Redundancy of Steel Bridges

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REDUNDANCY

Redundancy

- Crucial to recognize and identify the type of redundancy present in a bridge
- Redundancy allows the load that was previously carried by the failed member to be redistributed to other members – avoiding collapse
- Redundancy can be provided in one or more of the following ways:
  - Load Path Redundancy
  - System Redundancy
  - Internal Member Redundancy

Redundancy (23 CFR 650.305)

Load Path

A redundancy that exists based on the number of primary load-carrying members between points of support, such that fracture of the cross section at one location of a member will not cause a portion of or the entire bridge to collapse

System

A redundancy that exists in a bridge system without load path redundancy, such that fracture of the cross section at one location of a primary member will not cause a portion of or the entire bridge to collapse.

Internal

A redundancy that exists within a primary member cross-section without load path redundancy, such that fracture of one component will not propagate through the entire member, is discoverable by the applicable inspection procedures, and will not cause a portion of or the entire bridge to collapse.

Redundancy

Load Path

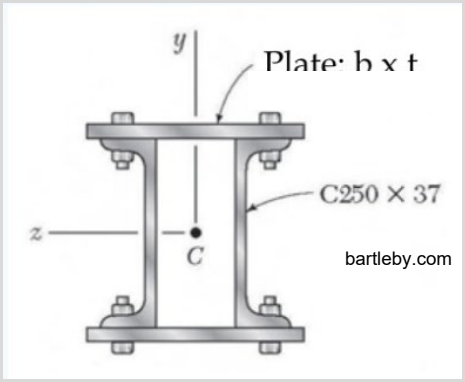
3 or more main load carrying members

System

UT-Austin twin tub research 0-5498 and analysis

Internal

Built up bolted members



FEDERAL RULES & GUIDANCE

Federal Guidance for Steel Tension Members

- May 2022 - new rules and guidance for steel tension members without load path redundancy
- Fracture Critical Member (FCM) classification term is replaced with Non-redundant Steel Tension Member (NSTM) term
- National Bridge Inspection Standards (NBIS) require hands-on inspection of NSTMs of in-service bridges.
- NSTMs must be identified in the bridge files.
- For bridges without load path redundancy, Agencies may choose to demonstrate that a member has system or internal redundancy such that it is not considered NSTM.

NSTM / FCM

Most Common NSTM/FCM

- Tension flanges and parts of webs of flexural members such as beams and girders
- Steel girders – two girder bridges not evaluated for system redundancy in accordance with the TxDOT BDM
- Two column steel bent caps
- Floor beams under certain conditions
- Lower chords of trusses
- Tied arch

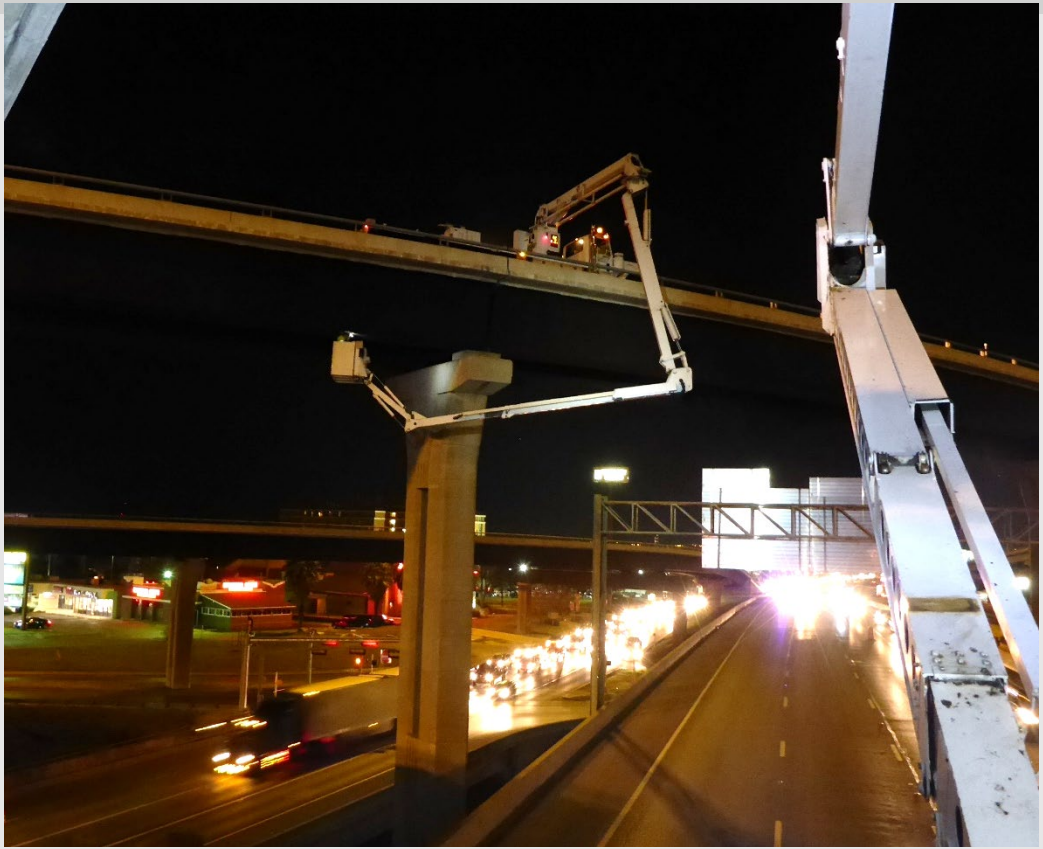
NSTM/FCM

- FCM/NSTM Classification =
  - Higher quality standard of fabrication
  - More in-depth inspection requirements than other steel bridges

Just because a bridge contains members that are classified as FCM/NSTM, does not mean there is anything wrong with the bridge or that it is unsafe

NSTM/Fracture Critical (FC) Inspection

- Require hands-on inspection every 2 years
- Limited to non-redundant load path steel tensile areas
- May include Non-Destructive Evaluation (NDE)



NSTM/FC Inspection

- Often take place at night
- High traffic volume
- Costly traffic control
- Over Railroads
  - A lot of waiting
  - Usually only a very narrow window to complete the inspection

NSTM/FC Inspection

- Total NSTM/FC Structures (2021) = 900 bridges currently
- Inspected every 2 years* **for the life of the structure**
- FC Inspection per year = 450
- Forces: In-house and 3 Consultants
- Estimated Cost:
  - Inspection Cost = $12M per year
  - Traffic Control = $3.75M per year

**New NBIS allows assessment of risk approach to increase inspection interval*

NSTM/FC Inspection - Access

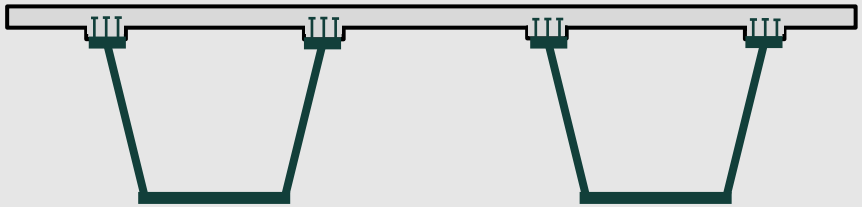
- Secure areas at airports
- Sensitive installations
- Logistics of getting equipment in place
- Confined spaces
  - Air quality
  - Heat

NSTM/FC Inspection - Access

TWIN TUB GIRDER BRIDGES

Redundancy of Steel Twin Tub Girder Bridges

- Consist of two steel box girders
- Composite with a concrete deck



TRANSVERSE SECTION

Steel Twin Tub Girders

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

Redundancy of Steel Twin Tub Girder Bridges

- Common type of fracture critical (FC) / NSTM classified bridge
- Texas has over 480 existing twin tub girder spans

Twin Tub Girder Bridges - Timeline

Published Requirements for Twin Tub Girder Bridges

- Bridge Design Manual-LRFD
- Chapter 3, Section 17 – System Redundancy Evaluation for Steel Twin Tub Girders
- Presents a LRFD based methodology to design twin tub girder spans such that the span will not collapse after the fracture of one of the girders
- http://onlinemanuals.txdot.gov/txdotmanuals/lrf/index.htm

Published Requirements for Twin Tub Girder Bridges

- Bridge Design Manual-LRFD
- Chapter 3, Section 17 – System Redundancy Evaluation for Steel Twin Tub Girders
- Presents a LRFD based methodology to design twin tub girder spans such that the

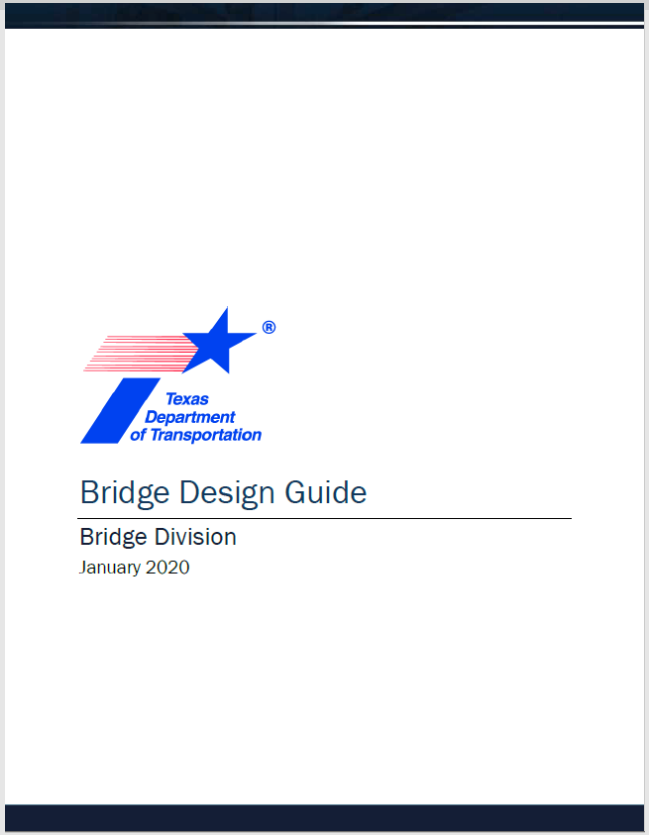
Bridge Design Manual - LRFD

Structural Analysis

All two tub girder bridges must satisfy the requirements in this manual and must be evaluated for system redundancy of spans at the Extreme Event Limit State III as described in Chapter 2. Two types of analysis can be used to evaluate the Extreme Event III:

Published Guide for Twin Tub Girder Bridges

- Bridge Design Guide
- Chapter 3, Section 12 – System Redundancy Evaluation for Steel Twin Tub Girders
- Appendix C – Steel Twin Tub Girder System Redundancy Simplified Method Guide
- http://ftp.dot.state.tx.us/pub/txdot-info/brg/design/bridge-design-guide.pdf



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)

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.

$$M_P \geq M_{EEIII}$$

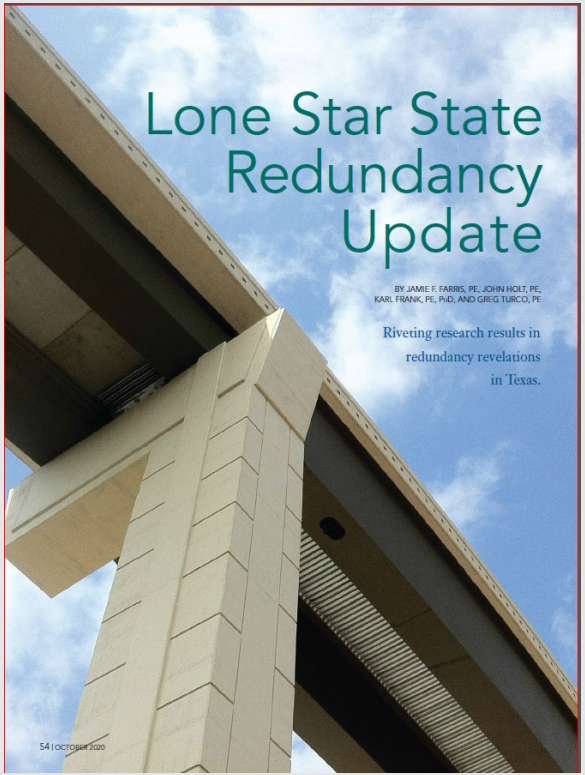
6. **Check the bending and shear capacity of the concrete deck** to ensure adequacy to resist the moment and shear produced by the unsupported load of the fractured girder.

   Positive Moment Capacity, M_n^+ of Concrete Deck

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

TxDOT Design Methodology – More Information

Modern Steel Construction, October 2020



To address concerns that current provisions do not reflect the performance of steel twin-tub girders during a fracture event, TxDOT and the FHWA sponsored a research project at UT Austin to characterize the level of redundancy that exists in a steel twin-tub girder bridge.

A COMMON BRIDGE TYPE historically assumed to include fracture-critical members (FCMs), based on a simplistic load-path redundancy assessment, is the steel twin-tub girder bridge.

These bridges consist of two steel box girders, frequently trapezoidal-shaped, and a concrete deck and are a very effective solution for curved ramps and connectors in multi-level interchanges. The two bottom flanges and webs of a steel twin-tub-girder bridge are considered to be fracture-critical elements in the positive bending moment region.

Texas has more than 480 existing twin-tub girder spans currently in use, and the Texas Department of Transportation (TxDOT) spends more than $2.3 million every two years inspecting twin-tub girder spans—not including traffic control costs, which can be up to $2,000 per span per day for a fracture-critical bridge (FCB) inspection. This added expense of the field inspections limits the use of what is a very efficient structural system.

Thanks to recent research, a simplified method for evaluating system redundancy in two-tub girder span bridges has been added to the state's bridge design policy. The *TxDOT Bridge Design Manual–LRFD* now presents an LRFD-based methodology to design spans with two tub girders in cross section such that the span will continue to safely carry traffic after the fracture of one of the girders. The 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. Therefore, the Texas method addresses the design of a simulated fracture as an extreme event limit state.

UT Twin-Tub Research

Several historical events have shown that severe damage can occur to a bridge without resulting in its collapse. Early research into multiple incidents, including a full-depth fracture of in-service fracture-critical bridges (FCB), suggests that in some cases, a redundant load path does exist for some FCBs. To address concerns that current provisions do not reflect the performance of steel twin-tub girders during a fracture event, TxDOT and the Federal Highway Administration (FHWA) sponsored a research project at the University of Texas at Austin to characterize the level of redundancy that exists in a steel twin-tub girder bridge. The main goal of Research Project 0-5498: "Modeling the Response of Fracture Critical Steel Box Girder Bridges" was to develop guidelines for modeling a bridge's behavior in the event that a critical bottom tension flange fractures. The research included a combination of laboratory testing, experimental evaluation of a full-scale tub girder bridge, and detailed structural analysis.

The tested bridge was taken out of service and reconstructed at the Ferguson Structural Engineering Laboratory (FSEL) at UT to evaluate the redundancy after a series of tests. The experimental bridge's geometry represented a worst-case scenario, as it was a 120-ft-long horizontally curved simple-span bridge with no external diaphragms. The first test included using a linear shape-

Jamie F. Farris is the Bridge Division deputy director and **Greg Turco** is a Bridge Design Group leader, both with the Texas Department of Transportation. **John Holt** is a senior project manager/regional director with Modjeski and Masters, and **Karl Frank** is a professor emeritus at the University of Texas at Austin, and a consultant.

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STEEL STRADDLE BENTS

Steel Straddle Bents

New TxDOT Policy for New Steel Straddle Bents

- New Section 6 in Chapter 4 Substructure
  - Steel Straddle Bent Caps

New TxDOT Policy for New Steel Straddle Bents

- Must be designed to be redundant
  - System redundant
  - Internally redundant

New TxDOT Policy for New Steel Straddle Bents

- All steel straddle bent caps :
  - Must satisfy the requirements of the TxDOT Bridge Design Manual-LRFD
  - Must be evaluated for redundancy according to:
    - *AASHTO Guide Specifications for Internal Redundancy of Mechanically-Fastened Built-up Steel Members* or
    - *AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members*, as applicable.

New TxDOT Policy for New Steel Straddle Bents

- Designate in the contract documents as SRMs (system redundant members) or IRMs (Internal redundant members) and need not be subject to the hands-on in-service inspection protocol for NSTM as described in 23 CFR 650.
- The SRMs or IRMs shall be fabricated according to the American Welding Society (AWS) D1.5 Bridge Welding Code Fracture Control Plan (FCP).

Designing New Steel Straddle Bents for Redundancy

- How???
- Several options

Straddle Bent Solutions

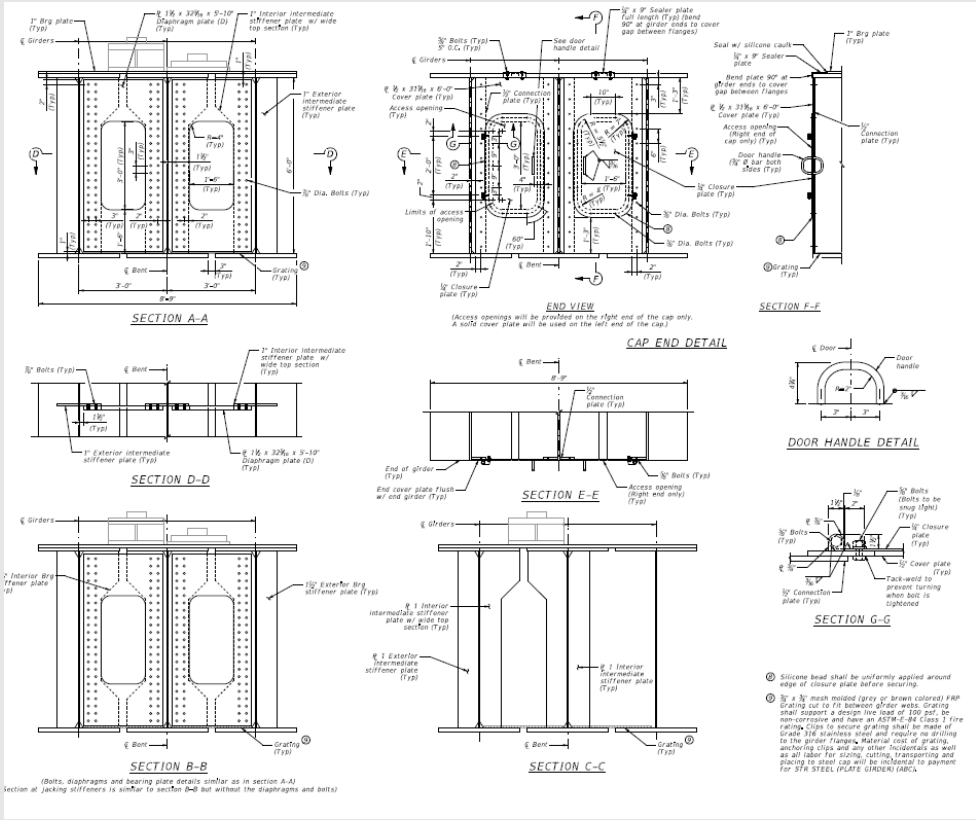
- Connecticut Three I-Girder Straddle Cap
- Presentation at March 2021 Texas Steel Quality Council Meeting
- Fabricated by High Steel
- Designed by CHA, inc.

Straddle Bent Solutions

Photos by: CHA, Inc.

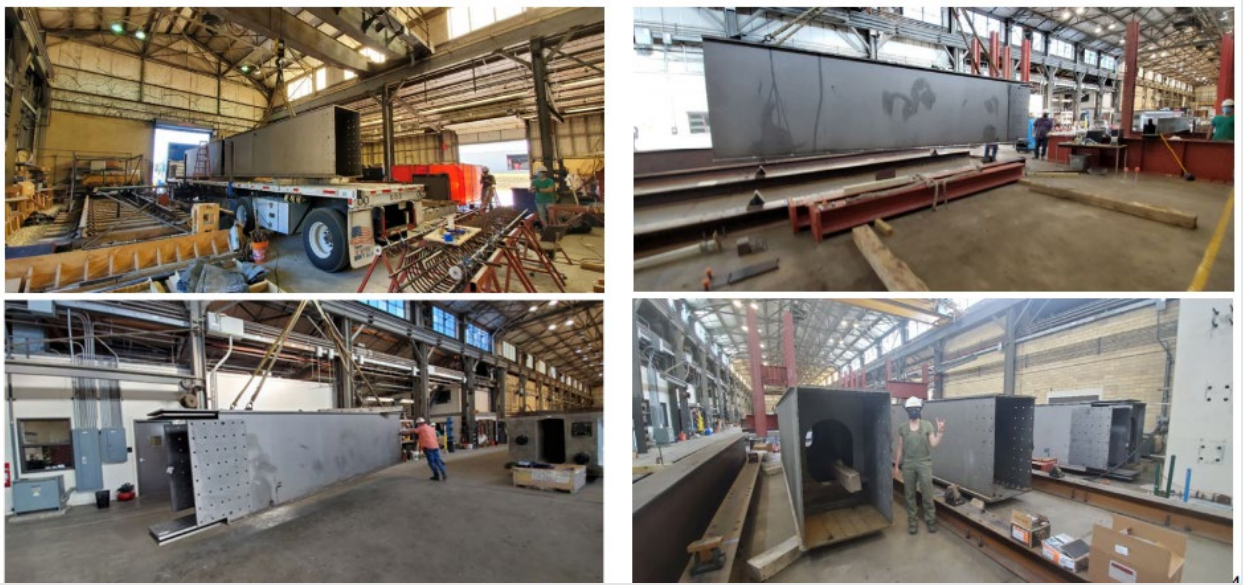
Straddle Bent Solutions

- Example plans available
- Texas consultants already designed for upcoming project



Steel Straddle Bent Research

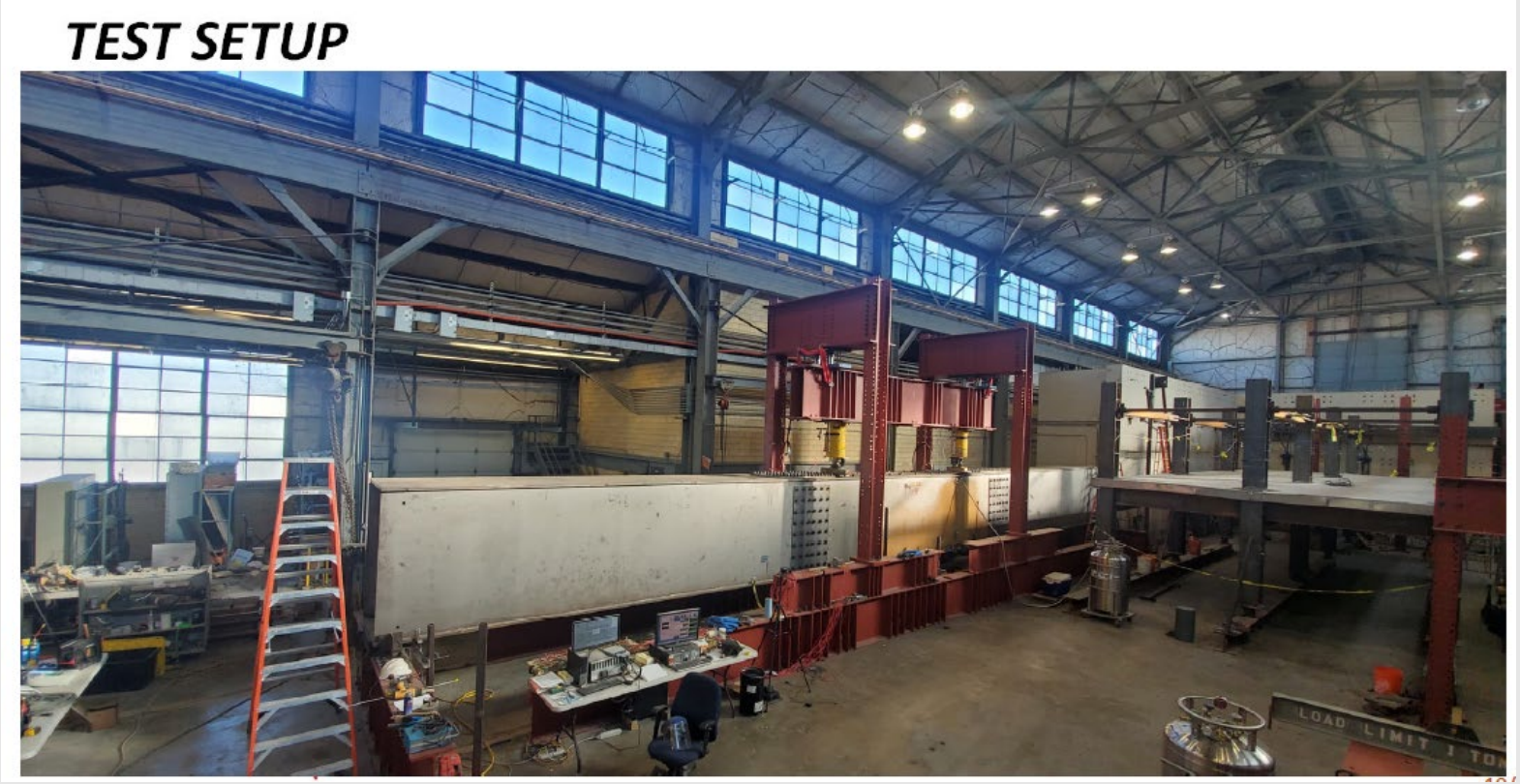
- 0-7012 Development of Non-Fracture Critical Steel Box Straddle Caps
- University of Texas at Austin



Steel Straddle Bent Research

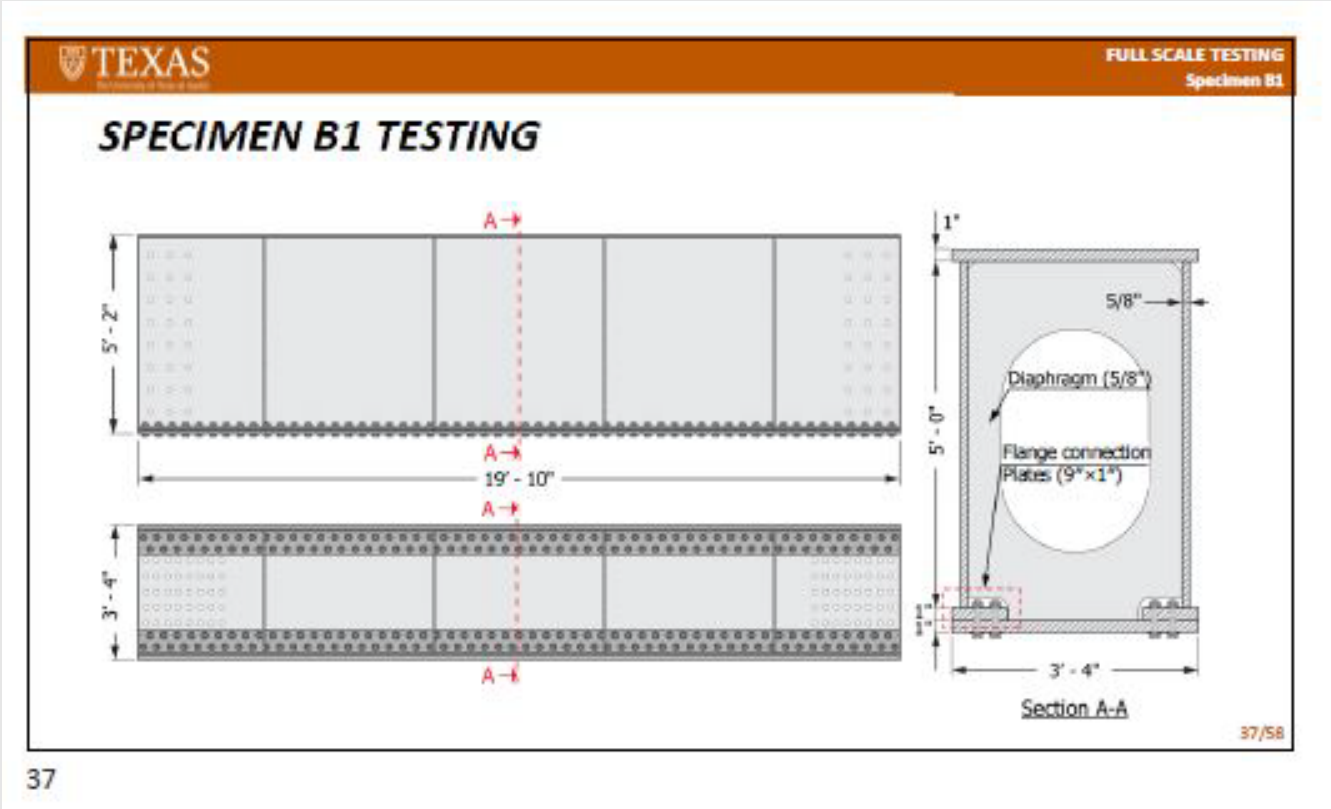
- Literature review
- Conceptual studies and industry input
- Preliminary analysis of design concepts
- Design of test setup and specimens
- Experimental testing for new construction
- Experimental testing for retrofitting existing
- Parametric FEA studies for new construction and retrofitting existing
- Design recommendations and examples

Steel Straddle Bent Research



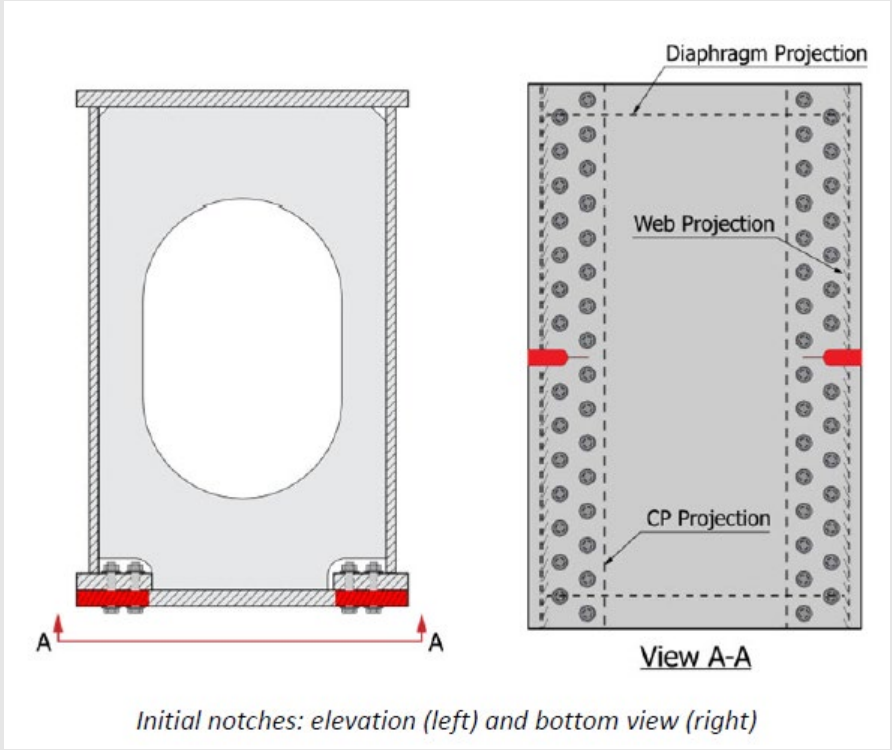
Steel Straddle Bent Research

- Bolted bottom flange



Steel Straddle Bent Research

- Bolted bottom flange
  - Notched specimen
  - Fatigue loading
  - Loaded to fracture
  - Cross-boundary separation provided by the bolted connections proved effective in restricting crack propagation between elements in tension



Initial notches: elevation (left) and bottom view (right)

SUBMITTAL AND APPROVAL

Submittal and Approval of SRM and IRMs

- **60% PS&E level** - in coordination with the District Bridge Engineer, send a pdf of the following documents to the Bridge Division Design Section Director for review and coordination with FHWA.
  - Bridge Layout
  - Steel straddle bent cap plan sheets or steel twin tub girder plan sheets
  - Steel straddle bent cap or steel twin tub girder design calculation package meeting the requirements of AASHTO Chapter 6, including the calculations demonstrating redundancy. Include explanation of assumptions for modeling and modeling method.

Submittal and Approval

- To satisfy FHWA requirements, TxDOT Bridge Division must submit each steel straddle bent cap or twin tub girder design for redundancy to FHWA.
- Upon FHWA and TxDOT's acceptance and approval of 100% Plans, submit final calculation package in accordance with TxDOT Bridge Design Manual – LRFD Chapter 6 (Design Notes and Calculations), including:
  - Final redundancy calculations
  - Full completed refined analysis records/computer models as this information will be retained and included with the bridge inspection management system.
- An approval memo will be sent to the District and filed in the bridge inspection management system.

Questions?