

Implementation of the Strut-and-Tie Method



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VIRTUAL



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1

The Strut-and-Tie Method

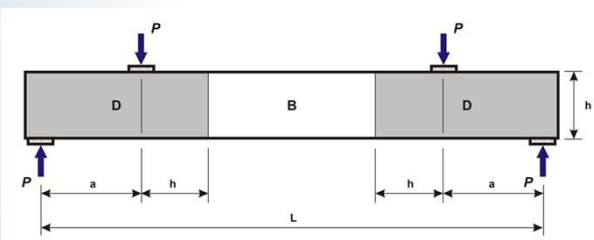


The strut-and-tie method is intended for the design of discontinuity regions, where concrete structures most often fail

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2

D-Regions and B-Regions



The diagram shows a beam of length L and height h . It is supported at both ends by upward forces P . Two downward point loads P are applied. The regions are defined as follows: D (Discontinuity) regions are shaded and occur near the supports and the point loads. B (Basic) regions are unshaded and occur between the D regions. The distance from each support to the first D region is a , and the length of each D region is h . The length of the B region between the two D regions is $L - 2a - 2h$.

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3

D-Regions and B-Regions

Geometric and Loading Discontinuities

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4

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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5

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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6

Strut Strength

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

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7

Strut Strength

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

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8

Strut Strength

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

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9

Tie Strength

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

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10

Tie Strength

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

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

Solutions for the Built World | 11

11

Node Strength

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

$$f_{ce} = 0.85\beta_c\beta_n f'_c$$

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

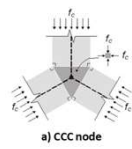
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12

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

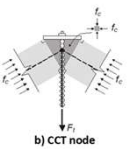
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13

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)



b) CCT node

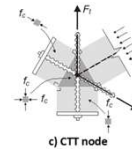
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14

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)

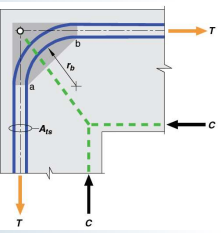


c) CTT node

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15

Note Strength: Curved-Bar Nodes



$$\beta_n = 0.6 \frac{y_{ie}}{r_b}$$

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

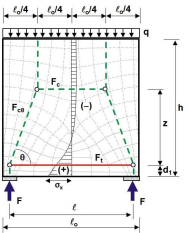
A curved-bar node is formed by the bend region of a continuous reinforcing bar (or bars) where two ties extending from the bend region are intersected by a strut or the resultant of two or more struts.

Curved-bar node (CTT)

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16

Deep Beams

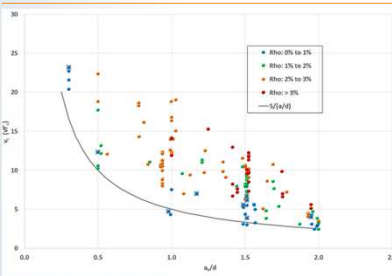


0.25% distributed reinforcement is required in each direction for deep beams

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17

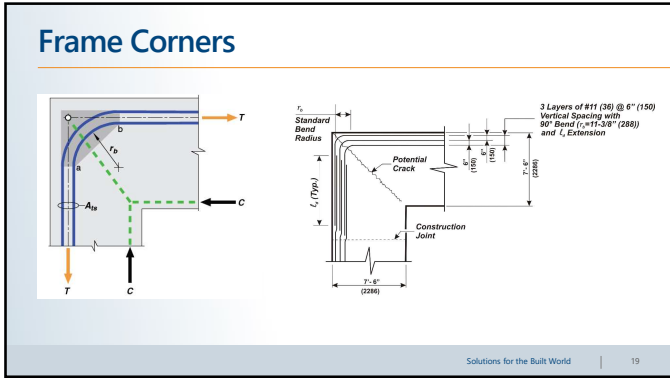
Deep Beams



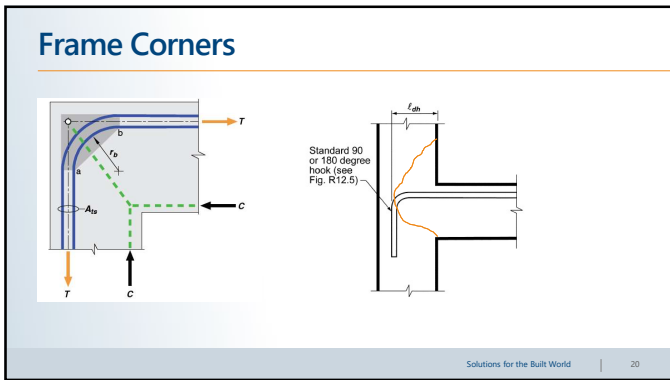
Transfer Girder Design 318-19: Shear stress is no longer limited to $10\sqrt{f'_c}$

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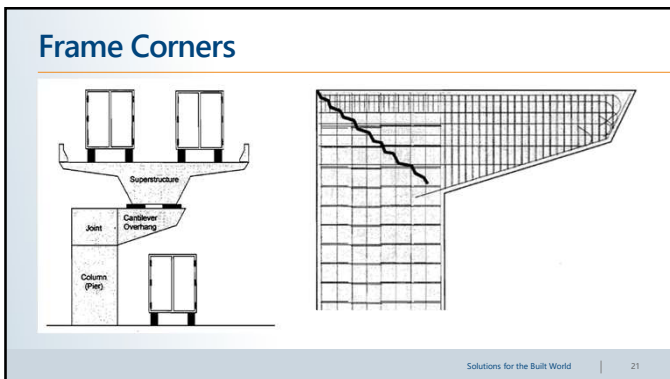
18



19



20



21

Frame Corners

The diagram illustrates a frame corner with various forces and components. At the top, there are vertical forces labeled 'C' (compression) and 'T' (tension). On the right side, there are horizontal forces labeled 'T' (tension) and 'N' (normal force). At the bottom, there are vertical forces labeled 'T' (tension) and 'C' (compression). A red line represents an 'Anchored Bar' extending from the top corner towards the bottom. The diagram is set against a light blue background.

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22

Frame Corners

This slide contains three diagrams related to frame corners. The leftmost diagram shows a corner with 'CCT Node' labels and forces 'C' and 'T'. The middle diagram shows a corner with a 'DIAGONAL STRUT' and 'JOINT SHEAR REINFORCEMENT'. The rightmost diagram shows a corner with forces 'C' and 'T' and a diagonal strut. The diagrams are set against a light blue background.

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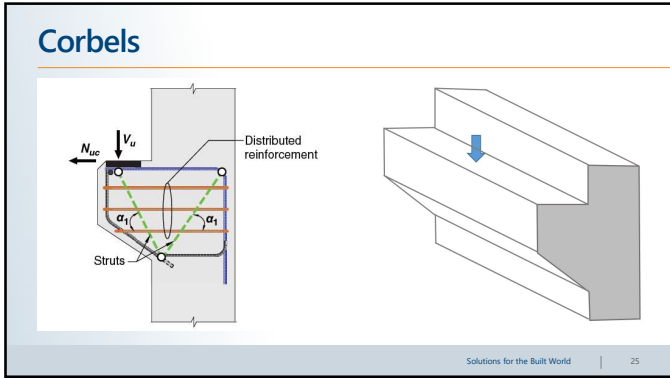
23

Corbels

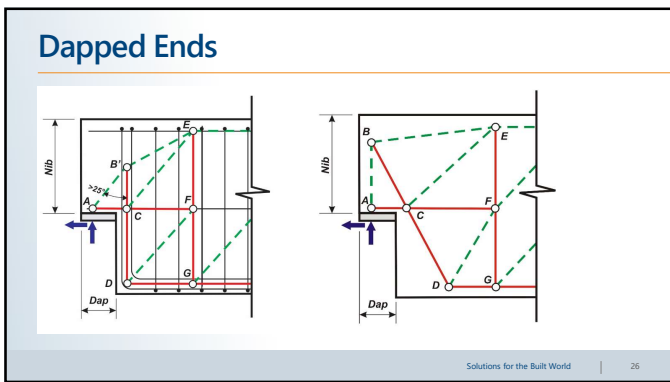
The slide features two diagrams of corbels. The left diagram shows a corbel with forces N_{sc} , V_{sc} , and N_{sc} at the top, and forces D' and A' at the bottom. It also shows dimensions a and d . The right diagram shows a corbel with forces $P_u/2$, V_{sc} , and N_{sc} at the top, and forces D' and A' at the bottom. It also shows dimensions a and d . The diagrams are set against a light blue background.

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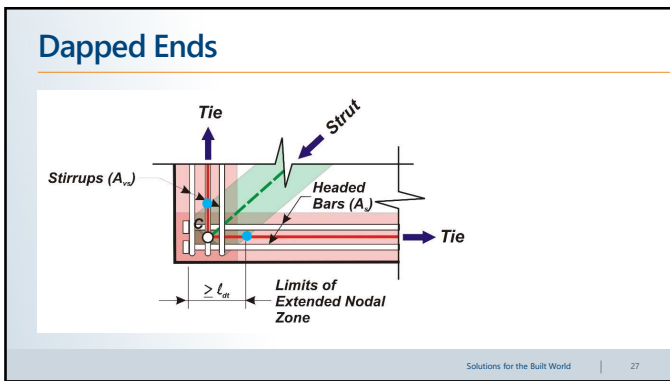
24



25

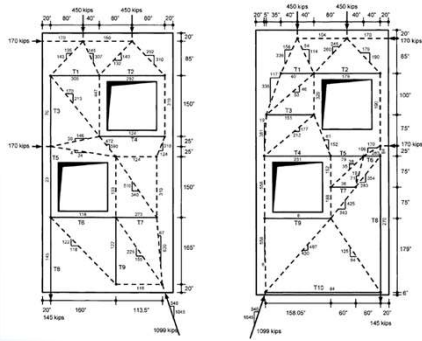


26



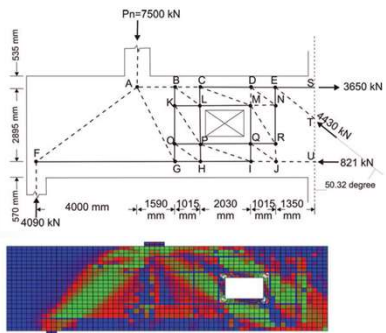
27

Walls and Beams with Openings



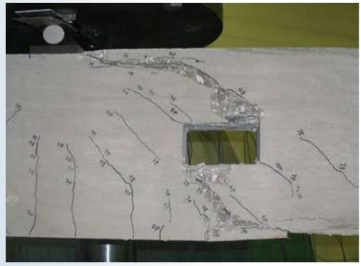
28

Walls and Beams with Openings



29

Walls and Beams with Openings



30

Footings

Shear crack

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

Soil pressure contributing to V_u

Soil pressure Resultant of soil pressure applied to strut-and-tie model

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31

Pile Caps

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

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32

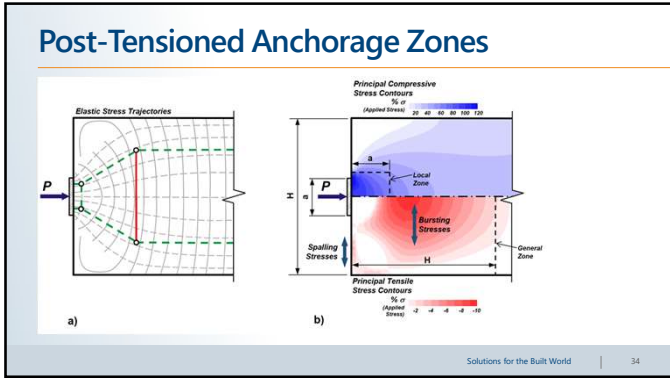
Pile Caps

Plan

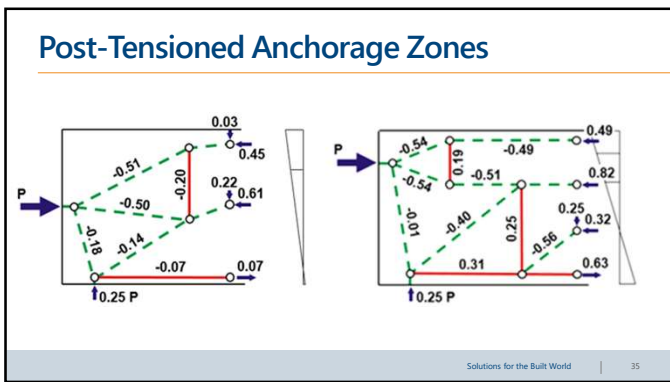
Elevation

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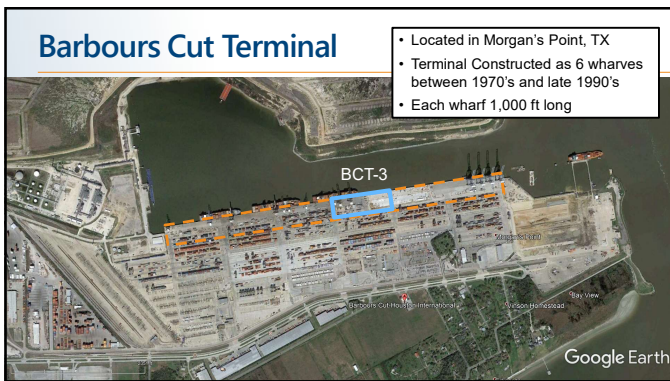
33



34

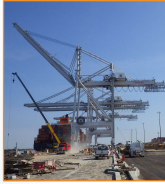


35



36

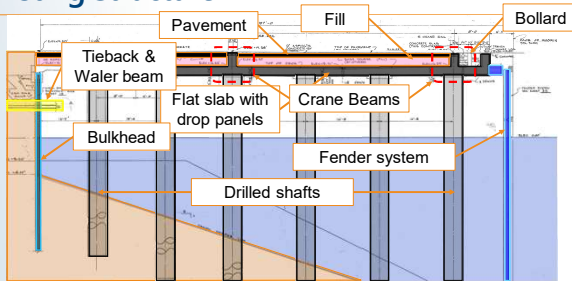
What Changes?



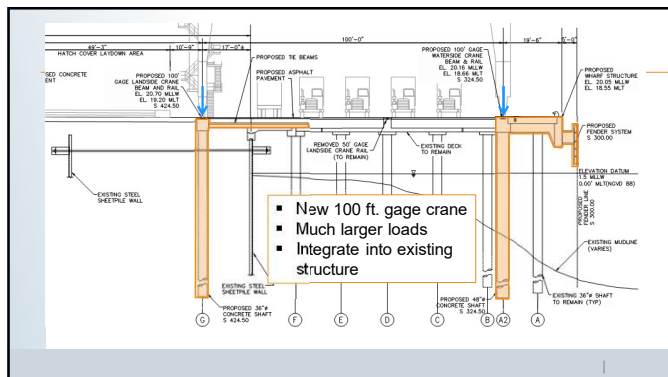
- New STS cranes, 100 ft. gage "Super Post-Panamax"
- Increased gravity and wind reactions
- Increased mooring and berthing forces
- 50-year service life extension

37

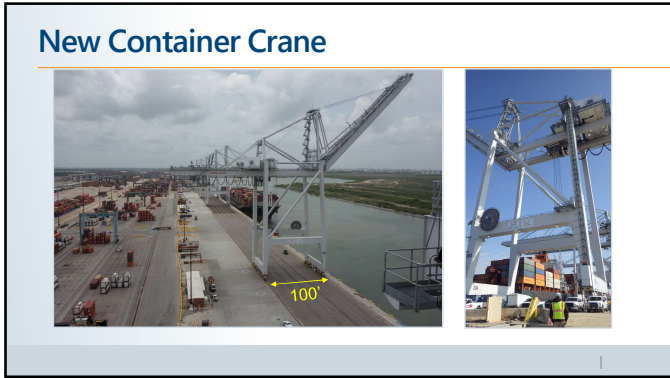
Existing Structure



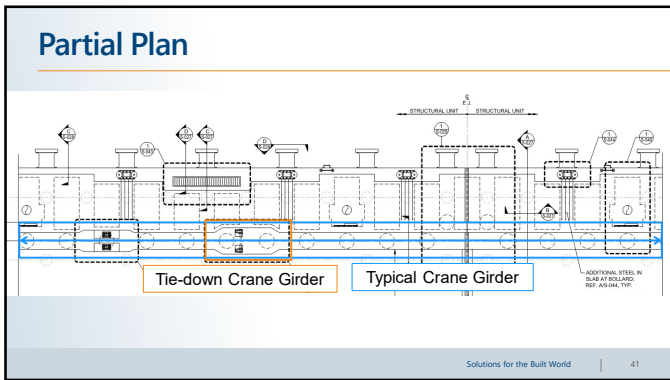
38



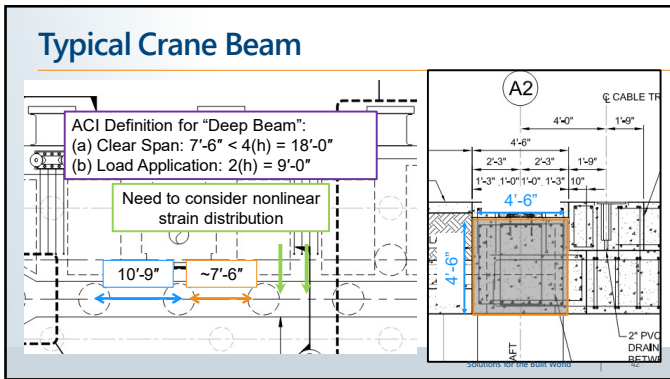
39



40



41



42

Analysis Options

The slide compares three analysis methods. On the left, 'Frame Analysis' is shown with a 3D model of a structure and a large red 'X' over it, indicating it is not the preferred option. On the right, 'Shell Elements' is shown with a 2D grid model and a green checkmark, indicating it is a preferred option. Below that, 'Strut-and-tie' is shown with a truss model and a green checkmark, also indicating it is a preferred option. The slide footer contains the text 'Solutions for the Built World' and the number '43'.

43

Strut-and-Tie Models Used for Design

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

A detailed diagram of a strut-and-tie model for a beam-column joint. It shows a truss structure with nodes and members. Members are labeled with numbers such as 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 810, 820, 830, 840, 850, 860, 870, 880, 890, 900, 910, 920, 930, 940, 950, 960, 970, 980, 990, 1000. The diagram also shows various forces and moments acting on the structure. The slide footer contains the text 'Solutions for the Built World' and the number '44'.

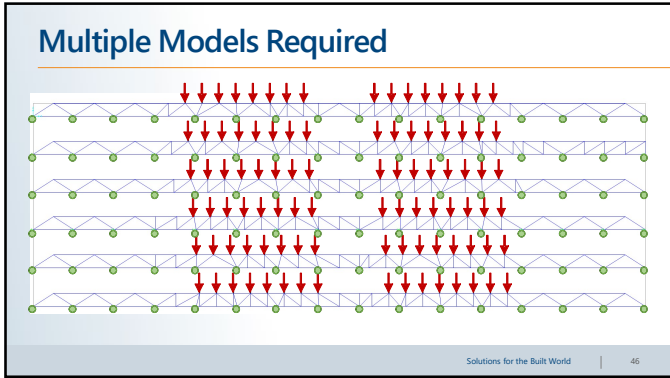
44

Moving Loads

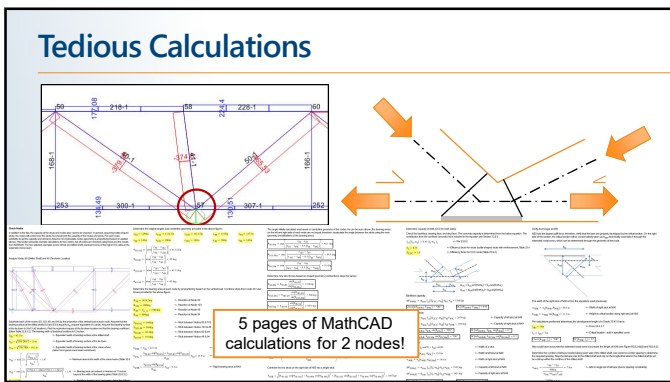
- Frame elements:
- Shell elements:
- STM?

The slide illustrates three different modeling approaches for moving loads on a beam. The first, 'Frame elements', shows a beam with a series of vertical arrows representing moving loads. The second, 'Shell elements', shows a beam with a grid of elements and vertical arrows representing moving loads. The third, 'STM?', shows a beam with a truss structure and vertical arrows representing moving loads. The slide footer contains the text 'Solutions for the Built World' and the number '45'.

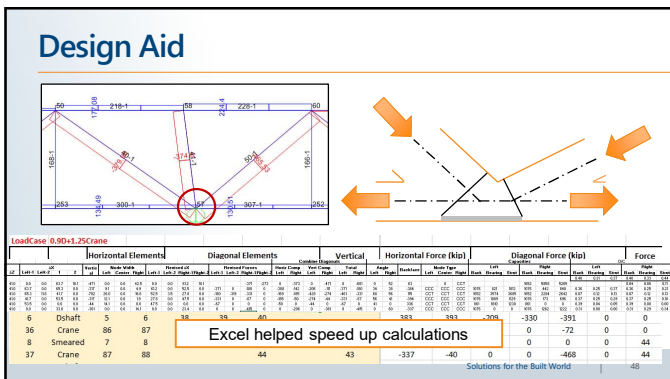
45



46



47



48

Moving Loads

The diagram shows two scenarios for handling moving loads. On the left, 'Frame Analysis' shows a truss structure with a moving load and a callout box containing reinforcement details: Top: $A_s = 1.7 \text{ in.}^2$ (2#10), Skin: $A_s = ??$, Bottom: $A_s = 1.4 \text{ in.}^2$ (2#10), and Stirrups: #6@9". Below this is a purple box that says "...but wait". On the right, 'Shell Elements' shows a cross-section of a beam with a moving load and a callout box containing reinforcement details: Top: $A_s = 5.6 \text{ in.}^2$ (5#10), Skin: $A_s = 3.1 \text{ in.}^2$ (4#8 EF), Bottom: $A_s = 2.7 \text{ in.}^2$ (3#10), and Stirrups: ???. Below this is a green box labeled 'Strut-and-tie' with reinforcement details: Top: $A_s = 5.0 \text{ in.}^2$ (4#10), Skin: $A_s = \text{ACI Min.}$ (4#8 EF), Bottom: $A_s = 3.6 \text{ in.}^2$ (3#10), and Stirrups: 2#6@9". At the bottom right of the slide, it says 'Solutions for the Built World | 49'.

49

Flexible Supports

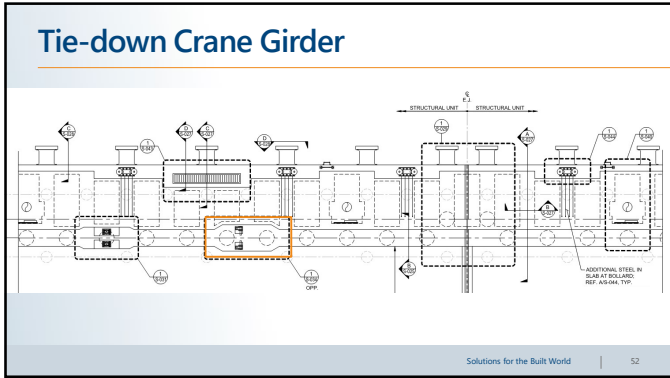
The diagram compares two support models for a truss. The top model, 'Pin Supports', shows a truss on four fixed pin supports with a callout box containing reinforcement details: Top: $A_s = 5.0 \text{ in.}^2$ (4#10), Skin: $A_s = \text{ACI Min.}$ (4#8 EF), Bottom: $A_s = 3.6 \text{ in.}^2$ (3#10), and Stirrups: ACI Min. (2#6@12"). The bottom model, 'Flexible Supports', shows a truss on three supports where the middle support is flexible, with a callout box containing reinforcement details: Top: $A_s = 10.2 \text{ in.}^2$ (8#10), Skin: $A_s = \text{ACI Min.}$ (4#8 EF), Bottom: $A_s = 8.0 \text{ in.}^2$ (7#10), and Stirrups: ACI Min. (2#6@12"). Below this is a box that says '(60-ft. unsupported length + flexible clay soil)'. To the right of the trusses is a blue box containing the following text: '- Increases effective span length', '- Forces in members depends on stiffness of truss', and '- Stiffness is more sensitive with the flexible support model'. At the bottom right of the slide, it says 'Solutions for the Built World | 50'.

50

Crane Beam Section

The diagram shows a detailed cross-section of a crane beam, labeled 'A2'. The top width is 4'-6". Reinforcement details include: #5 bars at 1'-6" o.c. on each side of the rail; (2) #8 bars continuous on each side of the rail; #8 bars at the top and bottom; (10) #10 bars in two layers; (4) #8 bars along each face; (10) #10 bars in two layers; U-bars #6 at 9" o.c.; and (2) #6 stirrups at 15" = 9" o.c. A new 48" diameter drilled shaft is shown at the bottom. The beam is supported by a 30" wide, 4'-5" high pier. At the bottom left of the slide, a callout box lists the following reinforcement: Top Bars: 10#10, Bottom Bars: 10#10, and Stirrups: 2#6 @ 9" o.c. At the bottom right of the slide, it says 'Solutions for the Built World | 51'.

51



52

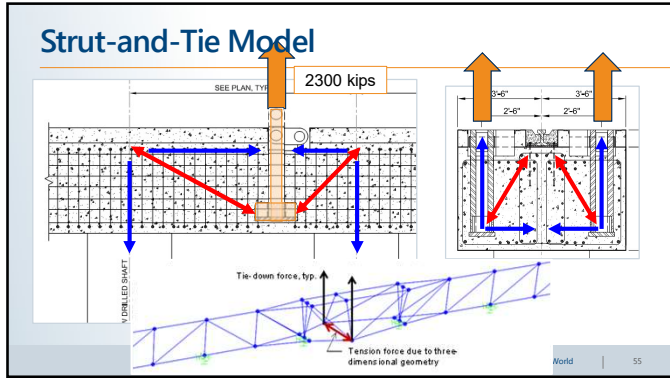
Tie Downs

- 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

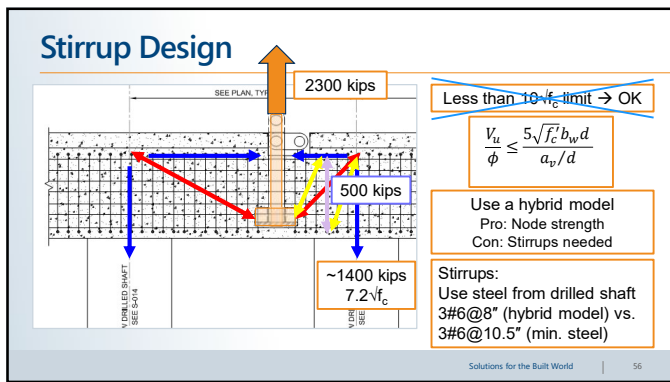
53

Tie Downs

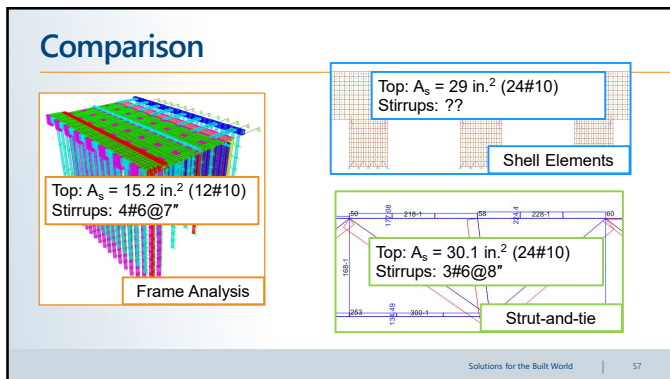
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55



56



57

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

58

Reinforcement Detailing is a Challenge

Tie Down Location

Drilled Shafts:
48" dia
16 #11 Grade 75
Hooks required for anchorage

ONLY TOP MAT OF LONGITUDINAL REINFORCEMENT SHOWN FOR CLARITY

FOR INFORMATIONAL PURPOSES ONLY

59

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

60

The Strut-and-Tie Method

IMPLEMENTATION

Questions?

