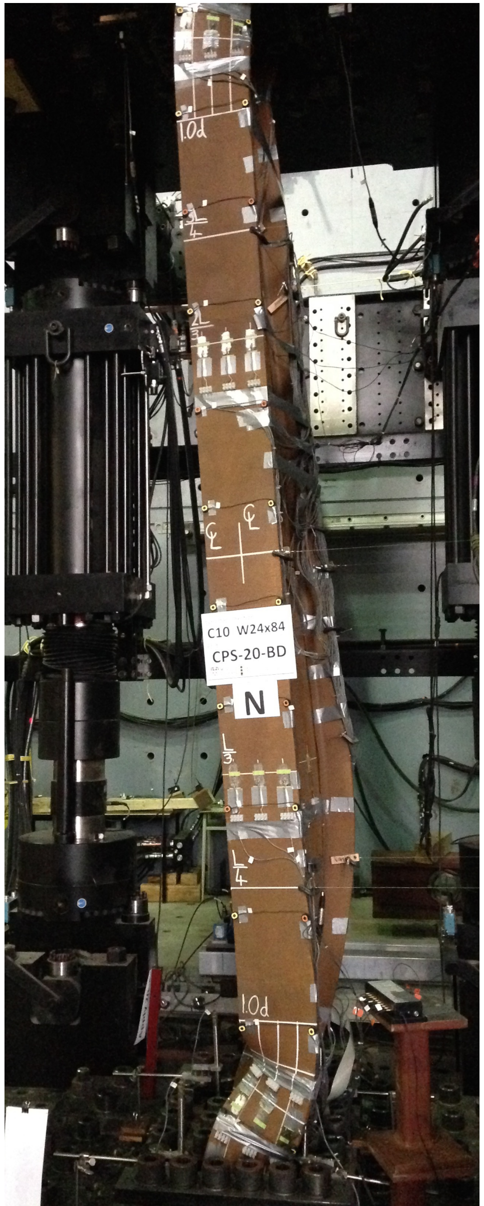
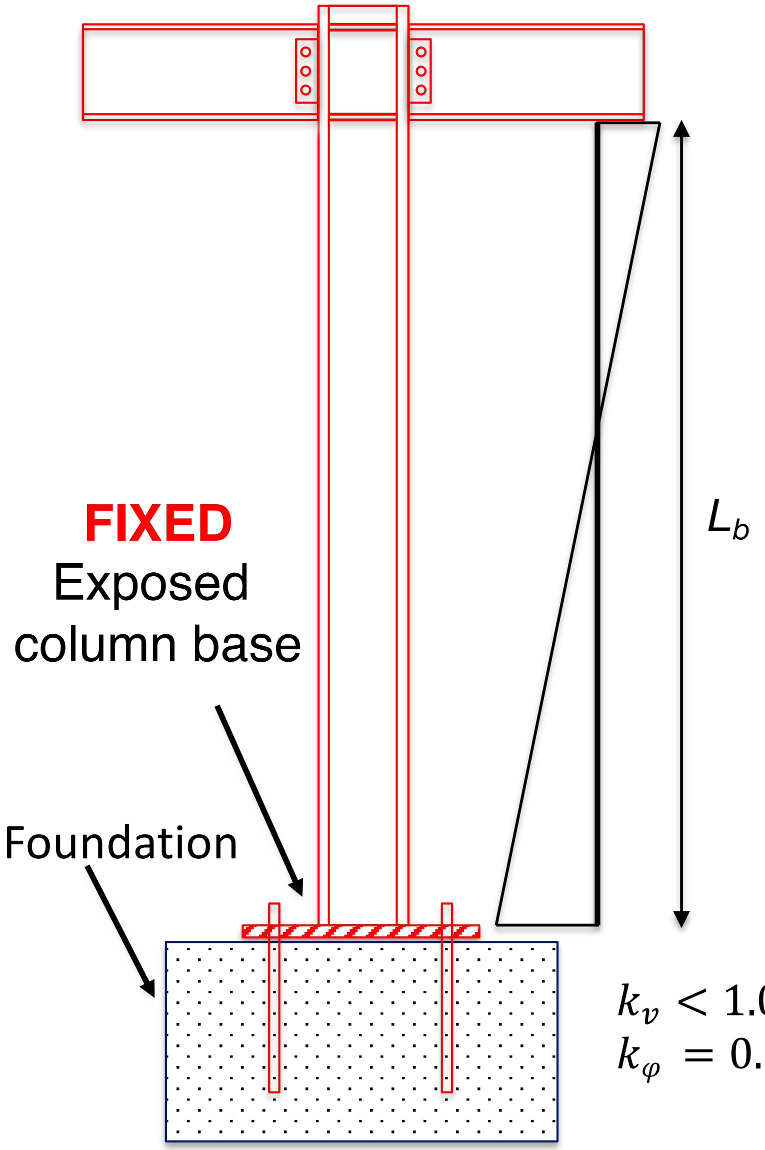
Some Discussion on Known Failures
-Steel Columns under Cyclic Loading

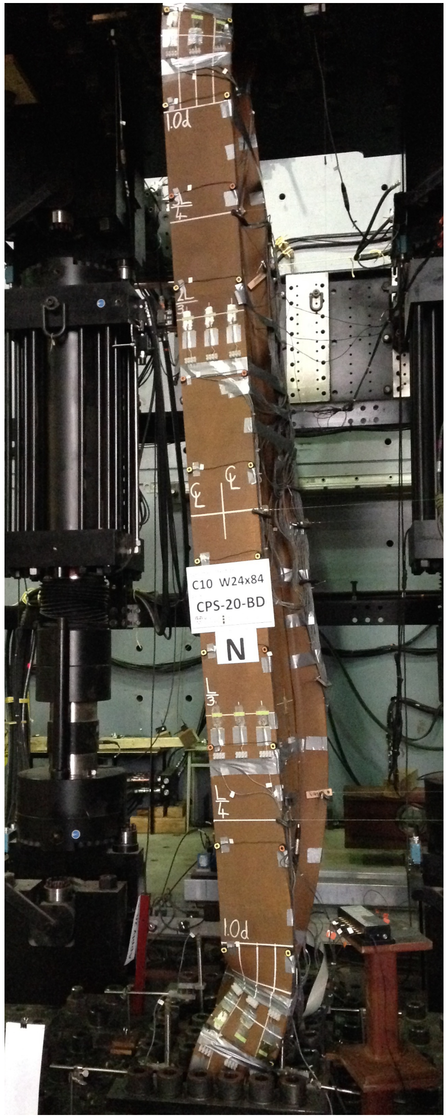




$k_v < 1.0$ (assume for safety $k_v = 1.0$)
$k_\varphi = 0.5$

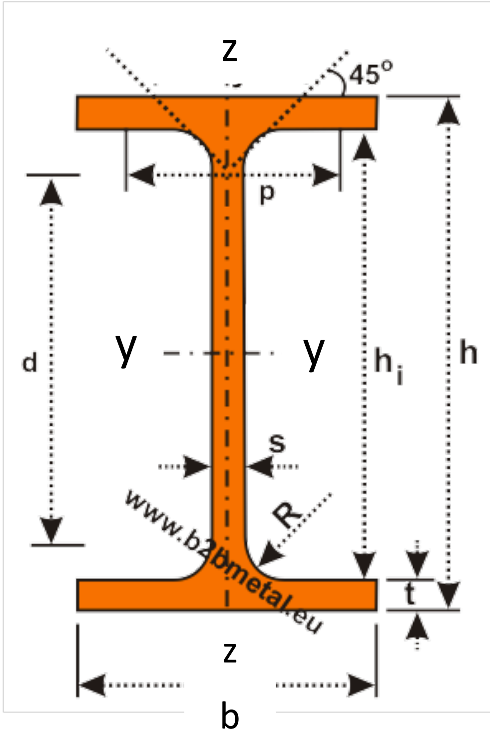
(Elkady and Lignos, 2018)

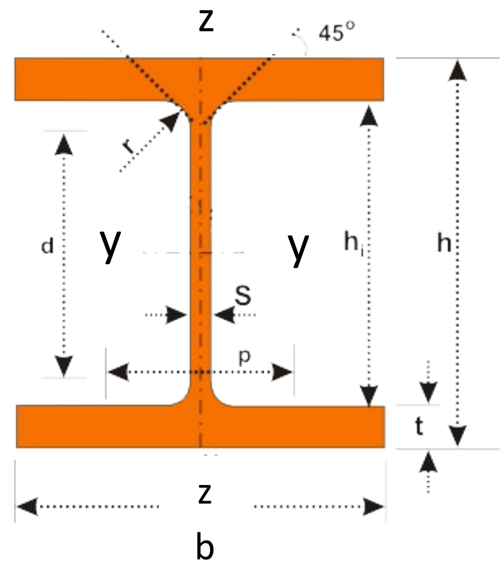
Some Discussion on Known Failures
-Steel Columns under Cyclic Loading



(Elkady and Lignos, 2018)

$$M_{cr} = \frac{C_1 \pi^2 E I_z}{k_v k_\varphi L_b^2} \sqrt{\frac{I_\omega}{I_z} \left(\frac{G K (k_\varphi L_b)^2}{\pi^2 E I_\omega} + 1 \right)}$$



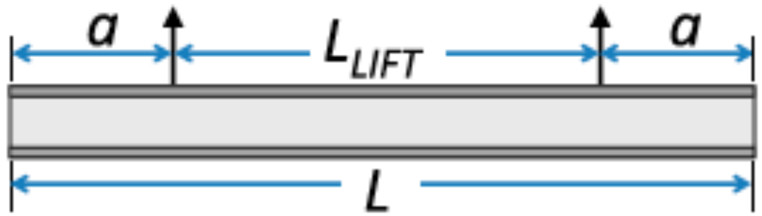


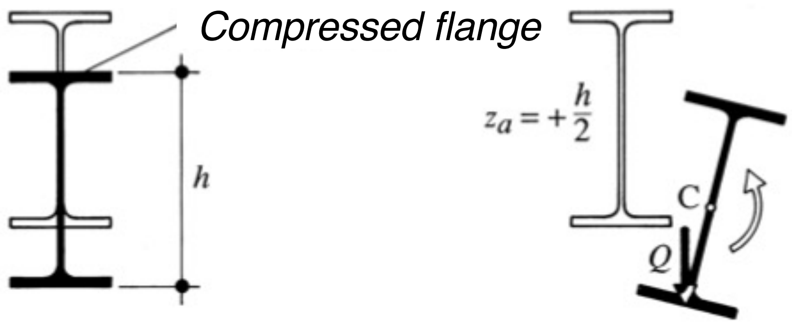
I_z - is the second moment of area about the minor axis *z-z*
I_ω - is the warping constant of the cross-section
K - is the torsional constant of the cross-section
L_b - Normally this is the column height)

Bridge Girder Lifting Operations

-Design during Construction Phase (Lifting)

Image courtesy of Prof. M. Engelhardt (UT Austin)



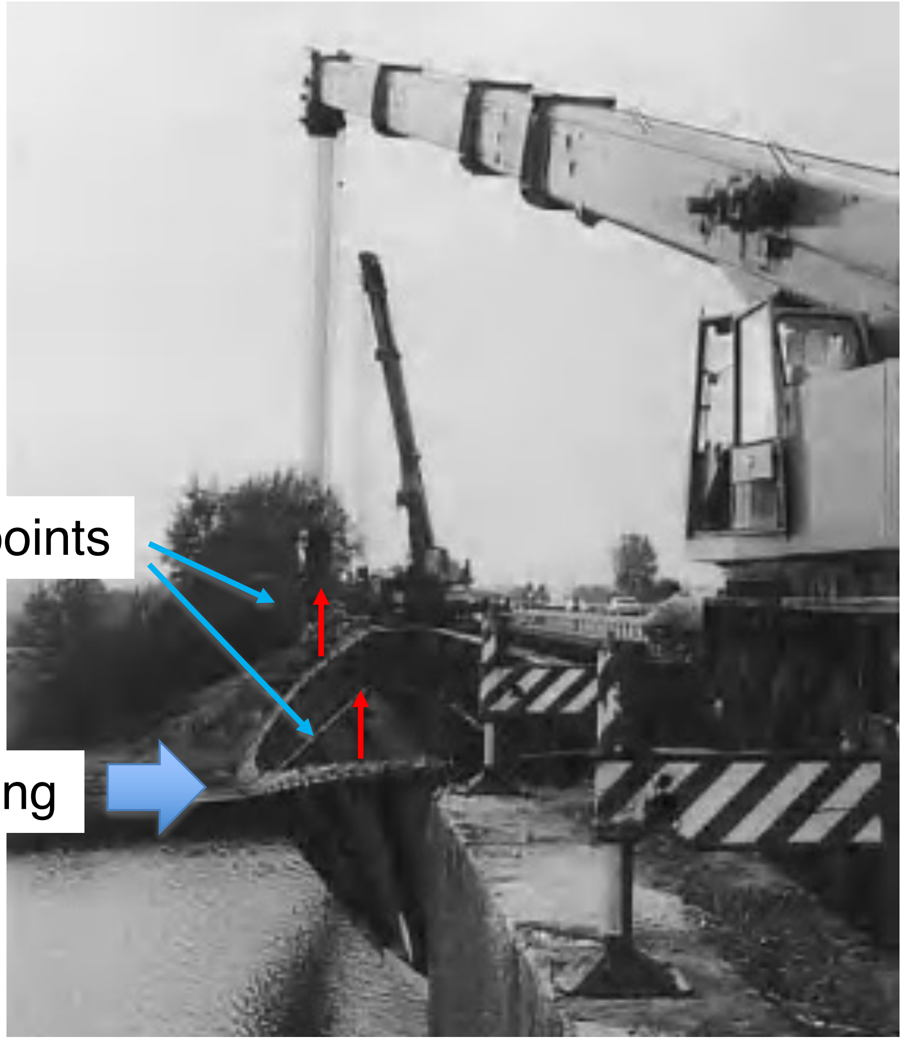


Secondary moment (helps stabilization)

$$M_{cr} = \frac{C_1 \pi^2 E I_z}{k_v k_\varphi L_b^2} [\sqrt{(C_2 z_a + C_3 \beta)^2 + \frac{I_\omega}{I_z} \left(\frac{G K k_\varphi^2 L_b^2}{\pi^2 E I_\omega} + 1 \right)} + (C_2 z_a + C_3 \beta)$$

Bridge Girder Lifting Operations

-Collapse during Construction Phase (due to lifting)



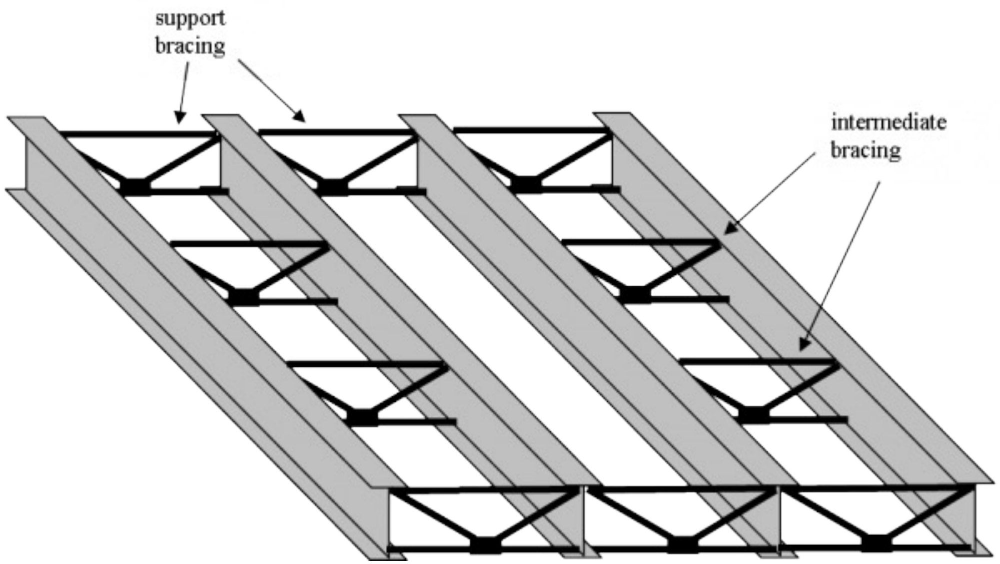
Mittelland Canal Bridge, Dedensen, Buckled main girder, 1982

Bridge Girder Collapses

Tacoma Narrows Bridge shortly before collapse 1940

$$M_{cr} = \frac{C_1 \pi^2 E I_z}{k_v k_\varphi L_b^2} [\sqrt{(C_2 z_a + C_3 \beta)^2 + \frac{I_\omega}{I_z} \left(\frac{G K k_\varphi^2 L_b^2}{\pi^2 E I_\omega} + 1 \right)} + (C_2 z_a + C_3 \beta)$$

Frame Cross and Plan Bracing



Main Functions:

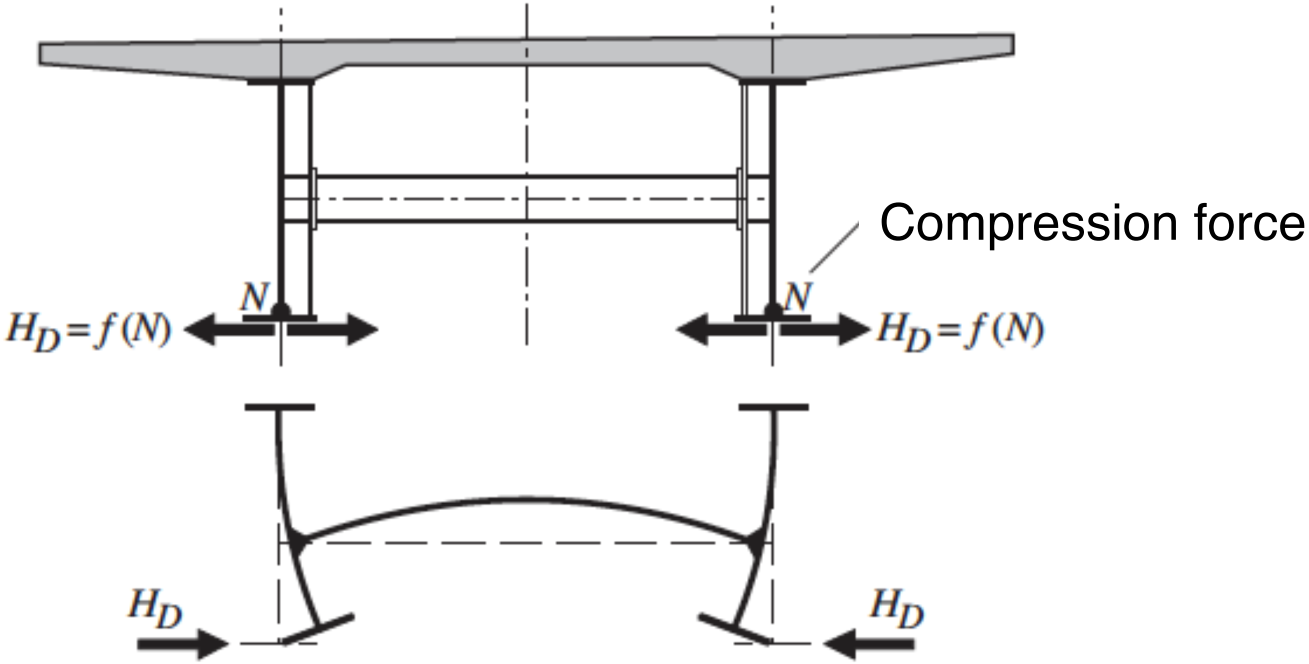
- To resist and transfer the horizontal forces due to wind
- Restrain the main beams/girders against lateral torsional buckling

Additional Functions:

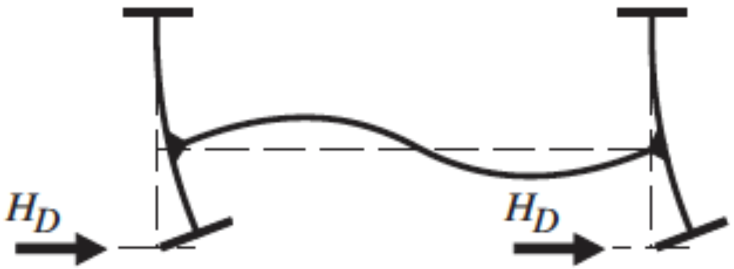
- Maintain the shape of the transverse cross-section of a bridge
- Introduce torsion into the beam
- During temporary construction, act as supports for slab formwork, depending on the method of construction of the slab

Plan Bracing

Lateral Torsional Buckling Restraint



(a) Symmetric lateral torsional buckling



(b) Antisymmetric lateral torsional buckling

Lateral Torsional Buckling Restraint

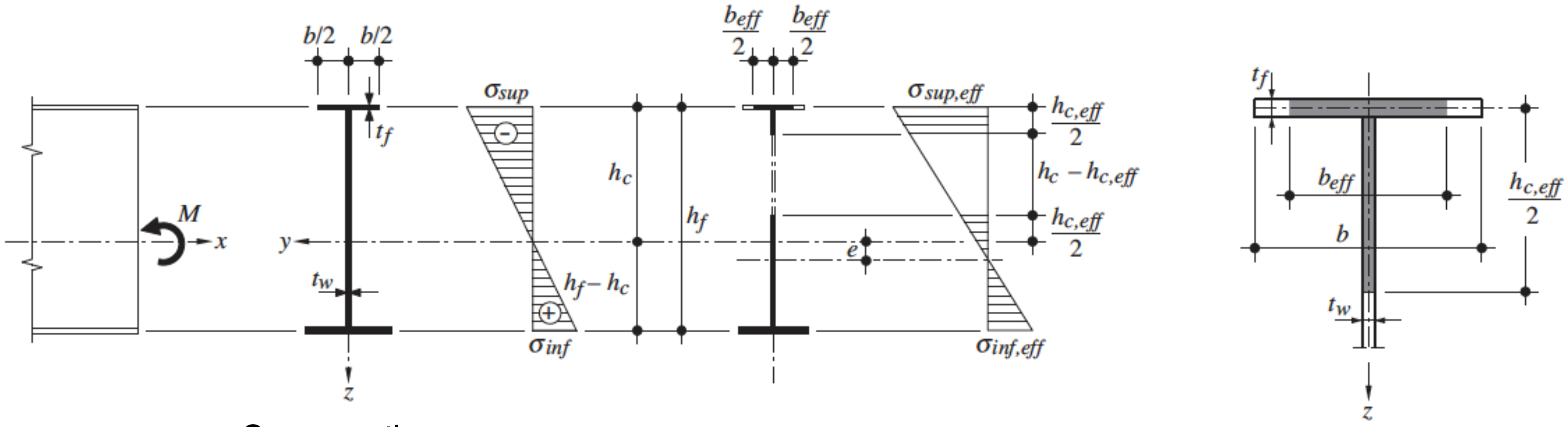
- When the compression flange is not restrained by the plan bracing, the buckling length is given by the spacing between adjacent cross bracings.

- The horizontal force H_D to restrain the compression flange against lateral torsional buckling is taken as 1% of the normal force *N* in the compression member.

- The area of the compression member, A_D: the area of the flange plus part of the web, namely half the effective web area but not more than one third of the are of web in compression.

$$A_D = b_{eff} \cdot t_f + \frac{h_{c,eff}}{2} \cdot t_w$$

Lateral Torsional Buckling Restraint



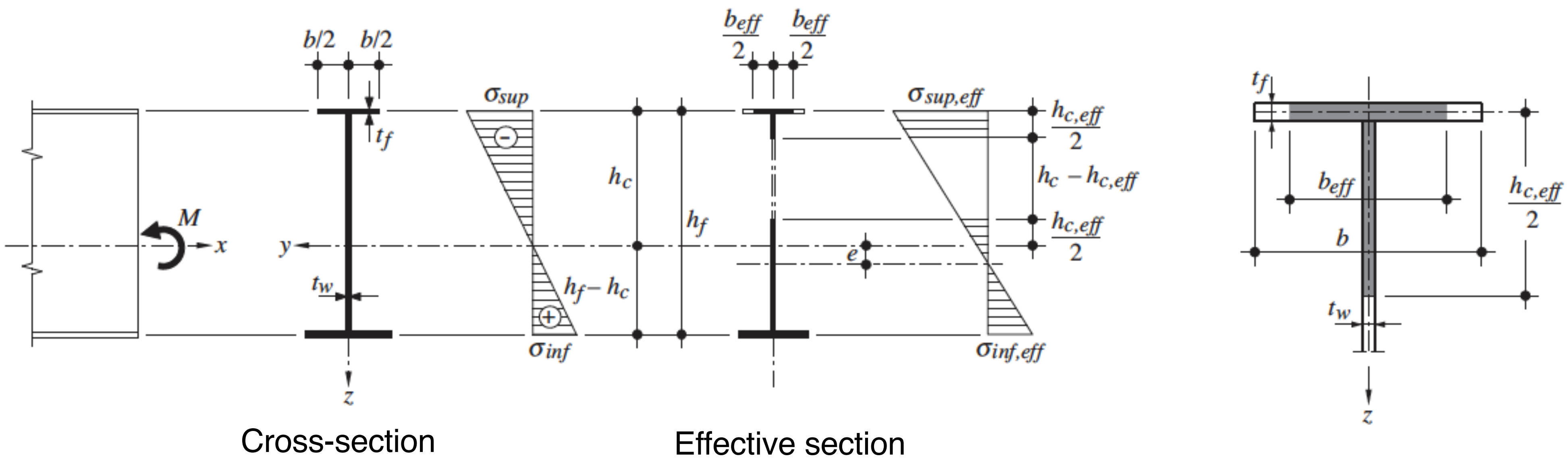
Cross-section

Effective section

b_{eff}: effective width of the compression flange, of thickness t_f:

$$\frac{b_{eff}}{2} = 0.56\sqrt{\frac{E}{f_y}} \cdot t_f \leq \frac{b}{2}$$

Lateral Torsional Buckling Restraint



$h_{c,eff}$: effective width of the of the web in compression, with thickness t_w:

Doubly symmetric section profiles

$$h_{c,eff} = 2.1\sqrt{\frac{E}{f_y}} \cdot t_w \leq h_c$$

Single symmetric section profiles

$$h_{c,eff} = 0.86 \cdot \sqrt{k} \cdot \sqrt{\frac{E}{f_y} \cdot \frac{h_c}{h_f}} \cdot t_w \leq h_c$$

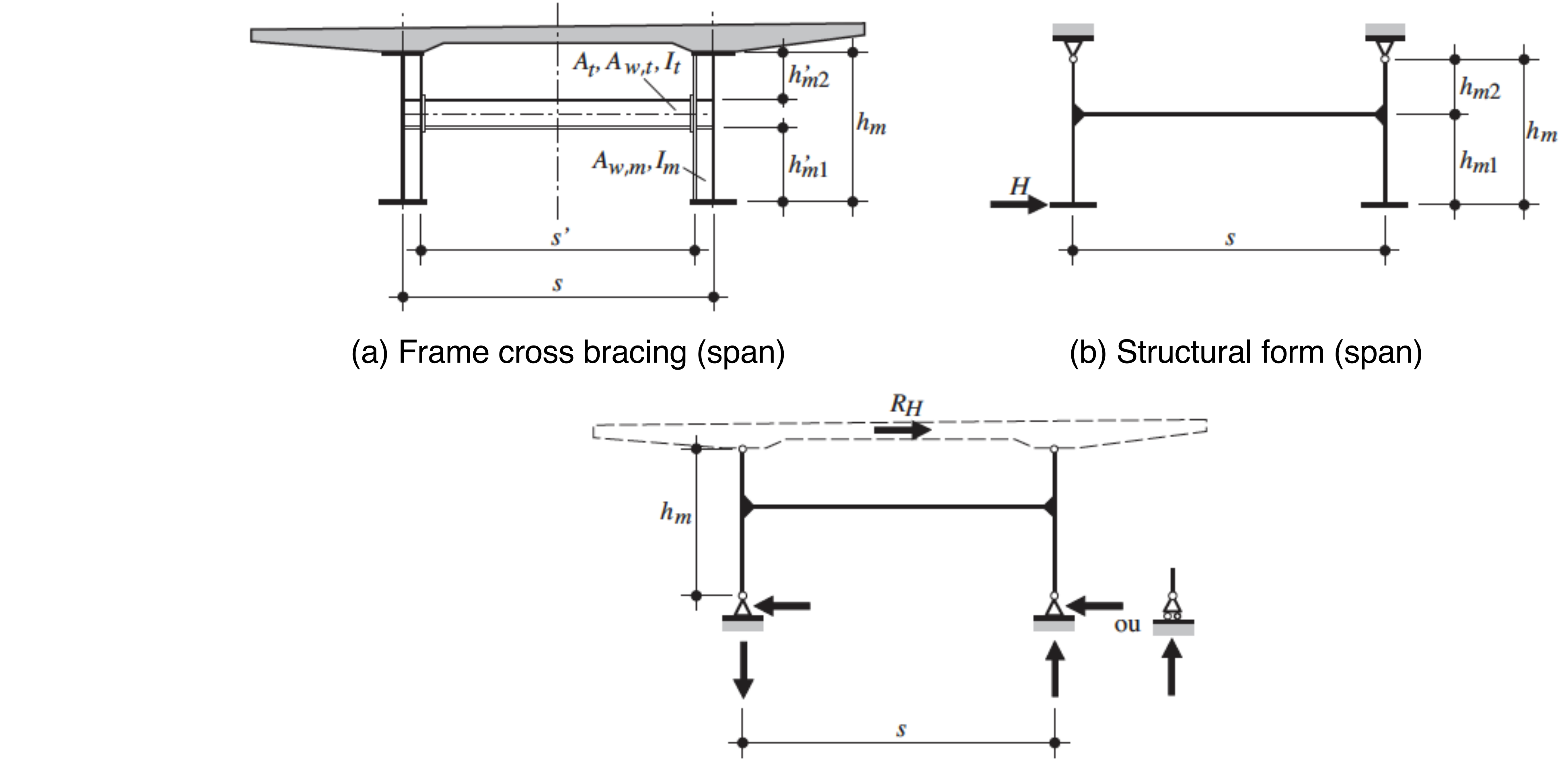
The buckling coefficient,

$$k = \frac{16}{1 + \psi + \sqrt{(1+\psi)^2 + 0.112 \cdot (1-\psi)^2}}$$

ψ: ratio (including its sign) between the min. and max. stresses, $\psi = \sigma_{inf}/\sigma_{sup}$

Moments and Forces on the Cross Bracing

Cross bracing is subjected to moments and forces that transfer the torque, which results from maintaining the cross-section shape.



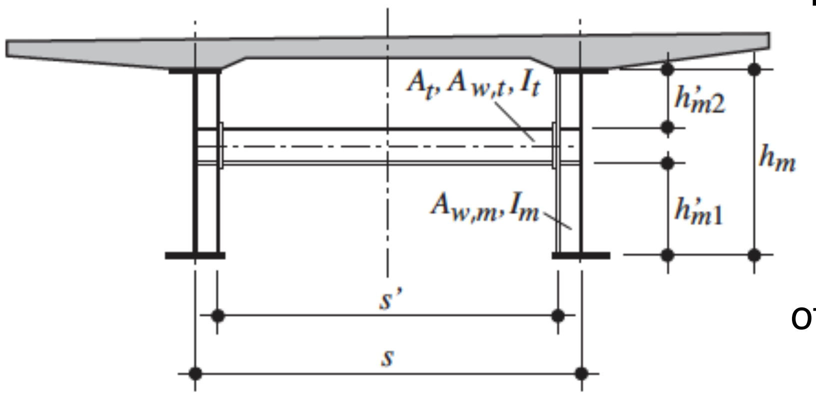
(a) Frame cross bracing (span)

(b) Structural form (span)

(c) Structural form (support)

Moments and Forces on the Cross Bracing

The spring constants K, relative to bending and normal force, as well as the constant K_v to take into account shear when calculating deformations,



Lower part of the upright

$$K_{m1} = \frac{h'^3_{m1}}{3EI_m}, \qquad K_{V,m1} = \frac{h'_{m1}}{GA_{w,m}}$$

Upper part of the upright

$$K_{m2} = \frac{h'^3_{m2}}{3EI_m}, \qquad K_{V,m2} = \frac{h'_{m2}}{GA_{w,m}}$$

$$K_{t1} = \frac{s' \cdot h^2_{m1}}{2EI_t}, \qquad K_{V,t} = \frac{2s'}{GA_{w,t}}$$

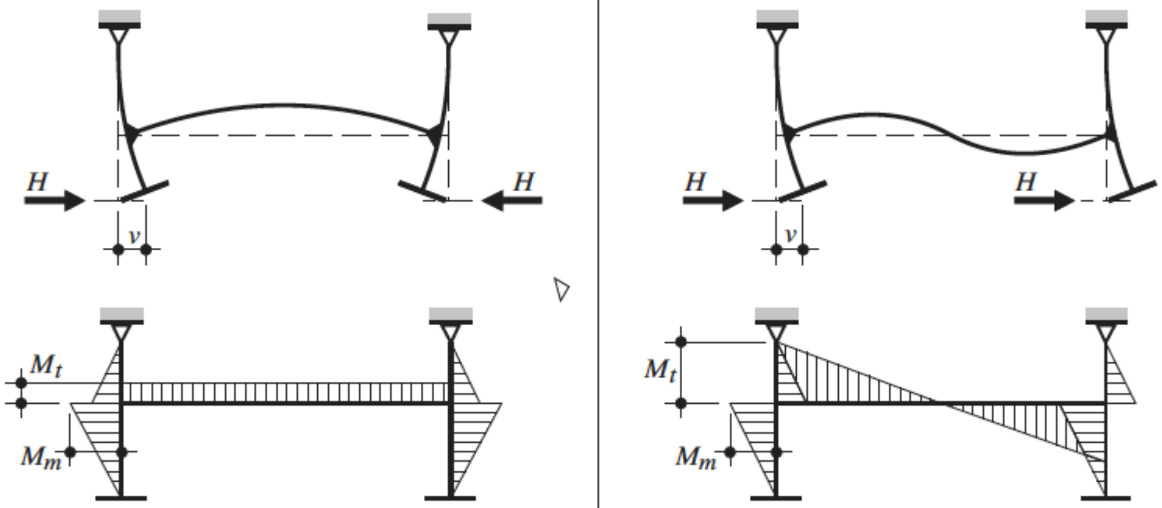
Cross girder

$$K_t = \frac{s' \cdot h^2_m}{2EI_t}$$

$$K_{t2} = \frac{s' \cdot h^2_{m2}}{2EI_t}$$

$$K_{tN} = \frac{s'}{2EA_t}$$

Moments and Forces on the Cross Bracing



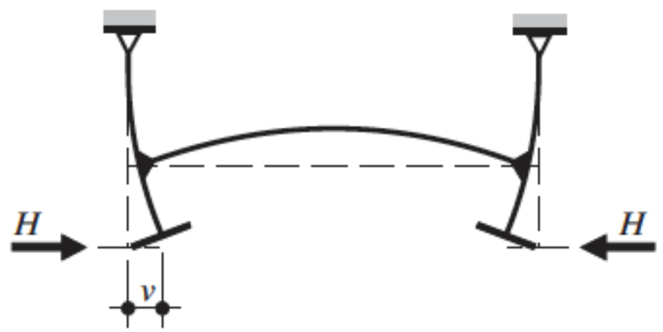
Internal moments and forces in the cross girder

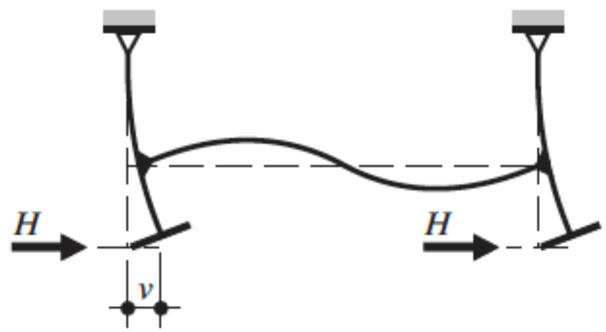
$M_t = Hh_m \cdot \dfrac{K_{tN} + K_{m2} \cdot \dfrac{h_{m1}}{h_m}}{K_{t2} + K_{tN} + K_{m2}}$	$M_t = H \cdot h_m$
$N_t = H \cdot \dfrac{K_{m2} + K_{t2} \cdot \dfrac{h_m}{h_{m2}}}{K_{t2} + K_{tN} + K_{m2}}$	$N_t = 0$
$V_t = 0$	$V_t = 2H \cdot \dfrac{h_m}{s}$

Internal moments and forces in the lower part of the upright

$M_m = Hh_{m1}$ $\quad$ $N_m = 0$ $\quad$ $V_m = H$

Moments and Forces on the Cross Bracing





Displacement of the cross bracing

$$v = H \cdot \left[K_{m1} + K_{V,\,m1} + K_{t1} + K_{tN} - \frac{\left(K_{tN} - K_{t2} \cdot \frac{h_{m1}}{h_{m2}} \right)^2}{K_{t2} + K_{tN} + K_{m2} + K_{V,\,m2}} \right]$$

$$v = H \cdot \left[K_{m1} + K_{V,\,m1} + K_{m2} + K_{V,\,m2} + \frac{K_t}{3} + K_{V,\,t} \cdot \left(\frac{h_m}{s} \right)^2 \right]$$