Implementation of the Strut-and-Tie Method

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MARCH 8, 2022
VIRTUAL

minnesota Concrete Council
Dedicated to Cast-in-Place Concrete

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The Strut-and-Tie Method

The strut-and-tie method is intended for the design of discontinuity regions, where concrete structures most often fail

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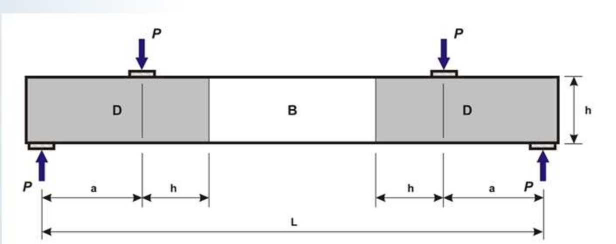
D-Regions and B-Regions



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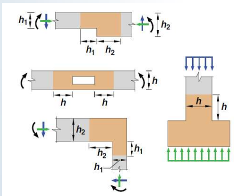
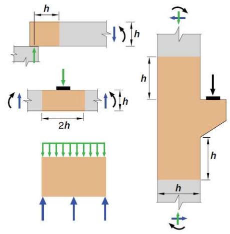
D-Regions and B-Regions



Geometric and Loading Discontinuities



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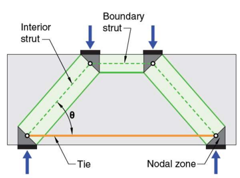
Definition of Strut-and-Tie Model

Definition (318-19)

strut-and-tie model–truss model of a member or discontinuity region made up of struts and ties connected at nodes and capable of transferring the factored loads to the supports or to adjacent beam regions

Terminology



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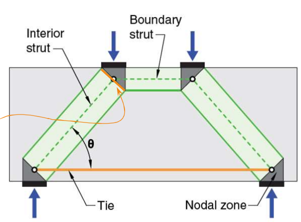
Strut Strength

$F_{ns} = A_{cs} f_{ce}$

$f_{ce} = 0.85 \beta_c \beta_s f_c'$

A_{cs} measured perpendicular to the strut at node strut interface



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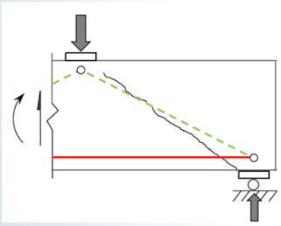
Strut Strength



Struts are weaker where they are crossed by skewed cracks (Schlaich et al. 1987). β_s is lower.

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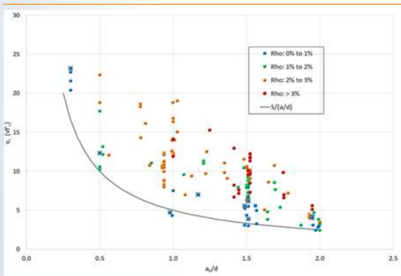
Strut Strength



$$\lambda_s = \sqrt{\frac{2}{1+\frac{d}{10}}} \le 1$$

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Strut Strength

Strut Location	Strut Type	Criteria	β_s	
Tension members or tension zones of members	Any	All cases	0.4	(a)
All other cases	Boundary struts	All cases	1.0	(b)
	Interior struts	Distributed reinforcement	0.75	(c)
		$V_u \le \phi 5 \lambda \lambda_s \sqrt{f'_c} b_w d \tan\theta$	0.75	(d)
		Beam-column joints	0.75	(e)
		All other cases	0.4	(f)

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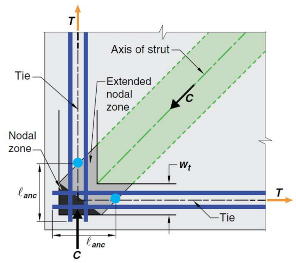
Tie Strength

$F_{nt} = A_{ts}f_y + A_{tp}\Delta f_p$



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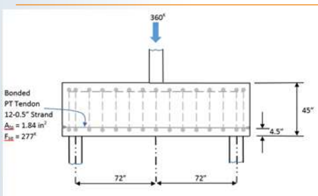
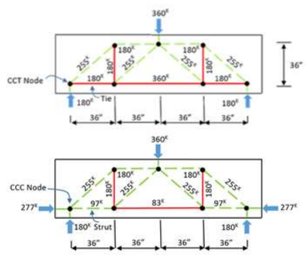
Tie Strength



$F_{nt} = A_{ts}f_y + A_{tp}\Delta f_p$

$\Delta f_p = f_{py} - f_{se}$ or $60\ ksi$



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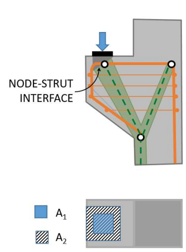
Node Strength

$F_{nn} = A_{nz}f_{ce}$

$f_{ce} = 0.85\beta_c\beta_n f_c'$

$\beta_c = \sqrt{A_2/A_1} \leq 2$ (at bearing surfaces)



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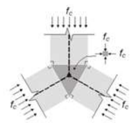
Node Strength

$F_{nn} = A_{nz} f_{ce}$

$f_{ce} = 0.85 \beta_c \beta_n f_c'$

Configuration of nodal zone	β_n	
Nodal zone bounded by struts, bearing areas, or both	1.0	(a)
Nodal zone anchoring one tie	0.8	(b)
Nodal zone anchoring two or more ties	0.6	(c)


a) CCC node

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Node Strength

$F_{nn} = A_{nz} f_{ce}$

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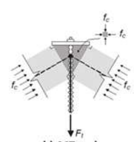
b) CCT node

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Node Strength

$F_{nn} = A_{nz} f_{ce}$

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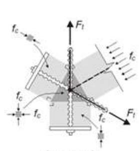
c) CTT node

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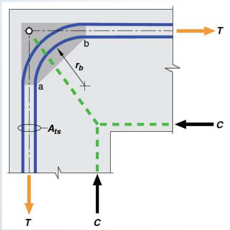
Note Strength: Curved-Bar Nodes



Curved-bar node (CTT)

$$\beta_n = 0.6 \xRightarrow{yie}$$

$$r_b \geq \frac{2A_{ts}f_y}{b_s f_c'}$$

A curved-bar node is formed by the bend region of a continuous reinforcing bar (or bars) where two ties extending from the bend region are intersected by a strut or the resultant of two or more struts.

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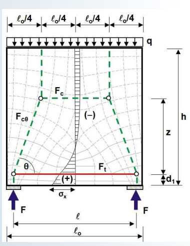
Deep Beams



0.25% distributed reinforcement is required in each direction for deep beams

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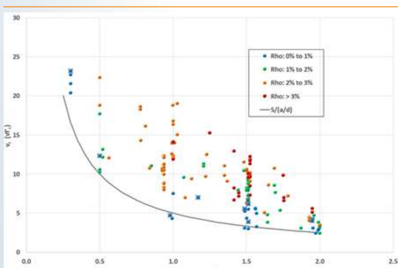
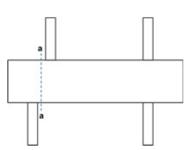
Deep Beams





Transfer Girder Design
318-19: Shear stress is no longer limited to 10 $\sqrt{f_c'}$

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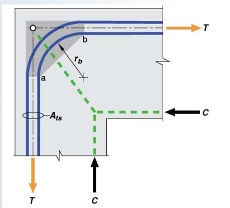
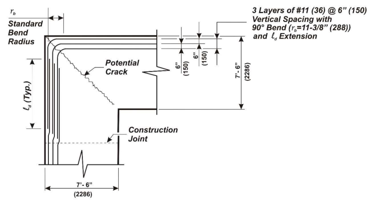
Frame Corners





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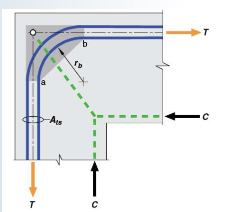
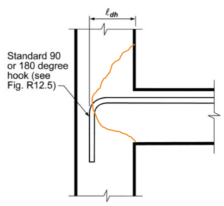
Frame Corners





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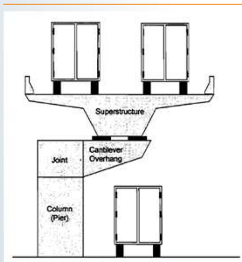
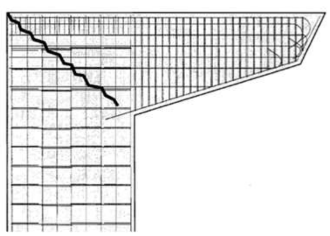
Frame Corners





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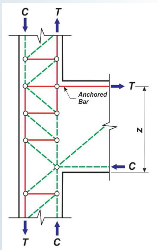
Frame Corners



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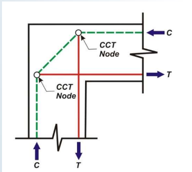
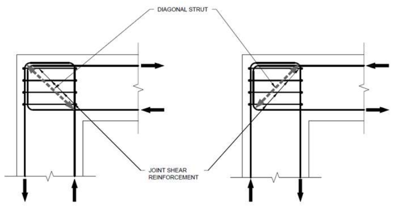
Frame Corners





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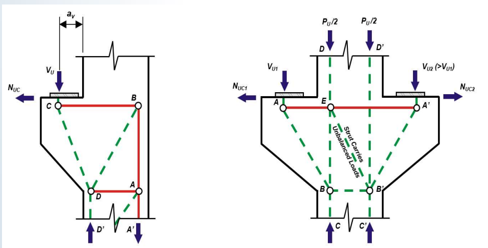
Corbels



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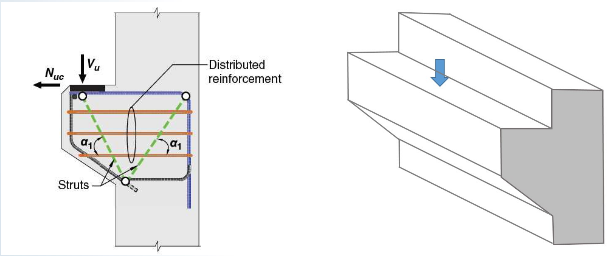
Corbels



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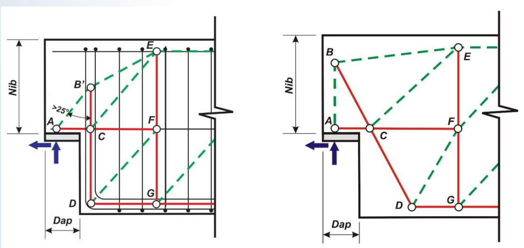
Dapped Ends



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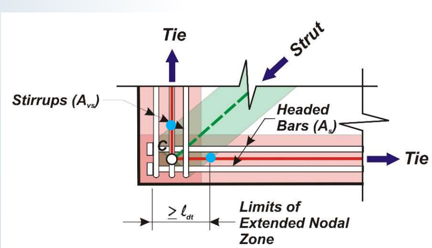
Dapped Ends



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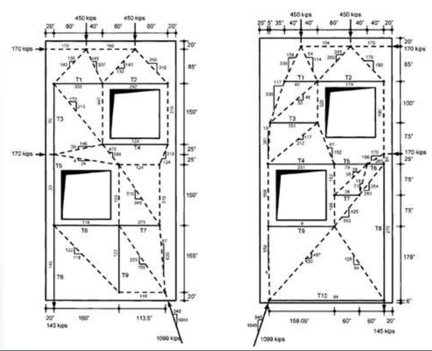
Walls and Beams with Openings



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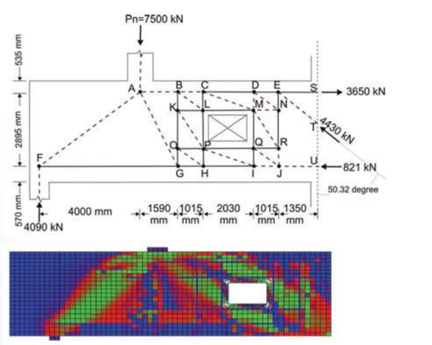
Walls and Beams with Openings



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Walls and Beams with Openings

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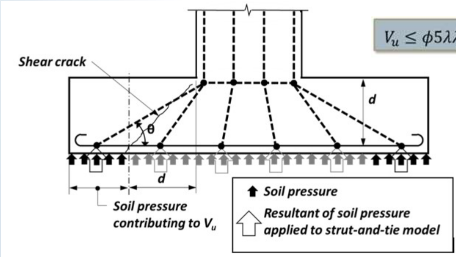
Footings



$$V_u \le \phi 5 \lambda \lambda_s \sqrt{f'_c}\, b_w d \tan\theta$$

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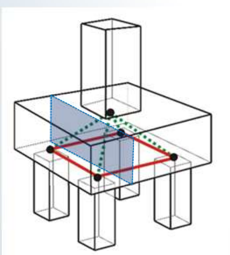
Pile Caps



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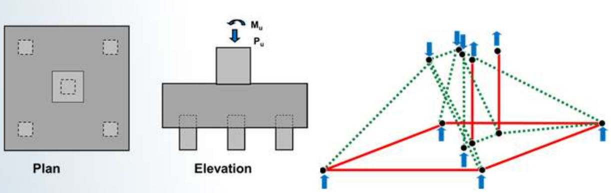
Pile Caps



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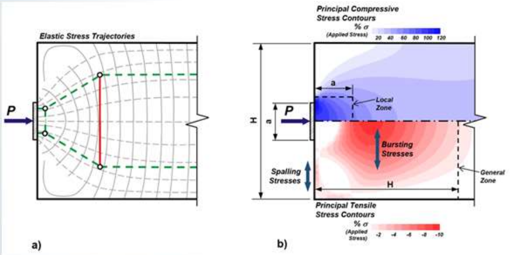
Post-Tensioned Anchorage Zones



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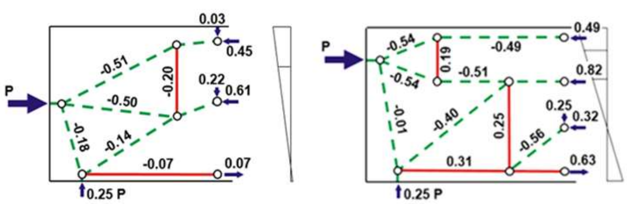
Post-Tensioned Anchorage Zones



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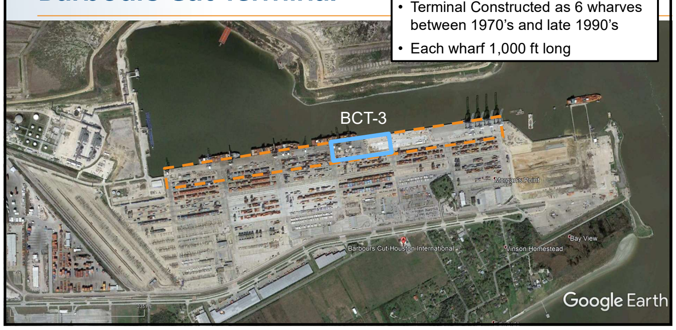
Barbours Cut Terminal

- Located in Morgan's Point, TX
- Terminal Constructed as 6 wharves between 1970's and late 1990's
- Each wharf 1,000 ft long



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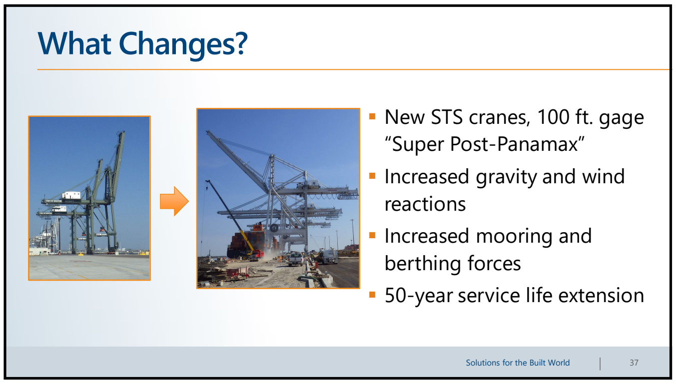
What Changes?
New STS cranes, 100 ft. gage "Super Post-Panamax"
Increased gravity and wind reactions
Increased mooring and berthing forces
50-year service life extension
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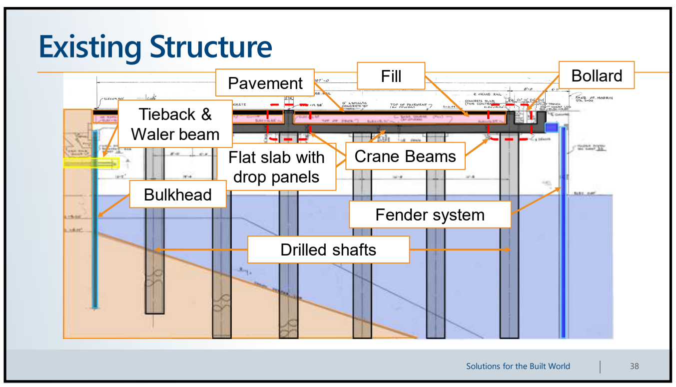
Existing Structure
Pavement
Fill
Bollard
Tieback & Waler beam
Flat slab with drop panels
Crane Beams
Bulkhead
Fender system
Drilled shafts
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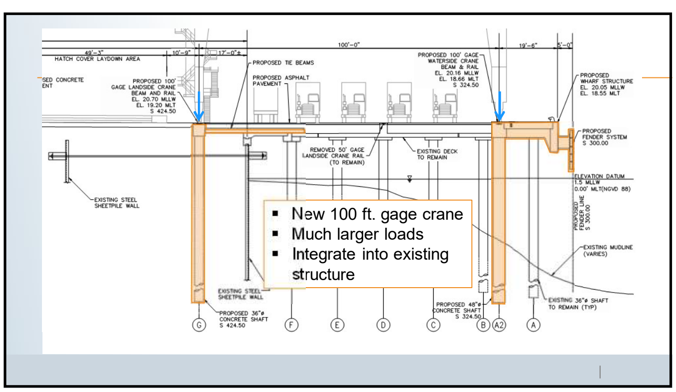
New 100 ft. gage crane
Much larger loads
Integrate into existing structure

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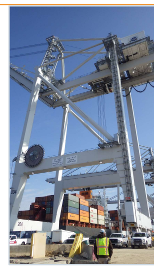
New Container Crane



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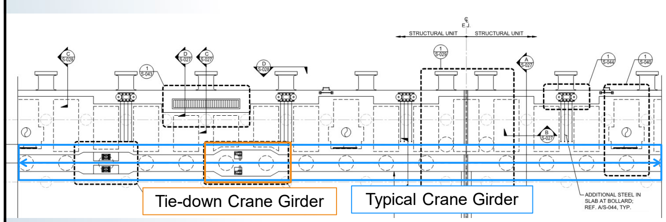
Partial Plan



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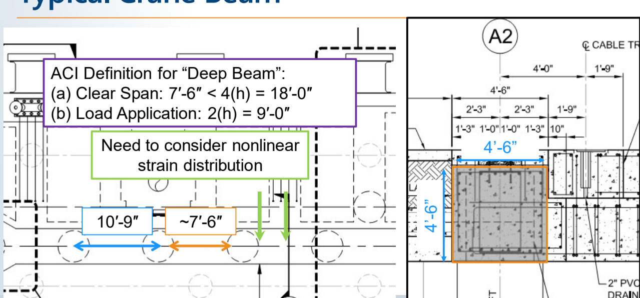
Typical Crane Beam



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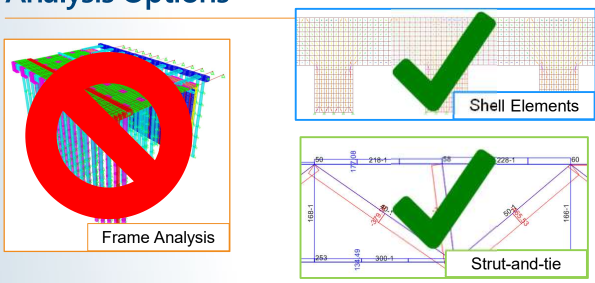
Analysis Options



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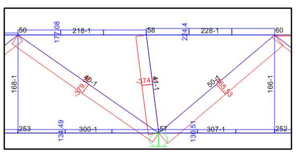
Strut-and-Tie Models Used for Design

- Multiple challenges
  - Moving loads
  - Flexible supports
  - Three-dimensional behavior



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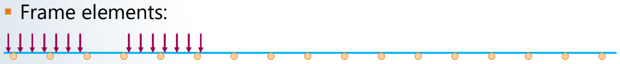
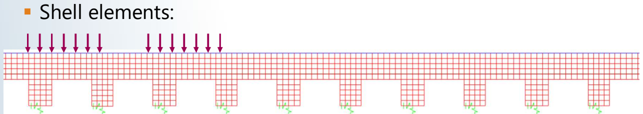
Moving Loads

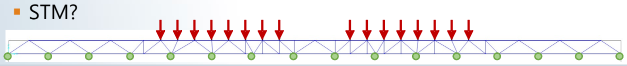
- Frame elements:



- Shell elements:



- STM?



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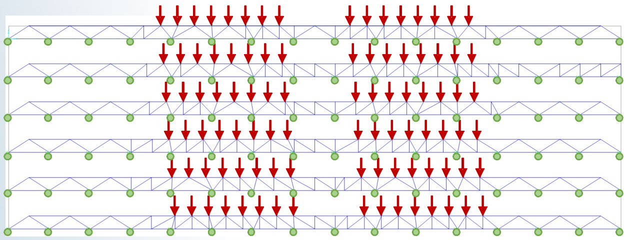
Multiple Models Required



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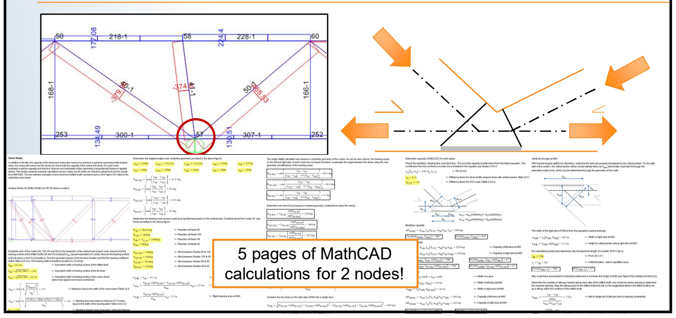
Tedious Calculations



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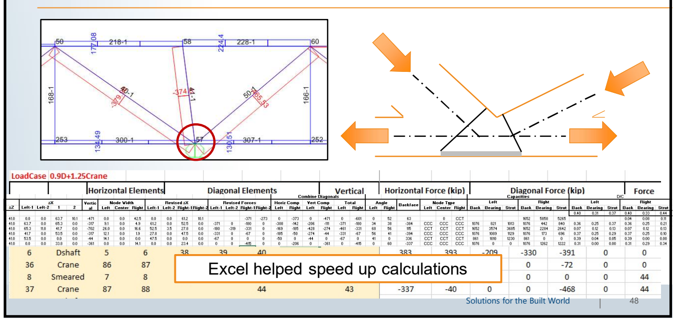
Design Aid



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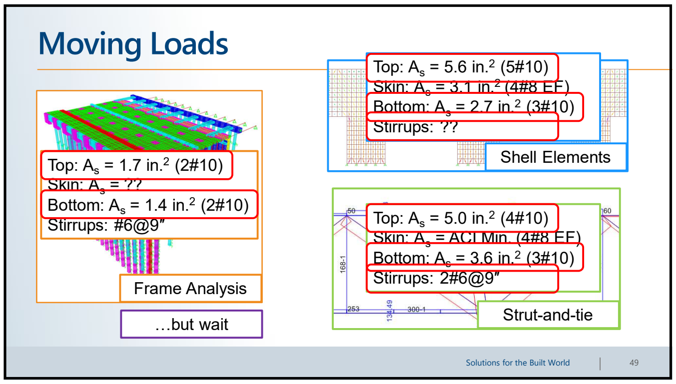
Moving Loads
Top: A_s = 5.6 in.^{2} (5#10)
Skin: A_s = 3.1 in.^{2} (4#8 EF)
Bottom: A_s = 2.7 in.^{2} (3#10)
Stirrups: ??
Shell Elements
Top: A_s = 1.7 in.^{2} (2#10)
Skin: A_s = ??
Bottom: A_s = 1.4 in.^{2} (2#10)
Stirrups: #6@9″
Frame Analysis
…but wait
Top: A_s = 5.0 in.^{2} (4#10)
Skin: A_s = ACI Min. (4#8 EF)
Bottom: A_s = 3.6 in.^{2} (3#10)
Stirrups: 2#6@9″
Strut-and-tie
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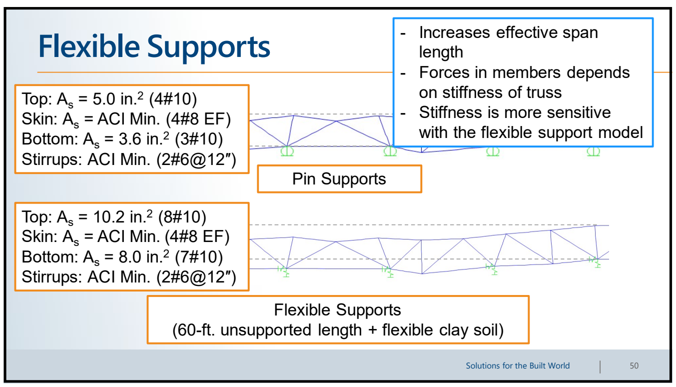
Flexible Supports
- Increases effective span length
- Forces in members depends on stiffness of truss
- Stiffness is more sensitive with the flexible support model
Top: A_s = 5.0 in.^{2} (4#10)
Skin: A_s = ACI Min. (4#8 EF)
Bottom: A_s = 3.6 in.^{2} (3#10)
Stirrups: ACI Min. (2#6@12″)
Pin Supports
Top: A_s = 10.2 in.^{2} (8#10)
Skin: A_s = ACI Min. (4#8 EF)
Bottom: A_s = 8.0 in.^{2} (7#10)
Stirrups: ACI Min. (2#6@12″)
Flexible Supports
(60-ft. unsupported length + flexible clay soil)
Solutions for the Built World
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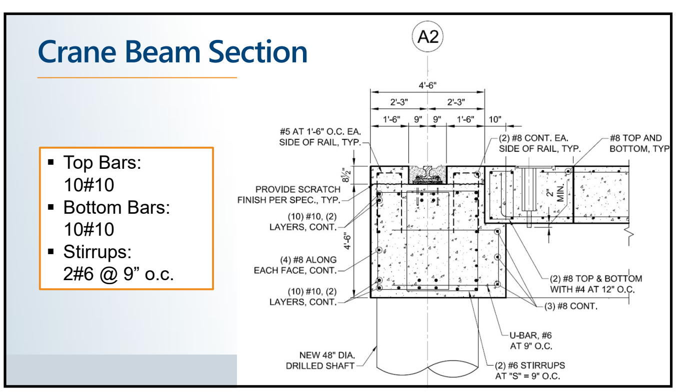
Crane Beam Section
A2
Top Bars: 10#10
Bottom Bars: 10#10
Stirrups: 2#6 @ 9" o.c.
4'-6"
2'-3"
2'-3"
1'-6"
9"
9"
1'-6"
10"
#5 AT 1'-6" O.C. EA. SIDE OF RAIL, TYP.
(2) #8 CONT. EA. SIDE OF RAIL, TYP.
#8 TOP AND BOTTOM, TYP.
PROVIDE SCRATCH FINISH PER SPEC., TYP.
(10) #10, (2) LAYERS, CONT.
(4) #8 ALONG EACH FACE, CONT.
(10) #10, (2) LAYERS, CONT.
(2) #8 TOP & BOTTOM WITH #4 AT 12" O.C.
(3) #8 CONT.
U-BAR, #6 AT 9" O.C.
NEW 48" DIA. DRILLED SHAFT
(2) #6 STIRRUPS AT "S" = 9" O.C.

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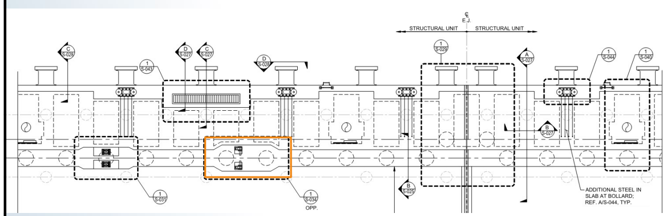
Tie-down Crane Girder



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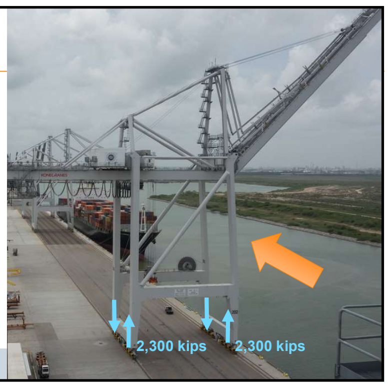
Tie Downs

- Required to restrain crane against overturning during hurricane wind event
- One tie down location per 8-wheel group on crane
- Max. uplift = 2,300 kips



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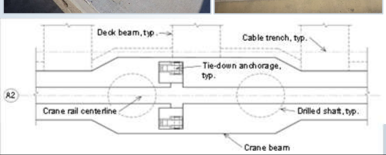
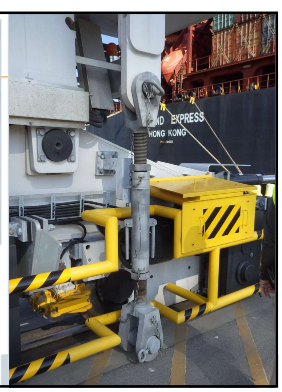
Tie Downs





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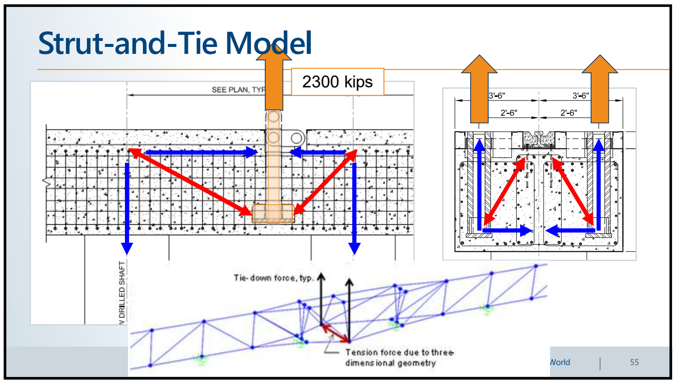
Strut-and-Tie Model
2300 kips
SEE PLAN, TYP
Tie-down force, typ.
Tension force due to three-dimensional geometry
3'-6"
2'-6"
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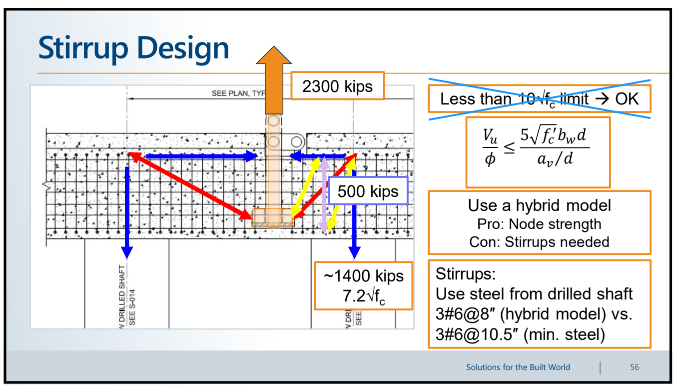
Stirrup Design
2300 kips
SEE PLAN, TYP
Less than 10√f'c limit → OK
$\frac{V_u}{\phi} \le \frac{5\sqrt{f'_c}\, b_w d}{a_v/d}$
500 kips
Use a hybrid model
Pro: Node strength
Con: Stirrups needed
~1400 kips
7.2√f'c
Stirrups:
Use steel from drilled shaft
3#6@8″ (hybrid model) vs.
3#6@10.5″ (min. steel)
Solutions for the Built World
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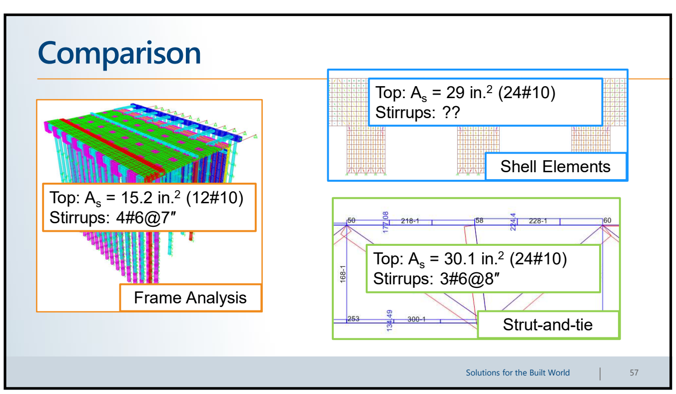
Comparison
Top: A_s = 15.2 in.^{2} (12#10)
Stirrups: 4#6@7″
Frame Analysis
Top: A_s = 29 in.^{2} (24#10)
Stirrups: ??
Shell Elements
Top: A_s = 30.1 in.^{2} (24#10)
Stirrups: 3#6@8″
Strut-and-tie
Solutions for the Built World
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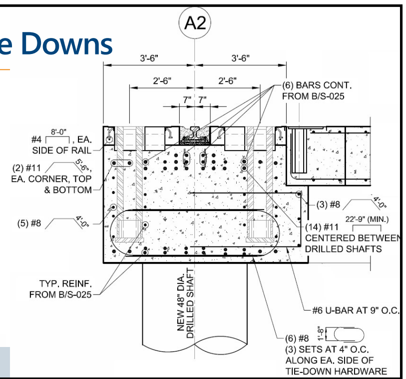
Crane Beam at Tie Downs

- Top Bars: 14#11 and 6#10
- Bottom Bars: 10#10
- Stirrups: 3#6
- Hairpins at base of tie down: 6#8



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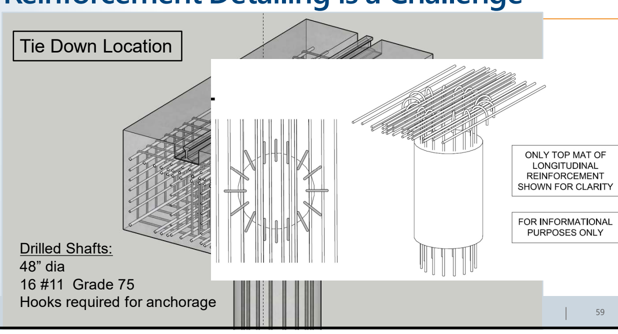
Reinforcement Detailing is a Challenge



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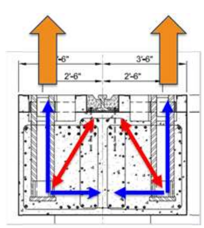
Summary

- Implementation for common discontinuity regions
  - Deep beams
  - Frame corners
  - Corbels
  - Dapped ends
  - Beams supporting beams
  - Inverted T-beams
  - Walls and beams with openings
  - Coupling beams
  - Footings
  - Pile caps
  - Post-tensioned anchorage zones
- Barbours Cut Terminal project example



Solutions for the Built World | 60

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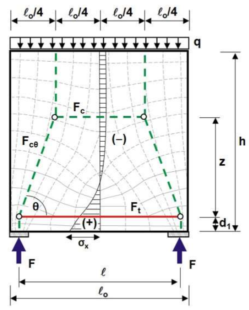
The Strut-and-Tie Method

IMPLEMENTATION

Questions?



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