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Maciej Nowicki, Uorton Arena, Raleigh, 1952
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![Diagram showing form-finding techniques and their applications]
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\[ q_i = \frac{F_i}{w_i} \]

\[ C^T \cdot Q^D \cdot C \cdot X + C^T \cdot Q^D \cdot C_f \cdot X_f = P_x \]

\[ C^T \cdot Q^D \cdot C \cdot Y + C^T \cdot Q^D \cdot C_f \cdot Y_f = P_y \]

\[ C^T \cdot Q^D \cdot C \cdot Z + C^T \cdot Q^D \cdot C_f \cdot Z_f = P_z \]
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Equivalent cable nets

\[ L_u = W_v = K \]

\[ L_v = W_u = H \]

\[ L_{vi} = r_i \times 2 \times \sin \left( \frac{\alpha}{2} \right) \]

\[ W_{ui} = \frac{L_{vi} + L_{vi+1}}{2} \]

\[ W_{vi} = L_{ui} = K \]

\[ L \approx w \]

\[ q = F/L \]

\[ F = s \times W \]

\[ q = s \times W/L \]
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\[ K_c = K_m \times W \]

\[ A_c \times E_c = \frac{s_t}{e_t} \times W \]

\[ A_c = \frac{s_t}{e_t \times E_c} \times W \]

\[ F_{max,\text{warp}} = \frac{s_{t,\text{warp}} \times W_{\text{warp}}}{y} \]

\[ F_{max,\text{weft}} = \frac{s_{t,\text{weft}} \times W_{\text{weft}}}{y} \]

\[ A_{c,\text{warp}} = \frac{s_{t,\text{warp}}}{e_{t,\text{warp}} \times E_c} \times W_{\text{warp}} \]

\[ A_{c,\text{weft}} = \frac{s_{t,\text{weft}}}{e_{t,\text{weft}} \times E_c} \times W_{\text{weft}} \]
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\[ E_f = \frac{E}{1 + E \cdot \frac{A \cdot q_0^2 \cdot L^2 \cdot \cos^2 \alpha}{12 \cdot T^3}} \]
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2D vertically loaded arch
2D vertically loaded arch

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\[
F_{y0} = - \frac{F_1 \left( \delta x_{1,2} + \delta x_{2,3} + \delta x_{3,4} \right) + F_2 \left( \delta x_{2,3} + \delta x_{3,4} \right) + F_3 \left( \delta x_{3,4} \right)}{\left( \delta x_{0,1} + \delta x_{1,2} + \delta x_{2,3} + \delta x_{3,4} \right)}
\]

\[
F_{y4} = -(F_{y0} + F_1 + F_2 + F_3)
\]

\[
F_{x0} = -F_{x4}
\]
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\[
\frac{F_{x0,1}}{F_{y0,1}} = \frac{\delta x_{0,1}}{\delta y_{thr0,1}} \quad ; \quad \delta y_{thr0,1} = \frac{F_{y0,1} \ast \delta x_{0,1}}{F_{x0,1}}
\]

\[
\frac{F_{x1,2}}{F_{y1,2}} = \frac{\delta x_{1,2}}{\delta y_{thr1,2}} \quad ; \quad \delta y_{thr1,2} = \frac{F_{y1,2} \ast \delta x_{1,2}}{F_{x1,2}}
\]

\[
\frac{F_{x2,3}}{F_{y2,3}} = \frac{\delta x_{2,3}}{\delta y_{thr2,3}} \quad ; \quad \delta y_{thr2,3} = \frac{F_{y2,3} \ast \delta x_{2,3}}{F_{x2,3}}
\]

\[
\frac{F_{x3,4}}{F_{y3,4}} = \frac{\delta x_{3,4}}{\delta y_{thr3,4}} \quad ; \quad \delta y_{thr3,4} = \frac{F_{y3,4} \ast \delta x_{3,4}}{F_{x3,4}}
\]

2D vertically loaded arch
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$\delta y_{str,0,1} + \delta y_{str,1,2} + \delta y_{str,2,3} + \delta y_{str,3,4} = K_{str} = K_{thr} = \delta y_{thr,0,1} + \delta y_{thr,1,2} + \delta y_{thr,2,3} + \delta y_{thr,3,4}$

$\delta y_{thr(i-1),i} = \frac{F_{y(i-1),i} \cdot \delta x(i-1),i}{F_{x(i-1),i}}$

$F_{y0} = -\frac{\delta x_{0,1}}{F_{x0}} + \frac{\delta x_{1,2}}{F_{x0} + F_{x1}} + \frac{(F_{y1} + F_{y2}) \cdot \delta x_{2,3}}{F_{x0} + F_{x1} + F_{x2}} + \frac{(F_{y1} + F_{y2} + F_{y3}) \cdot \delta x_{3,4}}{F_{x0} + F_{x1} + F_{x2} + F_{x3}}$
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2D vertically and horizontally loaded arch
2D vertically and horizontally loaded arch

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Complementary Normal Energy

\[ E_{C,N} = \frac{N^2 \cdot l}{2 \cdot E \cdot A} \]

Complementary Bending Energy

\[ E_{C,M} = \frac{M^2 \cdot l}{2 \cdot E \cdot I} \]
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Complementary Bending Energy

\[ M = F_x \cdot e_y \]

\[ E_{C\text{,factor}} = M^2 \]
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Keith Brownlie, Hulme Arch Bridge, Manchester, 1997
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3D generic arch
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Dead Load Combination, Nodal Translation

Dead + Wind Load Combination, Nodal Translation
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Dead Load Combination, Axial Forces

Dead + Wind Load Combination, Axial Forces
Mean and Gaussian Curvature

\[ \kappa_m = \frac{\kappa_1 + \kappa_2}{2} \]

\[ \kappa_g = \kappa_1 \times \kappa_2 \]

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\[ \kappa_g > 0 \]
\[ \kappa_g = 0 \]
\[ \kappa_g < 0 \]

synclastic
zeroclastic
monoclastic
anticlastic
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