Rigid beam splice  EC 3-1-8 (12.10), NA: Deutschland

1. input report

details (section A - A)

**steel grade**
steel grade S235

**bolts**
bolt class 10.9, bolt size M36

**large wrench size** (high strength bolt), preloaded (for info: preloading \( F_p,c^* = 0.7 f_y b A_b = 514.7 \text{ kN} \))
shear plane passes through the unthreaded portion of the bolt

**beam parameters**
section HE700M

**verification parameters**
bolted end-plate connection:
thickness \( t_p = 50.0 \text{ mm} \), width \( b_p = 440.0 \text{ mm} \), length \( l_p = 910.0 \text{ mm} \)
projections \( h_{p,o} = 155.0 \text{ mm} \), \( h_{p,u} = 39.0 \text{ mm} \)
bolts in connection:
3 bolt-rows with 4 bolts (maximum):
row 1: 4 bolts, row 2: 4 bolts, row 3: 2 inner bolts
all bolt-rows considered individually
all bolt-rows for shear transfer (rows 1-3)
verification with der Component method: MNV-interaction acc. to Cerfontaine (in Jaspart/Weynand)
calculation method (4 bolts per row) acc. to the final report of AIF-project 15059
centre distance between outer and inner bolt \( w_2 = 95.0 \text{ mm} \)
centre distance of the bolts to the lateral edge of the end-plate \( e_2 = 50.0 \text{ mm} \)
centre distance of the first bolt-row to the upper edge of the end-plate (end row) \( e_0 = 75.0 \text{ mm} \)
centre distance of the last bolt-row to the bottom edge of the end-plate (end row) \( e_\text{u} = 160.0 \text{ mm} \)
centre distance of the bolt-rows from each other \( p_{1,2} = 200.0 \text{ mm} \), \( p_{2,3} = 475.0 \text{ mm} \)
welds at the connection point:
- beam flange top: fillet weld, weld thickness \( a = 19.0 \text{ mm} \)
- beam web: fillet weld, weld thickness \( a = 10.0 \text{ mm} \)
- beam flange bottom: fillet weld, weld thickness \( a = 19.0 \text{ mm} \)

**Internal forces and moments in the intersection point of system axes**

Lk 1: \( M_{\text{b,Ed}} = -2200.00 \text{ kNm} \), \( V_{\text{b,Ed}} = 800.00 \text{ kN} \)
Lk 2: \( M_{\text{b,Ed}} = 650.00 \text{ kNm} \), \( V_{\text{b,Ed}} = 800.00 \text{ kN} \)
Lk 3: \( N_{\text{b,Ed}} = 2100.00 \text{ kN} \)
Lk 4: \( N_{\text{b,Ed}} = -7300.00 \text{ kN} \)

**Partial safety factors for material**
resistance of cross-sections \( \gamma_M = 1.00 \)
resistance of members in stability failure \( \gamma_M = 1.10 \)
resistance of bolts, welds, plates in bearing \( \gamma_M = 1.25 \)
presstressing of high strength bolts \( \gamma_M = 1.10 \)

**Check of data**

<table>
<thead>
<tr>
<th>Utilizations</th>
<th>( U_{\text{Lc}} )</th>
<th>( U_{\text{MNV}} )</th>
<th>( U_{\text{EP}} )</th>
<th>( U )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lk 1</td>
<td>0.892</td>
<td>0.968</td>
<td>0.331</td>
<td>0.968</td>
</tr>
<tr>
<td>Lk 2</td>
<td>0.416</td>
<td>0.933</td>
<td>0.331</td>
<td>0.933</td>
</tr>
<tr>
<td>Lk 3</td>
<td>0.232</td>
<td>0.858</td>
<td>-</td>
<td>0.858</td>
</tr>
<tr>
<td>Lk 4</td>
<td>0.807</td>
<td>0.996</td>
<td>-</td>
<td>0.996*</td>
</tr>
</tbody>
</table>

\( U_{\text{Lc}} \): stress utilization at the beam; \( U_{\text{MNV}} \): utilization due to MNV-interaction; \( U_{\text{EP}} \): utilization due to shear in end-plate
\( U \): utilization of the connection

*) maximum utilization

**2. Final result**

**Utilization/rotation of the connection**

<table>
<thead>
<tr>
<th>Lk</th>
<th>( S_{\text{J,Int}} ) ( \text{MM/m}^2 )</th>
<th>( S_{\text{J}} ) ( \text{MM/m}^2 )</th>
<th>( \varphi_{\text{J}} ) ( ^\circ )</th>
<th>( U_{\text{J}} )</th>
<th>( \Sigma I ) ( \text{kNm} )</th>
<th>( \Sigma J ) ( \text{kNm} )</th>
<th>( \Sigma M ) ( \text{kNm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3033.8</td>
<td>3033.8</td>
<td>0.042</td>
<td>0.968</td>
<td>0.00</td>
<td>800.00</td>
<td>2200.00</td>
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<tr>
<td>2</td>
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<td>647.9</td>
<td>0.047</td>
<td>0.933</td>
<td>0.00</td>
<td>800.00</td>
<td>650.00</td>
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<tr>
<td>3</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.858</td>
<td>2100.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>4</td>
<td>0.0</td>
<td>0.0</td>
<td>0</td>
<td>0.996</td>
<td>7300.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

\( S_{\text{J,Int}} \): initial rotational stiffness; \( S_{\text{J}} \): rotational stiffness; \( \varphi_{\text{J}} \): rotation; \( U_{\text{J}} \): utilization of the connection; tolerances of equilibrium \( 1 \text{kNm} / 1 \text{kNm} \)

*) maximum utilization

maximum utilization [Lk 4]: \( \max U = 0.996 < 1 \) **ok**

**Verification succeeded**

**3. Detailed edition of Lk 1**

**Notes**
no verification for welds within the connection.
connection is verified due to EC 3-1-8 regardless of preloading.
however, connections may be constructed with prestressed high strength bolts.
simplified calculation of shear force resistance takes all bolt-rows into account.
no consideration of bolt groups in joints with 4 bolts per row.

**3.1. Design values**
slope angle: \( \alpha_{\text{b}} = \alpha_{\text{w}} = \alpha = 0^\circ \)
**Internal forces and moments perpendicular to the connection planes**
periphery beam
\( M_{\text{d}} = 2200.00 \text{ kNm} \), \( V_{\text{d}} = 800.00 \text{ kN} \)
**Partial internal forces and moments**
internal forces and moments in the periphery end-plate-beam: \( M_{\text{d}} = M_{\text{d}} - V_{\text{d}} t_{\text{ep}} = 2160.00 \text{ kNm} \)
\( N_{\text{b,t}} = -N_{\text{d}} z_{\text{b}} / z_{\text{b}} + M_{\text{d}} / z_{\text{b}} = 3195.27 \text{ kN} \), \( z_{\text{b}} = 676.0 \text{ mm} \), \( z_{\text{bu}} = 338.0 \text{ mm} \)
\( N_{\text{b,c}} = N_{\text{d}} z_{\text{b}} / z_{\text{b}} + M_{\text{d}} / z_{\text{b}} = 3195.27 \text{ kN} \), \( z_{\text{b}} = 676.0 \text{ mm} \), \( z_{\text{bo}} = 338.0 \text{ mm} \)
3.2. resistance of cross-section

plastic cross-sectional check for $M_y = -2160.00 \text{ kNm}$, $V_Z = 800.00 \text{ kN}$
valid normal/shear stress: $zul_{rd} = 23.50 \text{ kN/cm}^2$, $zul_{rd} = 13.57 \text{ kN/cm}^2$
top flange: resistance forces $N_{max,c} = 2857.60 \text{ kN}$, $N_{min,c} = -2857.60 \text{ kN}$
bottom flange: resistance forces $N_{max,u} = 2857.60 \text{ kN}$, $N_{min,u} = -2857.60 \text{ kN}$
web: shear force $V_s = 800.00 \text{ kN}$, shear stress $\tau_s = 5.64 \text{ kN/cm}^2$ $\Rightarrow U_s = 0.415$
resistance forces $N_{max,\Sigma} = 3034.68 \text{ kN}$, $N_{min,\Sigma} = -3034.68 \text{ kN}$
main bending: moment $M_y = -2160.00 \text{ kNm}$, resistance moments $M_{y,max} = 2444.60 \text{ kNm}$, $M_{y,min} = -2444.60 \text{ kNm}$ $\Rightarrow U_M = 0.884$
total (possibly due to load increase): max $U = 0.892 < 1 \text{ ok}$
utilizations: resistance $U_s = 0.892 < 1 \text{ ok}$, $c/t$-ratio $U_{ct} = 0.334 < 1 \text{ ok}$

3.3. basic components

3.3.1. Gk 5: end-plate in bending

connections with 4 bolts per bolt-row are not treated in EC 3-1-8.
verification follows the final report of AIF-project 15059.

extended part of end-plate

in projecting part of end plate only one bolt-row $(n_b - 1)$ is considered (4 bolts per row).
effective length of the T-stub flange (end-plate):
  in mode 1: $\Sigma_{eff,1} = left,1 + min(left,nc, left,cp) = 220.0 \text{ mm}$, $left,cp = 473.8 \text{ mm}$
in mode 2: $\Sigma_{eff,2} = left,2 + left,nc = 220.0 \text{ mm}$
tension resistance of the T-stub flange:
in mode 1+2: $M_{pl,Rd} = (0.25 \Sigma_{eff,1} t^2 f_y) / \gamma_{M0} = 29.56 \text{ kNm}$
in mode 3: $\Sigma_{Ft,Rd} = 4 n_b Ft,Rd = 2352.96 \text{ kN}$
mode 1: complete yielding of the T-stub flange
$Ft_{,1,Rd} = (8(n-2)\omega f_{pl,1,rd}) / ((2m-n)\omega (m+n)) = 2550.80 \text{ kN}$
mode 2: bolt failure simultaneously with yielding of the T-stub flange
$Ft_{,2,Rd} = (2M_{pl,2,rd} + n\Sigma_{Ft,Rd}) / (m+n) = 1750.36 \text{ kN}$
mode 3: bolt failure
$Ft_{,3,Rd} = \Sigma_{Ft,Rd} = 2352.96 \text{ kN}$
tension resistance of the T-stub flange: $Ft_{,Rd} = min(Ft_{,1,Rd}, Ft_{,2,Rd}, Ft_{,3,Rd}) = 1756.36 \text{ kN}$
resistance of a weld (req. 1): $f_{w,d} = f_u / (f_y - f_u) = 360.0 \text{ N/mm}^2$
tension resistance of welds: $Ft_{,w,Rd} = 21.2 f_{w,d} \left(\Sigma_{eff,1}\right) = 2128.11 \text{ kN} \geq 1756.36 \text{ kN, not decisive}$
resistance and effective length of end-plate in bending (projection)
$Ft_{,ep,Rd,1} = 1756.36 \text{ kN}$, $left,1 = 220.0 \text{ mm}$
part of end-plate between beam flanges
equivalent T-stub flange (each individual bolt-row):
here: number of bolt-rows $n_b = 1$
row 2 (4 bolts per row)
effective length of the T-stub flange (end-plate):
in mode 1: $\Sigma_{eff,1} = left,1 + min(left,nc, left,cp) = 416.8 \text{ mm}$, $left,cp = 668.4 \text{ mm}$
in mode 2: $\Sigma_{eff,2} = left,2 + left,nc = 416.8 \text{ mm}$
tension resistance of the T-stub flange:
in mode 1+2: $M_{pl,Rd} = (0.25 \Sigma_{eff,1} t^2 f_y) / \gamma_{M0} = 56.01 \text{ kNm}$
in mode 3: $\Sigma_{Ft,Rd} = 4 n_b Ft,Rd = 2352.96 \text{ kN}$
mode 1: complete yielding of the T-stub flange
$Ft_{,1,Rd} = (8(n-2)\omega f_{pl,1,rd}) / ((2m-n)\omega (m+n)) = 5493.02 \text{ kN}$
mode 2: bolt failure simultaneously with yielding of the T-stub flange
$Ft_{,2,Rd} = (2M_{pl,2,rd} + 0.5\Sigma_{Ft,Rd}(n^2+2n+2)(n+m) / (m+n)) = 1528.31 \text{ kN}$
$Ft_{,2,wp,Rd} = (2M_{pl,2,rd} + 0.5\Sigma_{Ft,Rd}(n^2) / (m+n)) = 1510.13 \text{ kN}$
mode 3: bolt failure
$Ft_{,3,Rd} = 0.9 \Sigma_{Ft,Rd} = 2117.66 \text{ kN}$
tension resistance of the T-stub flange: $Ft_{,Rd} = min(Ft_{,1,Rd}, Ft_{,2,Rd}, Ft_{,3,Rd}) = 1510.13 \text{ kN}$
resistance of a weld (req. 1): $f_{w,d} = f_u / (f_y - f_u) = 360.0 \text{ N/mm}^2$
tension resistance of welds: $Ft_{,w,Rd} = 21.2 f_{w,d} \left(\Sigma_{eff,1}\right) = 2122.01 \text{ kN} \geq 1510.13 \text{ kN, not decisive}$
row 3 (3 bolts per row)
effective length of the T-stub flange (end-plate):
in mode 1: $\Sigma_{eff,1} = left,1 + min(left,nc, left,cp) = 334.2 \text{ mm}$, $left,cp = 334.2 \text{ mm}$
in mode 2: $\Sigma_{eff,2} = left,2 + left,nc = 418.4 \text{ mm}$
tension resistance of the T-stub flange:
in mode 1: $M_{pl,1,Rd} = (0.25 \Sigma_{eff,1} t^2 f_y) / \gamma_{M0} = 44.91 \text{ kNm}$
in mode 2: $M_{pl,2,Rd} = (0.25 \Sigma_{eff,2} t^2 f_y) / \gamma_{M0} = 56.22 \text{ kNm}$
in mode 3: $\Sigma_{Ft,Rd} = 2 n_b Ft,Rd = 1176.48 \text{ kN}$
mode 1: complete yielding of the T-stub flange
$Ft_{,1,Rd} = (8(n-2)\omega f_{pl,1,rd}) / ((2m-n)\omega (m+n)) = 4394.70 \text{ kN}$
mode 2: bolt failure simultaneously with yielding of the T-stub flange
$Ft_{,2,Rd} = (2M_{pl,2,rd} + n\Sigma_{Ft,Rd}) / (m+n) = 1593.16 \text{ kN}$
mode 3: bolt failure
$Ft_{,3,Rd} = \Sigma_{Ft,Rd} = 1176.48 \text{ kN}$
tension resistance of the T-stub flange: \( F_{t,Rd} = \min(F_{t,1,Rd}, F_{t,2,Rd}, F_{t,3,Rd}) = 1176.48 \text{ kN} \)
resistance of a weld (req.1): \( f_{w,d} = f_u / (\beta_w \cdot \gamma_M) = 360.0 \text{ N/mm}^2 \)

tension resistance of welds: \( F_{w,Rd} = 211/2 \cdot f_{w,d} \cdot A_{left} = 1701.36 \text{ kN} \) (\( \geq 1176.48 \text{ kN} \), not decisive)

**resistances and effective lengths of end-plate in bending (per bolt-row):**
\[
\begin{align*}
F_{ep,Rd,2} &= 1510.13 \text{ kN}, \quad A_{left} = 416.8 \text{ mm} \\
F_{ep,Rd,3} &= 1176.48 \text{ kN}, \quad A_{left} = 334.2 \text{ mm}
\end{align*}
\]

### 3.3.2. Gk 7: beam flange and web in compression

flange bottom: section class for \( c / (c-t) = 2.86: 1 \)
web: section class for \( \alpha = 0.50 \) and \( c / (c-t) = 27.71: 1 \)
section class of beam: 1

Taking into account the moment-shear force-interaction \( V_{Ed} = 800.0 \text{ kN} \)

stress due to bending with shear force: 
\( V_{Ed} = 800.0 \text{ kN} \leq 1152.0 \text{ kN} = V_{pl,Rd,2} \Rightarrow \) no effect

resistance \( M_{c,Rd} = M_{pl,Rd} = (W_{pl} f_y) / (\gamma_M) = 2476.67 \text{ kNm}, \quad W_{pl} = 10539.00 \text{ cm}^3 \)
resistance of a flange (and web) with compression
\[
F_{c,t,Rd} = M_{c,Rd} / (h - t) = 3663.71 \text{ kN}
\]

resistance of upper beam flange:

stress due to bending with shear force: 
\( V_{Ed} = 800.0 \text{ kN} \leq 1152.0 \text{ kN} = V_{pl,Rd,2} \Rightarrow \) no effect

resistance \( M_{c,Rd} = M_{pl,Rd} = (W_{pl} f_y) / (\gamma_M) = 2476.67 \text{ kNm}, \quad W_{pl} = 10539.00 \text{ cm}^3 \)
resistance of a flange (and web) with compression
\[
F_{c,t,Rd} = M_{c,Rd} / (h - t) = 3663.71 \text{ kN}
\]

### 3.3.3. Gk 8: beam web in tension

Each individual bolt-row:

row 2
- effective width \( b_{eff,t,wb} = 416.8 \text{ mm} \) (left from bc 5)
- resistance of a beam web in tension
\[
F_{t,wb,Rd} = b_{eff,t,wb} \cdot f_{wb} \cdot f_y / \gamma_M = 2056.9 \text{ kN}
\]

row 3
- effective width \( b_{eff,t,wb} = 334.2 \text{ mm} \) (left from bc 5)
- resistance of a beam web in tension
\[
F_{t,wb,Rd} = b_{eff,t,wb} \cdot f_{wb} \cdot f_y / \gamma_M = 1649.2 \text{ kN}
\]

### 3.3.4. Gk 10: bolts in tension

tension resistance of one bolt \( F_{t,Rd} = (k_2 \cdot f_u \cdot A_s) / (\gamma_M) = 588.24 \text{ kN}, \quad k_2 = 0.90 \)
punching shear load capacity \( B_{pl,Rd} = (0.6 \cdot d_m \cdot f_p / f_u) / (\gamma_M) = 1716.00 \text{ kN}, \quad f_p = 50.0 \text{ mm} \)
tension-punching shear load capacity for 4 bolts: \( \Sigma F_{pl,Rd} = 4 \cdot \min(F_{t,Rd}, B_{pl,Rd}) = 2352.96 \text{ kN} \)

row (shear): \( \Sigma F_{pl,Rd,1} = 1176.5 \text{ kN}, \quad \Sigma F_{pl,Rd,2} = 1176.5 \text{ kN}, \quad \Sigma F_{pl,Rd,3} = 1176.5 \text{ kN} \)

row (bending): \( \Sigma F_{pl,Rd,1} = 2353.0 \text{ kN}, \quad \Sigma F_{pl,Rd,2} = 2353.0 \text{ kN}, \quad \Sigma F_{pl,Rd,3} = 1176.5 \text{ kN} \)

### 3.3.5. Gk 11: bolts in shear

shear resistance per shear plane \( F_{v,Rd} = \alpha_v f_u \cdot A / (\gamma_M) = 488.58 \text{ kN}, \quad \alpha_v = 0.60 \)
shear resistance of 4 bolts (1-shear): \( \Sigma F_{v,Rd} = 4 \cdot F_{v,Rd} = 1954.32 \text{ kN} \)

row: \( \Sigma F_{v,Rd,1} = 977.2 \text{ kN}, \quad \Sigma F_{v,Rd,2} = 977.2 \text{ kN}, \quad \Sigma F_{v,Rd,3} = 977.2 \text{ kN} \)

### 3.3.6. Gk 12: plate with bearing resistance

row 1
- bolt 1: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 568.33 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 0.64 \)
- bolt 2: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 568.33 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 0.64 \)
- bearing resistance of 1x2 bolts: \( \Sigma F_{b,Rd} = 1136.66 \text{ kN} \)

row 2
- bolt 1: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 886.60 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 1.00 \)
- bolt 2: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 886.60 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 1.00 \)
- bearing resistance of 1x2 bolts: \( \Sigma F_{b,Rd} = 1773.19 \text{ kN} \)

row 3
- bolt 1: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 886.60 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 1.00 \)
- bolt 2: bearing resistance \( F_{b,Rd} = (k_1 \cdot f_u \cdot d_t) / (\gamma_M) = 886.60 \text{ kN}, \quad k_1 = 1.71, \quad \alpha_B = 1.00 \)
- bearing resistance of 1x2 bolts: \( \Sigma F_{b,Rd} = 1773.19 \text{ kN} \)

bearing resistance (3 rows)
\[
\begin{align*}
\Sigma F_{b,Rd,1} &= 1136.66 \text{ kN} \\
\Sigma F_{b,Rd,2} &= 1773.19 \text{ kN} \\
\Sigma F_{b,Rd,3} &= 1773.19 \text{ kN}
\end{align*}
\]
3.4. connection capacity

3.4.1. moment resistance

distance of tension-bolt-rows from centre of compression: \( h_1 = 776.0 \text{ mm}, \ h_2 = 576.0 \text{ mm}, \ h_3 = 101.0 \text{ mm} \)

**resistance per bolt-row** (MNV-interaction)

row 1: \( F_{r, Rd} = 1756.4 \text{ kN} \)
row 2: \( F_{r, Rd} = 1510.1 \text{ kN} \)
row 3: \( F_{r, Rd} = 397.2 \text{ kN} \)

**resistance of flanges** (MNV-interaction)

bottom: \( F_{c, Rd} = 3663.7 \text{ kN} \)

**moment resistance** (MNV-interaction)

\( M_{r, Rd} = \frac{\sum (F_{r, Rd} \cdot h)}{2272.9 \text{ kNm}} \)

**shear force resistance** (MNV-interaction)

\( V_{j, Rd} = 826.5 \text{ kN} \)

3.4.2. shear resistance

**shear resistance of end plate**

end-plate: \( V_{ep, Rd} = 3612.19 \text{ kN} \)

welds: \( F_{w, Rd} = 2419.33 \text{ kN} \)

shear resistance of end plate: \( V_{ep, Rd} = F_{w, Rd} = 2419.33 \text{ kN} \)

3.5. verifications

3.5.1. verification of the connection capacity by means of the component method

\( U_{MNV} = 0.968 < 1 \text{ ok} \)

\( V_{Ed} / V_{ep, Rd} = 0.331 < 1 \text{ ok} \)

3.5.2. verification result

maximum utilization: \( \max U = 0.968 < 1 \text{ ok} \)

3.6. rotational stiffness

**stiffness coefficients**

equivalent stiffness coefficient for 3 tension-bolt-rows:

1: \( k_s = 123.60 \text{ mm}, k_{10} = 9.49 \text{ mm} \Rightarrow k_{eff,1} = 1 / \left( \frac{1}{k_s} + \frac{1}{k_{10}} \right) = 14.520 \text{ mm} \)

2: \( k_s = 311.66 \text{ mm}, k_{10} = 9.49 \text{ mm} \Rightarrow k_{eff,2} = 1 / \left( \frac{1}{k_s} + \frac{1}{k_{10}} \right) = 16.919 \text{ mm} \)

3: \( k_s = 249.88 \text{ mm}, k_{10} = 9.49 \text{ mm} \Rightarrow k_{eff,3} = 1 / \left( \frac{1}{k_s} + \frac{1}{k_{10}} \right) = 8.820 \text{ mm} \)

\( k_{eq} = \frac{1}{k_{eff,r \cdot h_r}} / Z_{eq} = 33.209 \text{ mm}, \quad Z_{eq} = \frac{1}{k_{eff,r \cdot h_r^2}} / \left( \frac{k_{eff,r \cdot h_r}}{k_{eff,r \cdot h_r}} \right) = 659.6 \text{ mm} \)

**rotational stiffness**

initial rotational stiffness: \( S_{j, ini} = \frac{(E \cdot z^2)}{\sum (1/k)} = 3033835.4 \text{ kNm/rad}, \quad z = Z_{eq} = 659.6 \text{ mm}, \quad \sum (1/k) = 0.030 \text{ mm}^{-1} \)

rotational stiffness: \( S_{j, Rd} = \frac{S_{j, ini}}{\mu} = 3033835.4 \text{ kNm/rad}, \quad \mu = 1 \)

rotation: \( \varphi_0, Ed = \frac{M_{j, Ed}}{S_{j, Rd}} = 0.042^\circ \)