Experimental Evaluation of Guard Rail Systems for Bridges

For
Ministry of Forests and Range,
Engineering Branch,
Field Operations Division
(MoFR)

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Why experimental studies?

- To establish a baseline on “tried and true” systems of current guard rails
- To recommend improvements to current design
- To evaluate and develop new systems based on the results

Which systems were tested?

I. Timber guard rails and risers on timber cross ties

II. Timber guard rails and risers on timber brackets horizontally bolted to concrete deck panels

III. All steel retro-fit system with short posts and connection to deck edge

IV. All steel retro-fit system with long posts and connection to deck top

Static or Dynamic Testing?

- For the CTR research for T203 and T501 with mechanical anchors, the results from pendulum test and static test are as

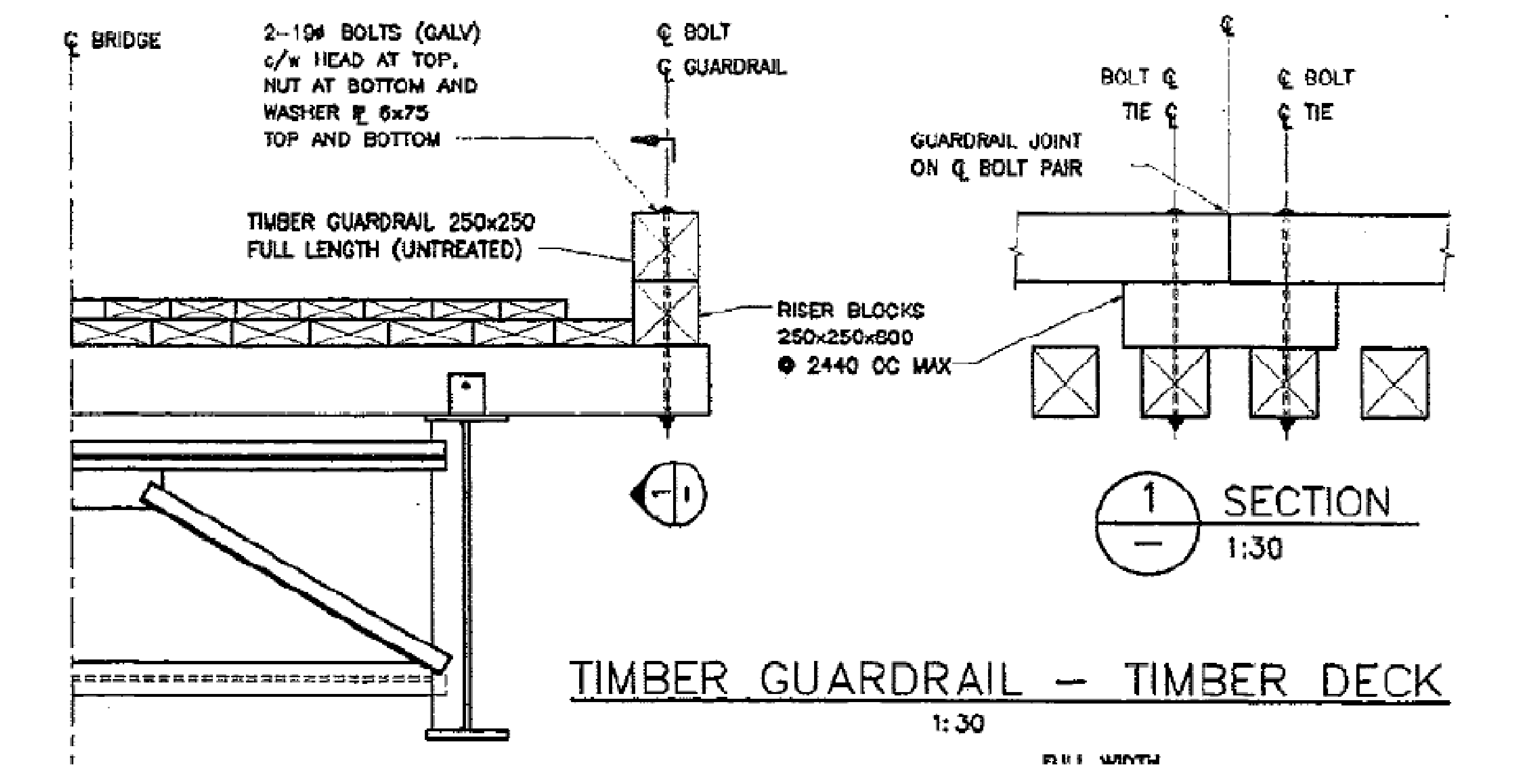
	Dynamic Capacity	Static Capacity
T203	271 kN	267 kN
T501	287 kN	258 kN

- Conclusion: **Dynamic effects** such as strain rates **do not play a role** in the relatively slow loading guardrails.
- **Static tests were performed** for improved accuracy and economy.

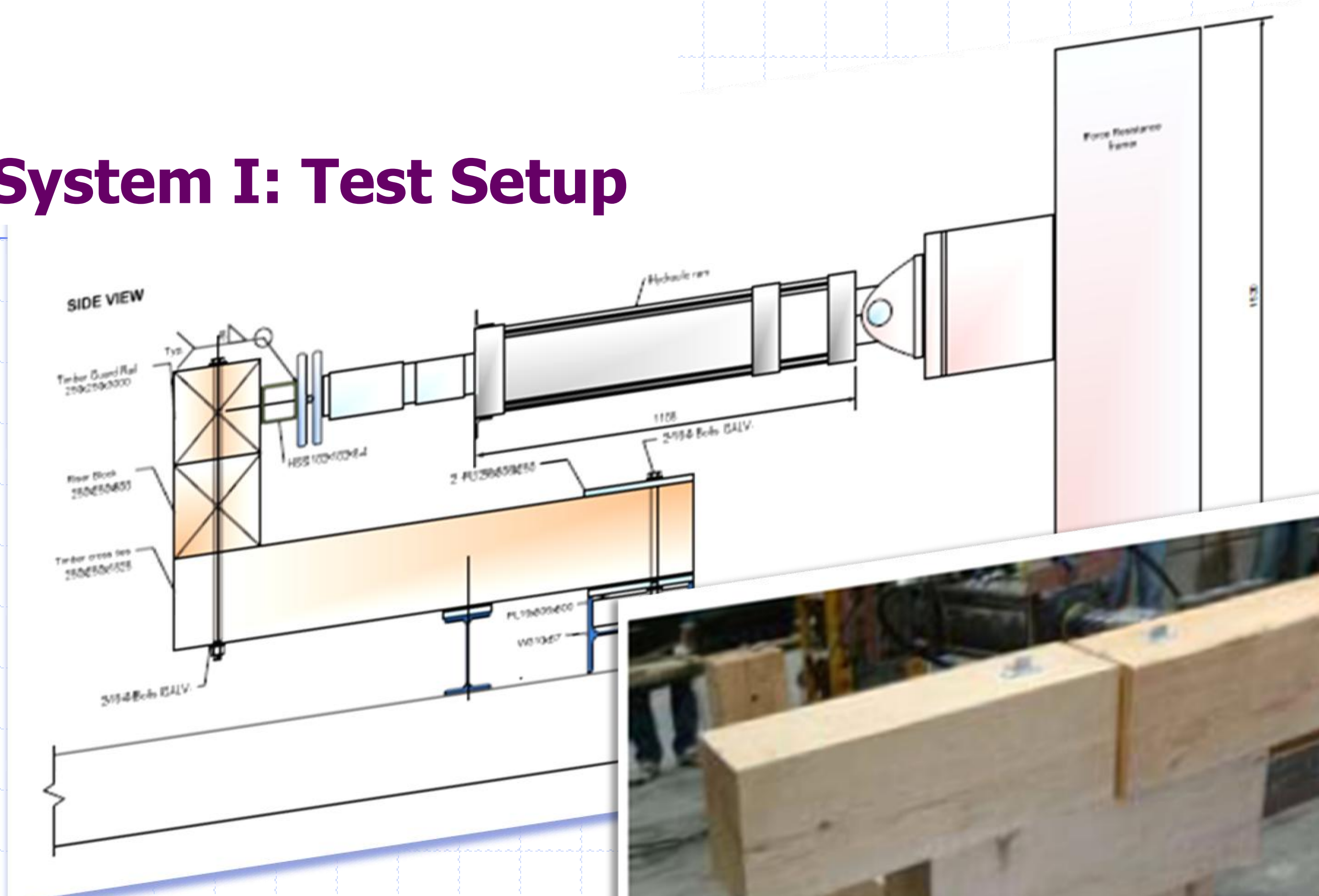
Experimental Testing

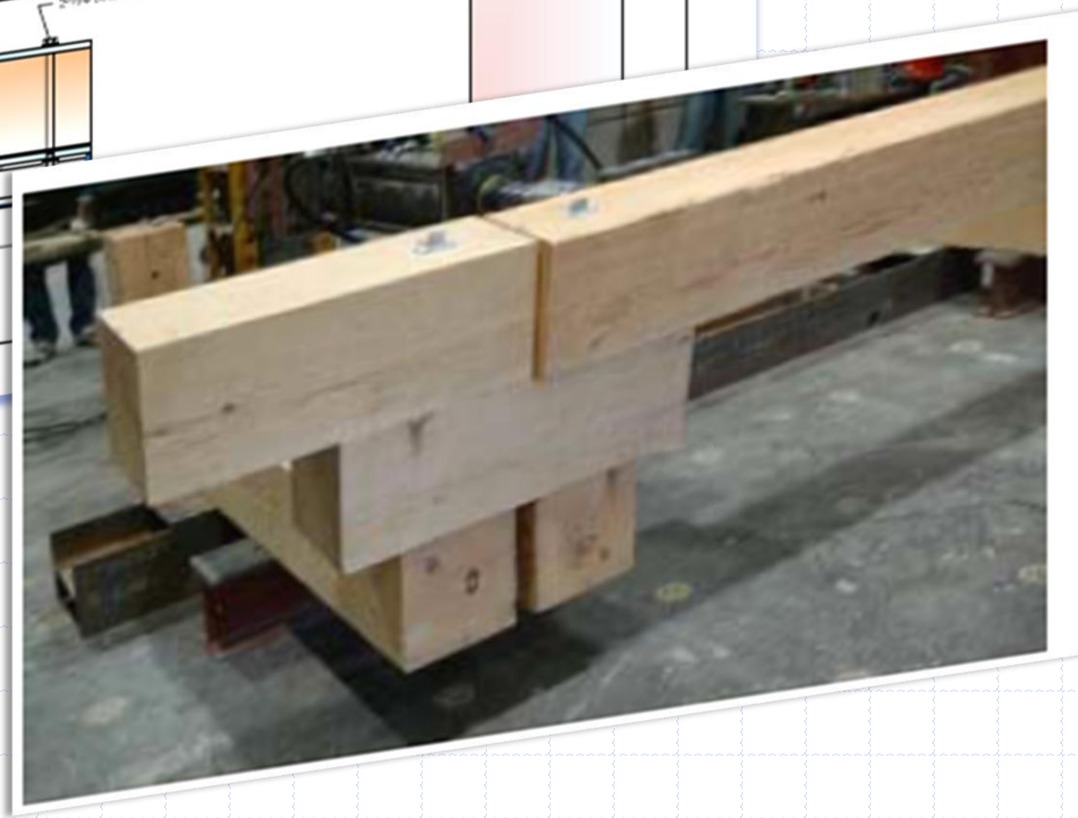
All testing was planned and performed with prior discussion and approval by MoFR of both method and detailing.

System I: Timber guard rail and risers on timber cross ties



System I: Test Setup





System I: Failure Mode

Pull-in of timber washers at the end of the cross ties.

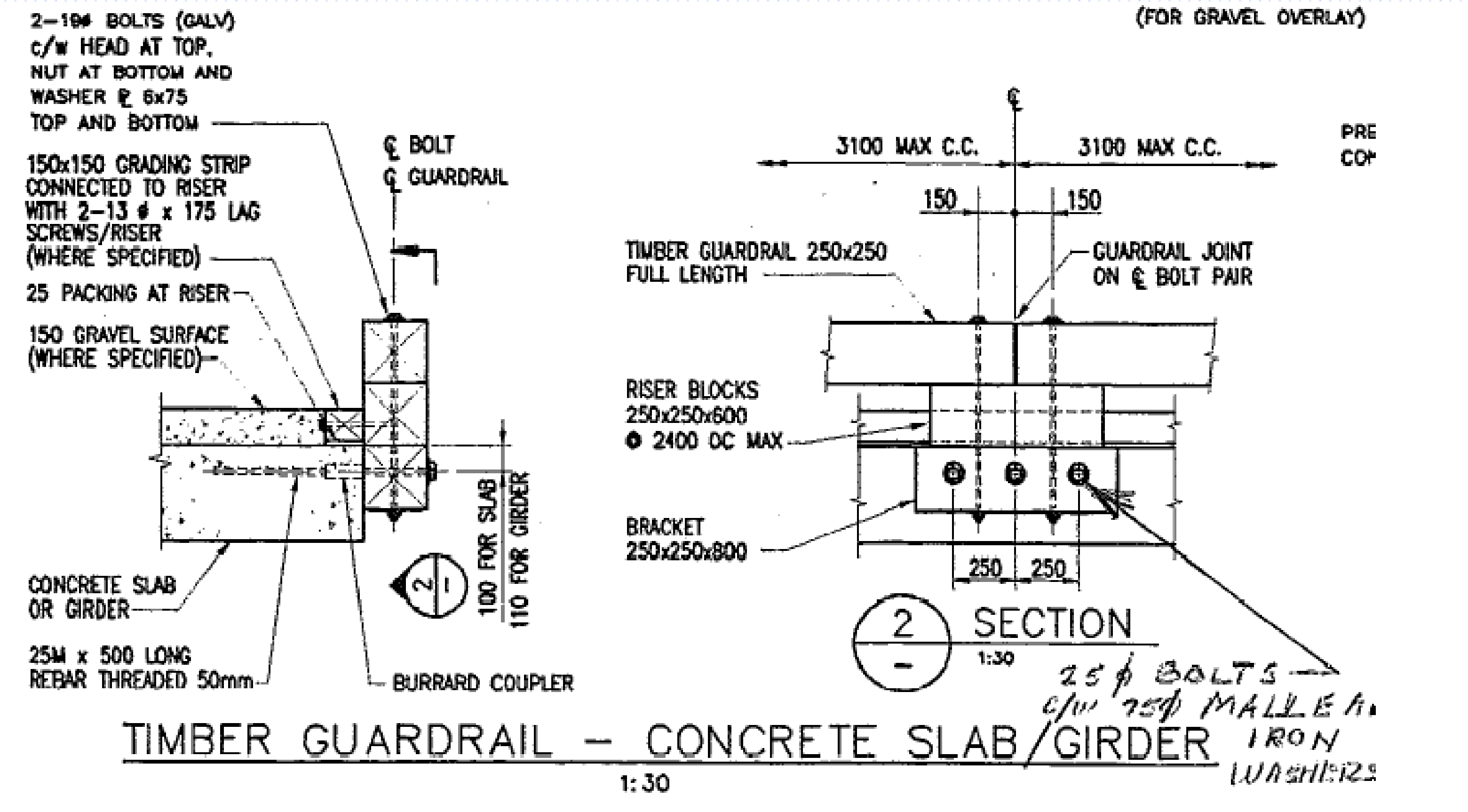
Fir

Hemlock

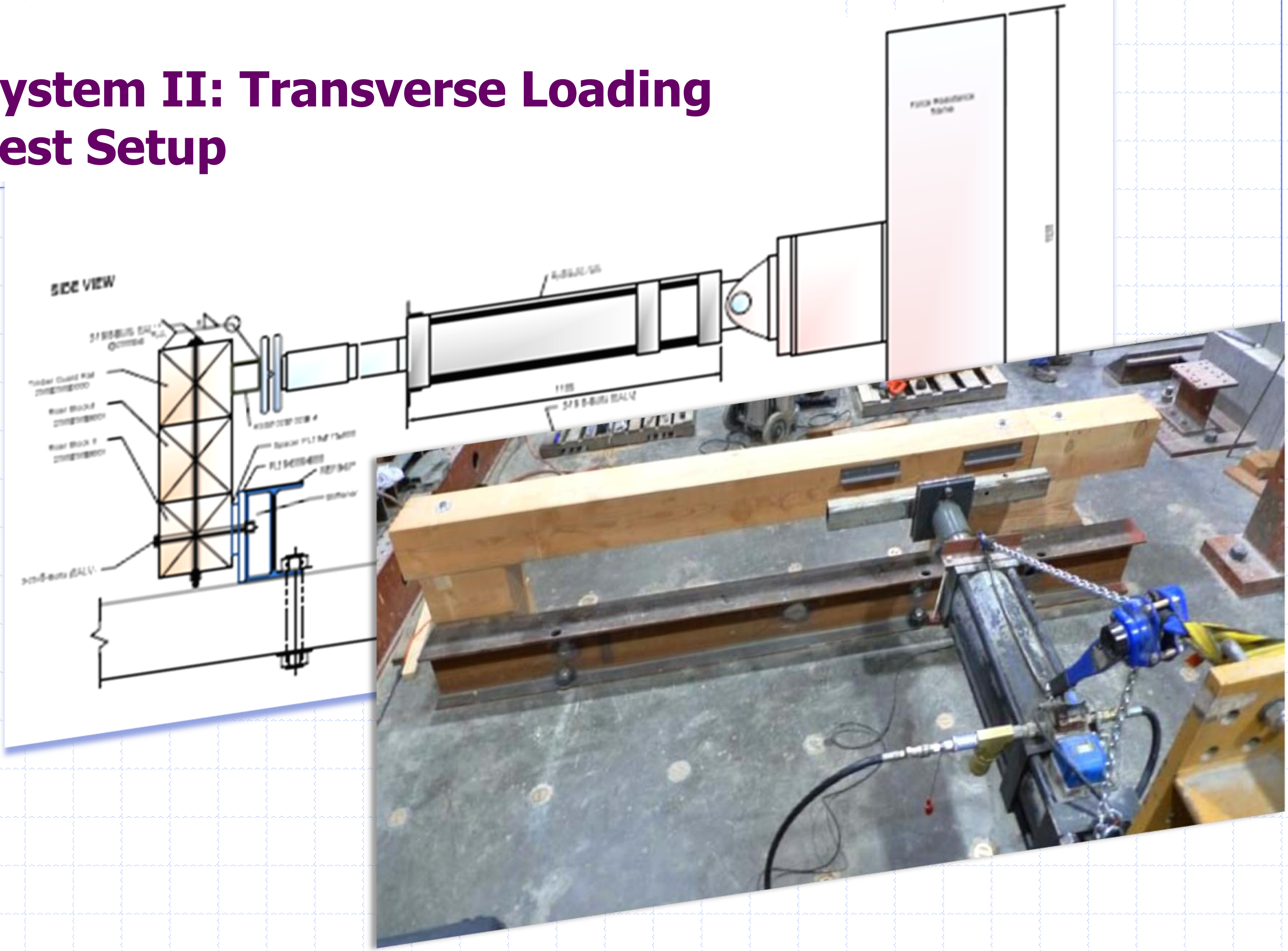
System I: Failure Mode

Cracks on end face of 8x10" cross beams and
pulled-in timber washers on the underside of cross beams

System II: Timber rails and timber risers on a timber bracket



System II: Transverse Loading Test Setup



System II: Transverse Loading Test Setup

System II: Failure Mode

Splitting of base timber bracket

Pull-trough of vertical bolt heads and timber washers

System II: Vertical Loading Test Setup

System II: Failure Mode

Failure by breaking at centre of rail and damaging ends

Damaged support on end side

System II: Alternate Failure Mode

Crushing of timber bracket

System II: Concrete Spalling in the Field

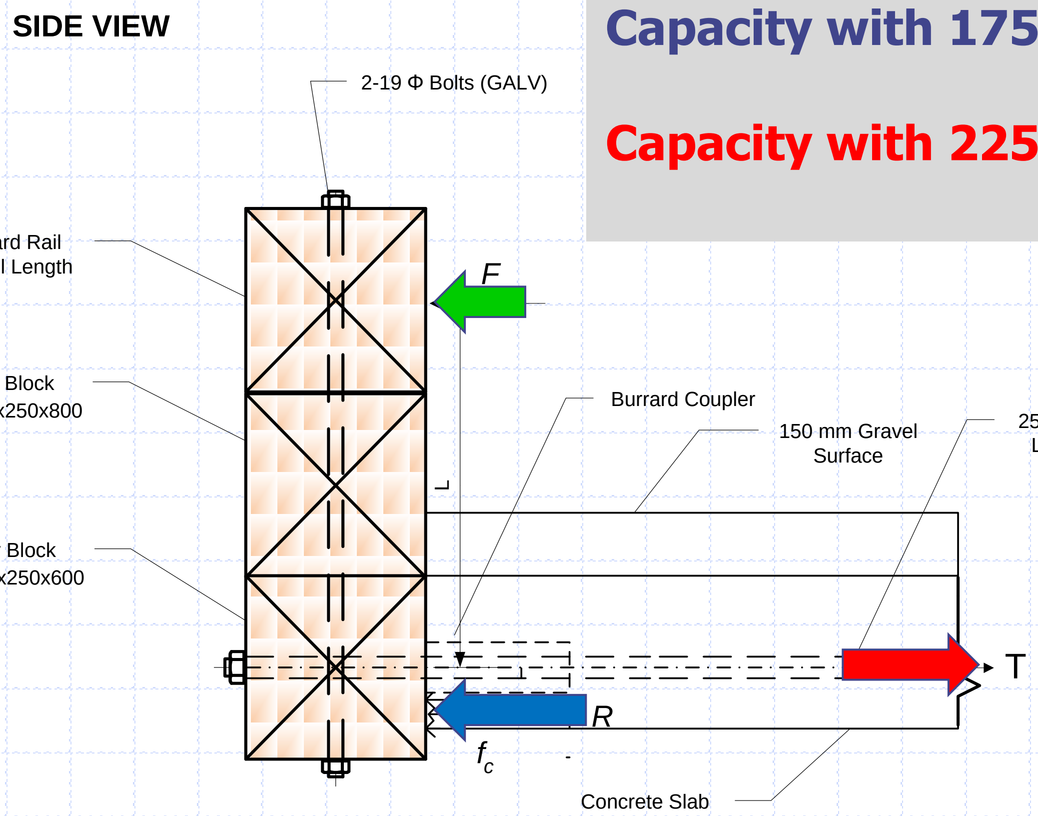
Causes

- Transverse Load = Compression force from the timber bracket
- Vertical Load = shift the bottom mat of rebar to cause spalling of the concrete
- Incorrectly sized concrete deck

Concrete Capacity Transversely Loaded

Capacity with 175 mm Slab = 33 kN

Capacity with 225 mm Slab = 179 kN



Vertical Load Punching Capacity vs Demand

Demand: ½ of axle weight of loaded logging truck = 100 - 120 kN

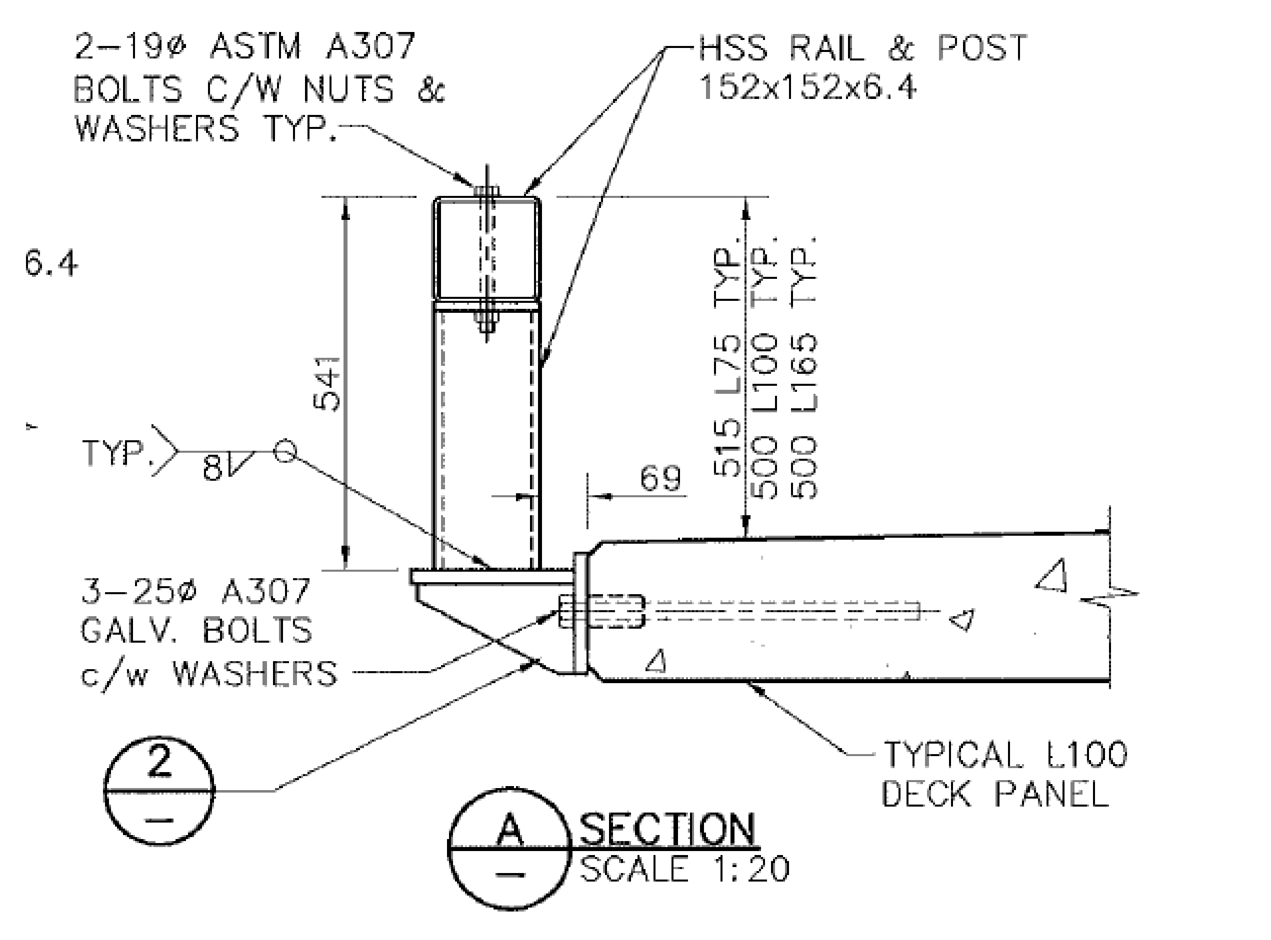
Capacity: 181 kN (f’c = 30 Mpa) , 165 kN (f’c = 25 Mpa)

Conclusions from System II

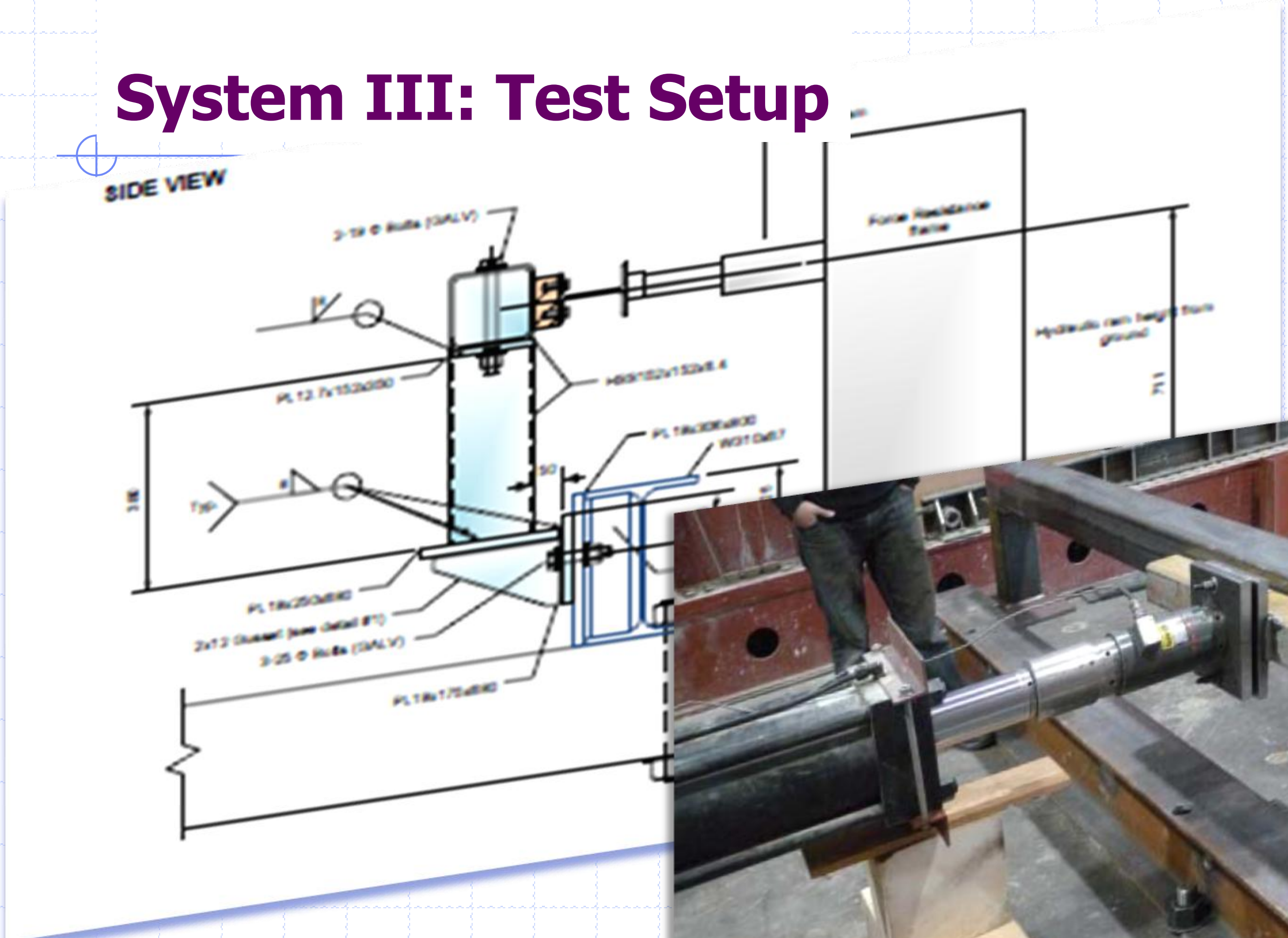
- Concrete spalling is due to the transverse load (not the vertical load)

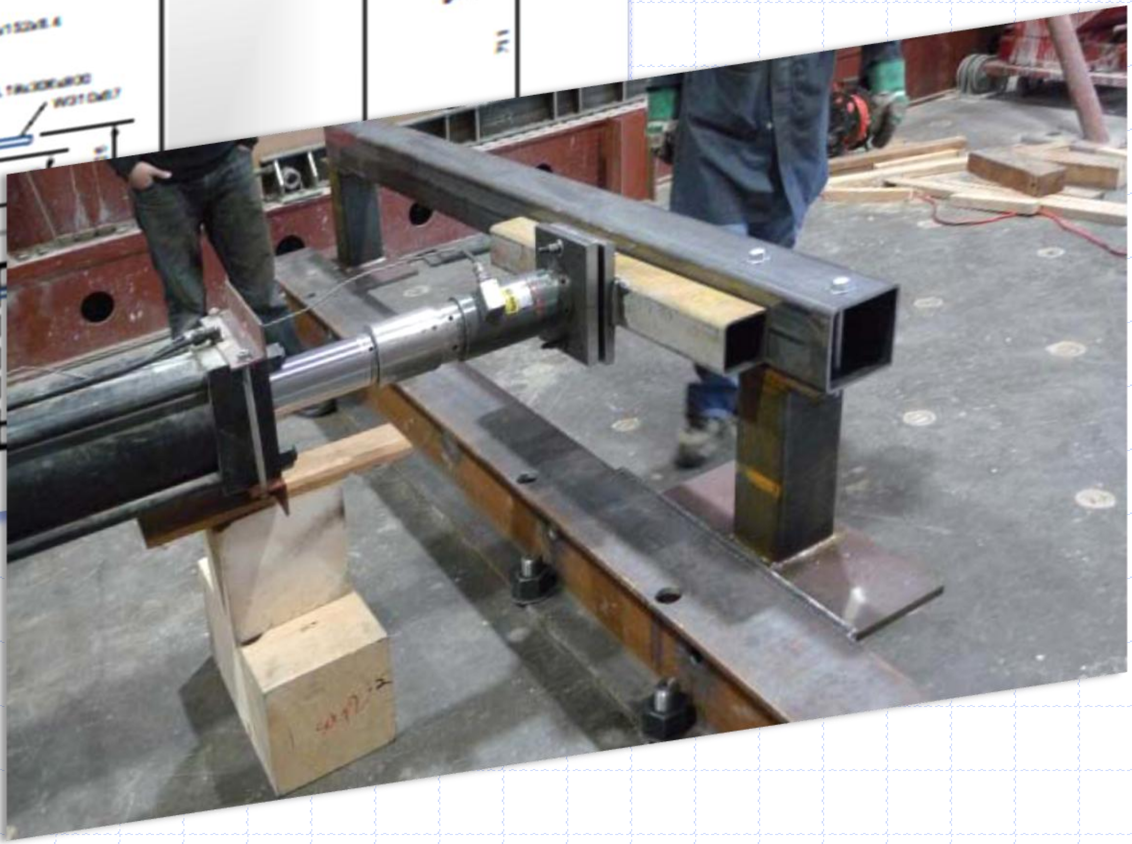
- Increasing concrete slab thickness by 50 mm (from 175 mm to 225 mm) will increase its crushing capacity under transverse load by about 5 times.

System III: All steel retro-fit with short posts and connection to deck edge.



System III: Test Setup





System III: Failure Mode

Failure by stripping and rupturing the horizontal anchor bolts

Gap opening between base and guard rail post

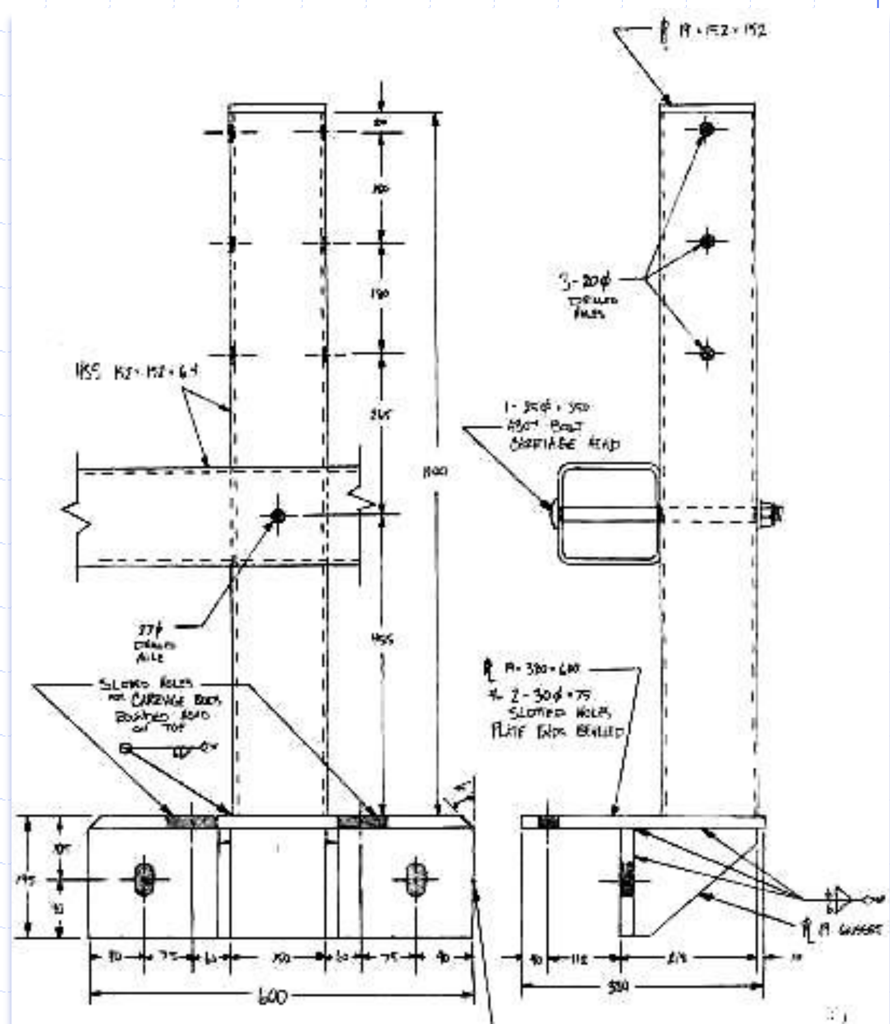
Stripped bolts after failure

System III: Failure Modes

Bolt Tension (45 degree shear) failure (rupture)

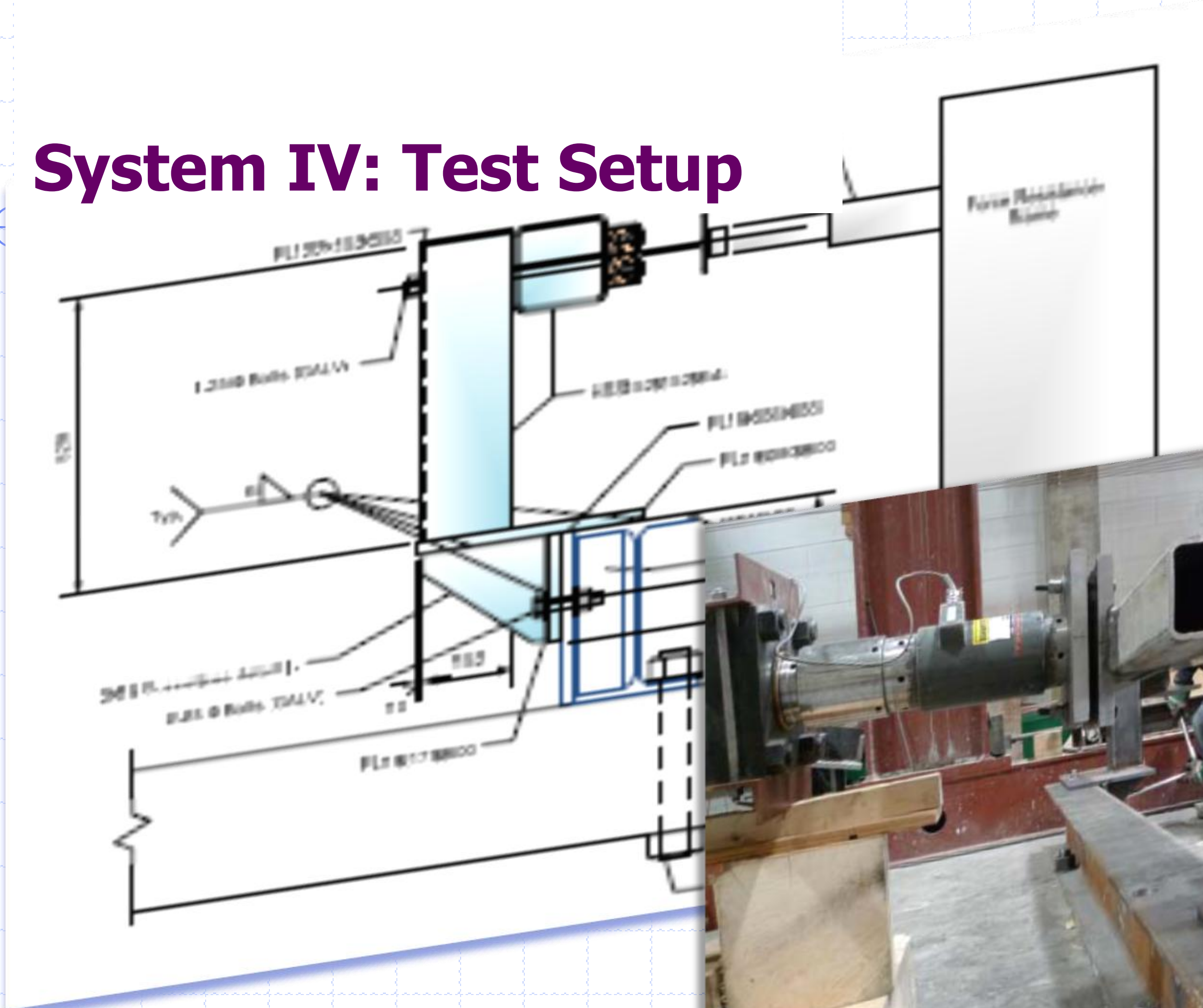
Stripped threads

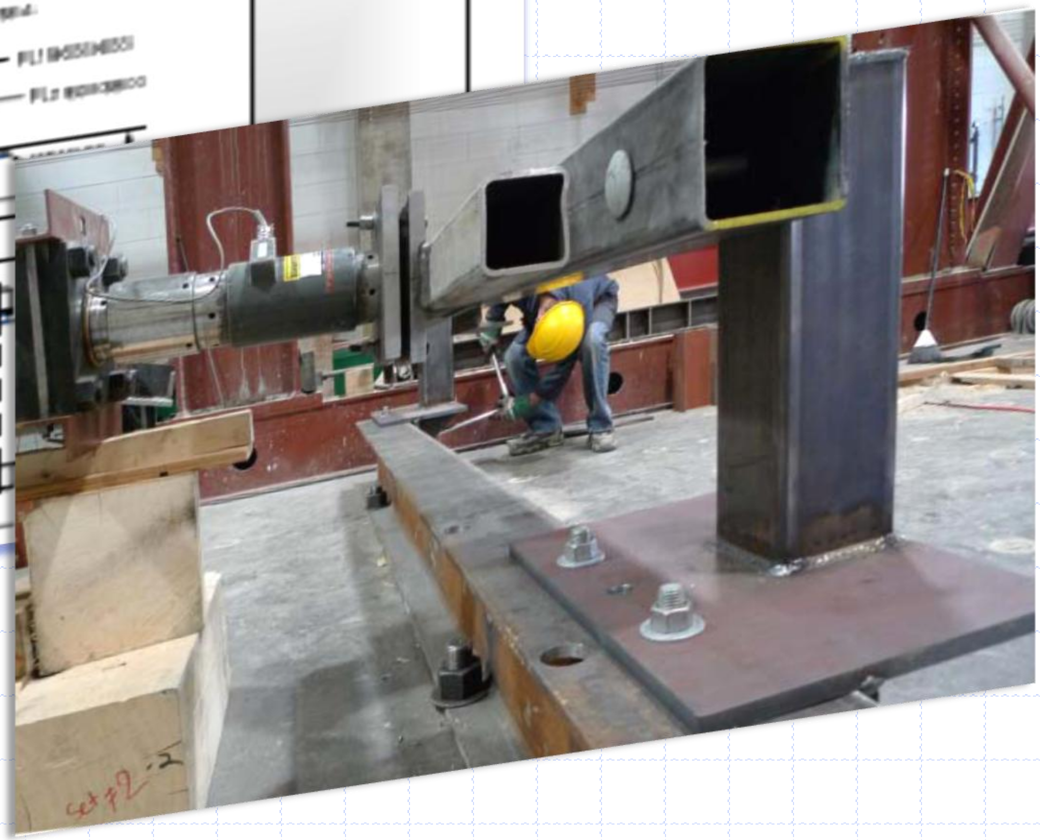
System IV: All steel retro-fit with long posts and connection to deck top.



Guard Rail System for Bridges

System IV: Test Setup





System IV: Failure Mode

Tension and shear failure of vertical bolts

Tension failure (shear under 45^{o})

Experimental Test Results

Data Summary

date	series / name	max. capacity in [kN]	comments
16.03.2010	System I_pre f	44.091	
19.03.2010	System I_2 f	44.091	
23.03.2010	System I_3 f	50.525	
24.03.2010	System I_4 f	44.091	
29.03.2010	System I_1 h	38.225	
30.03.2010	System I_2 h	39.551	
01.04.2010	System I_3 h	37.847	
11.03.2010	System II_1 f	38.414	
12.03.2010	System II_2 f	38.036	
12.03.2010	System II_3 f	37.468	
08.04.2010	System II_1 h vert	111.08	
09.04.2010	System II_2 h vert	96.509	
12.04.2010	System II_3 h vert	118.271	
14.04.2010	System III_1	108	
14.04.2010	System III_2	128.3	
15.04.2010	System IV_1	177.5	2 bolts fail simultaneously
15.04.2010	System IV_2	168.796	2 bolts fail simultaneously
16.04.2010	System IV_3	222.16	3 bolts fail simultaneously
20.04.2010	System IV_4	166.715	2 bolts fail simultaneously, then third bolt

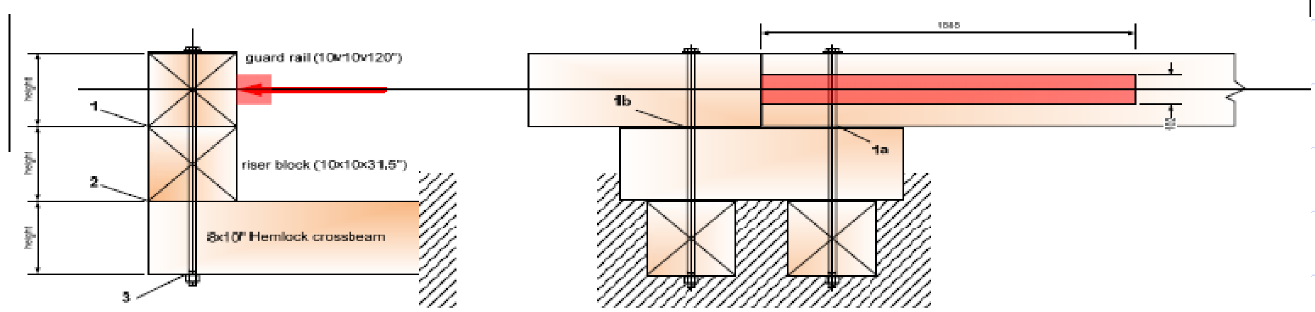
Introduction to "Formatted" Spreadsheets

- A "formatted" spreadsheet applies macros in Microsoft Excel to perform the required calculations.
- Therefore, the user should have enabled macros option in Excel for the spreadsheet to perform properly.

Formatted Spreadsheet

- A “formatted” spreadsheet starts with a diagram or an image

DESCRIPTION



INPUT

Bolt Dimension and Properties				
Bolt length	L	=	750	mm
Bolt diameter	d_b	=	20	mm

Formatted Spreadsheet

- The next section is reserved for user input.
- Only this section allows user interaction.

24	*INPUT*			
25	performance factor	phiw	0.67	
26	load factor	lf	1.4	
27	weld size (leg)	ws	10	mm
28	lug thickness	tlug	25	mm
29	lug length	llength	300	mm
30	wall thickness	twall	32	mm
31	applied force	Vf	212	kN
32	ultimate plate strength	Fu	0.45	kN/mm2
33	ultimate electrode strength	Xu	0.48	kN/mm2
34	angle of axis force/weld line	theta	45	degree

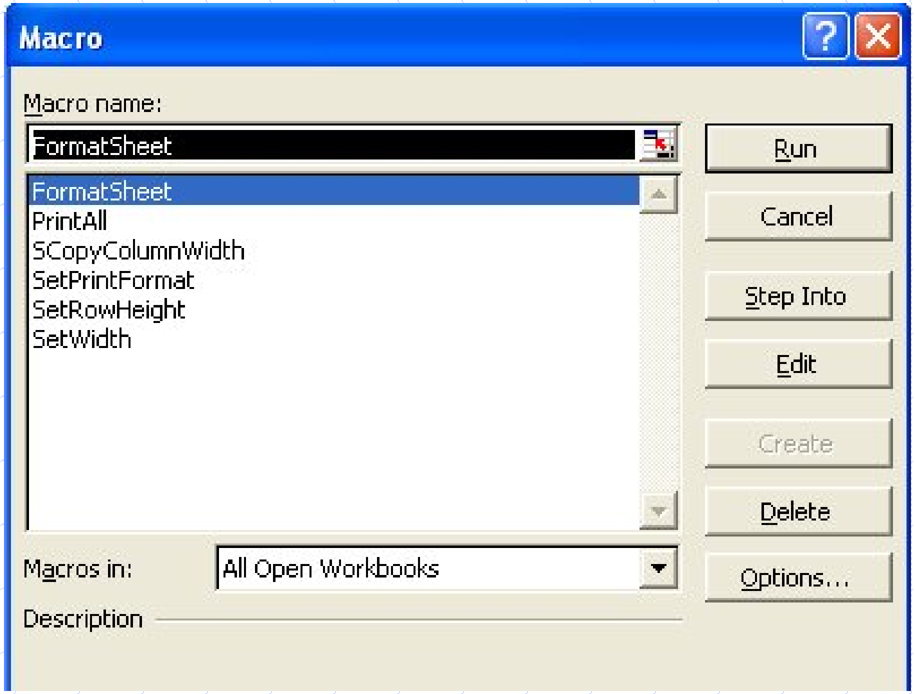
Formatted Spreadsheet

- The last section is the calculation section. The user does not require to enter any inputs here. Column E represents the equations used.

36	*CALCULATIONS*				
37	min. plate thickness	t	MIN(tlug,twall)	mm	
38	cross section plate	Am	t*wlength	mm2	
39	weld length	wlength	llength*2	mm	
40	cross section weld	Aw	ws*wlength	mm2	
41	shear resistance base metal	Vrfb	0.67*phiw*Am*Fu	kN	§13.13.2.2
42	shear resistance weld	Vrfw	0.67*phiw*Aw*Xu*(1+.5*SIN(RADIANS(30))^1.5)	kN	§13.13.2.2
43	resulting shear resistance	Vrf	MIN(Vrfb,Vrfw)	kN	§13.13.2.2
44					
45	design efficiency (<1 = o.k.)	de	Vrf/(Vf*lf)		

Formatted Spreadsheet

- To update equations, the user must press ***Alt/F8***, to in order to invoke the macro "*FormatSheet.*



Formatted Spreadsheet

- If the user wants to change something in the input, as long as it is the numerical value in column G is changed, the entire spreadsheet will immediately change the results.
- Therefore, it is not required to press ***Alt/F8*** after modifying any value in the input section.

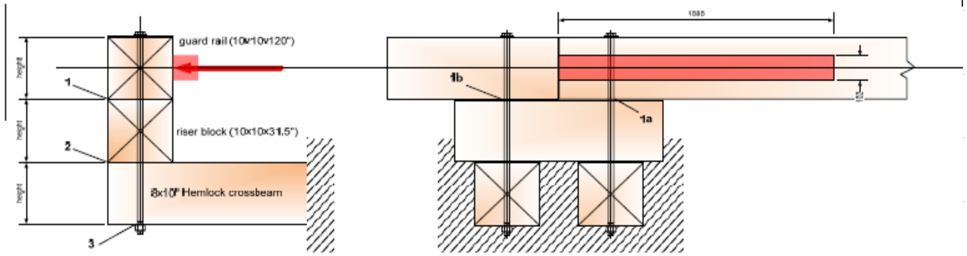
Spreadsheets that compute ultimate capacities:

- Employ solid mechanics / strength of materials approach
- Use median/common material characteristics (not Code values)
- Analyze every possible failure mode in order to identify the weakest mode as ultimate capacity of the system

- No performance factors were applied because the prediction of test results was desired.

Example appearance of "formatted" spreadsheet

DESCRIPTION



Display diagram for the performance level in question and barrier design parameters definitions

INPUT

Bolt Dimension and Properties

Bolt length	L	=	750	mm
Bolt diameter	d_b	=	20	mm
Compression strength (Hemlock)	f_c	=	4.60	Mpa
Shear strength (Hemlock)	f_v	=	0.70	Mpa
Bending strength (Hemlock)	f_b	=	10.20	Mpa
distance load cylinder from bolt 1a	d1a	=	325	mm
distance bolt1a from other end bolt	l1a	=	2600	mm

User input

CALCULATIONS

TRANSVERSE LOAD

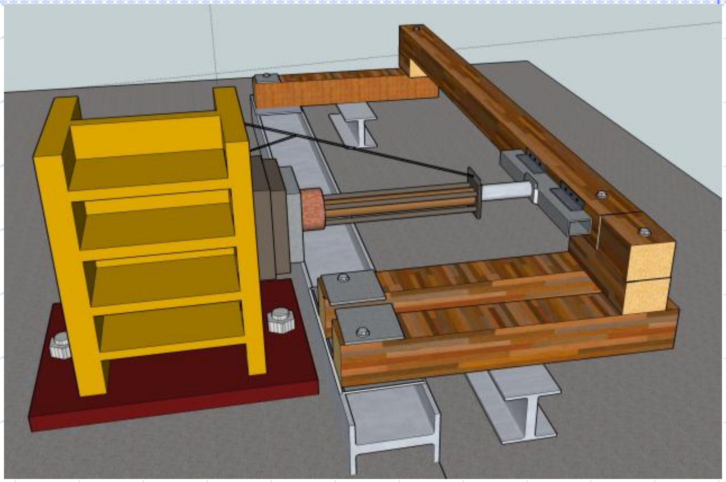
Failure at location 1

Bending of Vertical Bolt

Bolt sectional modulus	Z	=	(d_b^3)/6	=	1333	mm^3
Bolt moment resistance	M1_rb	=	(Z*F_y)/1000	=	**400**	Nm
Crushing of Timber Block (triangular pressure block on timber = prestressed)						
compressed area	A1c	=	b*(r_l)/2	=	100000	mm^2
compression stress resultant	R1_c	=	A1c*f_c/2/1000	=	230	kN
lever arm bolt to resultant	l1_t	=	(b/2)*(2/3)	=	83	mm

Calculation for failure load for each mode of failure

Spreadsheet Capability Overview



- Computation of ultimate failure load based on solid mechanics/strength of material approach
- Computation of performance level required based on CHBDC
- Computation of the new ultimate failure load of the improved systems

Experimental Results vs. Predicted Results

System	Test Results (average)	Predicted Results
System I_f	45.7 kN	36.7 kN
System I_h	38.5 kN	29.7 kN
System II_transverse_f	38 kN	45 kN
System II_vertical_h	108.6 kN	71 kN
System III	118.1 kN	101 kN
System IV	173.1 kN	141 kN

About Performance Levels

- Strength requirements for barrier depends on the condition of the highway and are classified into 3 different Performance Level (PL)

- Performance Level is dependent on:
  - Barrier Exposure Index (Be)
  - Percentage of Trucks on Road
  - Design Speed
  - Barrier Clearance

About the Exposure Index (Be)

$$Be = (AADT1)\ Kh\ Kc\ Kg\ Ks\ /\ 1000$$

where:

- AADT1 = Average Annual Daily Traffic for the first year after construction
- Kh = Highway Type Factors (Table 12.1 CHBDC)
- Kc = Highway Curvature Factors (Table 12.2 CHBDC)
- Kg = Highway Grade Factors (Table 12.3 CHBDC)
- Ks = Superstructure Height Factors (Table 12.4 CHBDC)

Tables to determine performance level

Table 12.5
Optimum performance levels — Barrier clearance less than or equal to 2.25 m
(See Clause 12.4.3.2.4.)

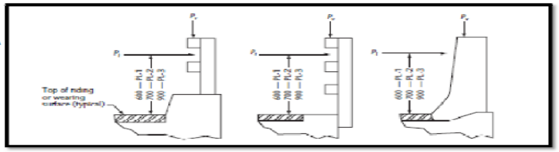
Design speed, km/h	Trucks, %	Barrier exposure index PL-1	PL-2	PL-3
50	0	< 224.8	≥ 224.8	—
	5	< 75.2	≥ 75.2	—
	10	< 32.0	32.0–222.5	> 222.5
	15	< 20.5	20.5–126.3	> 126.3
	20	< 15.1	15.1–88.3	> 88.3
	25	< 12.0	12.0–67.7	> 67.7
	40	< 7.4	7.4–40.0	> 40.0
60	0	< 53.2	≥ 53.2	—
	5	< 27.4	≥ 27.4	—
	10	< 16.5	16.5–111.3	> 111.3
	15	< 12.0	12.0–63.8	> 63.8
	20	< 9.6	9.6–44.8	> 44.8
	25	< 7.8	7.8–34.4	> 34.4
	40	< 5.2	5.2–20.4	> 20.4

Performance level spreadsheet based on CHBDC

PROJECT	**Guard Rail**	SECTION	
TITLE	Performance Level calculation	DATE	06/14/10
FILE	Example	TIME	10:12:21 PM

DESCRIPTION

Performance Level applied load (Pt) height according to the CAN/CSA S6-06.



INPUT

Barrier clearance	Bc	=	2	
Average annual daily traffic	AADT	=	500.0	vehicles
Highway type	Htyp	=	2wayu	***choose from drop-down list
Design speed	Sd	=	80.0	km/h
Radius of curve	Rc	=	410.0	m
Position barrier vs curve	Pos	=	out	***choose from drop-down list
Grade	Gr	=	0	%
Superstructure height	Hs	=	5	m
Occupancy beneath bridge	Occ	=	Low	***choose from drop-down list
Percentage of trucks	Tr	=	40	%

CALCULATIONS

Highway type factor	Kh	=	IF(Htyp="1way",2,IF(OR(Htyp="2way",Htyp="2wayu"),1,IF(Htyp="2wayu4",lookup(Sd,Smartsheet!I:I,Smartsheet!J:J),error)))	=	1.00
Highway curvature factor	Kc	=	if(Pos="in",lookup(Rc,Smartsheet!A:A,Smartsheet!C:C),lookup(Rc,Smartsheet!A:A,Smartsheet!B:B))	=	2.30
Highway grade factor	Kg	=	if(Gr>-2,1,if(Gr<-6,2,lookup(Gr,Smartsheet!R:R,Smartsheet!S:S)))	=	1.00
Superstructure height factor	Ks	=	if(Occ="High",lookup(Hs,Smartsheet!W:W,Smartsheet!X:X),lookup(Hs,Smartsheet!W:W,Smartsheet!Y:Y))	=	0.70
Barrier exposure index	Be	=	AADT*Kh*Kc*Kg*Ks/1000	=	0.81

Performance level evaluation

Table 12.5

Refer to the following tab by using appropriate road characteristics:

Tr =	**40.0**	%
Sd =	**80.0**	km/h
Be =	**0.81**	

Assigning Minimum barrier height

Type of barrier	H, m
Traffic	
PL-1	0.68
PL-2	0.80
PL-3	1.05†
Combination (pedestrian)	1.05
Combination (bicycle)	1.37
Pedestrian	1.05
Bicycle	1.37

Display diagram for the performance level in question and barrier design parameters definitions

User input for bridge/road condition

Calculation for performance level

Performance level required

- Barrier exposure index (Be) = 3.2
- Percentage of truck = 40%
- Design Speed = 60 km/h

Required performance level is 1

Strength required by CHBDC?

CHBDC Performance Level 1 Requirements for barriers:

	Forces	Height of Load Application	Spread of Load
a) Transverse Load	**50 kN**	**600 mm from base**	**1200 mm**
b) Vertical Load	**10 kN**	**top of barrier**	**5500 mm**
c) Longitudinal Load	**20 kN**	**600 mm from base**	**1200 mm**

Performance level satisfied?

	Performance Level 1 (averaged values)					
	Experimental results			Testing equivalent code values		
	Resisting load [kN]	Load app. length [m]	Dist. load [kN/m]	Load [kN]	Load app. length [m]	Dist. load [kN/m]
SYSTEM #1	42.63	1.05	38.75	60	1.2	50.0
SYSTEM #2	37.97	1.05	34.52	60	1.2	50.0
SYSTEM #3	118.15	1.05	107.41	60	1.2	50.0
SYSTEM #4	173.15	1.05	157.41	60	1.2	50.0

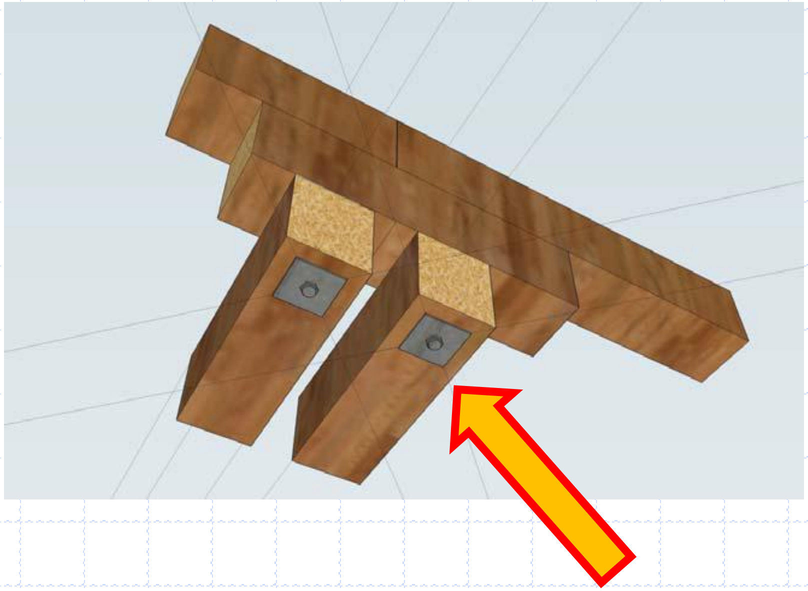
How to improve performance by design modifications? (1/2)

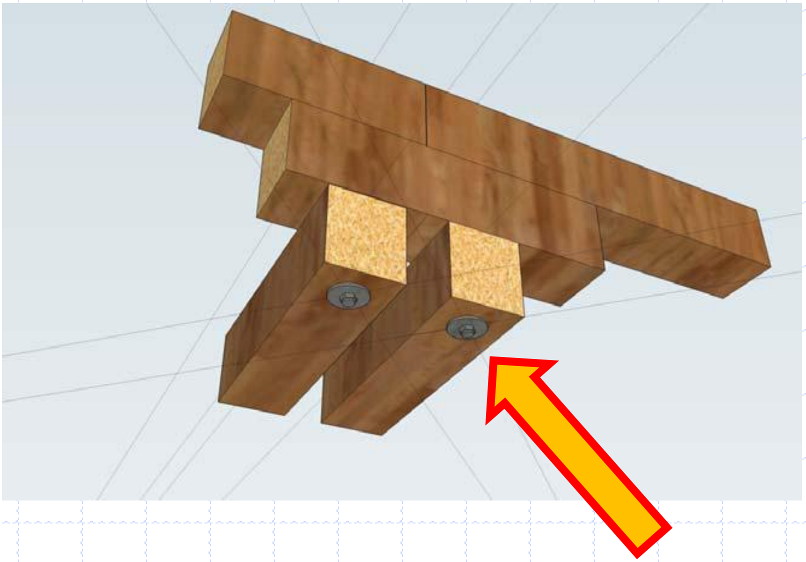
- Timber washers could be larger, at best of a size 10x10" in order to cover the complete cross beam or guard rail.
- Timber washers could be replaced by perforated plates or segments of structural channels.
- Vertical bolts could be located eccentrically to provide a larger compression area between the interconnection blocks in order to increase compression.

How to improve performance by design modifications? (2/2)

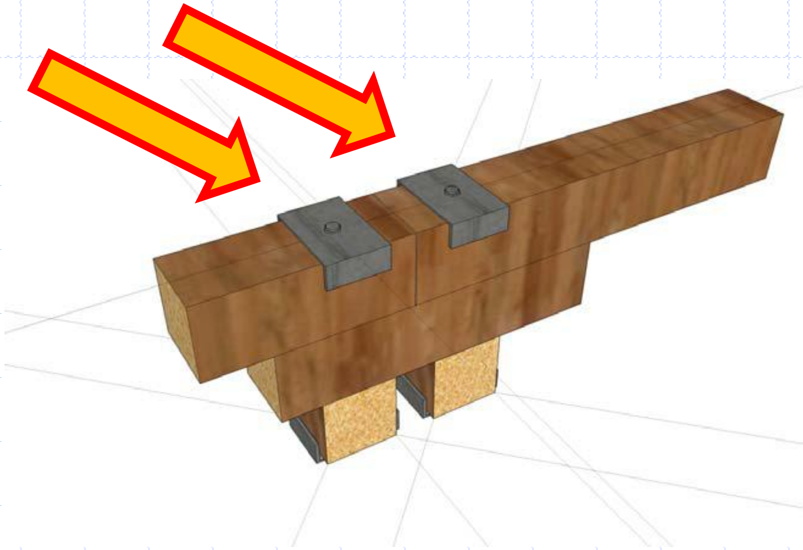
- Strategically located straps on riser blocks can prevent premature splitting by bolt prying action.
- Concrete deck thickness should be increased to a level to match guard rail capacity. In the current version for timber rail system, an increase from 175 mm to 225 mm (the latter quasi standard in Canada) would achieve this.

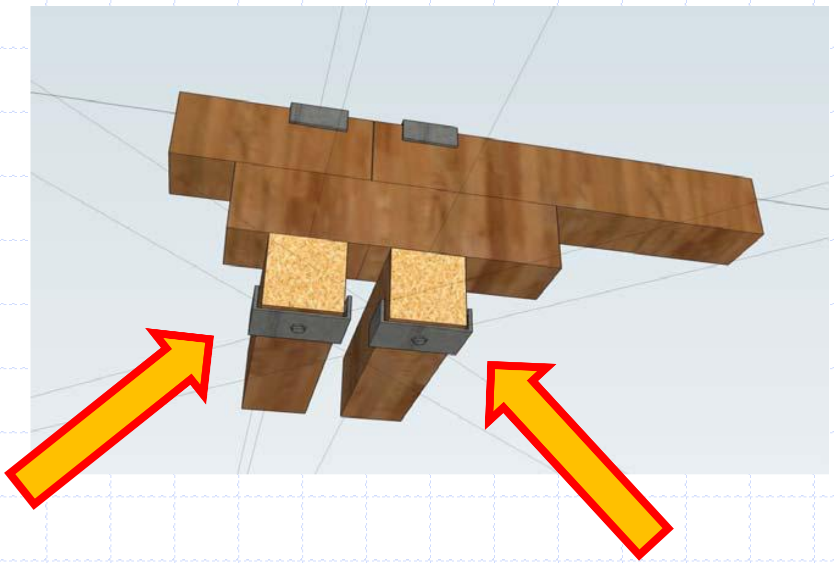
Larger washers to prevent pull-through (circular or square shaped)



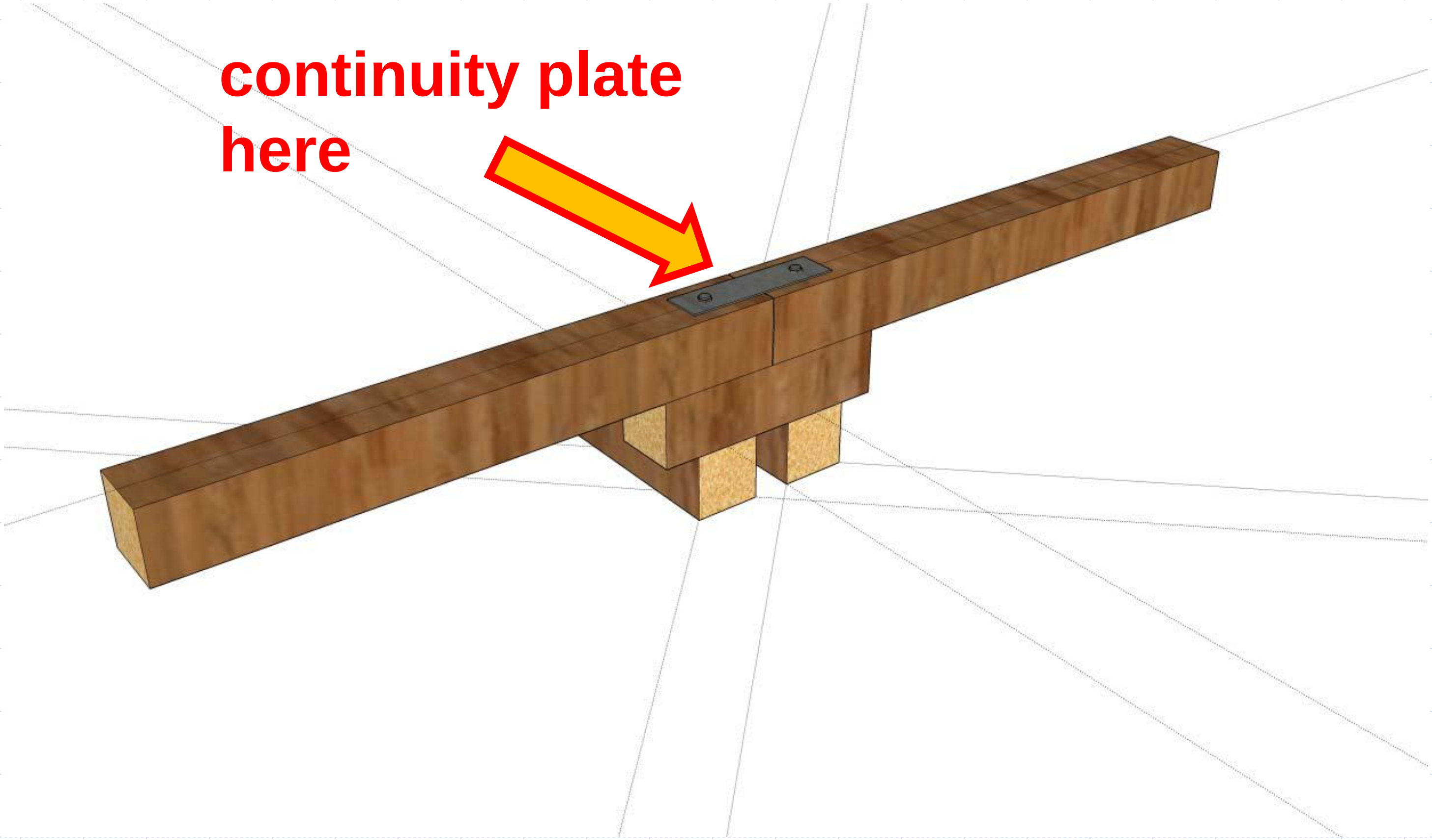


Larger washer cut from structural channel to contain splitting

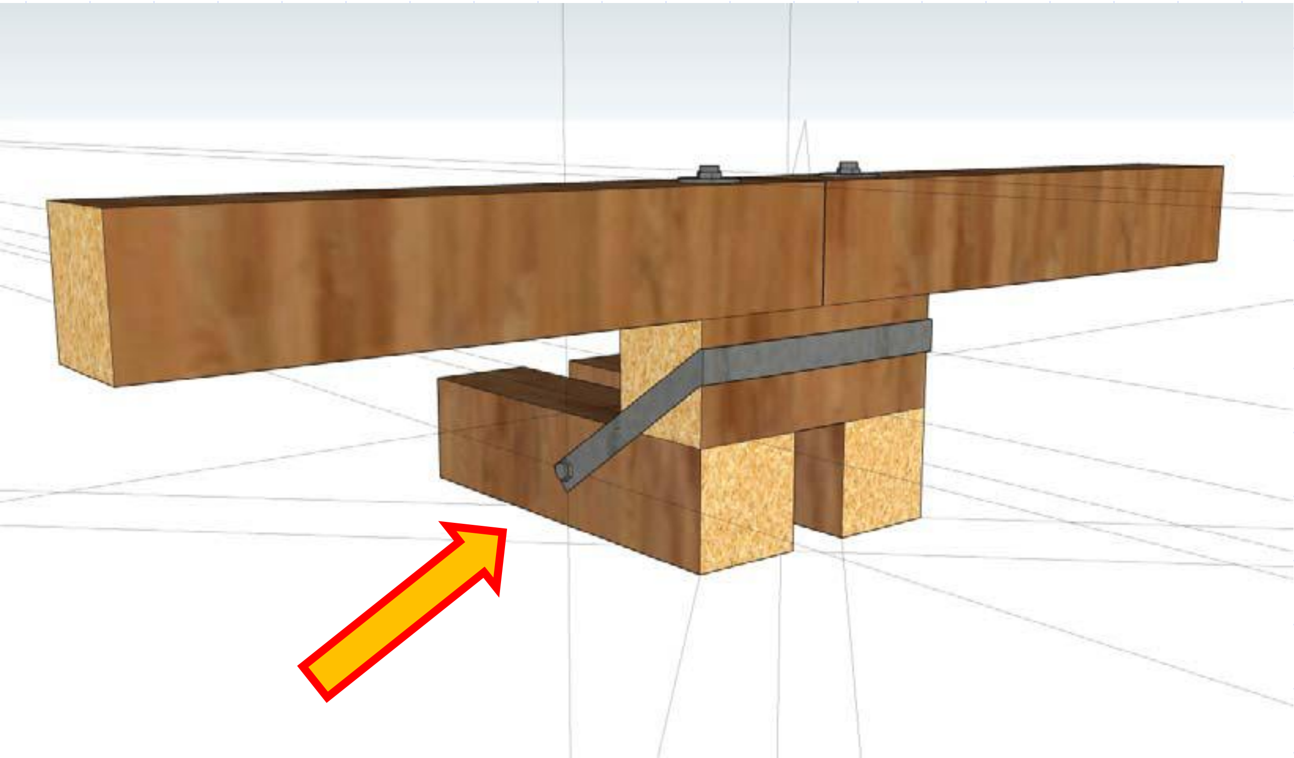




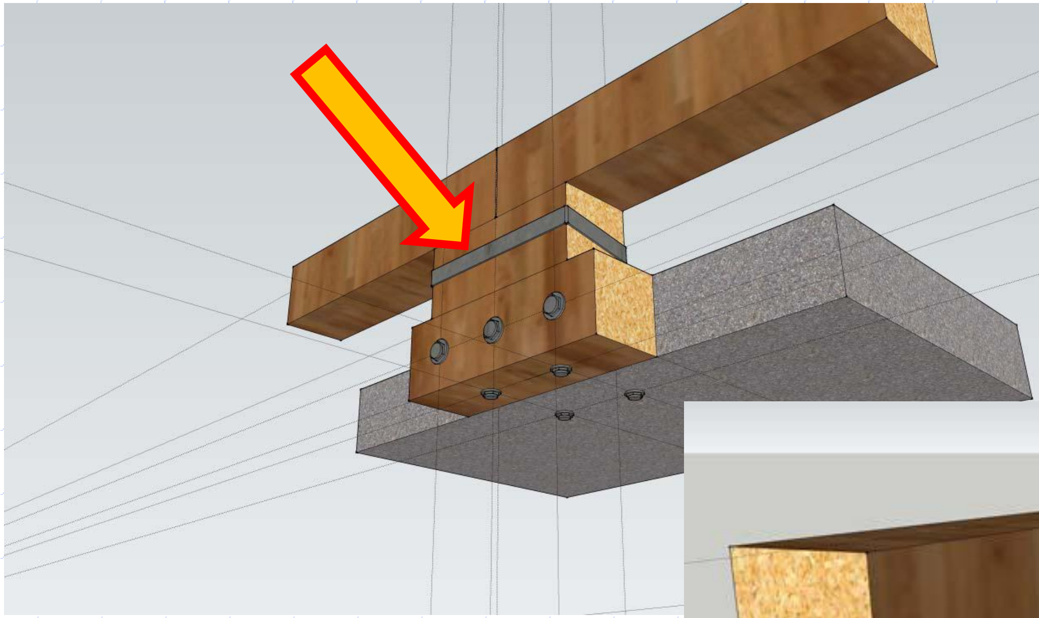
Providing continuity to rails to achieve catenary action (System I)

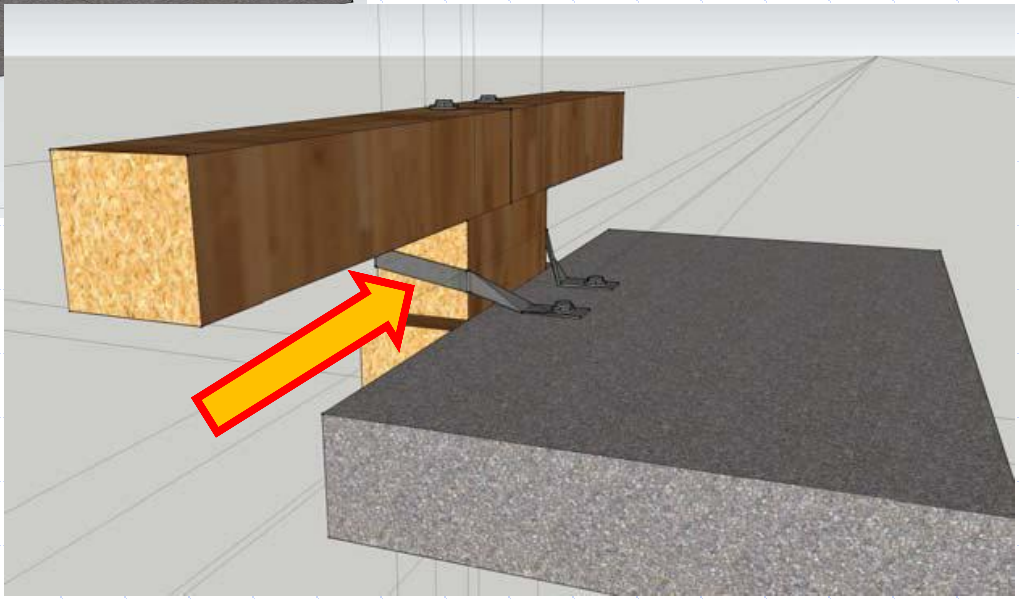


Metal straps with horizontal fasteners to cross beams (System I)

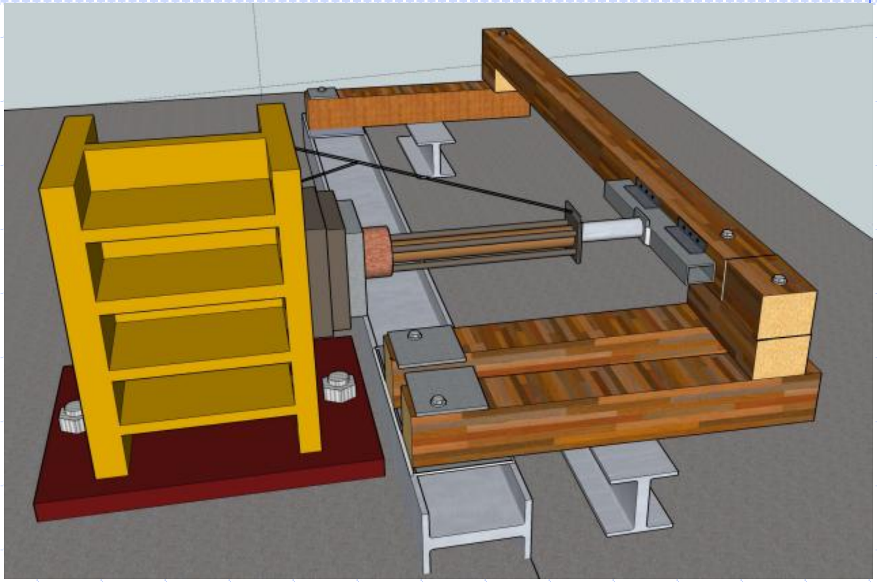


Metal strap to increase bending resistance to avoid splitting of riser block (System II)



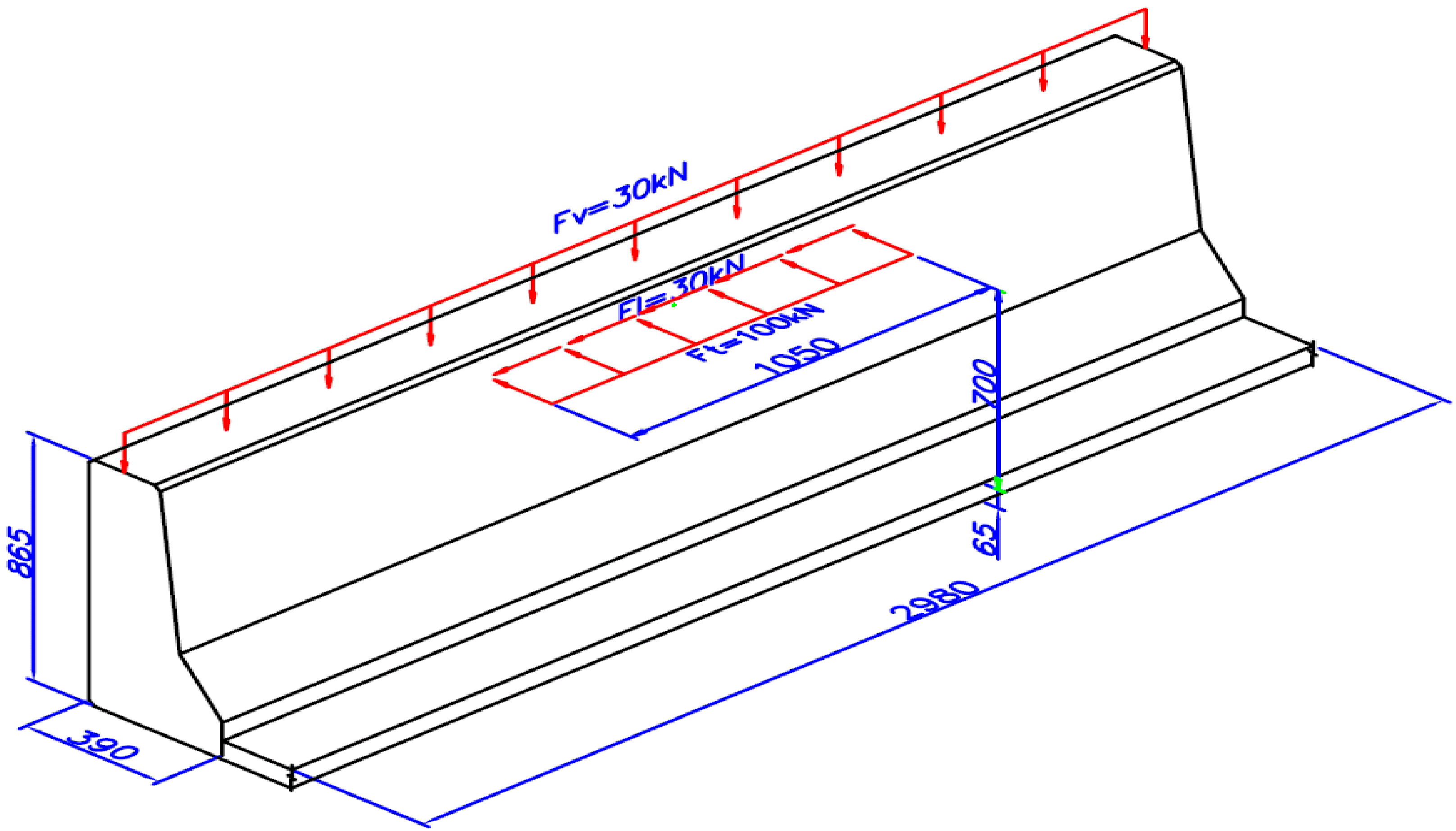


Where to go from here?



- Analysis of the new systems based on the new images from the ministry.
- Impact of the longitudinal loads on the guardrails.
- Sensitivity analysis
- Design of all new systems with
- Cost analysis/optimization

The End



Video: Crash testing I

Timber guard rails, chained

Video:Crash testing II

Steel guard rails, chained