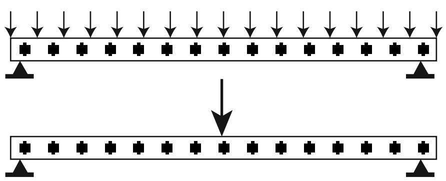
14) Calculate M_u

Because there is no side thrust, we cannot use the flexure analogy.

The equation 13.6(e) (ii) can be modified for loading other than at the shear centre by using the following equation for the equivalent moment factor.

$\omega_3 = \omega_2 B^r R \leq 2.5$

Where ω_2 is the equivalent moment factor for the moment distribution along the laterally unsupported length; B is as defined below; the exponent r is 0 for loading through the shear centre, -1 for loading at the top flange (to account for the destabilizing effect of loading a beam at the level of the compression flange) and +1 for loading at the bottom flange (stabilizing effect); R is a factor to account for double curvature loading of mono-symmetric sections, taken as 1.0 for single curvature between points of lateral supports.



$B = 1 + 0.535\sqrt{W} - 0.154\,W$

$B = 1 + 0.649\sqrt{W} - 0.180\,W$

Where $W = \left(\dfrac{\pi}{L_s}\right)^2 \dfrac{EC_w}{GJ}$ and Ls is the laterally unsupported length.

A simplification is shown in the SSRC Guide (Ziemian 2010) where the effects of load height and load condition can be approximated by taking B = 1.4. This approach will be used herein.

Then $\omega_3 = 1.185 \times 1.4^{-1} = 0.846$

2017 01

$$M_u = \frac{0.846 \times \pi^2 \times 200\,000 \times 221.7 \times 10^6}{2 \times 10\,670^2}\left[142.3 + \sqrt{142.3^2 + 4\left(\frac{77\,000 \times 10.69 \times 10^6 \times 10\,670^2}{\pi^2 \times 200\,000 \times 221.7 \times 10^6} + \frac{19 \times 10^{12}}{221.7 \times 10^6}\right)}\right]$$

$$= 2.027 \times 10^9\ \text{N}\cdot\text{mm} = 2\,027\ \text{kN}\cdot\text{m}$$

15) Calculate M_{yr}

$$M_{yr} = 0.7 S_x F_y\,,\ \text{with } S_x \text{ minimum}$$

$$= \frac{0.7 \times 6\,409 \times 10^3 \times 350}{10^6} = 1\,570\ \text{kN}\cdot\text{m}$$

The factor 0.7 was introduced in S16 to account for residual stresses. See comment by Trahair (2011), p. 8.

16) Calculate L_u

$$L_u = 1.1 r_t \sqrt{\frac{E}{F_y}} = \frac{490 r_t}{\sqrt{F_y}}$$

where

$$r_t = \frac{b_c}{\sqrt{12\left(1 + \dfrac{h_c w}{3 b_c t_c}\right)}}$$

h_c = depth of the web in compression

b_c = width of compression flange

t_c = thickness of compression flange

$$r_t = \frac{347.4}{\sqrt{12\left(1+\dfrac{239.1\times 16.5}{3\times 347.4\times 40.07}\right)}} = 95.86 \text{ mm}$$

$$L_u = \frac{490\times 95.86}{\sqrt{350}} = 2\,511 \text{ mm}$$

17) Since $M_u > M_{yr}$, calculate M_r

$$M_r = \phi\left[M_p - \left(M_p - M_{yr}\right)\left(\frac{L-L_u}{L_{yr}-L_u}\right)\right] \le \phi M_p$$

L_{yr} = length L obtained by setting $M_u = M_{yr}$

To find L_{yr}, M_u can be expressed as follows

$$M_u = \frac{1.851\times 10^{14}}{L_{yr}^2}\left[142.3+\sqrt{20\,249+4\left(1.881\times 10^{-3} L_{yr}^2 + 85\,701\right)}\right]$$

2016 03

L_{yr}, *mm*	M_u, *kN·m*
12 000	*1 729 < 1 570*
13 000	*1 556 < 1570, but close enough, can be refined if necessary*

18) Calculate M_r

From step 11, M_p = 2 797 kN·m, ϕM_p = 0.9 × 2 797 = 2 517 kN·m

2016 03

$$\begin{aligned} M_r &= 0.9\left[2\,797 - \left(2\,797 - 1\,570\right)\left(\frac{10670 - 2\,511}{13000 - 2\,511}\right)\right] \\ &= 0.9\times 1843 \\ &= 1658 \text{ kN}\cdot\text{m} < 2\,517 \text{ kN}\cdot\text{m OK} \end{aligned}$$

19) Calculate the strength in bending for the load combination of side thrust, no impact.

2017 01

$$\begin{aligned} M_u &= \frac{1.185\times\pi^2\times 200\,000\times 221.7\times 10^6}{2\times 10\,670^2}\left[142.3+\sqrt{142.3^2+4\left(\frac{77\,000\times 10.69\times 10^6\times 10\,670^2}{\pi^2\times 200\,000\times 221.7\times 10^6}+\frac{19\times 10^{12}}{221.7\times 10^6}\right)}\right] \\ &= 2.839\times 10^9 \text{ N}\cdot\text{mm} = 2\,839 \text{ kN}\cdot\text{m} \end{aligned}$$

20) Calculate M_{yr}

Refer to step 15

M_{yr} = 1570 kNm

21) Calculate L_u

Refer to step 16

L_u = 2511mm

22) Since $M_u > M_{yr}$, calculate M_r

$$M_r = \phi\left[M_p - \left(M_p - M_{yr}\right)\left(\frac{L - L_u}{L_{yr} - L_u}\right)\right] \le \phi M_p$$

L_{yr} = length L obtained by setting $M_u = M_{yr}$

To find L_{yr}, M_u can be expressed as follows

$$M_u = \frac{2.593\times10^{14}}{L_{yr}^2}\left[142.3 + \sqrt{20\,249 + 4\left(1.881\times10^{-3}L_{yr}^2 + 85\,701\right)}\right]$$

2017 01

L_{yr}, *mm*	M_u, *kN·m*
14 000	*1973 > 1570*
15 000	*1816 > 1570*
17 000	*1557 < 1570, but close enough*

23) Calculate M_r

From step 11, M_p = 2 797 kN·m, ϕM_p = 0.9 × 2 797 = 2 517 kN·m

2017 01

$$M_r = 0.9\left[2\,797 - \left(2\,797 - 1\,570\right)\left(\frac{10670 - 2\,511}{17000 - 2\,511}\right)\right]$$
$$= 0.9\times2106$$
$$= 1895\ \text{kN}\cdot\text{m} < 2\,517\ \text{kN}\cdot\text{m}\ \text{OK}$$

24) Calculate distribution of the side thrust C*s* by flexural analogy

See figures A10 and A11.

Moment at Shear Centre

$$= C_s(243 + 89) = 332C_s$$

Couple, applied to each flange

$$= \frac{332C_s}{223 + 384} = 0.5470C_s$$

2016 03

Note: This dimension should be to the centroid of the top flange, Close enough in this case.

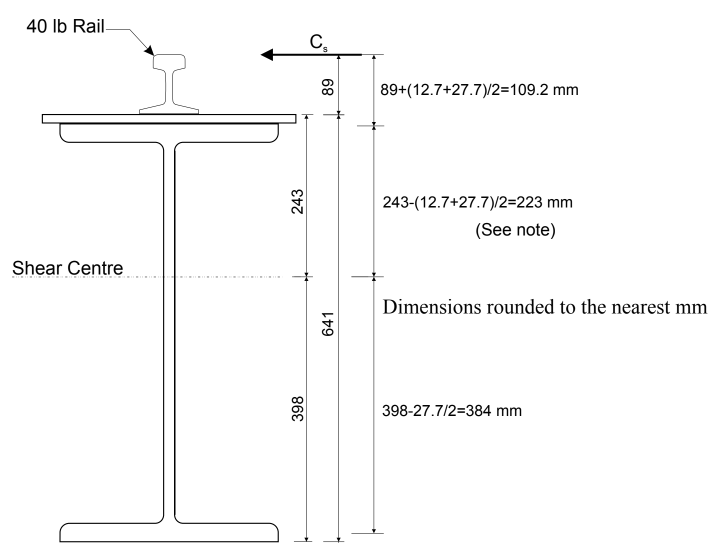


Figure A10
Distribution of Side Thrust

Distribution of horizontal load applied at shear centre, as a simple beam analogy

- to top flange $\dfrac{C_s \times 384}{(223 + 384)} = 0.6326\, C_s$

- to bottom flange $= 0.3674\, C_s$

M_{fyt} (top flange) $= 1.18 \times 73.19 = 86.36$ kN·m

M_{fyb} (bottom flange) $= 0.1796 \times 73.19 = 13.15$ kN·m

$M_{fx} = 1\,289$ kN·m

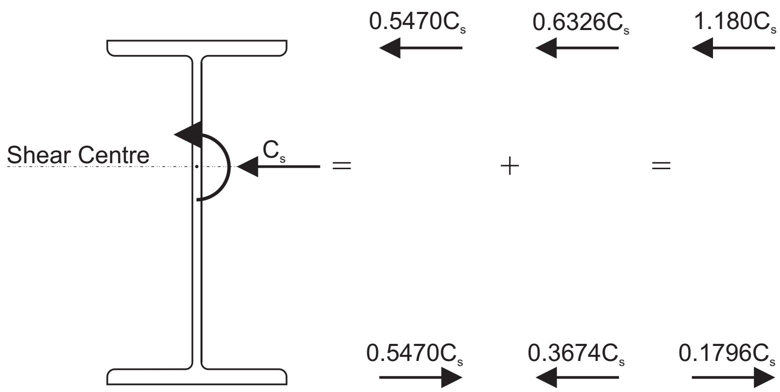


Figure A11

Moments about Shear Centre

25) Check overall member strength with impact, no side thrust

$$\frac{M_{fx}}{M_{rx}} + \frac{M_{fy}}{M_{ry}} \leq 1.0$$

$$\frac{1\,289}{0.9 \times 2797} + \frac{0.0}{0.9 \times 422} = 0.511 + 0.0 = 0.511 < 1.0 \;\; \text{OK}$$

26) Check stability (lateral-torsional buckling) with impact, no side thrust

2016 03

$$\frac{1\,289}{0.9 \times 1843} + \frac{0.0}{0.9 \times 422} = 0.777 + 0.0 = 0.777 < 1.0 \;\; \text{OK}$$

27) Check overall member strength with side thrust, no impact.

Because side thrust produces calculated M_y, we are entitled to use the flexure analogy as in step 24.

$$\frac{1\,040}{0.9 \times 2797} + \frac{86.36}{0.9 \times 422} = 0.413 + 0.227 = 0.640 < 1.0 \;\; \text{OK}$$

28) Check stability with side thrust, no impact

$$\frac{1\,040}{0.9 \times 2054} + \frac{86.36}{0.9 \times 422} = 0.563 + 0.227 = 0.790 < 1.0 \;\; \text{OK}$$

29) By clause 13.5(a), check that flanges do not yield under service load. A quick check shows OK.

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No further checks are required (see Section 5.10)

Conclusion: Section is adequate in bending.

Check Local Wheel Support

(a) Check Web Crippling and Yielding (Clause 14.3.2)

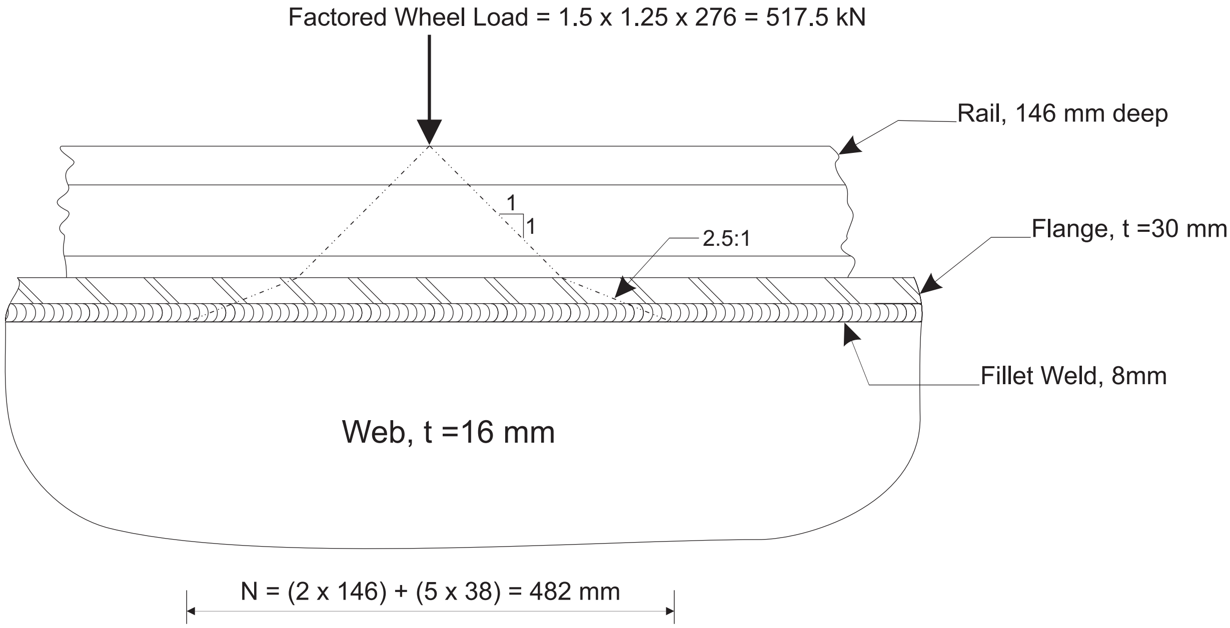

Figure A21
Web Crippling Under Crane Wheel

2017 01

Check Interior

(i)	$B_r = 0.8 \times 16 \times 482 \times \dfrac{350}{1\,000} = 2159 \text{ kN}$	14.3.2(i)	Governs
(ii)	$B_r = 1.45 \times \dfrac{0.8 \times 16^2}{1000} \sqrt{350 \times 200\,000} = 2\,485 \text{ kN}$	14.3.2(ii)	

The factored resistance of 2 159 kN > 517.5 kN OK

A check at the ends is not necessary because bearing stiffeners will be used.

(b) Check torsional effects on web under a wheel load including rail eccentricity and side thrust.

Factored Vertical Load $= 1.5 \times 1.25 \times 276 = 517.5 \text{ kN}$, including impact

Factored moment due to eccentricity $= 1.5 \times 1.25 \times 276 \times \dfrac{12}{1\,000} = 6.21 \text{ kN·m}$

Factored moment due to side thrust $= 1.5 \times 22.21 \times \dfrac{184}{1\,000} = 6.13 \text{ kN·m}$

$$M_f = 6.21 + 6.13 = 12.34 \text{ kN·m}$$