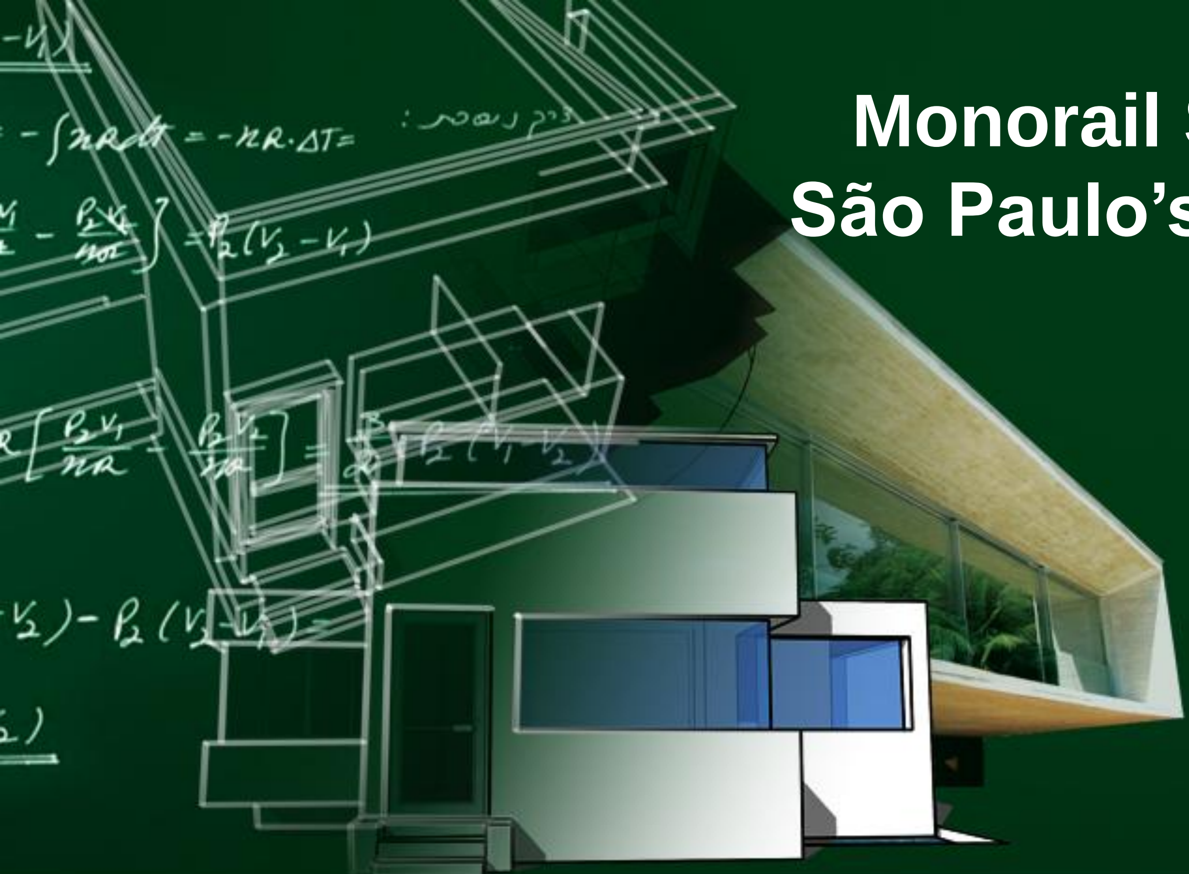
Monorail Solution for Metro São Paulo’s Linha 2 Extension



Carlos Banchik
Marcos Beier

14º ENECE 2011

Encontro Nacional de Engenharia e Consultoria Estrutural

As Normas Valorizando a Engenharia Estrutural

EXPRESSO TIRADENTES
Ground breaking new alternative in São Paulo's public transportation technologies

Presentation Structure

Background

- Metropolitan São Paulo Statistics
- Comparison to other Metropolitan Areas
- Metropolitan São Paulo Transportation
- Implementation of Monorail Technology

Structure Characteristics

- Codes on Design
- Loads
- Load Combinations
- Construction Sequence
- Tolerances
- Closure Pours
- Emergency Walkway
- Expansion Joints and Pintel

Structural Components

- Structural Models
- Ride Comfort
- Beams
- Columns
- Foundations

Beam Fabrication

- Precast Yard
- Forms

Summary

- **Highlights**
- **Recognitions**
- **Questions**

Background

Background – Metropolitan São Paulo Statistics

- Metropolitan São Paulo consists of 39 municipalities
- Population 19.6 million in metropolitan area
- 2.470 inhabitants/km^2 in metropolitan area
- 26 Billion Reals (14.5 Billion US)to be spent until 2015
- Transportation Systems:
  - São Paulo Metro
  - Rail Transport
  - Underground Rail System
  - Fast-Lane Bus System

Transportation:
A Citizen's Right;
A Government Duty.

Background – Comparison to other Metropolitan Areas

Metro Area Name	São Paulo Municipality	Greater São Paulo	Greater New York	Southland	Chicagoland
Cities	City of São Paulo	39 Municipalities	New York-Northern New Jersey-Long Island, New York-New Jersey-Pennsylvania	Los Angeles-Long Beach-Santa Ana	Chicago-Joliet-Naperville
Population [million]	11	19.6 (6 million cars)	18.9	12.8	9.4
Area [km^2]	1,523	7,943	17,400	12,561	24,814.7
Density [inhabitants /km^2]	7,216	2,470	1,065	393	509
Transportation Solutions	SP Metro SP Trans (Busses) CPTM (Trains)	• EMTU (Busses) • CPTM (Trains)	• Commuter Rail (LIRR, MNRR, NJT) • Light Rail (NYC Subway, Port Auth. Trans-Hudson, Staten Island Railways) • Bus lines	• Los Angeles County Metro Transportation Authority: • Light Rail, Subway, • Busses Metro Local, Rapid, Express • Amtrak • Metrolink, • Rapid Transit Bus	• Chicago Transit Authority • Elevated (“L”) • Busses • Northeast Illinois Regional Commuter Railroad Corporation (Metra) • Metrolink • Amtrak
	Major Highway	Major Highway	Major Highway	Major Highway	Major Highway

Ref. 2010 U.S. Census

Background – Implementation of Monorail Technology

The decision to use monorail technology in the extension of Line 2 was taken in 2009, when the Government of the State of São Paulo and the Prefecture of the municipality of São Paulo signed an agreement of Technical and Financial cooperation to substitute the original project for a monorail one that would duplicate the capacity of the dedicated bus line previously considered.

Current Cost Comparison:

- Highway cost 19.3 million / mile (T-Rex Project)
- HRT Underground: 250 -300 millions / km (www.lrt.daxack.ca)
- LRT Underground: 130 – 225 millions /km (www.lrt.daxack.ca)
- LRT Surface: 20 millions / mile (E. L. Tennyson, P.E)
- LRT Elevated: 78 million / km (PRT Strategies)
- Monorail systems $ 60 million /km (Monorails.org)

Background **–**Implementation of Monorail Technology–SP Lines

***Background* –** Implementation of Monorail Technology – Line 2

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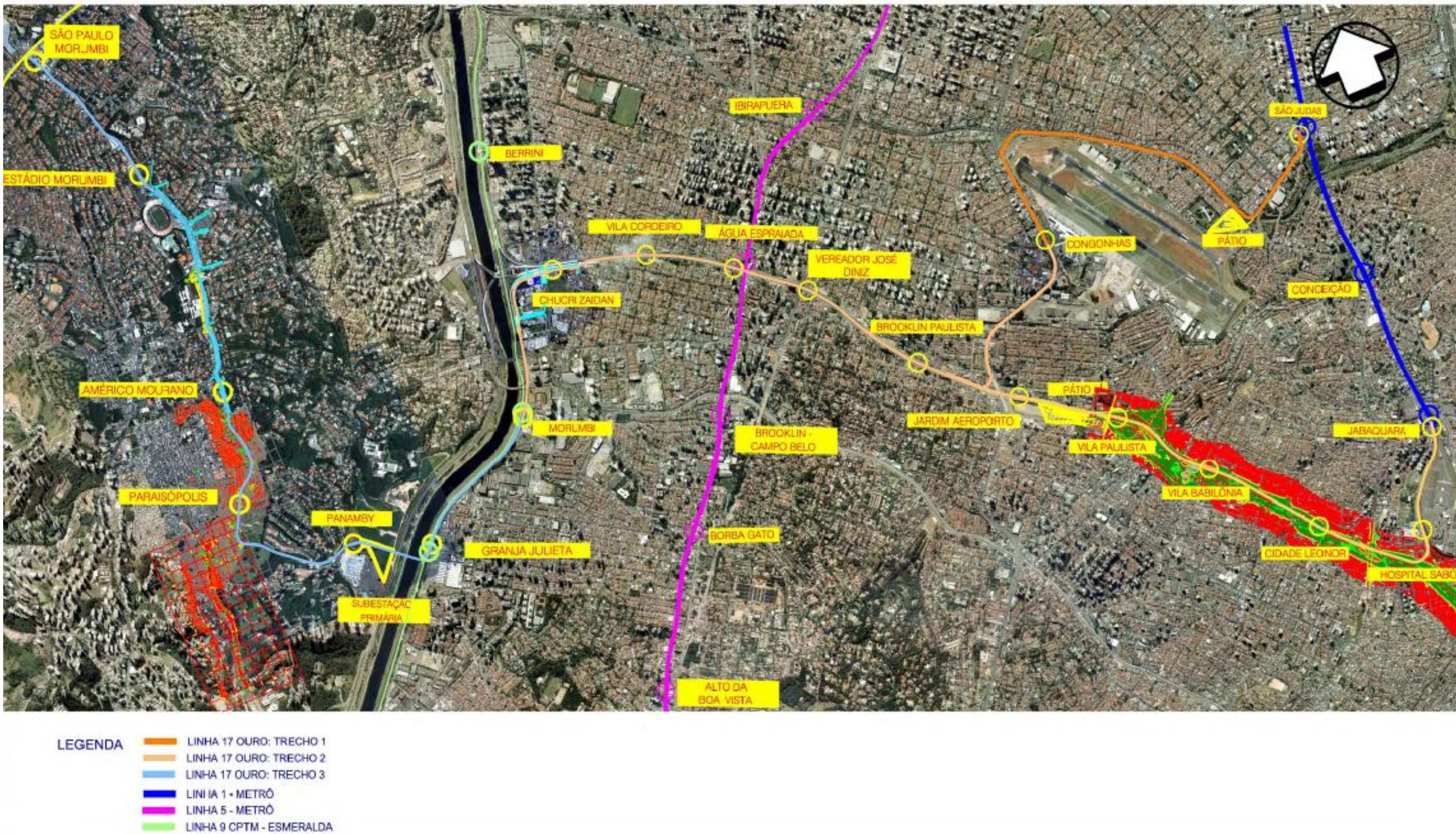
Background – Implementation of Monorail Technology Line 17



Structure Characteristics

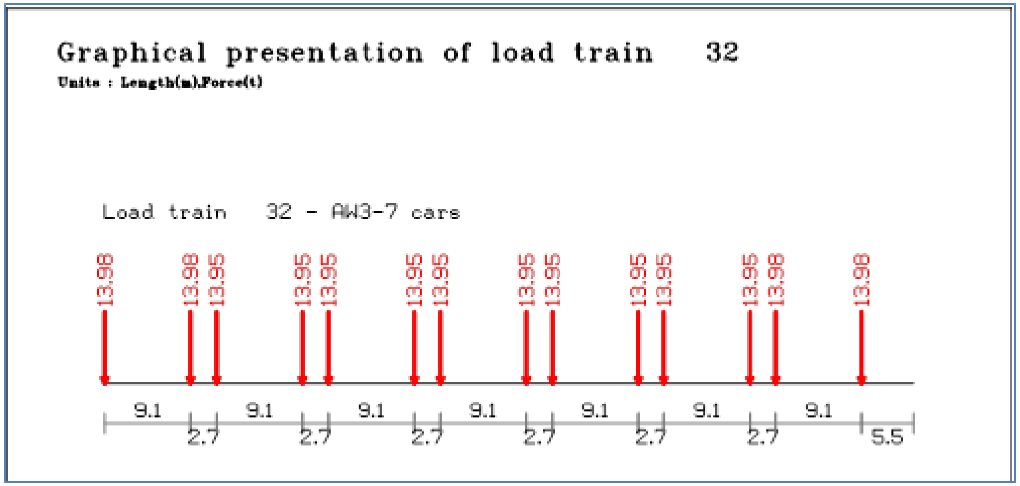
Structure Characteristics – Codes on Design

INTERNATIONAL BID No. 41889213 EXTENSION OF LINE 2 – GREEN VILA PRUDENTE – CIDADE TIRADENTES Metro SP	ACI 358 Analysis and Design of Reinforced and Prestressed Concrete Guidebeam Structures. American Concrete Institute, ACI 358.1R-92	ANSI / ASCE / T&DI 21 *Automated People Mover Standards* *Part 1 – Operating Environment 21-05* *Part 2 – Vehicle and Propulsion 21.2-08* *Part 3 – E*lectrical Systems, Stations, and Guideway 21.3-08 Part 4 - Security, Emergency preparedness
AASHTO LRFD Bridge Design Specifications – US, 4th Edition, and interims including 2007. American Association of State Highway and Transportation Officials.	ACI 318 Building Code and Commentary. American Concrete Institute, ACI 318-08.	Bombardier Design and Construction Interface Manual Part 2. Geometric Design BTS Document No. 453-SWD-ICD-010002 R0
Bombardier Design and Construction Interface Manual Part 2. Part 3 Guideway; BTS Document No. 453-SWD-ICD-010003 R0	ABNT NBR 6118-Projeto de estruturas de concreto Associação Brasileira de Normas Técnicas. Marzo de 2004	ABNT NBR 6123-Forças devido ao vento em edificações Associação Brasileira de Normas Técnicas. Junho de 1988

***Structure Characteristics* – Loads**

SYMBOL	LOADS	CARGAS
(D)	DEAD LOADS	CARGA PERMANENTE OU PESO PRÓPRIO
(LL)	LIVE LOADS	CARGAS MÓVEIS
(EM)	LIVE LOAD ON EMERGENCY WALKWAY	CARGA MÓVEL NA PASSAGEM DE EMERGÊNCIA
(I)	IMPACT	IMPACTO OU EFEITO DINÂMICO DA CARGA MÓVEL
(P)	PRE-STRESSING OR POST-TENSION LOADS	FORÇA DE ESFORÇO PRÉ / PÓS-TRAÇÃO
(WS)	WIND ON STRUCTURE	VENTO SOBRE A ESTRUTURA
(WL)	WIND ON VEHICLES	VENTO SOBRE CARGAS MÓVEIS
(LFN, LFE)	BRAKING LOADS (NORMAL, EMERGENCY)	FORÇA DE FRENAÇÃO
(HF)	HUNTING FORCE	IMPACTO LATERAL
(CF)	CENTRIFUGAL FORCE	FORÇA CENTRÍFUGA
(CR, SH)	CREEP AND SHRINKAGE	FLUÊNCIA E RETRAÇÃO
(T)	TEMPERATURE	TEMPERATURA
(CO)	COLLISION	CARGA DE COLISÃO

Structure Characteristics – Loads



Condição de carga		no de passageiros / trem	Carga / Carro
AW0	Vazio	0	15 Tons
AW1	Passageiros sentados	122 pasageiros	16 Tons
AW2	Passageiros sentados + em pé (6 pass/m² a 70 kg)	122 sentados + 880 em pé = 1022 passageiros	25 Tons
AW3	Passageiros sentados + em pé (8 pass/m² a 70 kg)	122 sentados + 1172 em pé= 1294 passageiros	28 Tons
AW4	Passageiros sentados + em pé (10 pass/m² a 70 kg)	122 sentados +1467 em pé= 1589 passageiros	31 Tons

Structure Characteristics – Load Combinations

CARGAS DE SERVIÇO

As cargas de serviço são utilizadas para verificação dos esforços nas vigas e colunas.
O veículo AW2 é utilizado para essa verificação.

COMBINAÇÕES ACI 358
S0= D + 0.9/1.0(PS + CR + SH)
S1= D + 0.9/1.0 (PS + CR + SH) +max of (L+I) or (L + I + LFn) + (CF or HF)
S2= S1 + (0.3(WL + WS)) hor. & vert.
S3= S2 + T
S4 = D + 0.9/1.0 (PS + CR + SH) + max of (WS or EQ) + T

COMBINAÇÕES QUASE PERMANENTE - (CQP)

COMBINAÇÕES FREQUENTE - (CF)

COMBINAÇÕES RARA - (CR)

Todas as cargas permanentes também são combinadas utilizando-se um fator de 0,9 se isto criar uma combinação pior.

CARGAS DE FADIGA (com base no trabalho de Planservi e Metro)

Structure Characteristics – Load Combinations

ESTADO LIMITE ULTIMO - (ELU)

As cargas de cálculo são utilizadas para verificação das cargas finais na viga guia e nos demais elementos estruturais.
As cargas do AW4 (ou veículos de controle) são utilizadas para essas combinações.

COMBINAÇÕES ACI 358
U0 = 1.3 D + 0.9/1.2 (PS + CR + SH) + 1.7 (LL+I + CF or HF)
U1 = 1.3 D + 0.9/1.2 (PS + CR + SH) + 1.4 (LL+I + CF or HF) + 1.5(WL + WS)
U2 = 1.3 D + 0.9/1.2 (PS + CR + SH) + 1.4 (LL+I + CF or HF) + WS
U3 = 1.3 D + 0.9/1.2 (PS + CR + SH) + 1.4 (LL+I + CF or HF + LFe) + 1.5T
U6 = 1.3 D + 0.9/1.2 (PS + CR + SH) + CO
U7 = 1.3 D + 0.9/1.2 (PS + CR + SH) + EM

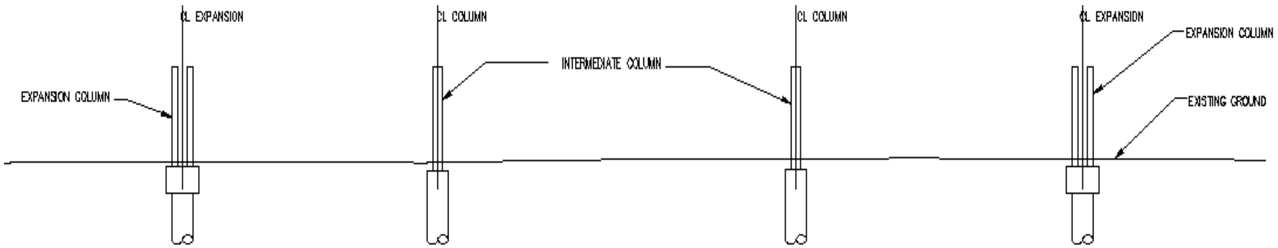
COMBINAÇÕES ÚLTIMAS NORMAIS

COMBINAÇÕES ÚLTIMAS EXCEPCIONAIS

Todas as cargas permanentes também são combinadas utilizando-se um fator de 0,9 se isto criar uma combinação pior.

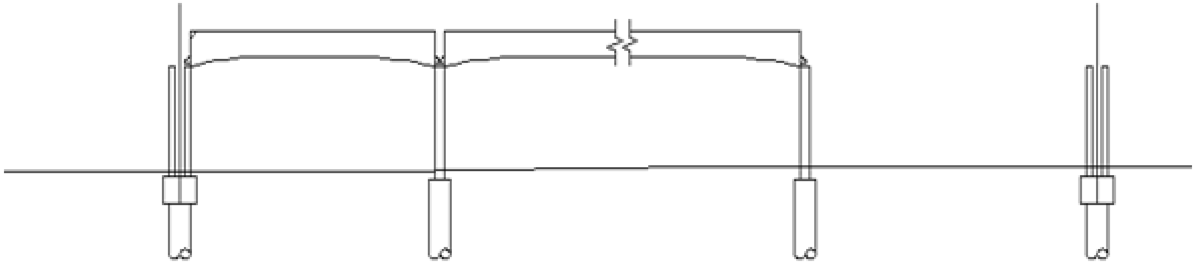
Structure Characteristics – Construction Sequence

ESTÁGIO 1



- Identificar todas as necessidades de instalações utilitárias, fiações elétricas, aterramento e dutos em cada local de pilar.
- Executar as estacas, blocos e pilares (capitéis), conforme projeto.

ESTÁGIO 2

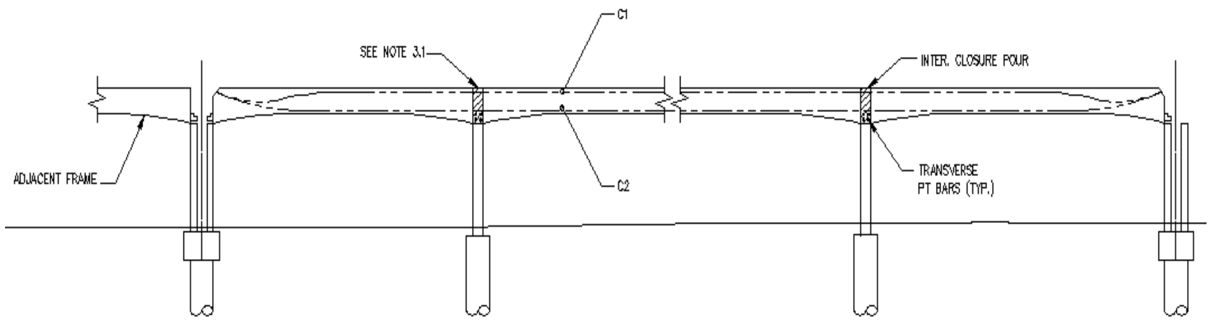


•Fazer a verificação topográfica dos suportes de apoio das vigas. Montagem das vigas guia no sentido leste (via 1) e no sentido oeste (via 2) em cada vão. Instalar os travamentos, à medida que cada viga é colocada.

•Quando todas as vigas de um módulo estiverem lançadas, verificar o alinhamento e a superelevação e ajustar os travamentos se necessário.

Structure Characteristics – Construction Sequence

ESTÁGIO 3



- Executar os fechamentos entre as vigas dos pilares intermedários.
- Protender os cabos de continuidade C1 e C2 em ambas as extremidades nos pilares de junta, injetar nata de cimento nos cabos.
- Verificar o alongamento dos cabos e o encurtamento elástico inicial nas juntas de dilatação.
- Protender as barras transversais de pós-tração (barras PT) nos fechamentos entre vigas dos pilares intermediários, uma vez que o concreto atinja a resistência especificada no projeto.
- Remover os travamentos das vigas guia intermediárias.

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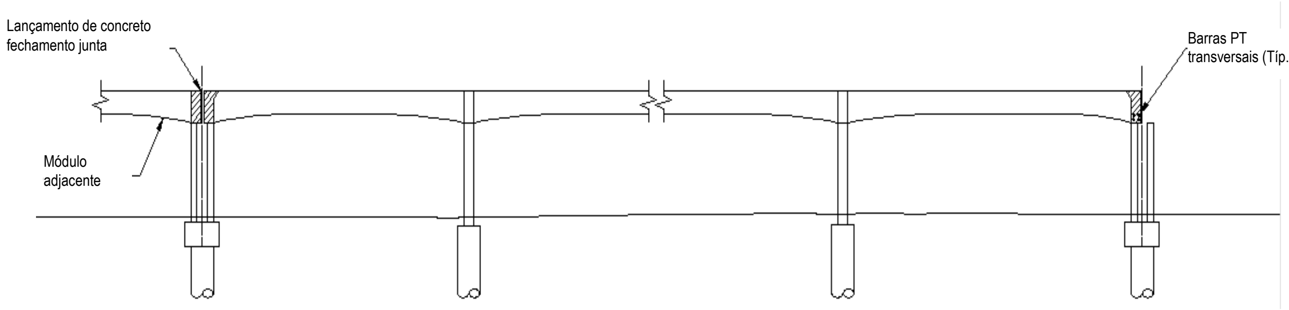
Structure Characteristics – Construction Sequence

ESTÁGIO 4

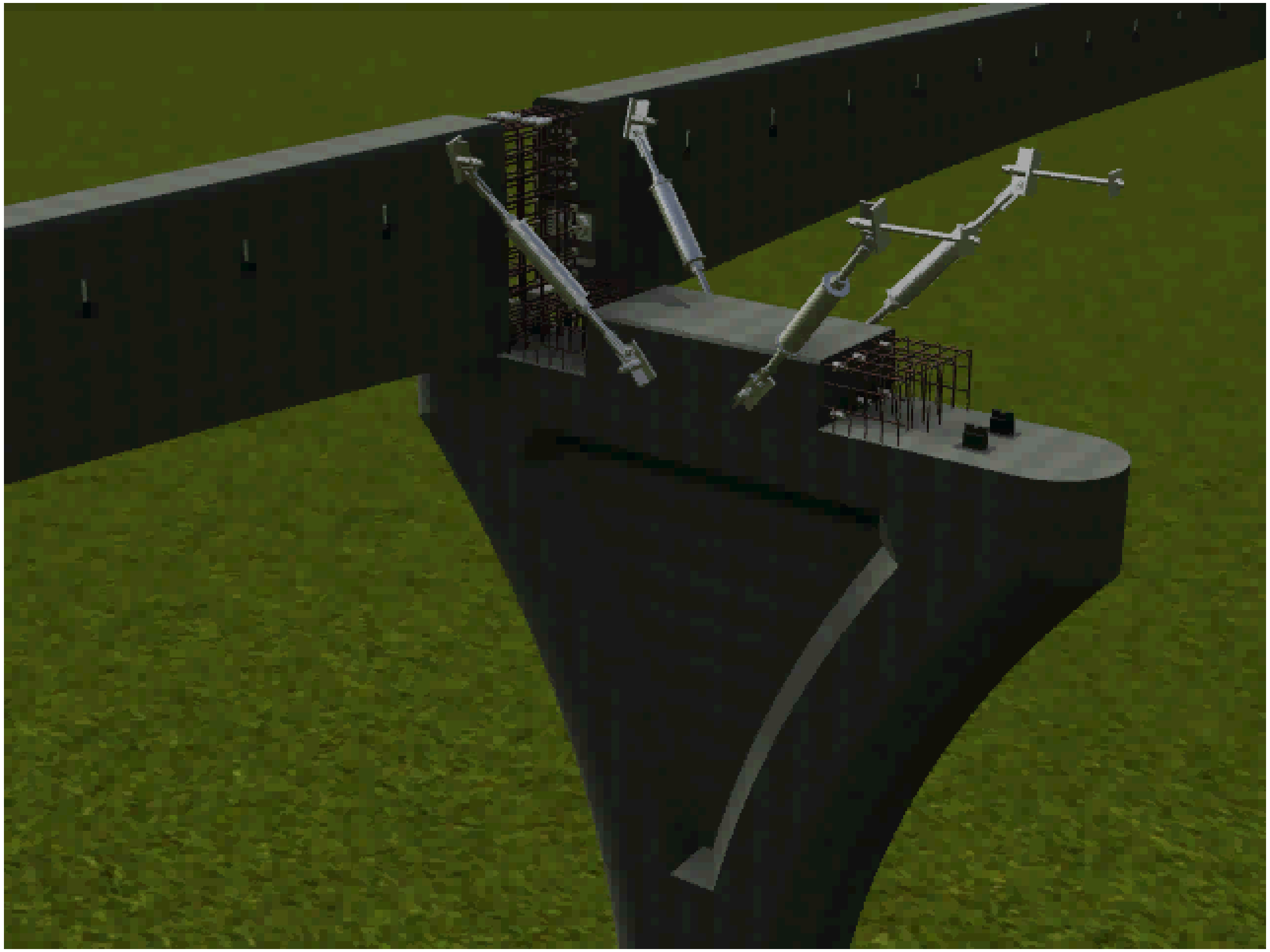


- Executar o fechamento entre vigas dos pilares externos (típicos nos locais de juntas de dilatação), mantendo a junta entre os módulos. Incluem as placas de expansão e pivô de travamento no fechamento.
- Protender as barras transversais de pós-tração (barras PT) dos fechamentos entre vigas dos pilares externos, uma vez que o concreto atinja a resistência total.
- Executar a concretagem da segunda fase do fechamento dos pilares intermediários e externos.
- Remover os travamentos das vigas guia, nos pilares externos.
- Instalar passagem de emergência, bandejas de cabos, trilhos de alimentação elétrica e equipamentos relativos.

Structure Characteristics – Tolerances

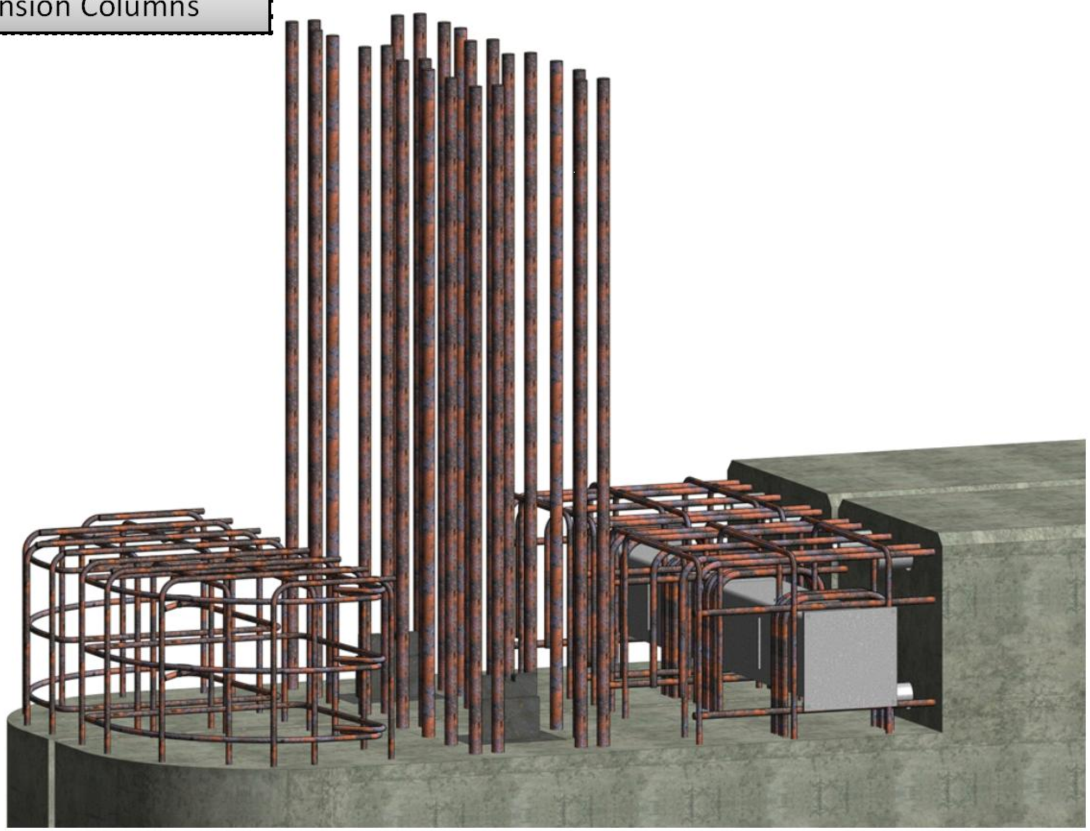
Tolerance	PCI	ACI 358.1R (Track construction)	Typical Bombardier Monorail Project
Width of precast piece (Gage)	± 6 mm (± ¼ in)	± 3 mm (± 1/8 in)	±3 mm (± 1/16 in)
Camber, variation from design	± 12 mm (± ½ in)	± 6 mm (± ¼ in)	± 12 mm (± ½ in)
Straightness criteria	±6 mm in 3 m (± ¼ in per 10 ft.)	3 mm in 3 m (1/8 in per 10 ft.)	±3 mm in 3 m (±1/8 in per 10 ft)
Variation in plan, column/beams, structural applications	± 12 mm (± ½ in)	± 6 mm (± ¼ in)	± 12 mm (± ½ in)
Variation from plumb	12 mm in 3m (¼ in any 10 ft) of height	3 mm in 3 mm (1/8 in any 10 ft)	15 mm in 3m (3/8 in any 10 ft) of height

Structure Characteristics – Closure Pours



Structure Characteristics – Closure Pours

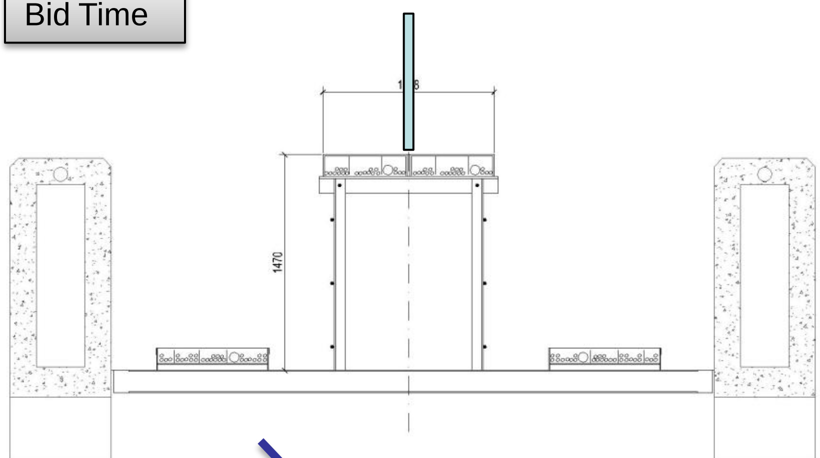
Expansion Columns



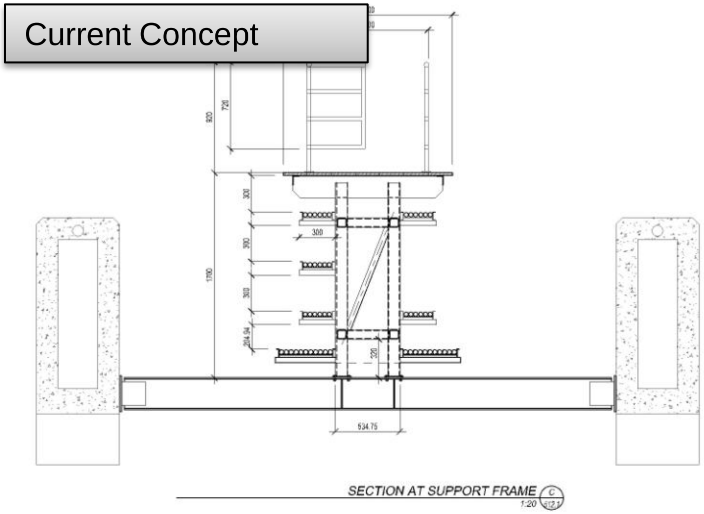
Click For Sequence

Structure Characteristics – Emergency Walkway

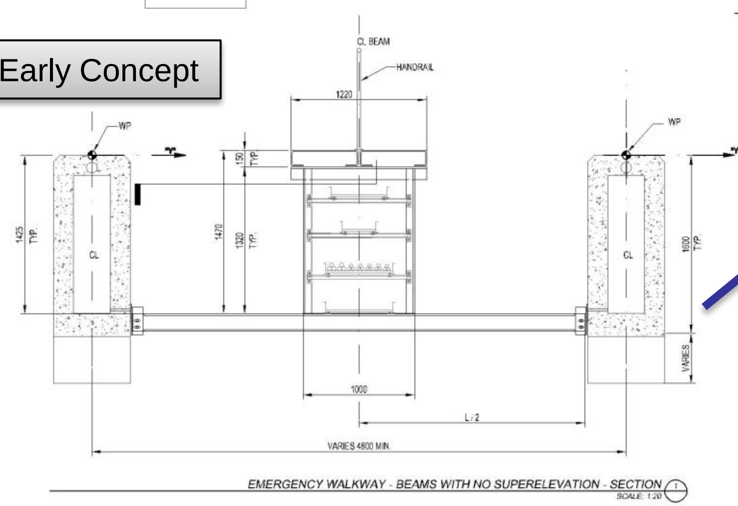
Bid Time



Current Concept



Early Concept



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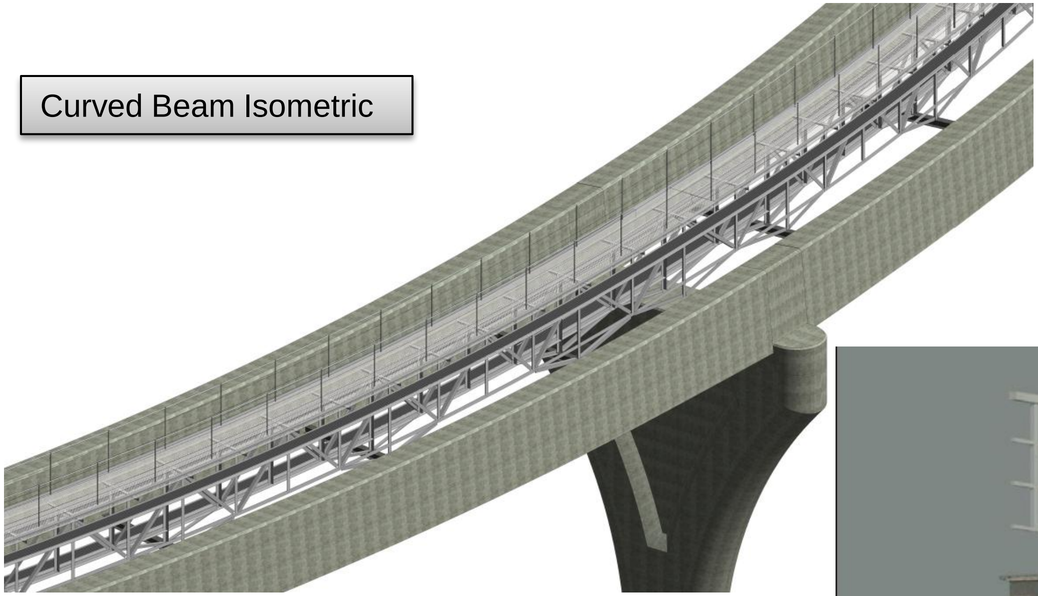
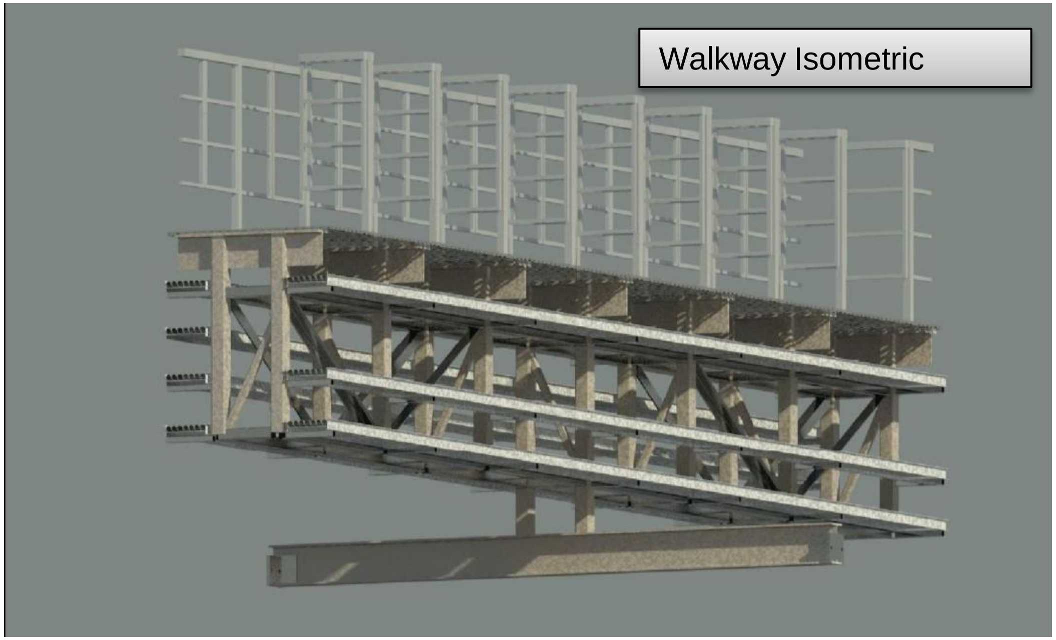
Structure Characteristics – Emergency Walkway

Curved Beam Isometric

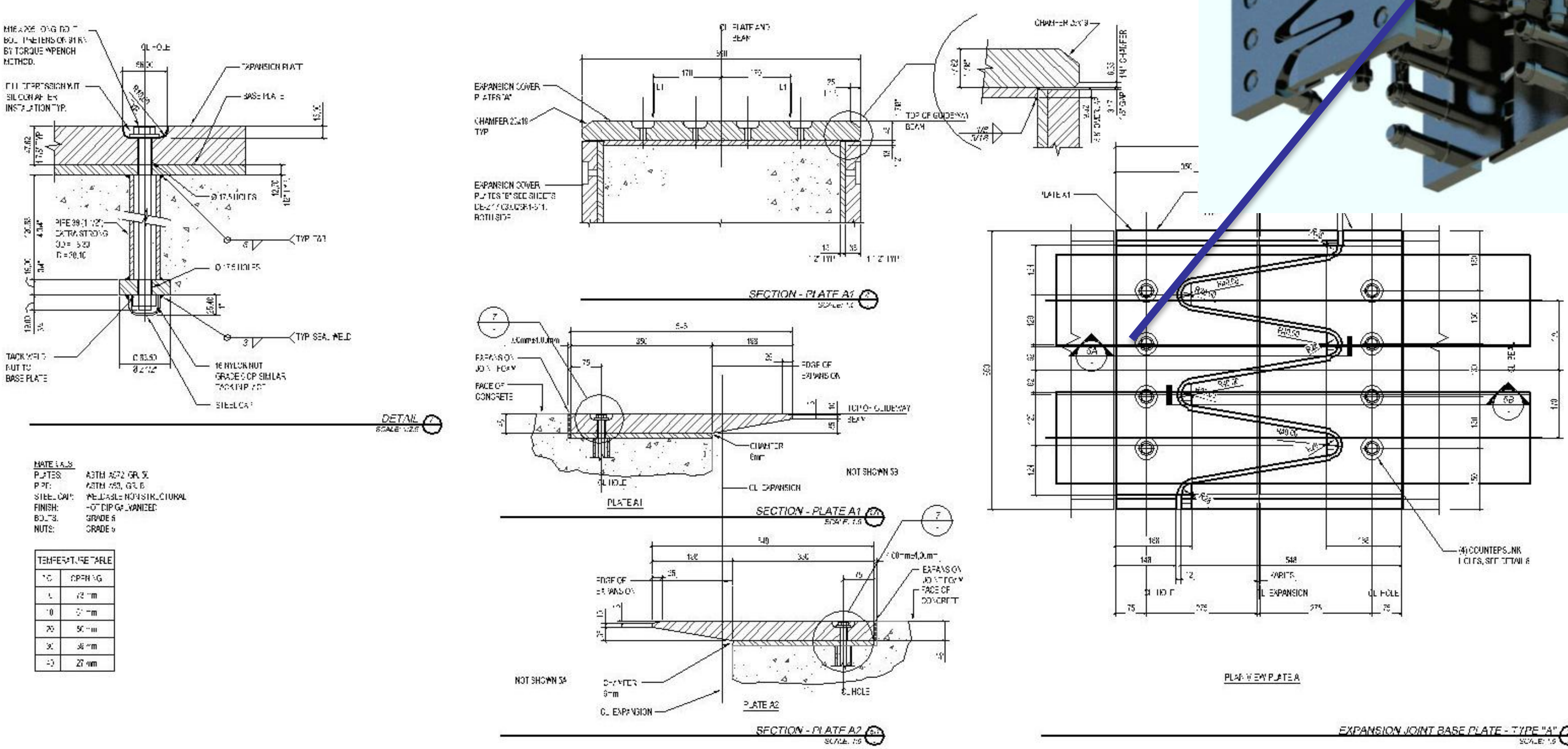


Walkway Isometric

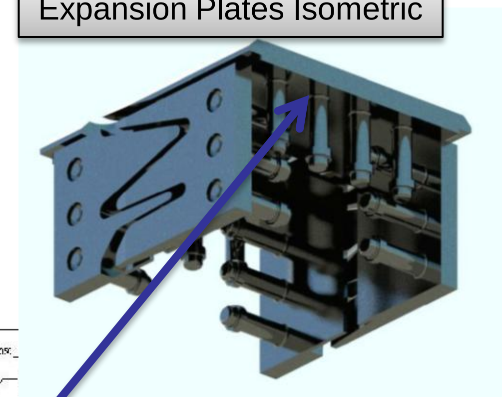


Structure Characteristics – Expansion Joints and Pintels

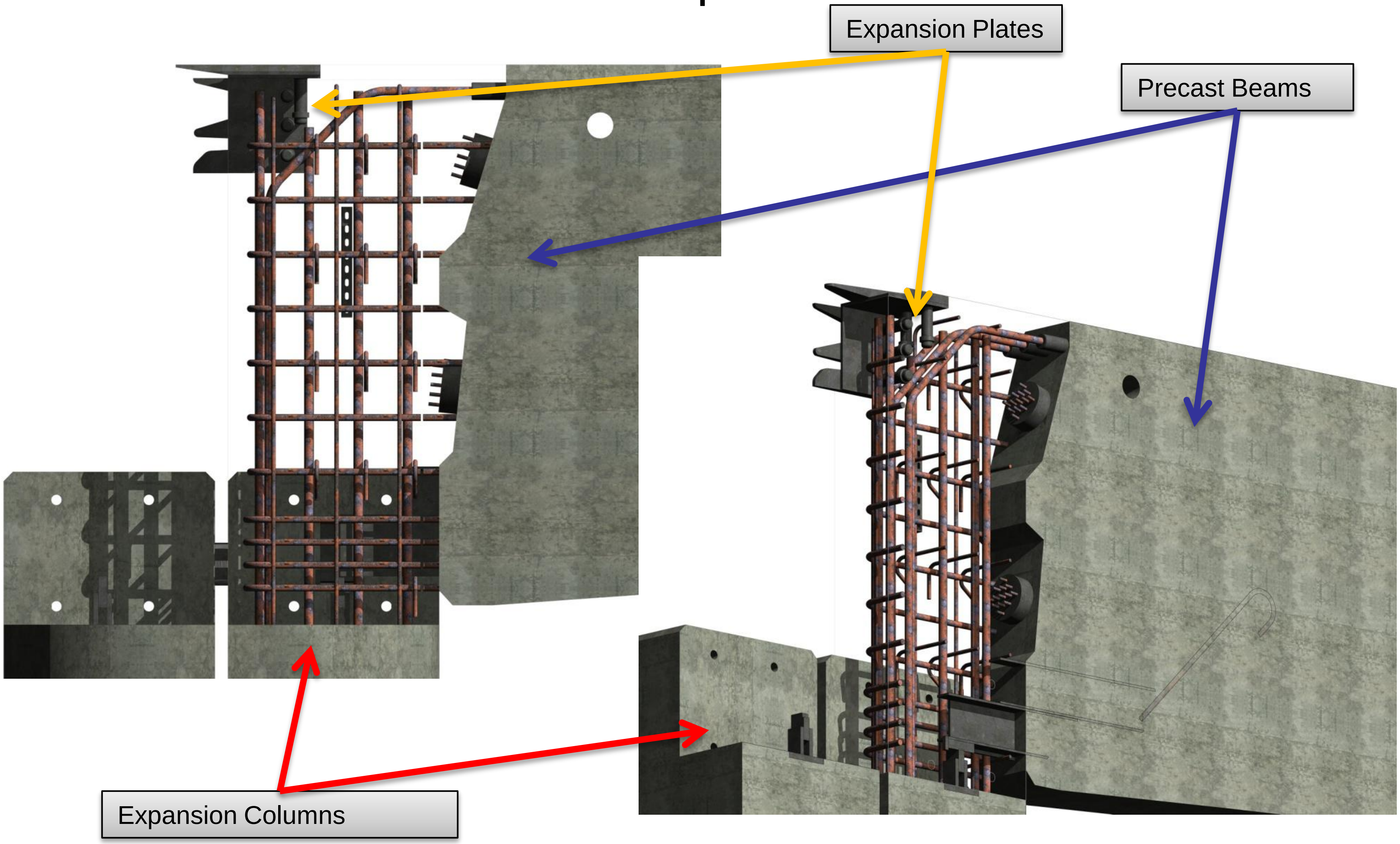
Top Expansion Plates



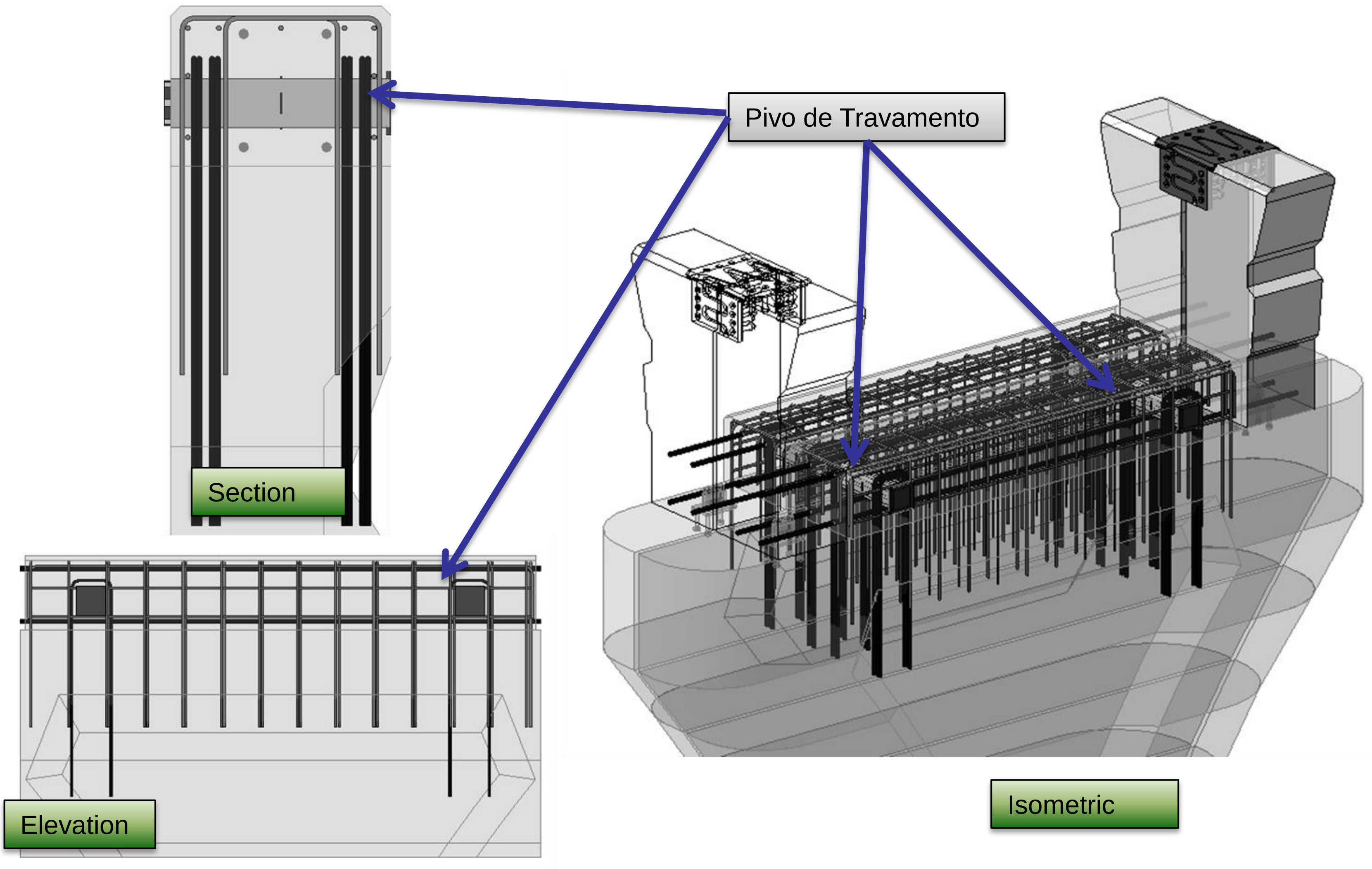
Expansion Plates Isometric



Structure Characteristics – Expansion Joints and Pintels



Structure Characteristics – Expansion Joints and Pintels



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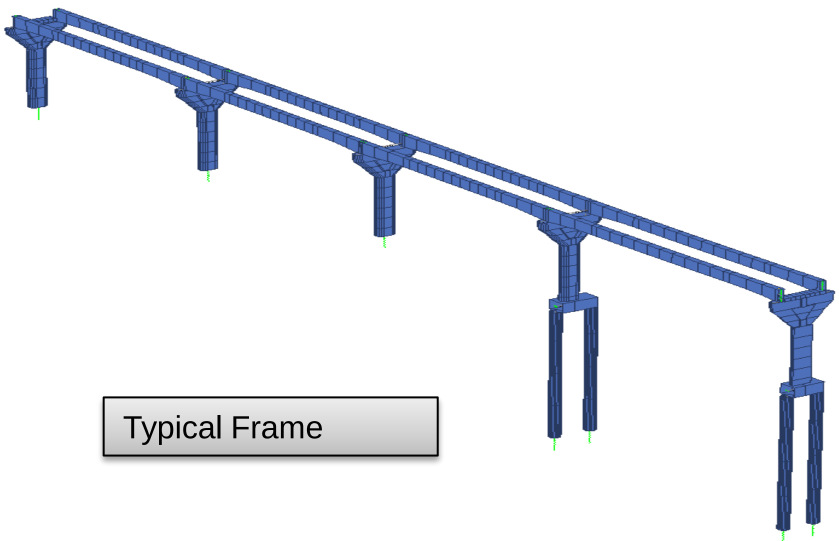
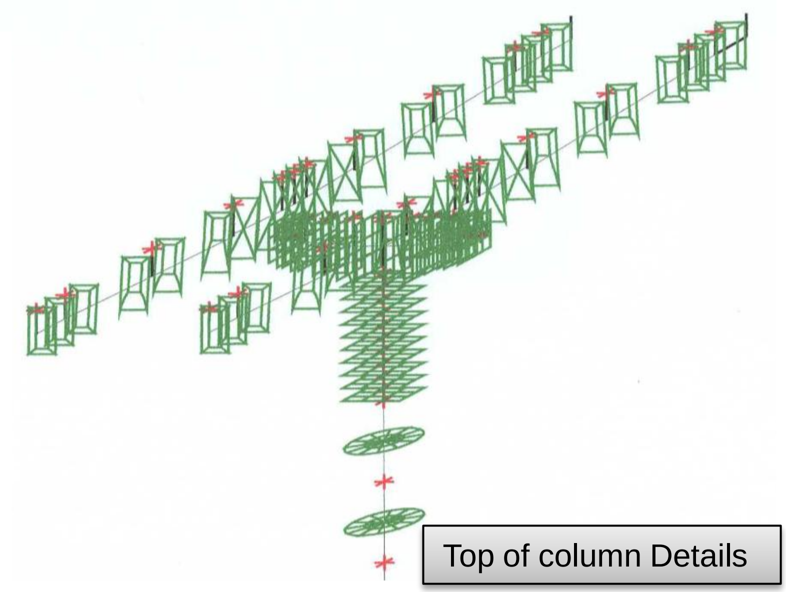
Structural Components

Structural Components – Structural Models

RM 2000

- *State of the Art 3D Finite Element*
- *Section Properties based on Input Shape*
- *Soil Structure Interaction with Soil Springs*

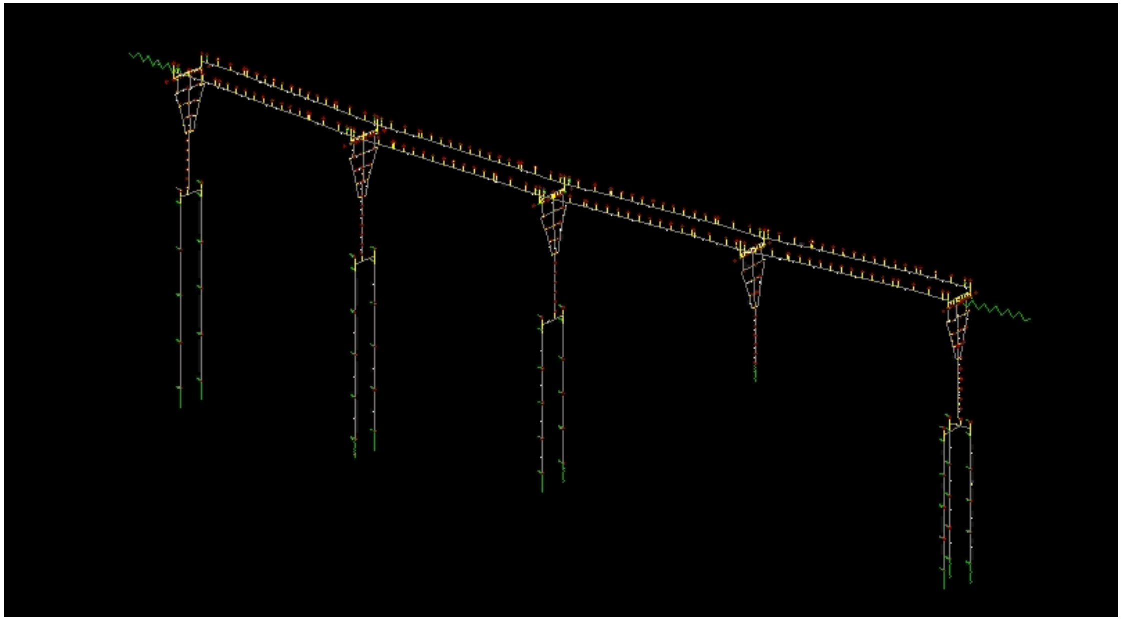




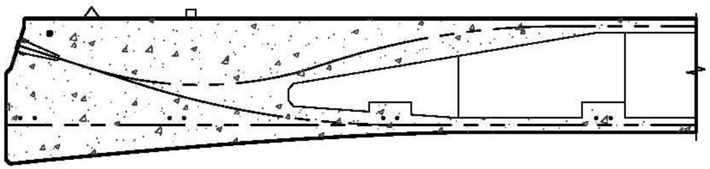
Structural Components – Ride Comfort

TDV – RM Lateral Displacement Analysis

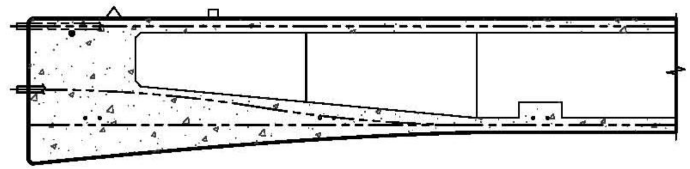
- *Accurate modeling of Train Spring-Dampers*
- *Modeling of Vehicle-Structure Interface*
- *Graphical Results*



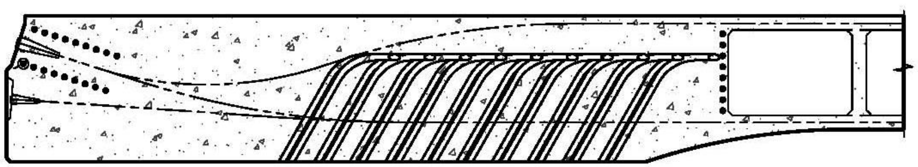
Structural Components – Beams



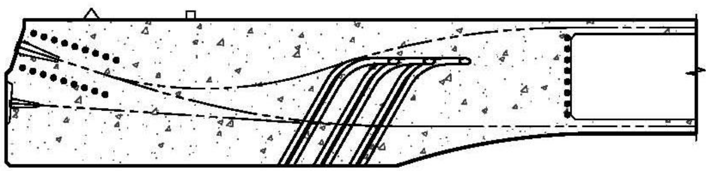
Exterior Beam



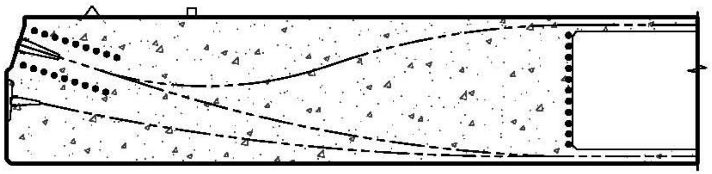
Interior Beam



Power Feed Beam (10 Ducts)



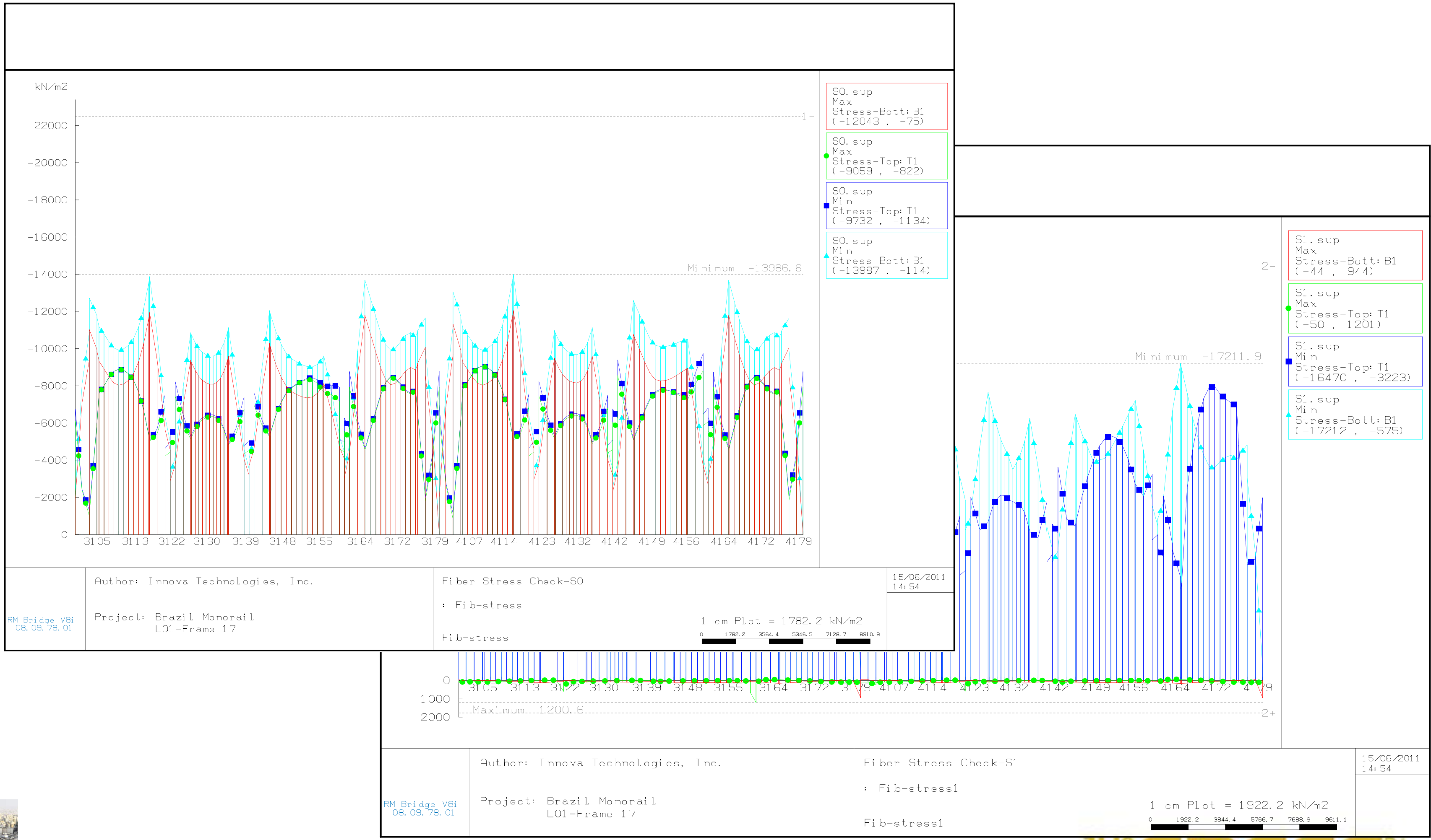
Power Feed Beam (3 Ducts)



Specialty Beam

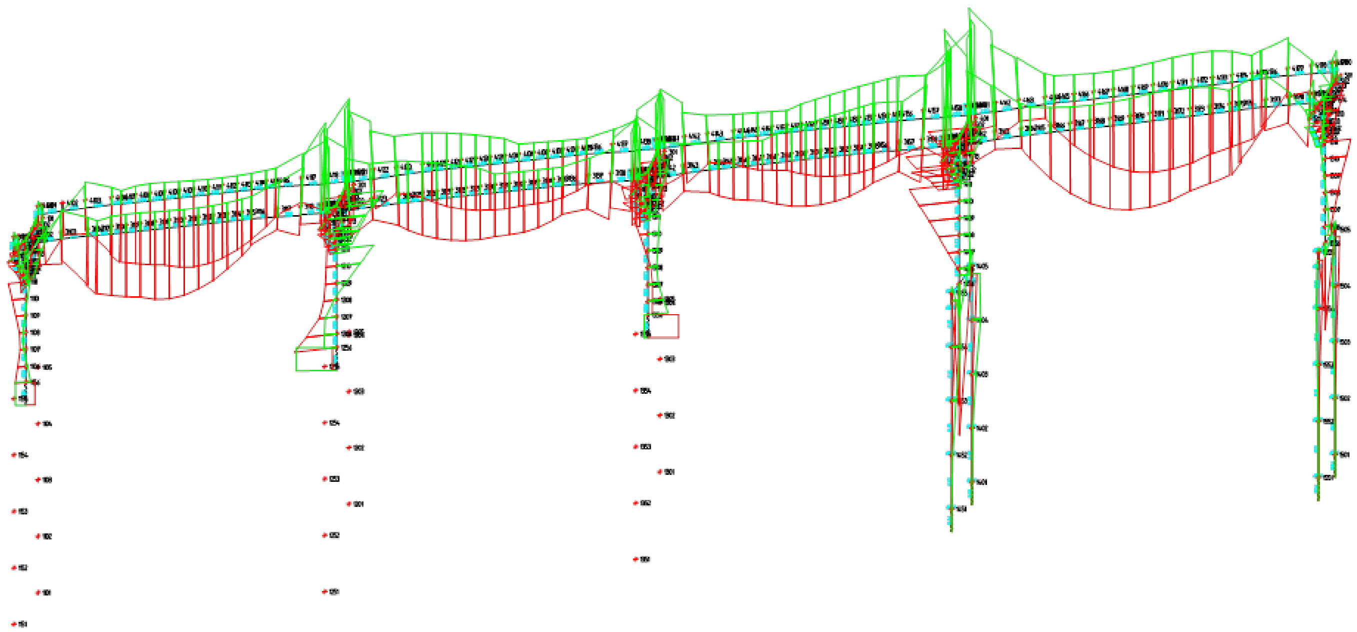
***Structural Components* – Beams**

RM Beam Analysis - Stresses



Structural Components – Beams

RM Beam Analysis – Demand Displays



Monotrilho Brasil

U4 Carga fatorada

max Mz – momento de flexao

min Mz - momento de flexao

Exemplo de Carga de Cálculo Caso U4 – Gráfico dos momentos Mz

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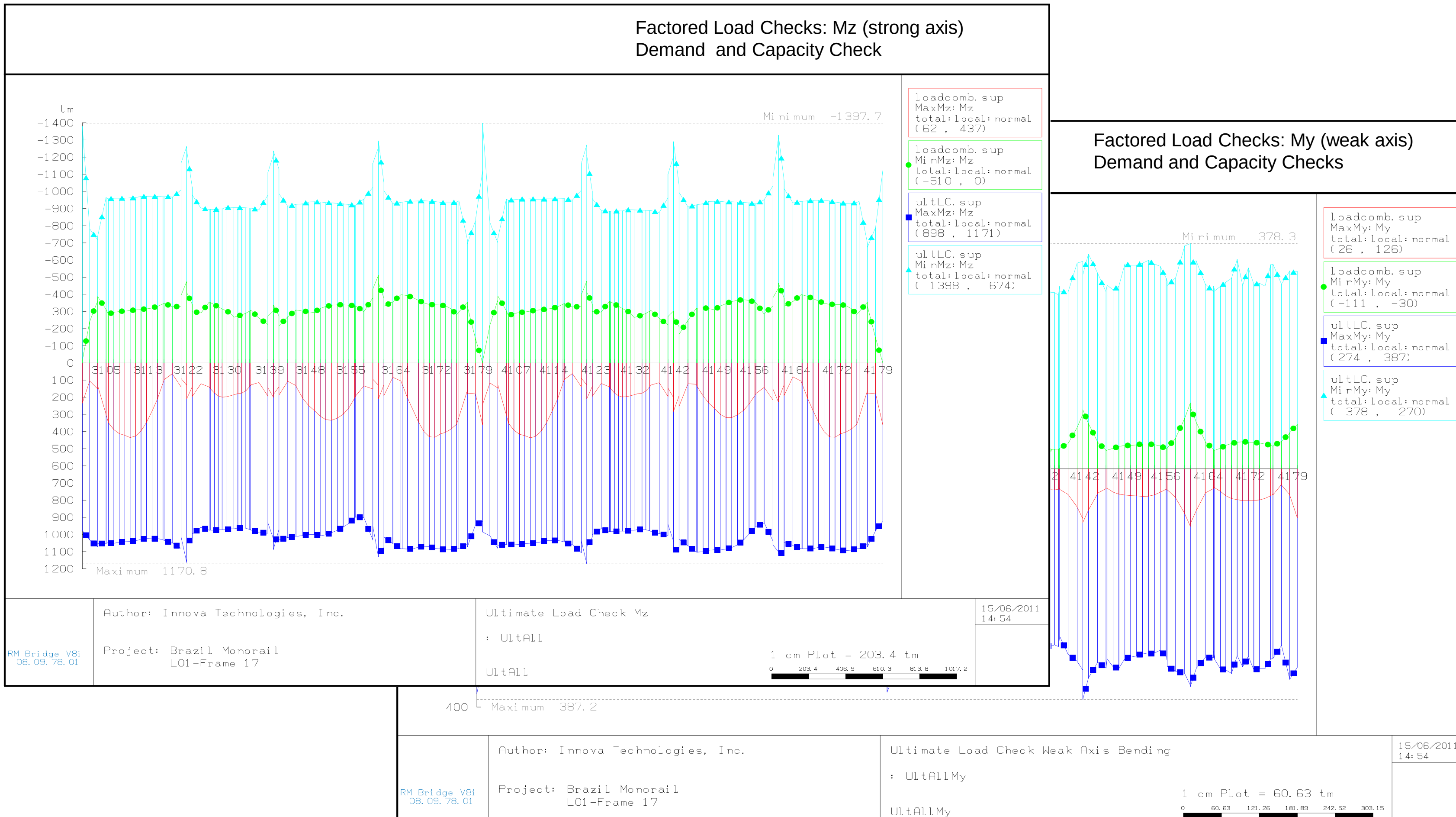
Structural Components – Beams

RM Beam Analysis – Factored Loads



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Structural Components – Beams

RM Beam Analysis – Shear and Torsion

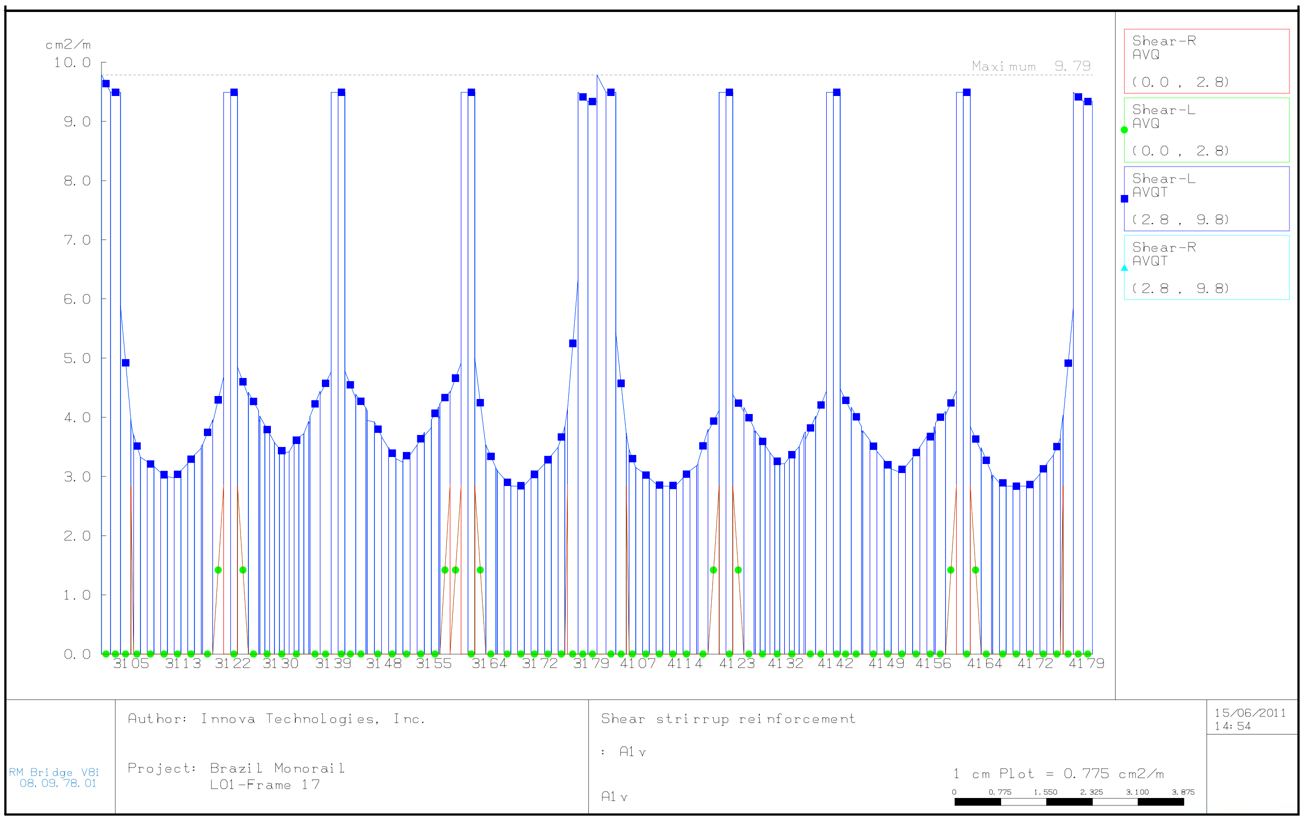
Structural Components – Beams

RM Beam Analysis – Shear and Torsion

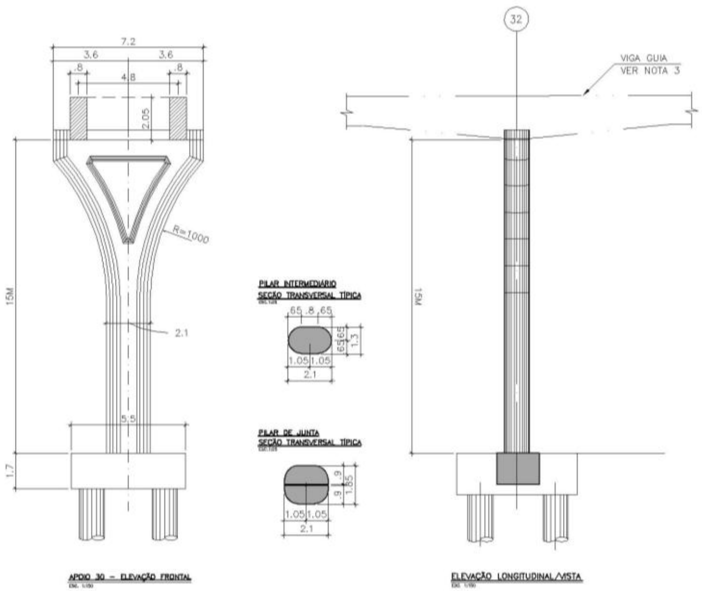
The following diagram shows the shear and torsion steel required-stirrups:

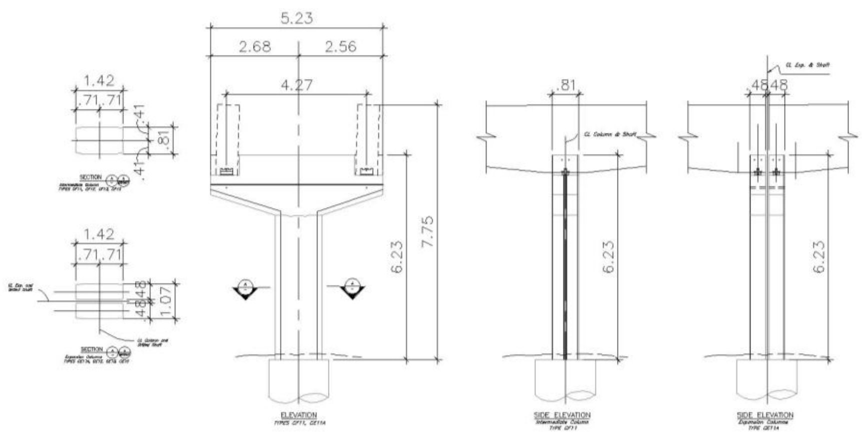
- Blue Lines AVQT are Torsion Requirements
- Red Lines AVQ are Shear Requirements

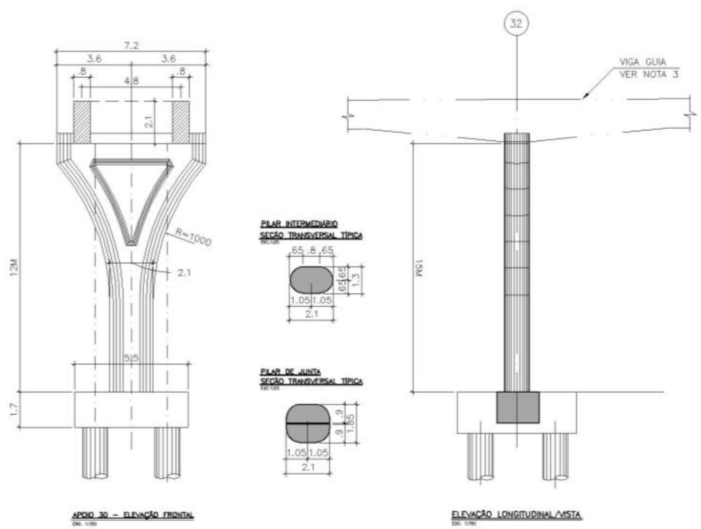
Both of these quantities are provided for in the design drawings provided with these calculations.



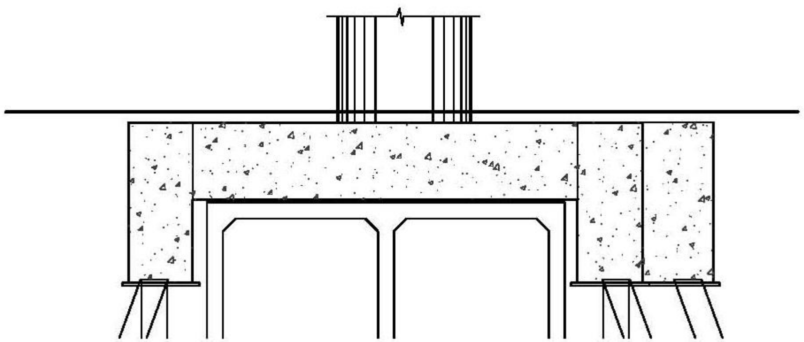
Structural Components – Columns



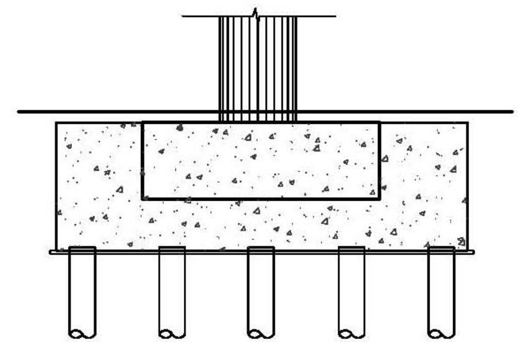




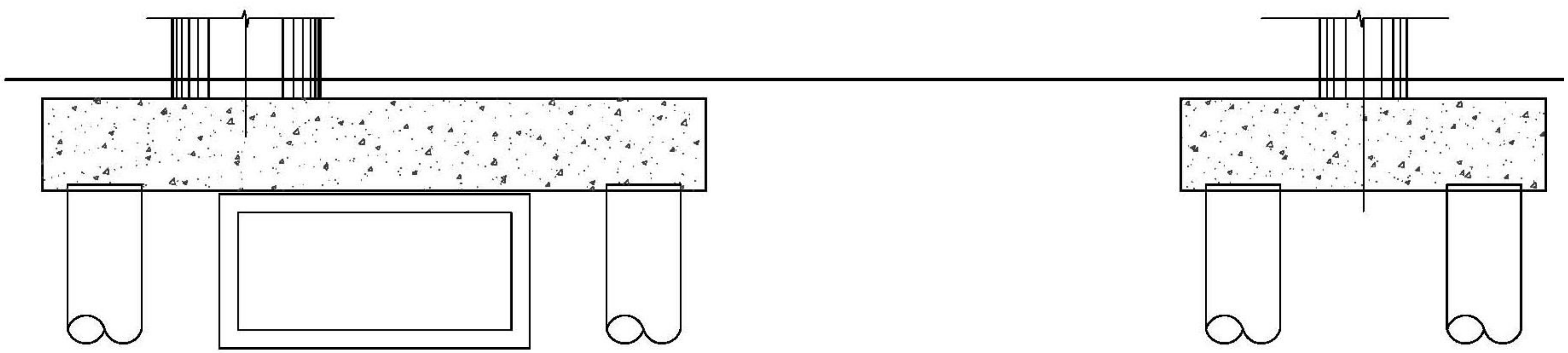
Structural Components – Foundations



Foundation over Existing Culvert



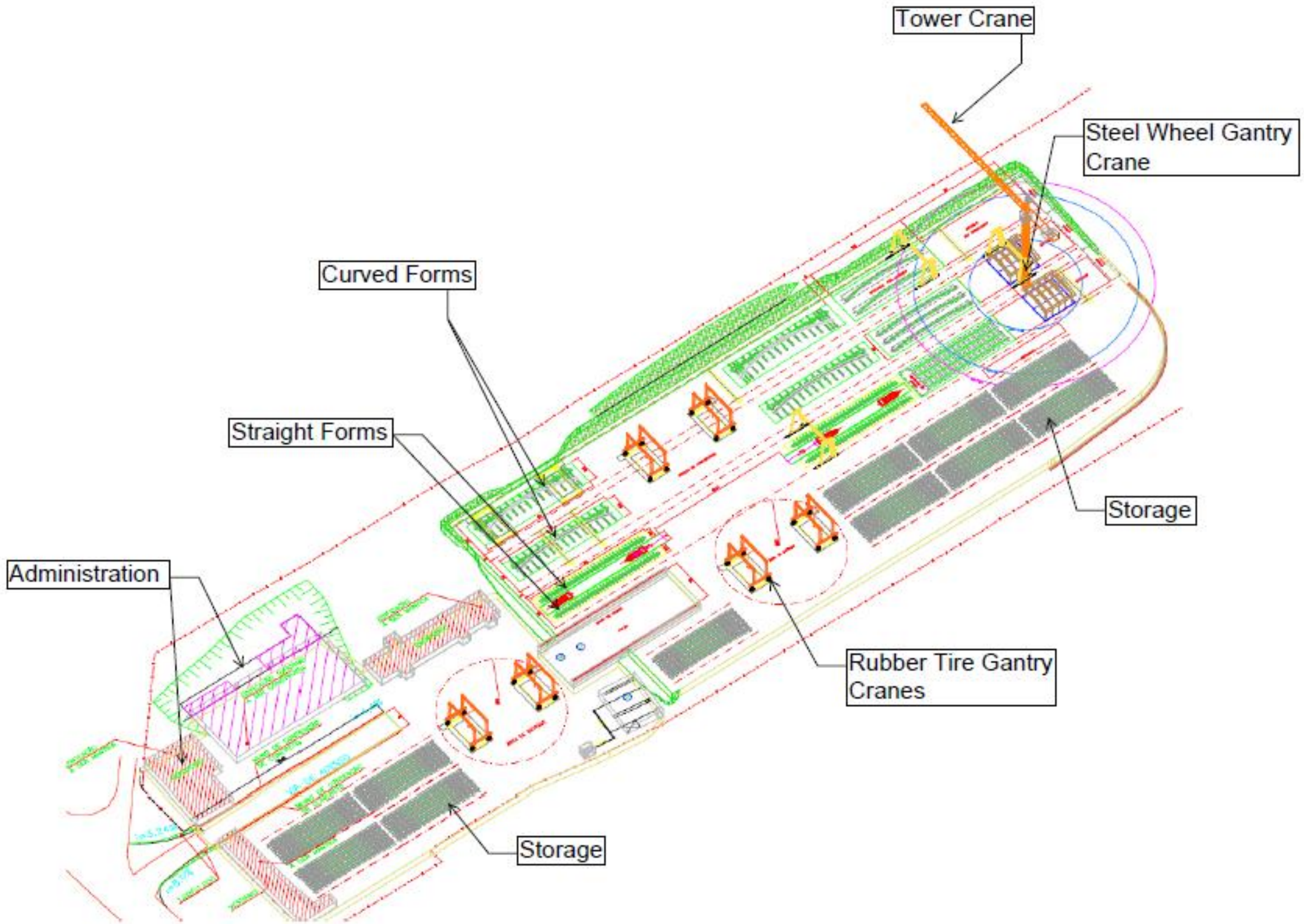
Foundation at Single Columns



Foundation Under Existing Street

Beam Fabrication

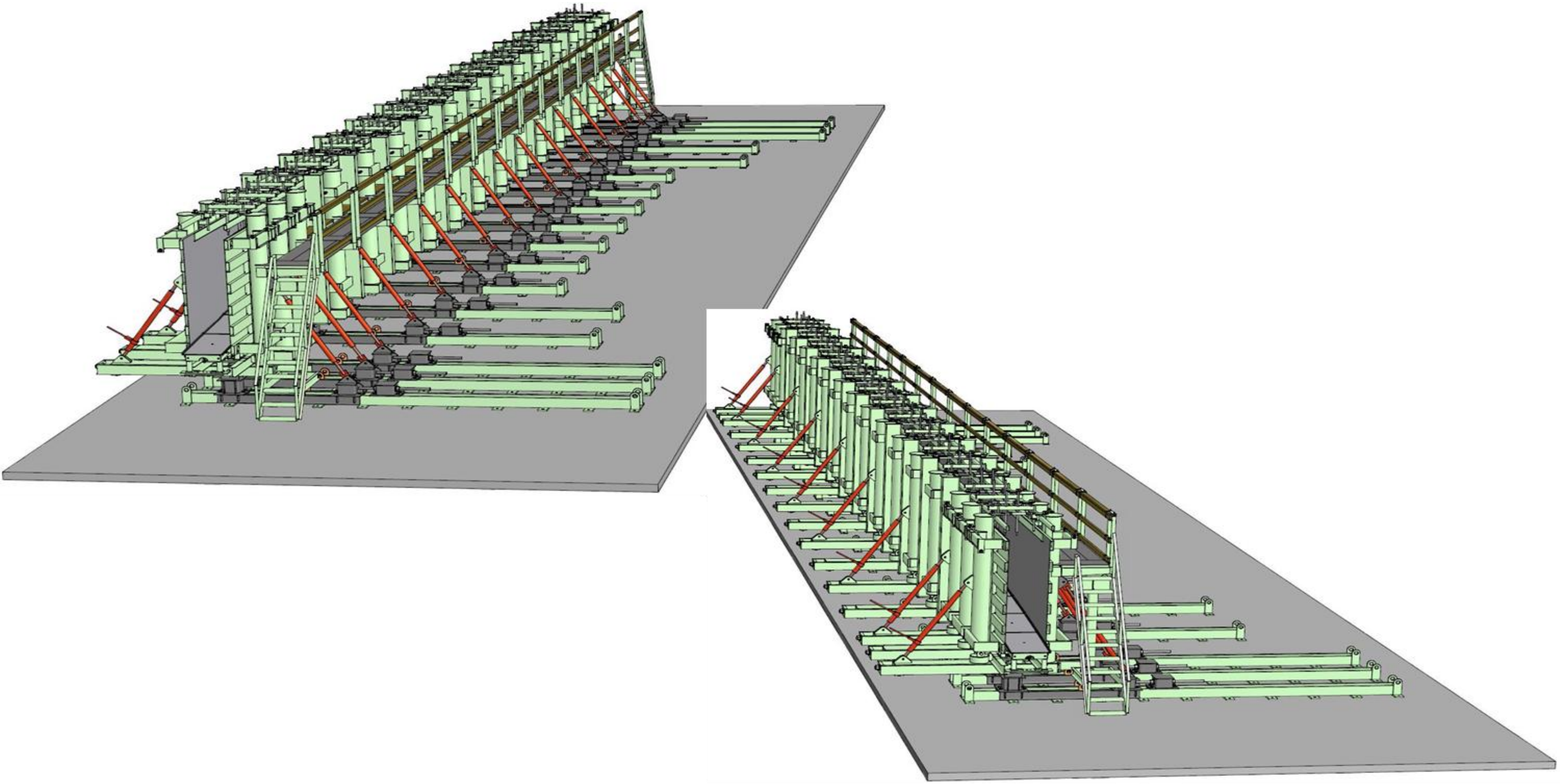
Structural Components – Precast Yard



***Structural Components* – Forms**

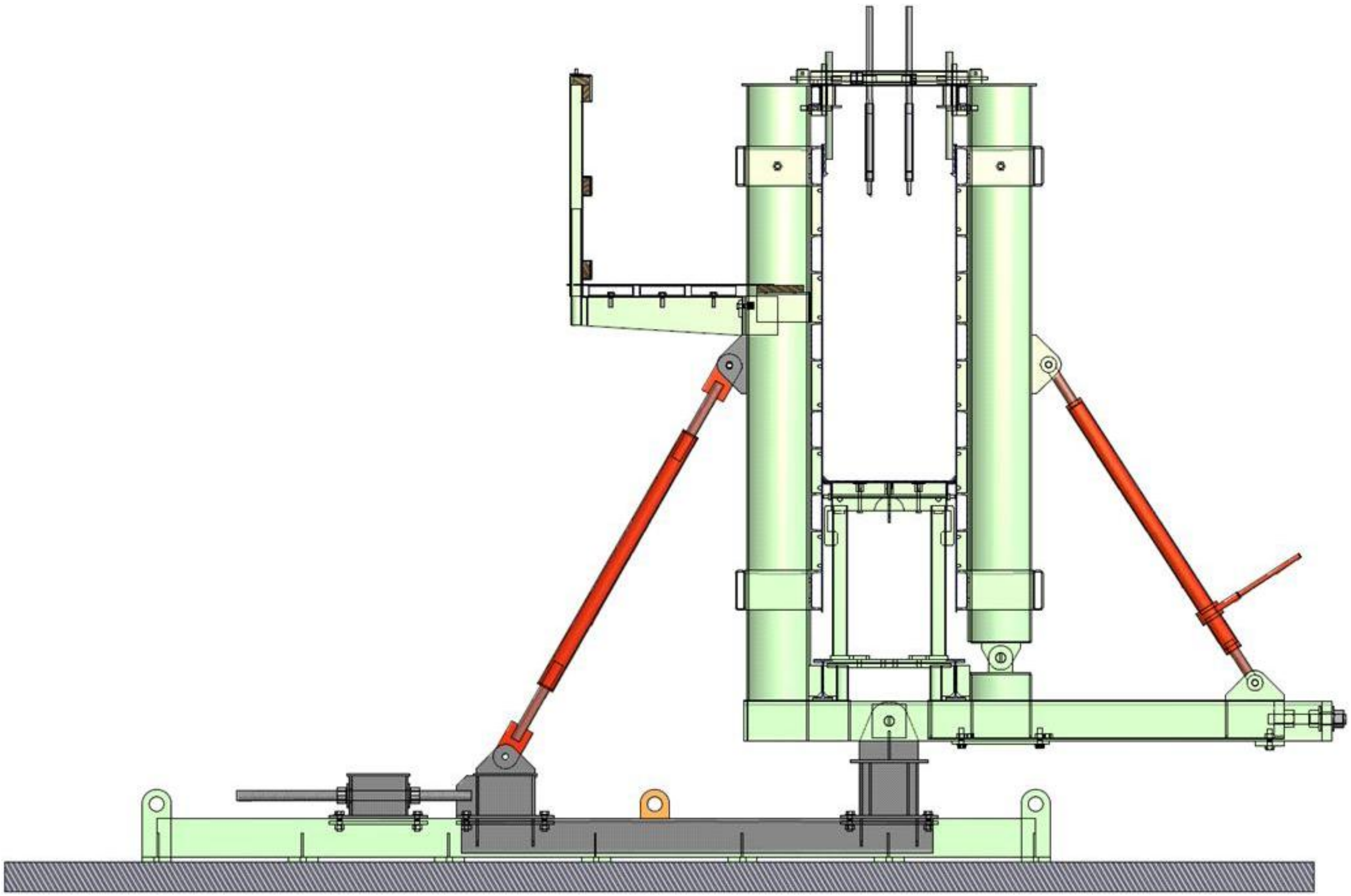
Pré-montagem das formas
na fábrica da Helser,
Tualatin, Oregon

Structural Components – Forms



Vista da forma em perspectiva

Structural Components – Forms



Vista da forma em perfil

Structural Components – Forms







Summary

Summary– Highlights

Monorail Structures are:

- Cost Effective
- Fast Fabrication and Deployment
- Visually pleasing
- Provide Structural Engineer Project Leadership

As Result:

- Communities maximize Infrastructure Funding
- Improve quality of life
- Mitigate consumption of non renewable resources

Summary– Recognition

Bentley – RM / Innova:

- Marcos Beier
- Adriana Gonorazky
- Steve Moore
- Laura Thompson
- Huijun Dong
- Robert Naples
- Ben Hicks
- Stephen Cupp
- Michael Shipler
- Alan Saastad

Metro SP:

- Paulo Meca
- Orlando Ferreira
- Deborah XXXX
- Ary Toledo
- Ivan Piccoli

Construtora Queiroz Galvao:

- Jose Henrique de Avila
- Adriano Cunha
- Francisco de Asis Serafim
- Henrique Ferraz
- Marcos Viena Pecly

CEML, Consortio Monotrilho Leste:

- Fernando de Oliviera Gomes
- Antonio Carlos do Nascimento
- Arthur Venuto
- Nadia Moura de Souza
- Jose Evandro Santos

Bombardier Transportation

- Chris Fifield
- Ivan Vrabac
- Sarah Byers
- Bob Needermeyer
- Nelson Aidar
- Pat McGinley
- Bruce MacDonald
- Doug Heitzenrater
- Halil Oznan
- Jayson Nestor

Planservi

- Carlos Akira Murakami
- Silvia Silmão
- Eder Toshio Iguti
- Roberta Leopoldo e Silva
- Jean Le Guevellou
- Marcos Silva

Setepla / Tecnifer

- Yanagi Yoshiaki
- Marcio Cecci

PROENGE

- Valter Braga
- Marc André Chamouton
- Alberto Vitale

Zamarion Millen / Nucleo

- Eduardo Barros Millen
- Rogerio Martinati
- Murilo Martins

And the many more not named, but who made this project possible with their daily interfaces with the principal author

T H A N K   Y O U - O B R I G A D O

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Summary– Questions?