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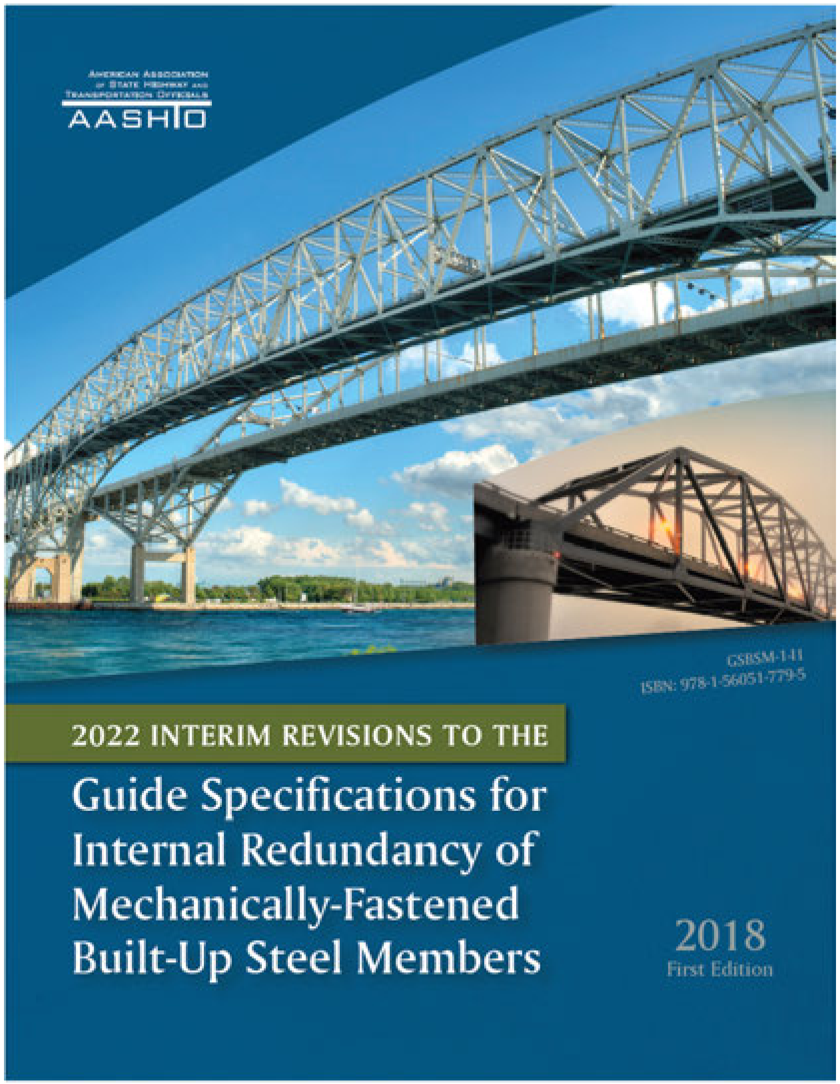
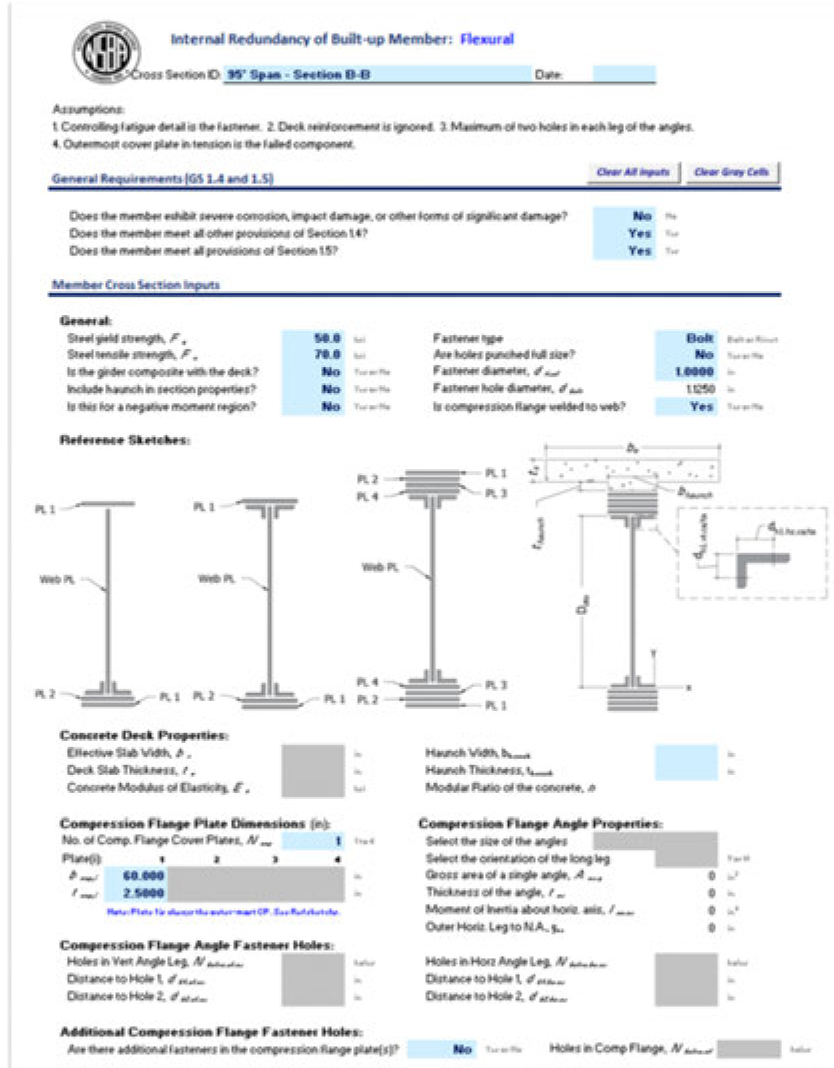
IRM CASE STUDY

BUILT-UP STEEL BENT

PC: “Flying By”, Modern Steel Construction,
Vinod Patel & Hemal Patel. Feb 2024, pg. 32.


American Association of State Highway and Transportation Officials
AASHTO
GSBSM-1-I1
ISBN: 978-1-56051-779-5
2022 INTERIM REVISIONS TO THE
Guide Specifications for Internal Redundancy of Mechanically-Fastened Built-Up Steel Members
2018
First Edition


Internal Redundancy of Built-up Member: Flexural
Cross Section ID: 95' Span - Section B-B
Date:
Assumptions:
1. Controlling fatigue detail is the fastener. 2. Deck reinforcement is ignored. 3. Maximum of two holes in each leg of the angles.
4. Outermost cover plate in tension is the failed component.
General Requirements (GS 1.4 and 1.5)
Clear All Inputs
Clear Gray Cells
Does the member exhibit severe corrosion, impact damage, or other forms of significant damage? No
Does the member meet all other provisions of Section 1.4? Yes
Does the member meet all provisions of Section 1.5? Yes
Member Cross Section Inputs
General:
Steel yield strength 50.0
Steel tensile strength 70.0
Is the girder composite with the deck? No
Include haunch in section properties? No
Is this for a negative moment region? No
Fastener type Bolt
Are holes punched full size? No
Fastener diameter 1.0000
Fastener hole diameter 1.1250
Is compression flange welded to web? Yes
Reference Sketches:
PL 1
PL 2
PL 3
PL 4
Web PL
Concrete Deck Properties:
Effective Slab Width
Deck Slab Thickness
Concrete Modulus of Elasticity
Haunch Width
Haunch Thickness
Modular Ratio of the concrete
Compression Flange Plate Dimensions (in):
No. of Comp. Flange Cover Plates 1
Plate(i): 1 2 3 4
60.000
2.5000
Compression Flange Angle Properties:
Select the size of the angles
Select the orientation of the long leg
Gross area of a single angle 0
Thickness of the angle 0
Moment of Inertia about horiz. axis 0
Outer Horiz. Leg to N.A. 0
Compression Flange Angle Fastener Holes:
Holes in Vert Angle Leg
Distance to Hole 1
Distance to Hole 2
Holes in Horz Angle Leg
Distance to Hole 1
Distance to Hole 2
Additional Compression Flange Fastener Holes:
Are there additional fasteners in the compression flange plate(s)? No
Holes in Comp Flange

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METHODOLOGY

1. Screening Criteria
2. Check fatigue life in *unfaulted* state
3. Check strength in *faulted* state
4. Check fatigue life in *faulted* state
5. Calculate Special Inspection Interval

EXAMPLE DESIGN – STRADDLE BENT

- A709-50W steel
- Drilled 1-1/8” Φ bolt holes
- F_y = 50 ksi, F_u = 70 ksi
- $(ADTT)_{SL}$ = 2,000
- g = 1% (annual $ADTT_{SL}$ growth rate)

PC: Ronnie Medlock, High Steel

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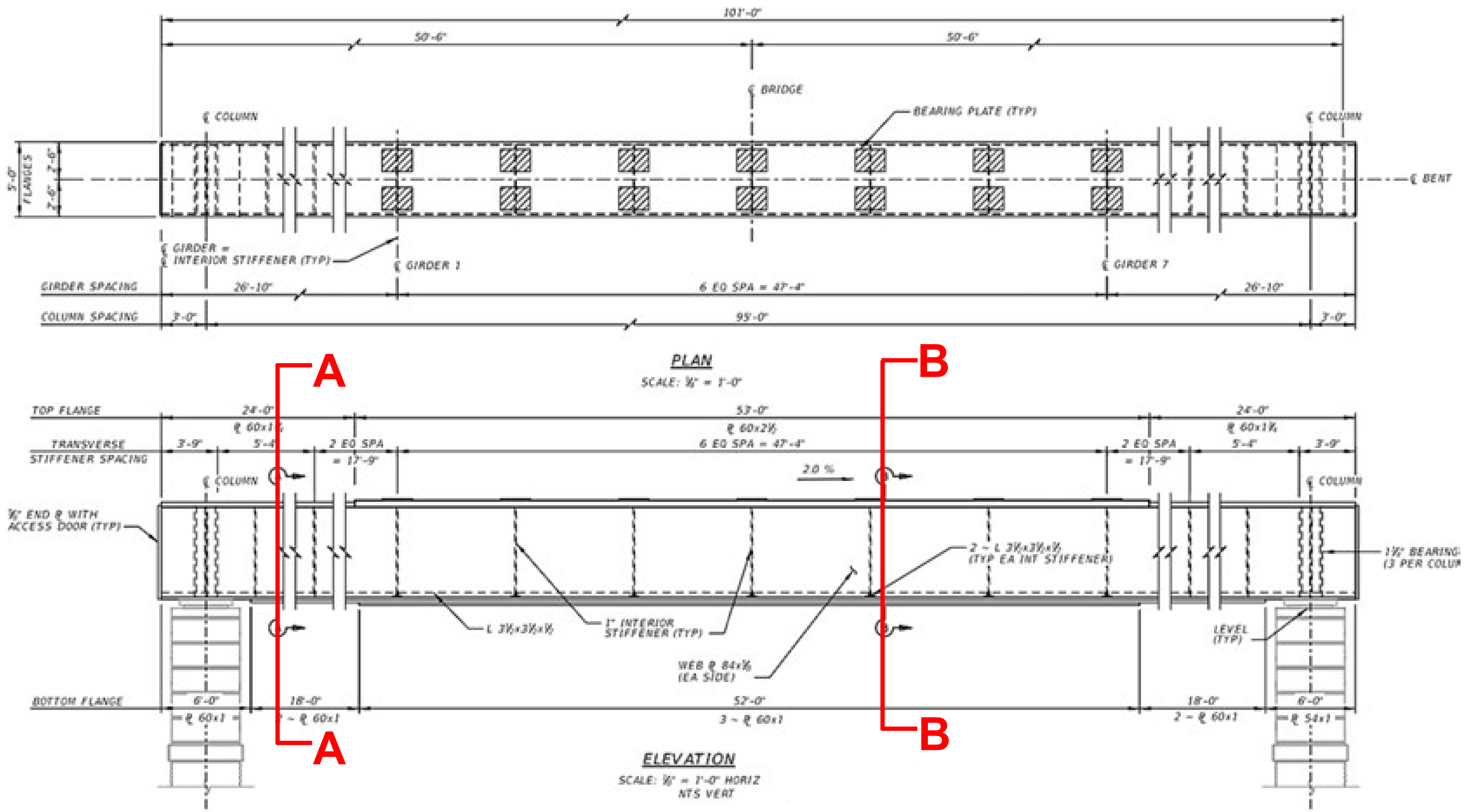
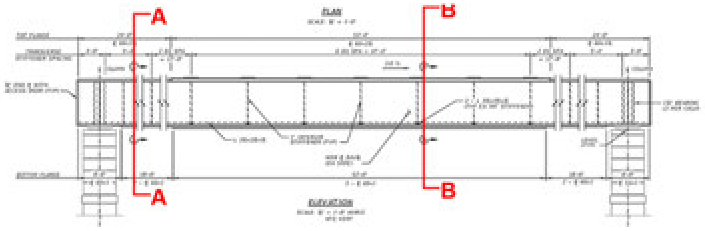
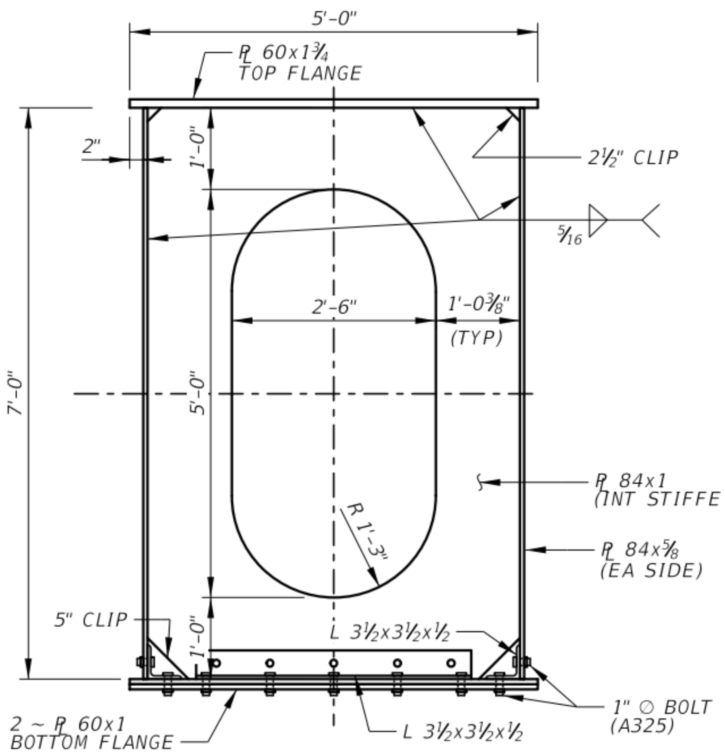
SPAN LAYOUT, (101 FT. LONG, 95' OC)



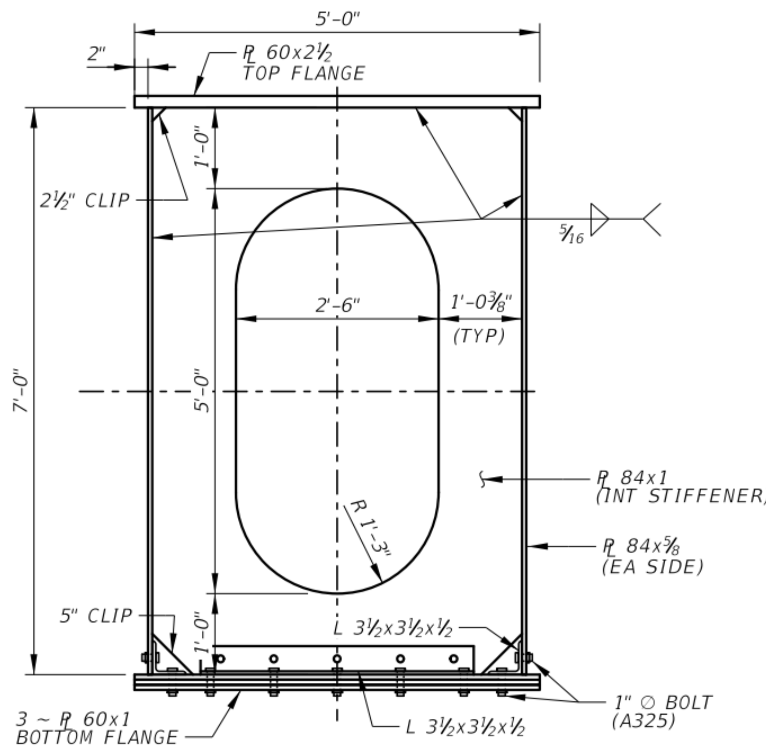


SECTION A-A



SECTION A-A
SCALE: ¼" = 1'-0"

SECTION B-B



SECTION B-B
SCALE: ¼" = 1'-0"

SECTION PROPERTIES (B-B)

General:

Steel yield strength, F_y	50.0	ksi	Fastener type	Bolt	Bolt or Rivet
Steel tensile strength, F_u	70.0	ksi	Are holes punched full size?	No	Yes or No
Is the girder composite with the deck?	No	Yes or No	Fastener diameter, d_{fast}	1.0000	in
Include haunch in section properties?	No	Yes or No	Fastener hole diameter, d_{hole}	1.1250	in
Is this for a negative moment region?	No	Yes or No	Is compression flange welded to web?	Yes	Yes or No

Compression Flange Cover Plate Dimensions (in)**:**

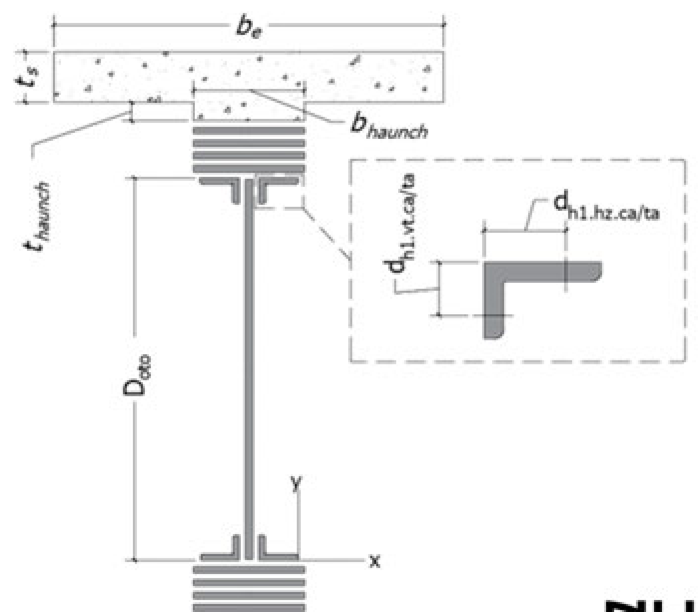
No. of Comp. Flange Cover Plates, N_{ccp} — **1** (1 to 4)

Plate(i):	1	2	3	4	
$b_{ccp,i}$	60.000				in
$t_{ccp,i}$	2.5000				in

Note: Plate 1 is always the outer-most CP. See Ref sketchs.

Web Plate Dimensions:

Web Plate Depth, D_w	84.00	in
Web Thickness, t_w	1.2500	in
Flange Angles Out-to-out Depth, D_{oto}	84.00	in



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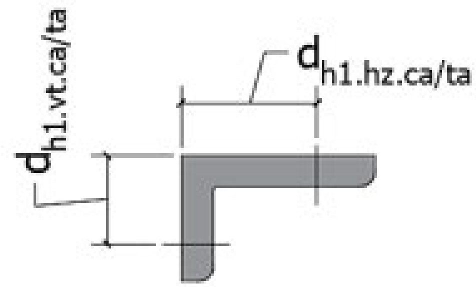
SECTION PROPERTIES CONT. (B-B)



Tension Flange Cover Plate Dimensions (in):

No. of Tension Flange Cover Plates, N_{tcp}				3	1 to 4
Plate(i):	1	2	3	4	
$b_{tcp,i}$	60.000	60.000	60.000		in
$t_{tcp,i}$	1.0000	1.0000	1.0000		in

Note: Plate 1 is always the outer-most CP, see Ref Sketches

Tension Flange Angle Fastener Holes:

Holes in Vert Angle Leg, $N_{holes.vt.ta}$	1	holes
Distance to Hole 1, $d_{h1.vt.ta}$	2.00	in
Distance to Hole 2, $d_{h2.vt.ta}$		in

Tension Flange Angle Properties:

Select the size of the angles	L3-1/2X3-1/2X1/2	
Select the orientation of the long leg	Vert	V or H
Gross area of a single angle, $A_{ta.g}$	3.25	in^2
Thickness of the angle, t_{ta}	0.5	in
Moment of Inertia about horiz. axis, $I_{xx.ta}$	3.63	in^4
Outer Horiz. Leg to N.A., y_{ta}	1.05	in

Holes in Horz Angle Leg, $N_{holes.hz.ta}$	1	holes
Distance to Hole 1, $d_{h1.hz.ta}$	2.00	in
Distance to Hole 2, $d_{h2.hz.ta}$		in

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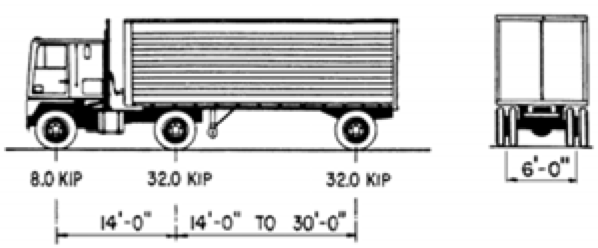
IRM EVALUATION LOADS

Redundancy II Load Case:

- HL-93 design trucks (w/12 config.)
- IM = 15% (not on lane)
- Multiple presence factors
- γ_{DC} = 1.05, γ_{DW} = 1.05, γ_{LL} = 1.30, γ_{FATI} = 1.75, γ_{FATII} = 0.80



	Unfactored		
Section	M_{DC1} (kip-ft)	M_{LL+IM} (kip-ft)	M_{FAT+IM} (kip-ft)
A-A	19,248	5,239	2,518
B-B	31,500	8,574	4,122

SECTION PROPERTIES CONT. (B-B)

Unfaulted Member Section Properties:

Assumed no failed components

Gross Section Properties: Unfaulted (composite if applicable)

Composite			Noncomposite		
$\bar{y}_{G,COMP}$	-	in	$\bar{y}_{C,G,NC}$	38.8	in
$c_{G,COMP}$	-	in	$c_{G,NC}$	41.8	in
$A_{G,COMP}$	-	in^2	$A_{G,NC}$	441.5	in^2
$I_{xG,COMP}$	-	in^4	$I_{xG,NC}$	705,928.0	in^4
$S_{xG,COMP}$	-	in^3	$S_{xG,NC}$	16,895.9	in^3

Net Section Properties: Unfaulted (composite if applicable)

Composite			Noncomposite		
$\bar{y}_{N,COMP}$	-	in	$\bar{y}_{N,NC}$	39.7	in
$c_{N,COMP}$	-	in	$c_{N,NC}$	42.7	in
$A_{N,COMP}$	-	in^2	$A_{N,NC}$	431.1	in^2
$I_{xN,COMP}$	-	in^4	$I_{xN,NC}$	689,092.8	in^4
$S_{xN,COMP}$	-	in^3	$S_{xN,NC}$	16,127.3	in^3

Faulted Member Section Properties:

Assumed failed component is Tension Cover PL 1 (outer-most cover plate)

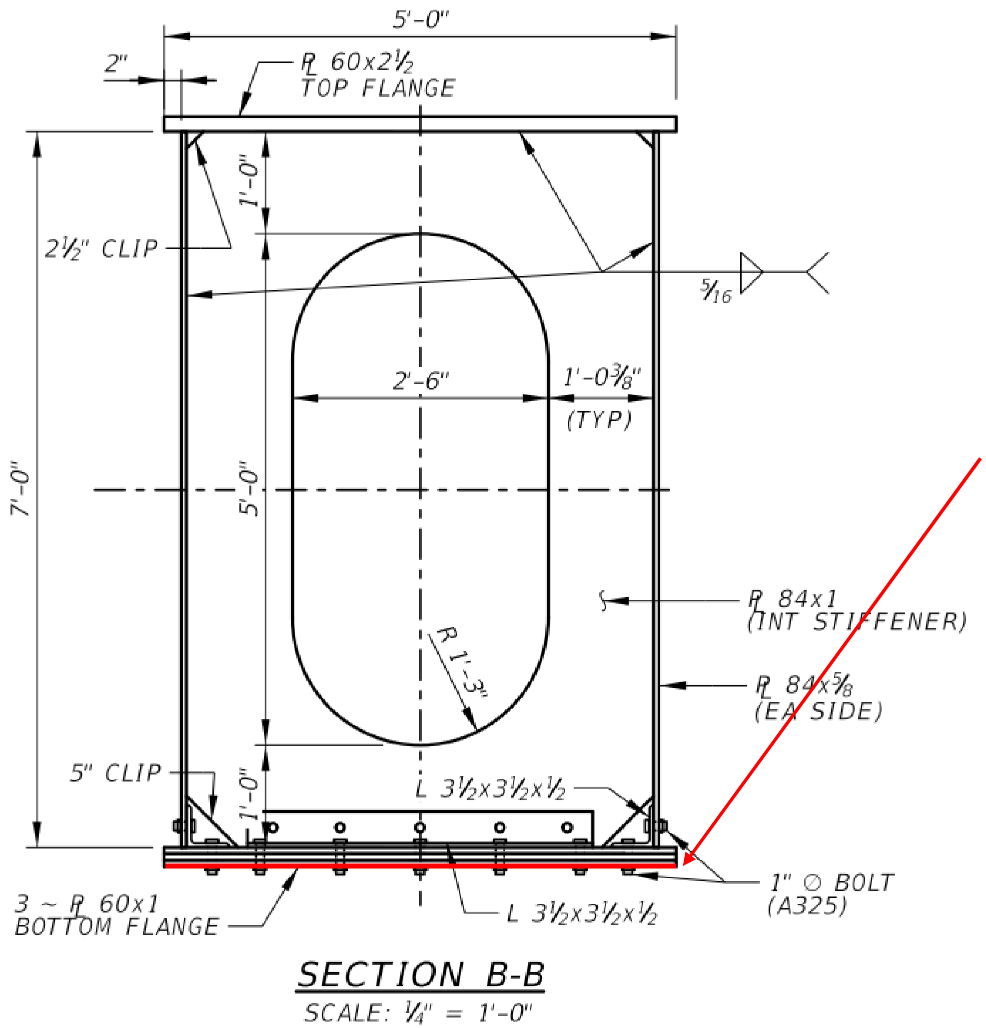
Gross Section Properties: Faulted (composite if applicable)

Composite			Noncomposite		
$\bar{y}_{AFG,COMP}$	-	in	$\bar{y}_{AFG,NC}$	45.3	in
$c_{AFG,COMP}$	-	in	$c_{AFG,NC}$	47.3	in
$A_{AFG,COMP}$	-	in^2	$A_{AFG,NC}$	381.5	in^2
$I_{x,AFG,COMP}$	-	in^4	$I_{x,AFG,NC}$	587,594.8	in^4
$S_{x\text{-}AFG,COMP}$	-	in^3	$S_{x\text{-}AFG,NC}$	12,429.7	in^3

Net Section Properties: Faulted (composite if applicable)

Composite			Noncomposite		
$\bar{y}_{AFN,COMP}$	-	in	$\bar{y}_{AFN,NC}$	46.3	in
$c_{AFN,COMP}$	-	in	$c_{AFN,NC}$	48.3	in
$A_{AFN,COMP}$	-	in^2	$A_{AFN,NC}$	373.3	in^2
$I_{x,AFN,COMP}$	-	in^4	$I_{x,AFN,NC}$	570,201.9	in^4
$S_{x\text{-}AFN,COMP}$	-	in^3	$S_{x\text{-}AFN,NC}$	11,815.1	in^3

FAULTED CONDITION



Assume failure of outer plate

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UNFAULTED FATIGUE & FAULTED STRENGTH (B-B)

Total unfaulted state remaining fatigue life, Y_{REM}	**Infinite**	Years	MBE 7.2.5.1	Unfaulted fatigue life?	OK
Case I or II for unfaulted state?	**I**	I or II	GS 2.5		

Redundancy II Factored Moment:

$M_u = \gamma_{DC}(M_{DC1} + M_{DC2}) + \gamma_{DW}M_{DW} + \gamma_{LL}M_{LL+IM} =$	44,221	k-ft	GS Eq. 1.7.1-1

Factored Resistance:

$f_{u,n} = \varphi_u F_u =$	56.00	ksi	GS Eq. 2.3-2
$f_{u,g} = \varphi_y F_y =$	47.50	ksi	GS Eq. 2.3-1

Factored Stress in the Faulted State: (*Note:* $\beta_{AF} = 1.0$)

Noncomposite Section:

$f_{AFN} = \beta_{AF}(M_u / S_{x\text{-}AFN}) =$	44.91	ksi	GS Eq. 2.1.2-1
$f_{AFG} = \beta_{AF}(M_u / S_{x\text{-}AFG}) =$	42.69	ksi	GS Eq. 2.1.2-2

Strength Criteria Check:				Performance Ratio (D/C)
$f_{AFN} \leq f_{u,n}$?	OK	OK or NG	GS Eq. 2.3-2	0.80
$f_{AFG} \leq f_{u,g}$?	OK	OK or NG	GS Eq. 2.3-1	0.90

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METHODOLOGY CHECK-IN:

1. Screening Criteria - **PASS**
2. Check fatigue life in unfaulted state - **INFINITE**
3. Check strength in faulted state - **PASS**
4. Check fatigue life in faulted state - **?**
5. Calculate Special Inspection Interval - **?**

FATIGUE LIFE IN FAULTED STATE

Effective Fatigue Stress Range & Max Fatigue Stress Range in Faulted State:

Noncomposite Section:

$f_{AFN} = \beta_{AF}(M_{FAT+IM} / S_{x\text{-}AFN}) =$	4.8	ksi	GS Eq. 2.1.2-1

$$(\Delta f)_{max} = (\gamma_{FATI}/\gamma_{FATII})(\Delta f)_{eff} = (1.75/0.8)(4.8\text{ksi}) = 10.5 \text{ ksi}$$

Use Cat. C (CATH = 10 ksi), therefore **FINITE** life

Total faulted state remaining fatigue life, Y_{REM}	**43.1**	Years	MBE 7.2.5.1	Faulted fatigue life?	OK
Case I or II for faulted state?	**I(b)**	I(a), I(b), II	GS 2.5		
Total Remaining Fatigue Life:					
No. of accumulated years in unfaulted state, N_u	0.0	Years	GS 2.5.3		
Total fatigue life only in **unfaulted** state, Y_u	∞	Years	GS 2.5.3		
Total remaining fatigue life only in **faulted** state, Y_f	43.1	Years	GS 2.5.3		
Total remaining fatigue life, $N_f = Y_f(1-N_u/Y_u)$	**43.1**	Years	GS Eq. 2.5.3-1		

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SECTION B-B RESULT SUMMARY

- Passed screening criteria
- Possessed positive fatigue life - unfaulted state
- Passed strength checks – faulted state
- Possessed positive fatigue life - faulted state

Qualifies as IRM

- Next – calculate Special Inspection Interval

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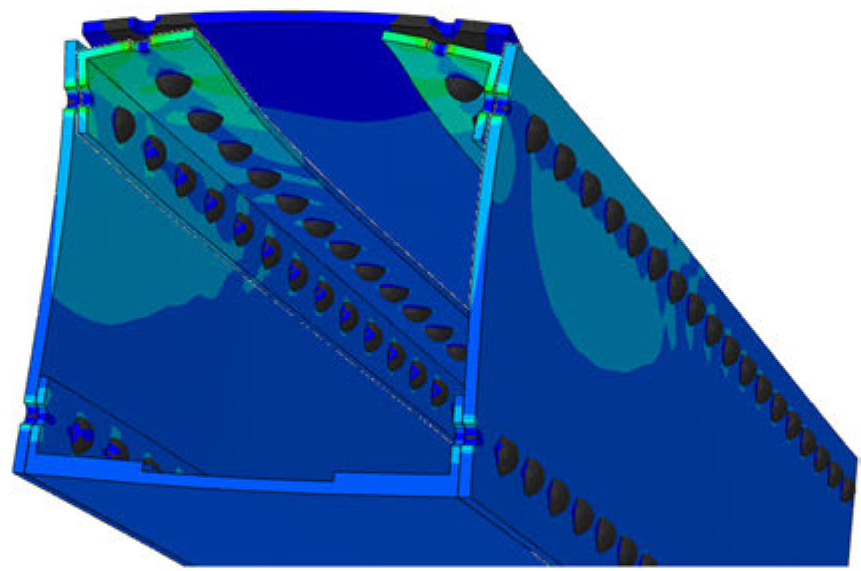
SUMMARY & INSPECTION INTERVAL (B-B)

Summary of Results

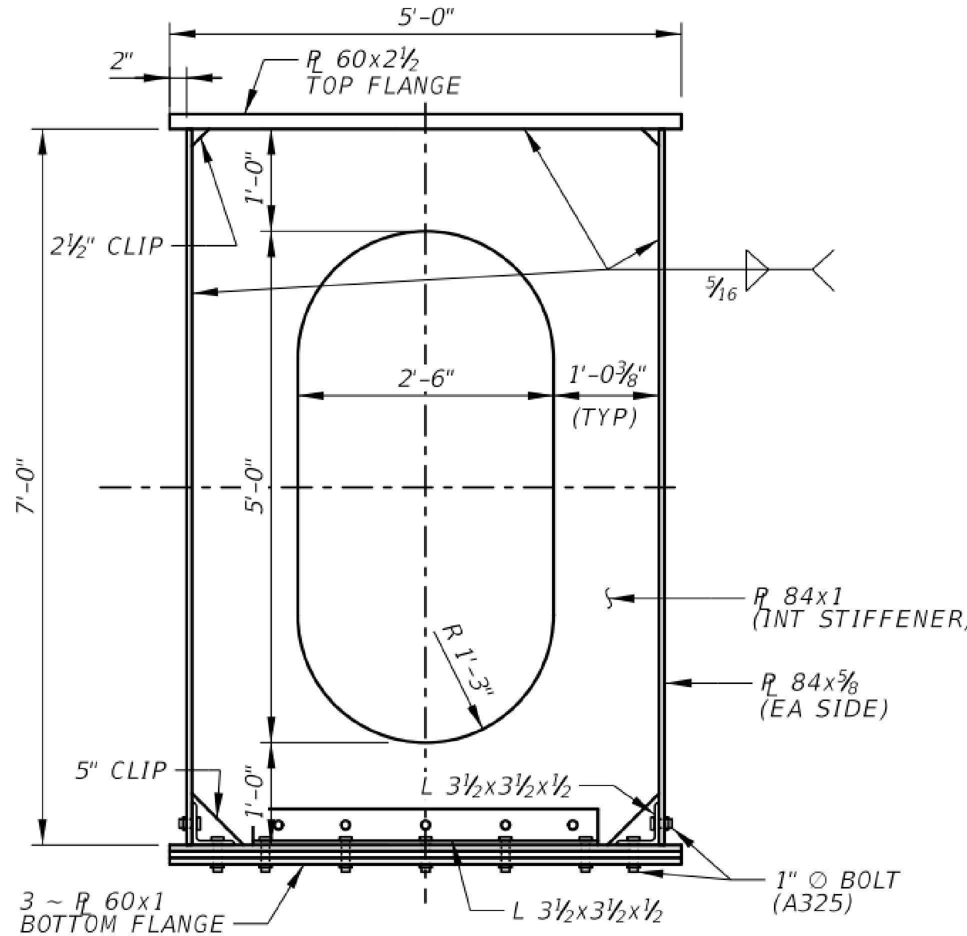
Strength check =	OK	OK or NG	GS 2.1 & 2.3
Fatigue case =	I(b)	I(a), I(b), II	GS 2.5
Stress range in unfaulted state, Δf_{UFS} =	2.42	ksi	
Controlling stress range in faulted state, Δf_{FS} =	4.72	ksi	
Controlling faulted state remaining fatigue life, Y_{REM}	45.1	Years	
Total remaining fatigue life, N_f	45.1	Years	GS Eq. 2.5.3-1
Maximum Interval for Special Inspections =	10.0	Years	GS 3



SUMMARY OF EVALUATION RESULTS

Section ID	Faulted Condition Strength Checks	IRM Special Inspection Interval
A-A	OK	
B-B	OK	

IS THERE A MORE EFFICIENT/ECONOMICAL DESIGN?



SECTION B-B

SCALE: ¼" = 1'-0"

Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs

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Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs

Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs
3	1.5	1.5	-	No	-	-

Misses gross section yield limit by 7%

Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs
3	1.5	1.5	-	No	-	-
4	1.0	2.0	-	Yes	Infinite Life	10 yrs

Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs
3	1.5	1.5	-	No	-	-
~~4~~	~~1.0~~	~~2.0~~		~~Yes~~	~~Infinite Life~~	~~10 yrs~~

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Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs
3	1.5	1.5	-	No	-	-
~~4~~	~~1.0~~	~~2.0~~		~~Yes~~	~~Infinite Life~~	~~10 yrs~~
5	1.25	1.75	-	Yes	39.7 yrs	10 yrs

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SPECIAL
INSPECTION

IRM INSPECTION ADVANTAGE (RISK-BASED):

Member Type	Reduced Intervals	Max Extended Interval (Method 1*)	Max Extended Interval (Method 2**)	Inspection Type
LPRM	12 months (risk based)	48 months	72 months	Unchanged: routine
NSTM	12 months (risk-based)	48 months	48 months	Unchanged: hands-on
SRM	12 months (risk based)	48 months	72 months	Routine
IRM	12 months (risk based)	48 months	120 months → (72 months) →	IRM Special Insp. (Routine inspection)

*Method 1: Interval determined by a "simplified" assessment of risk (criteria are defined in NBIS)
**Method 2: Interval determined by a "more rigorous" assessment of risk using a Risk Assessment Panel (RAP) and documented as a formal policy.


BAY CRANE
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Assumed Fractured

Trial	Plate 1 Thickness (in.)	Plate 2 Thickness (in.)	Plate 3 Thickness (in.)	Meets Strength Req.?	Remaining Fatigue Life in Faulted Condition	Special Inspection Interval
1	1.0	1.0	1.0	Yes	45.1 yrs	10 yrs
2	0.625	0.875	1.5	Yes	Infinite Life	10 yrs
3	1.5	1.5	-	No	-	-
4	1.0	2.0		Yes	Infinite Life	10 yrs
5	1.25	1.75	-	Yes	39.7 yrs	10 yrs
I-Beam	*34 x 1.5*	*34 x 2*	*34 x 2*	*Yes*	*Infinite Life*	*10 yrs*

IRM CONSIDERATIONS: COST & WEIGHT

COST APPROXIMATIONS: (Listed $ to $$$)

1. Fillet-welded box (fillets on outside of box only)
2. Built-up bolted I-girder (+1-2%)
3. Built-up bolted box girder (+15-18%)
4. CJP-welded box girder (+17-20%) –

   Don't use CJPs!

WEIGHT APPROXIMATIONS: (Listed # to ###)

1. Built-up bolted I-girder
2. Welded box girders (10-14% heavier)
3. Built-up bolted box girder (16-20% heavier)

These are "front" costs only…consider life cycle costs (in-service inspection!)

Consider POD of inspections…

Consider safety related to arms-length inspection requirements…

SAFETY

❖ Bridge inspection is directly motivated by pursuit for safety

❖ 2015 Purdue study for INDOT found:

- Congested crash rate increased **24x** on Indiana interstates with queue ≥ 5 min
- And safety of the inspection crews?

❖ Intend to find damage *before* it's an issue:

- What about Probability of Detection (POD)?
- Are we able to find what we think we can find?

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FINAL THOUGHTS & WRAP-UP

REDUNDANCY & INSPECTION:

- Goes without saying that IRMs are more redundant than welded boxes
- Faulted state strength capacity calculations are very conservative (on-going research)
- Special inspection intervals are very conservative
  - 95% confidence interval, SF = 2, fracture propagation unlikely
- IRMs are robust against over height vehicle impacts
- POD of severed plate is very high – changes the inspection reliability without compromising safety

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THANK YOU

NUCOR CORPORATION

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