and common software (e.g. MDX)

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A Simplified Approach for Designing SRMs

- Design Details
  - Shear stud requirements (e.g. layout, height)
  - External diaphragm requirements (spacing and geometry)
- Design Checks
  - With geometric limitations and minimum design details in place, expected failure mode is isolated
  - *Negative* Moment Region (near flange transitions): minimum D/C ratio to prevent local bottom flange buckling
  - *Positive* Moment Region: minimum D/C ratio to avoid plastification of intact girder in faulted state

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FHWA encourages proper use of SRMs:

- State DOTs and researchers may propose procedures for SRM determination (not limited to twin-tub girder bridges).
- The review/acceptance process should go through FHWA Division Offices to FHWA HQ.
- A bridge owner may seek FHWA approval of using another bridge owner's procedure that had been accepted by FHWA.
- All determined SRMs with their supporting documents should be recorded in the bridge files.

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Webinar Related AASHTO Specifications

The presenters in this webinar referenced three AASHTO publications that owners and designers will find useful for steel bridge design and evaluating System Redundant Members. Obtain these important AASHTO publications at the links provided below:

AASHTO Guide Specifications for Internal Redundancy of Mechanically-fastened Built-up Steel Members (AASHTO Pub Code: GSFCM-1)

- *https://tinyurl.com/fcm-1-aug2020*

AASHTO LRFD Bridge Design Specifications (AASHTO Pub Code: LRFDBDS-9)

- *https://tinyurl.com/bds-9-aug2020*

AASHTO Manual for Bridge Evaluation, 3rd Edition (AASHTO Pub Code: MBE-3)

- *https://tinyurl.com/mbe-3-aug2020*

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PDH Certificates

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

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- Reporting site (URL will be provided in the forthcoming email).
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