EN 1994 - Eurocode 4: Design of composite steel and concrete structures

Composite Slabs

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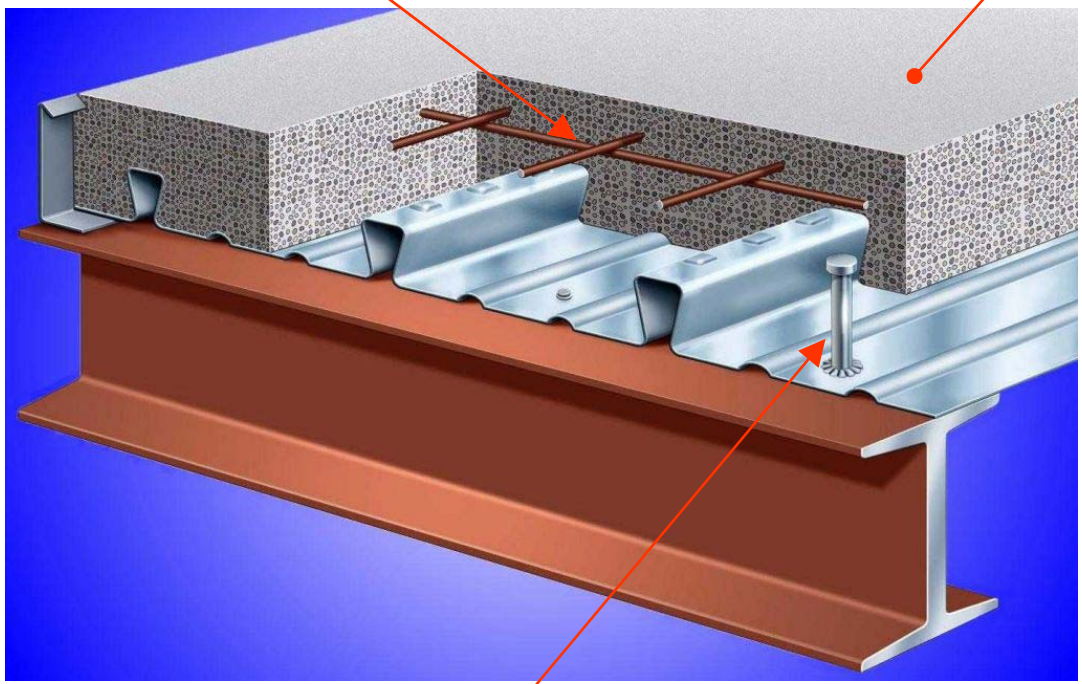
Composite slabs

Welded mesh reinforcement for crack control, transverse load distribution and fire resistance

Concrete cast *in situ*



Headed stud connectors for shear connection to the composite beam and, when required, end anchorage to the slab

Through-deck welding of headed stud shear connectors

Conventional composite construction

Benefits of composite beams

- Bending resistance increased by a factor of 1.5 to 2.5
- Stiffness increased by a factor of 3 to 4.5
- Steel weight reduced by typically 30 to 50%
- Reduction in beam depth (span:depth ≈ 25)
- Lightweight construction

Benefits of composite slabs

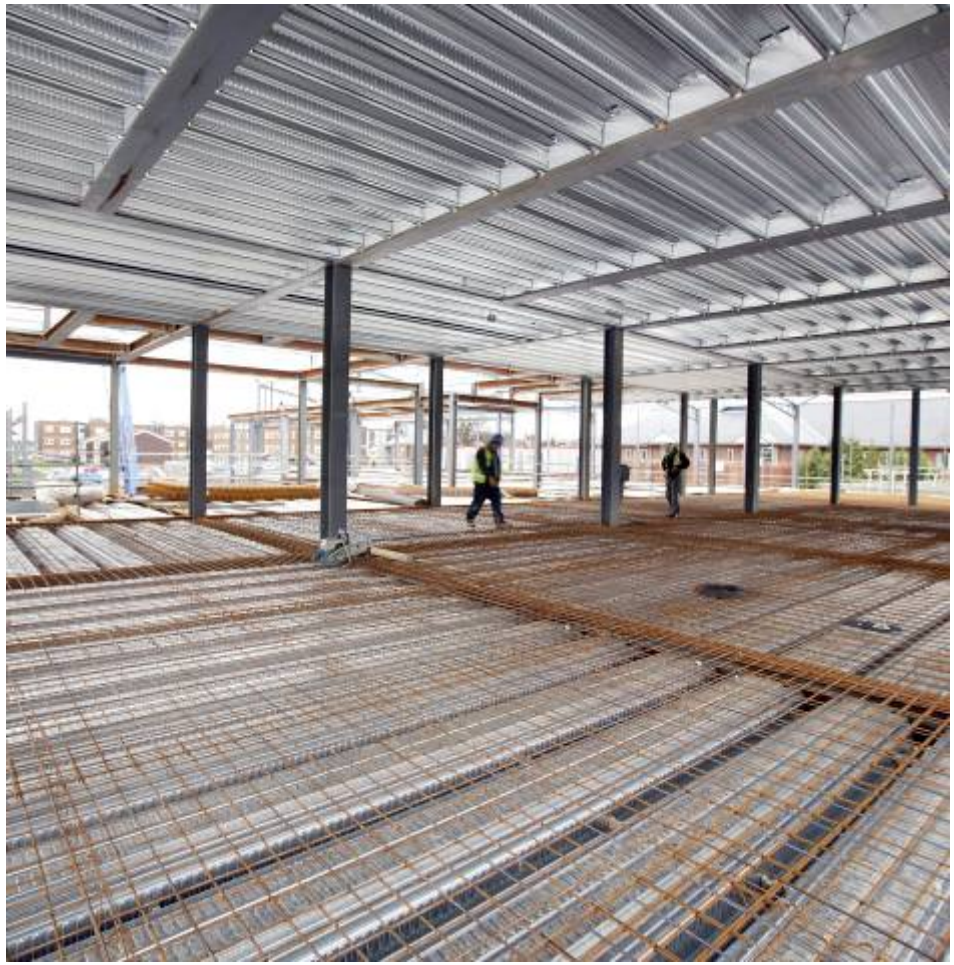
- Profiled steel sheeting acts as a safe working platform and permanent formwork.
- Unpropped construction may be achieved.
- Sheeting can stabilise beams during construction.
- Sheeting can provide all, or part, of the main tension reinforcement to the slab.

Examples of composite construction in UK

Commercial sector

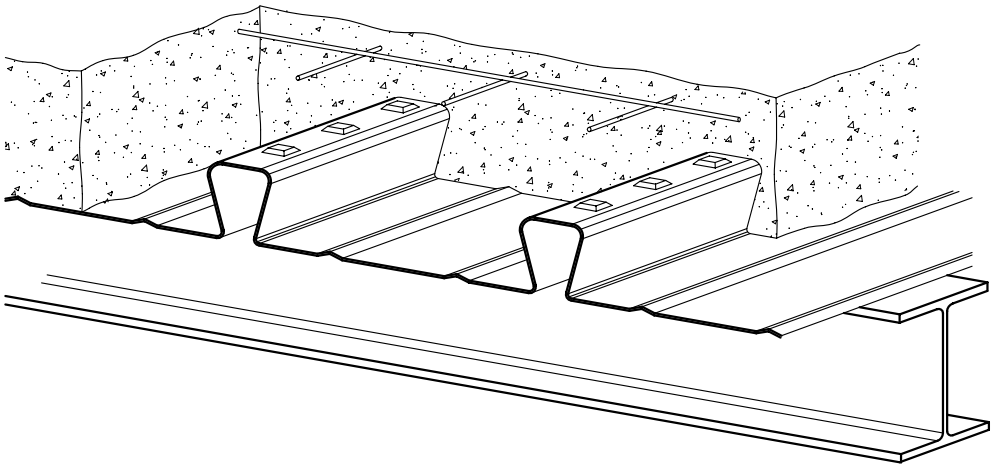
Residential sector

Examples of composite construction in UK

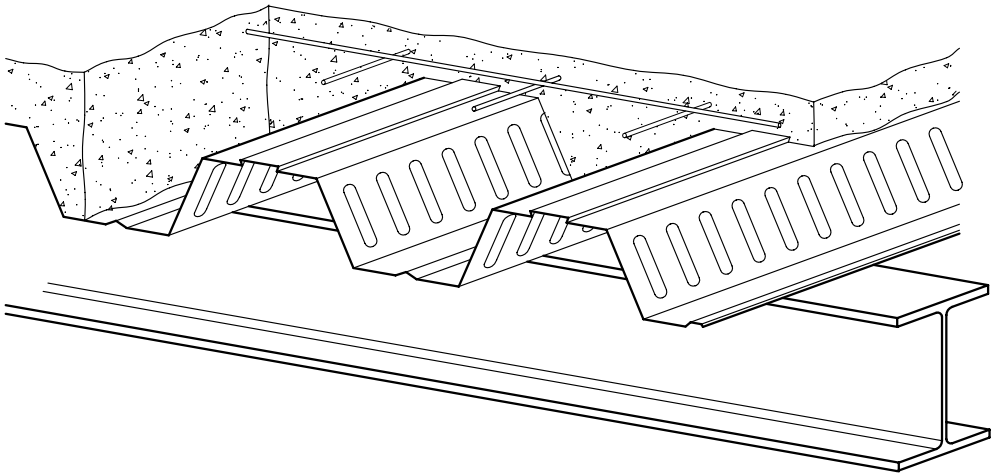


Health sector

Types of profiled steel sheeting defined in EN 1994-1-1

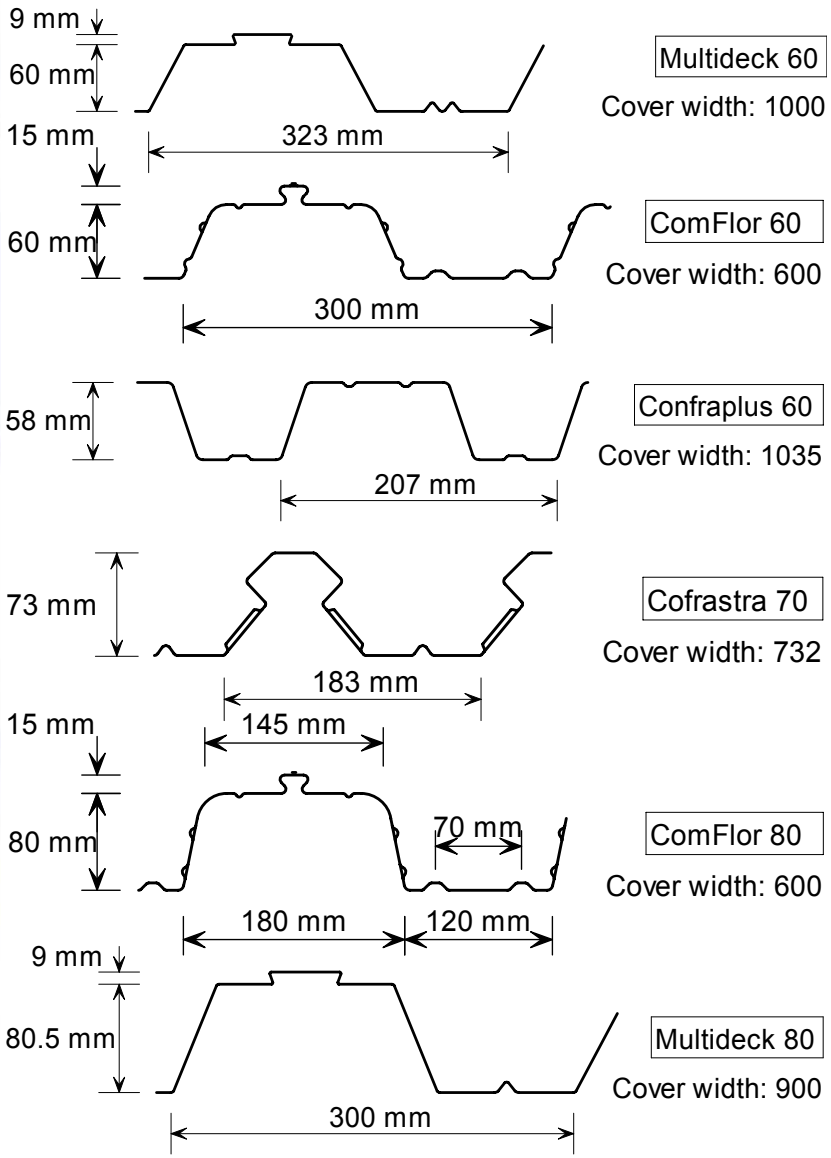


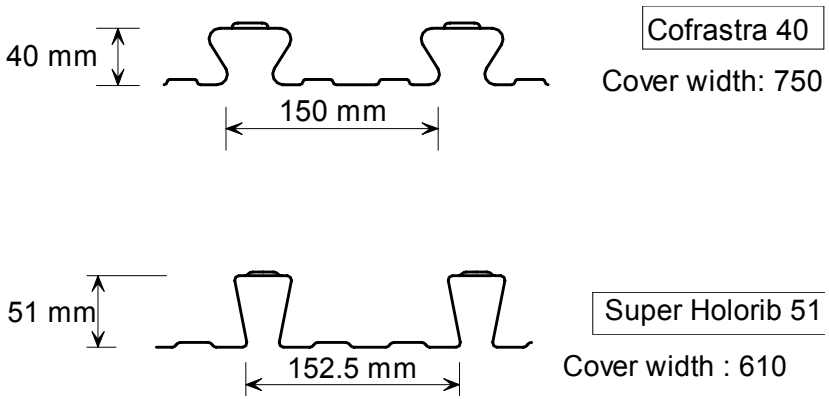
Re-entrant profiled steel sheet



Open trough profiled steel sheet

Practical examples of open trough and re-entrant profiled steel sheets used for composite slabs



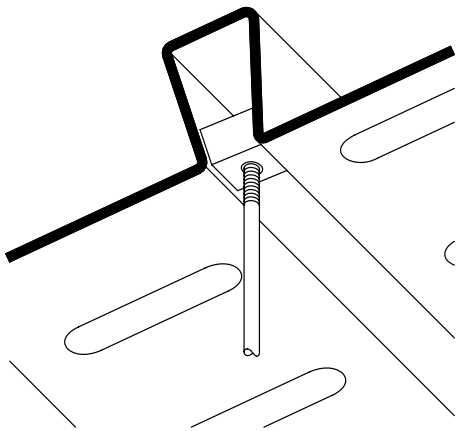


Composite construction with services passed under structural zone

Examples of fixings for ceilings and services

Wedge attachment

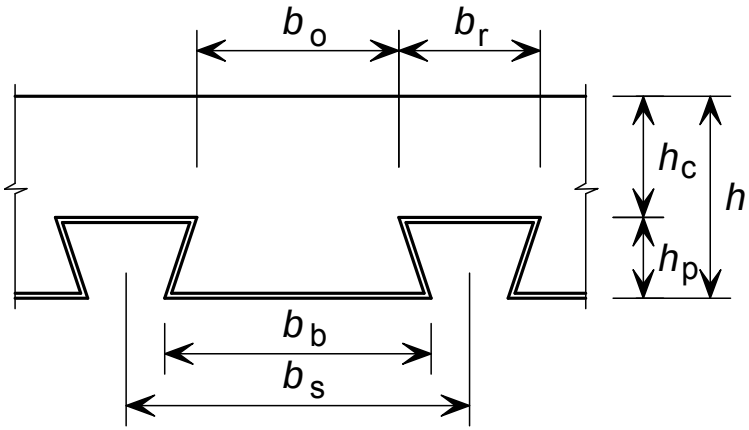
Clip attachment



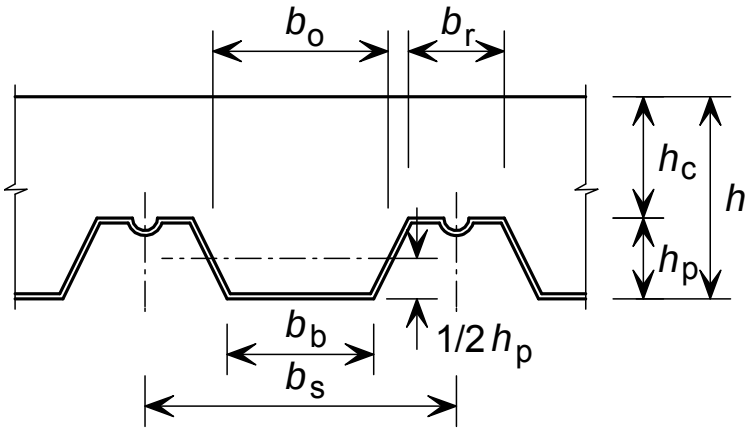
Alternative wedge attachment

EN 1994-1-1 detailing requirements

Re-entrant trough profile



Open trough profile



Scope limited to sheets with narrowly spaced ribs : $b_r / b_s \leq 0,6$

Slab thickness
When slab is acting compositely with beam or is used as a diaphragm:
$h \geq 90$ mm & $h_c \geq 90$ mm

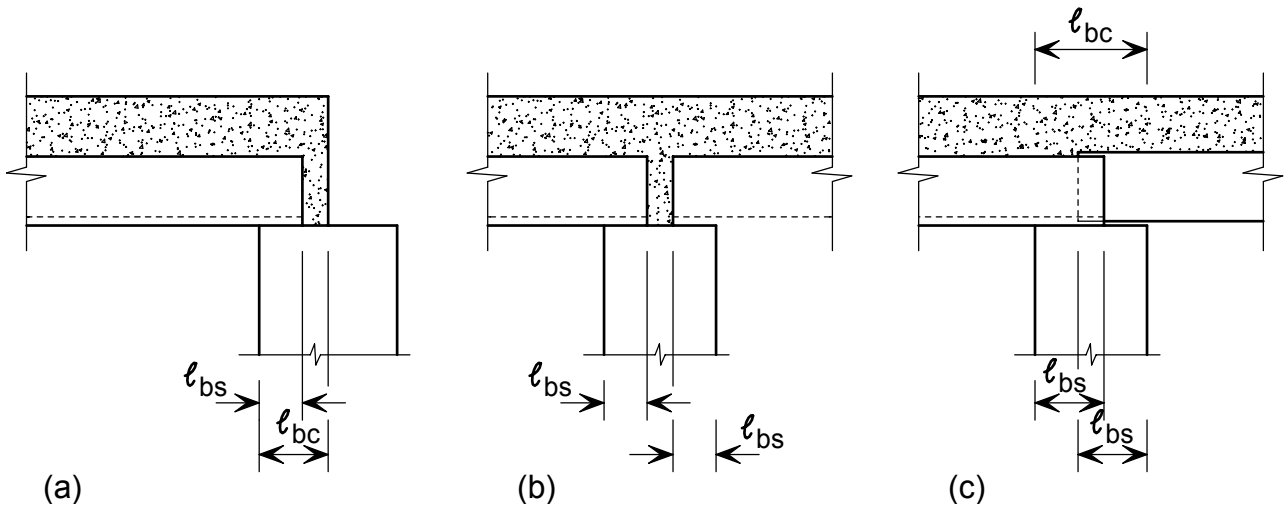
When slab is not acting compositely with beam or has no stabilizing function:
$h \geq 80$ mm & $h_c \geq 40$ mm

Reinforcement ≥ 80 mm²/m in both directions

Spacing of reinforcement bars
$s \leq 2h$ & 350 mm

Maximum aggregate size
$d_g \leq 0,4\ h_c$, $b_0 / 3$ and 31,5 mm

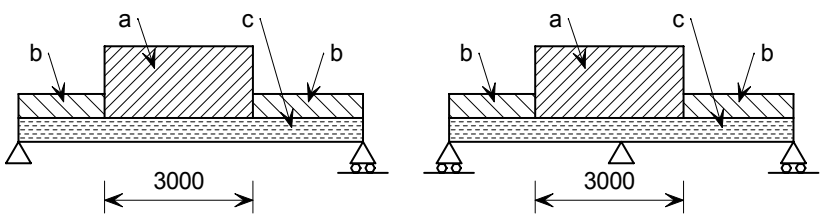
EN 1994-1-1 composite slab bearing requirements



The bearing length shall be such that damage to the slab and the bearing is avoided; that fastening of the sheet to the bearing can be achieved without damage to the bearing and that collapse cannot occur as a result of accidental displacement during erection.

- **For bearing on steel or concrete: l_{bc} = 75 mm and l_{bs} = 50 mm**
- **For bearing on other materials: l_{bc} = 100 mm and l_{bs} = 70 mm**

Actions and action effects on profiled steel sheeting

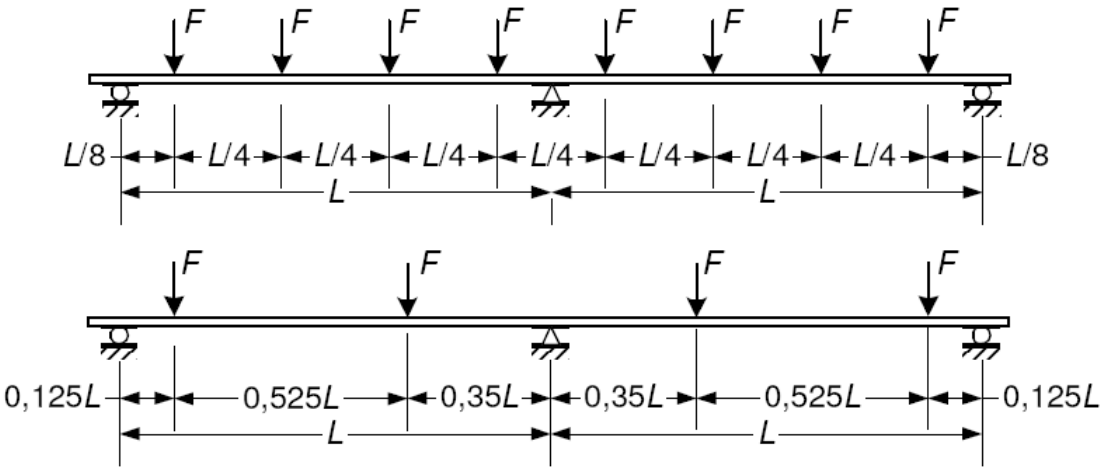


a) Imposed load on a 3 m × 3 m working area (or the length of the span if less), with an intensity of 10% of the self-weight of the concrete but ≤ 1,5kN/m² and ≥ 0,75 kN/m

b) Imposed load of 0,75 kN/m²

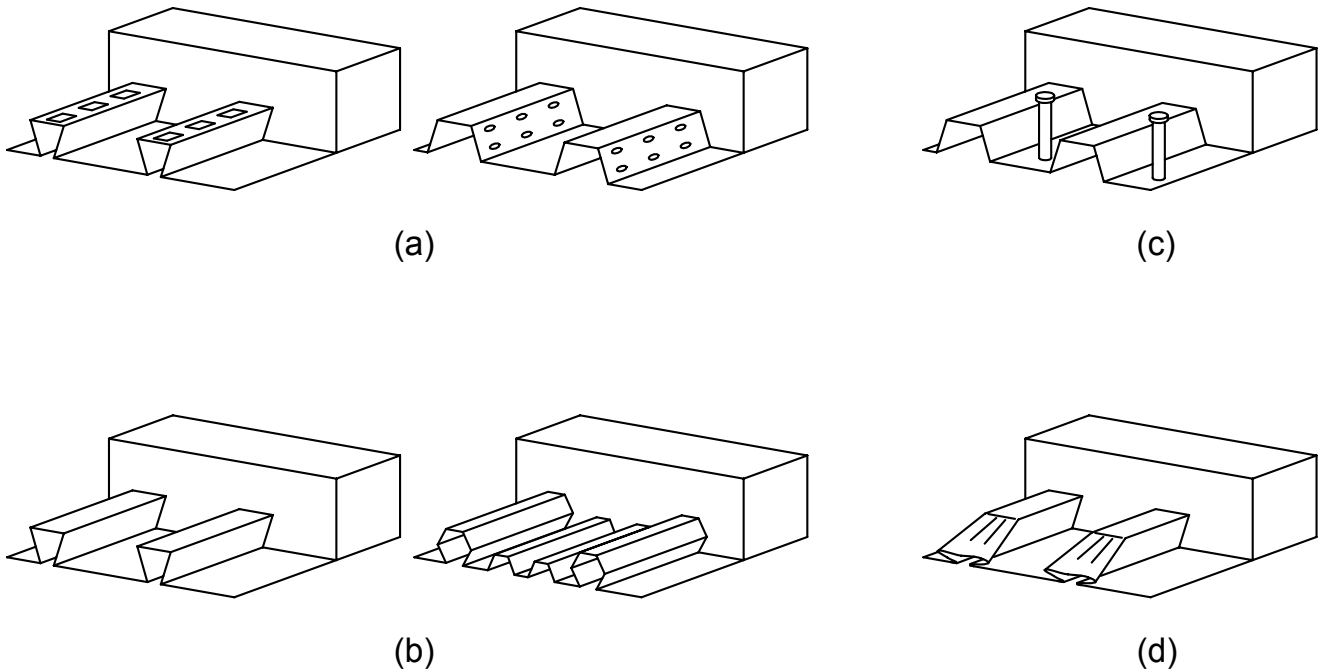
c) Self weight load corresponding to the design thickness of the slab plus ponding effects if $\delta > h / 10$

Analysis for internal forces and moments - set-up for double span tests on profiled steel sheeting



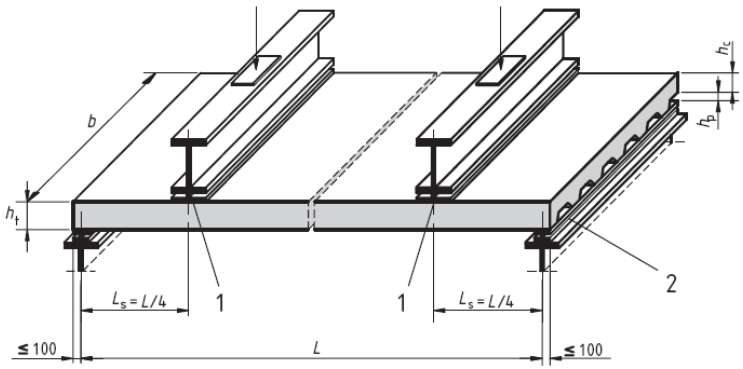
Combined bending and crushing at internal support

Typical forms of shear connection in composite slabs



a) Mechanical interlock through the provision of indentations or embossments rolled into the profile.
b) Frictional interlock for re-entrant profiles.
c) End anchorage from through-deck welded stud connectors or other local connection.
d) End anchorage from deformation of the ends of the ribs at the end of the sheeting.

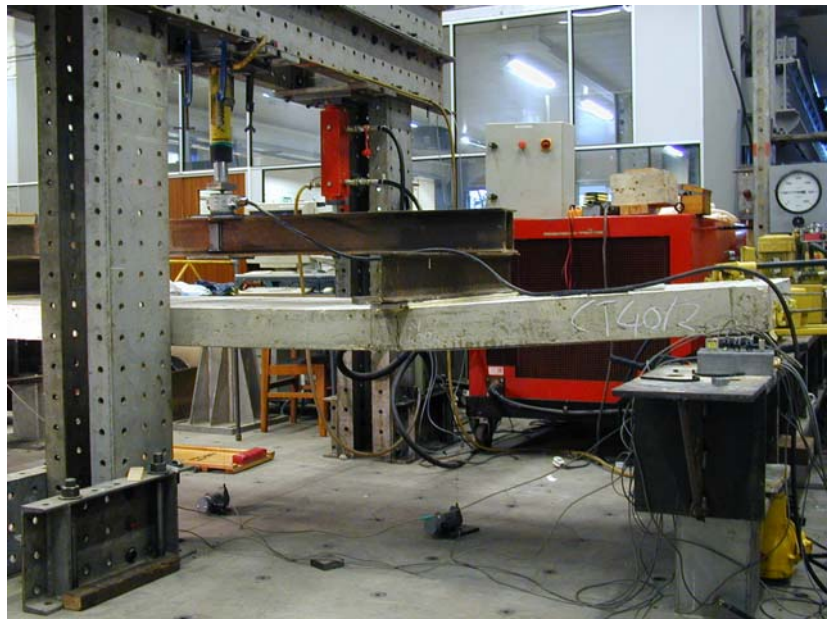
Longitudinal shear resistance



Key

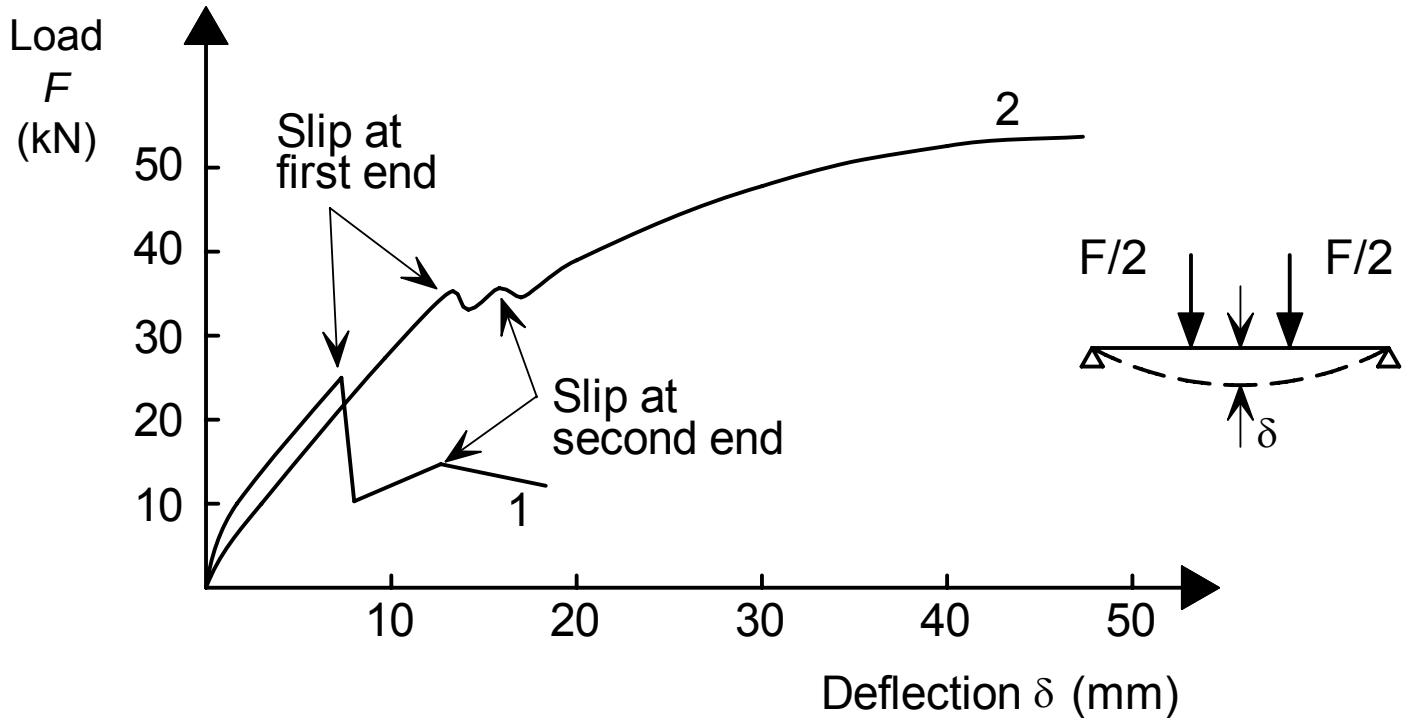
1 neoprene pad or equivalent ≤ 100 mm x *b*

2 support bearing plate ≤ 100 mm x *b* x 10 mm (min) (typical for all bearing plates)



Test set-up from EN 1994-1-1, Annex B

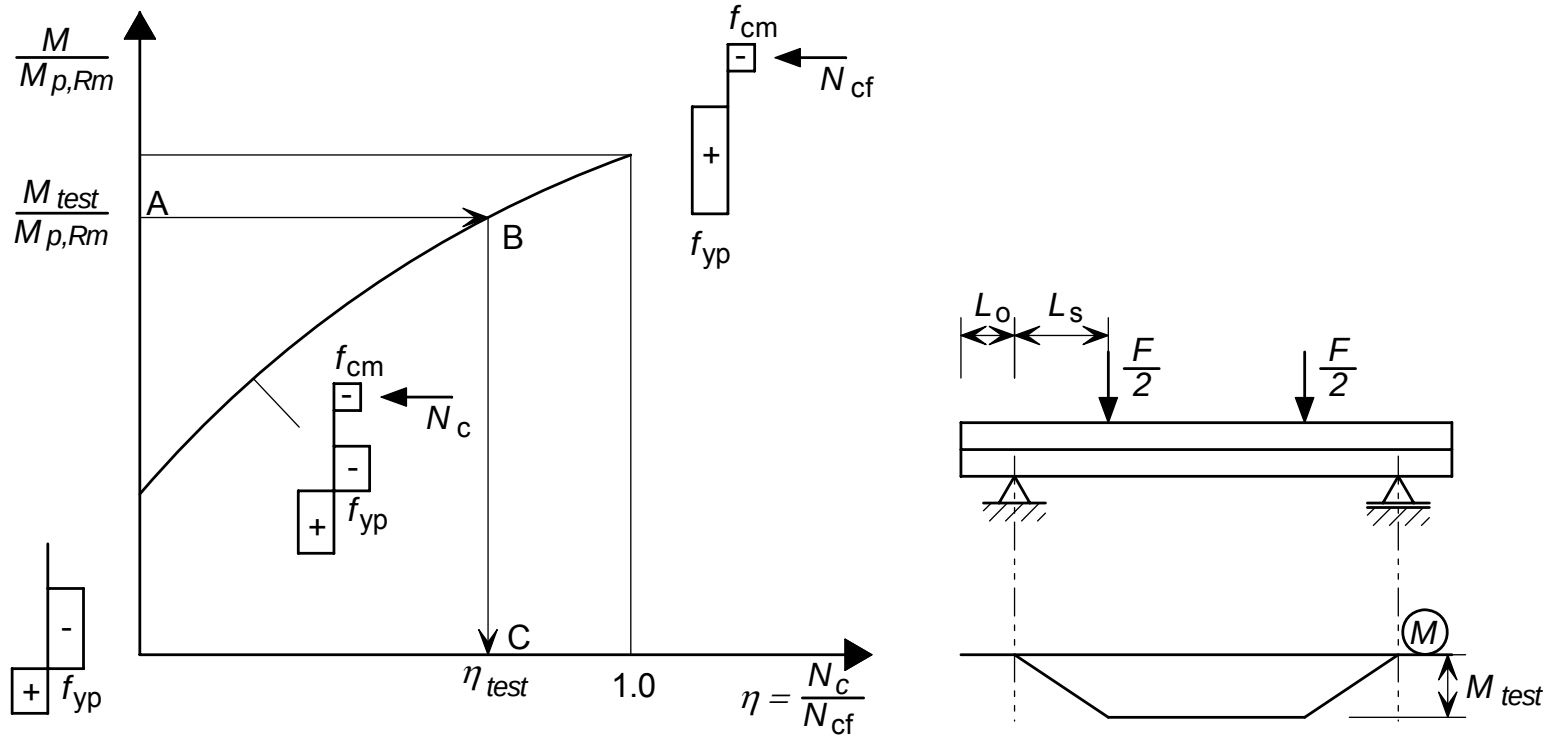
Classification of ductile or brittle behaviour



1. **Brittle behaviour**
   - o *m-k* method

2. **Ductile behaviour - failure load exceeds the load causing a recorded end slip of 0,1 mm by more than 10%**
   - o Partial connection method
   - o *m-k* method

Determination of longitudinal shear resistance without end anchorage for the partial connection method



Mean value for the ultimate shear stress:

$$\tau_u = \frac{\eta_{test} N_{cf}}{b(L_s + L_o)}$$

Mean value for the ultimate shear stress with additional longitudinal shear resistance caused by the support reaction:

$$\tau_u = \frac{\eta_{test} N_{cf} - \mu V_t}{b(L_s + L_o)}$$

Determination of design value for $\tau_{u,Rd}$ from tests

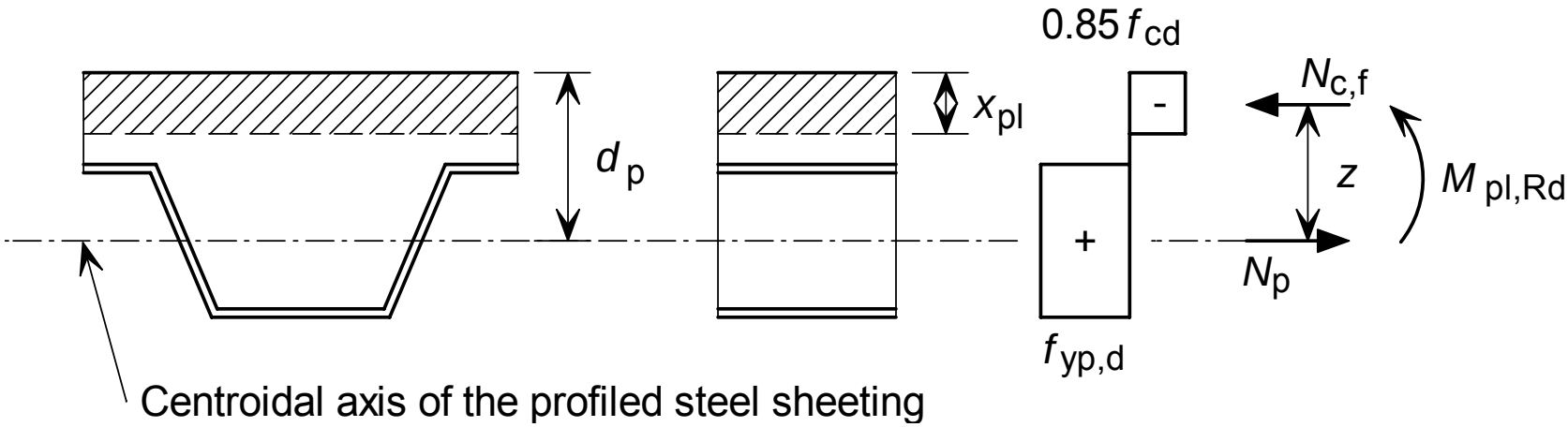
For each variable investigated:

- **3 test specimens with the shear span L_s as long as possible, whilst still providing failure in longitudinal shear.**
- **1 test specimen with the shear span L_s as short as possible (but not less than 3 × overall slab thickness), whilst still providing failure in longitudinal shear to classify the behaviour**

Characteristic value of the longitudinal shear strength $\tau_{u,Rk}$ calculated from the test values as the 5% fractile from EN1990, Annex D

$\tau_{u,Rk}$ is divided by the partial safety factor γ_{VS} to obtain a design value $\tau_{u,Rd}$

Neutral axis above the sheeting and full shear connection ($\eta = 1$)



Design compressive normal force in the concrete flange:

$N_{c,f} = N_p = A_{pe}\, f_{yp,d}$

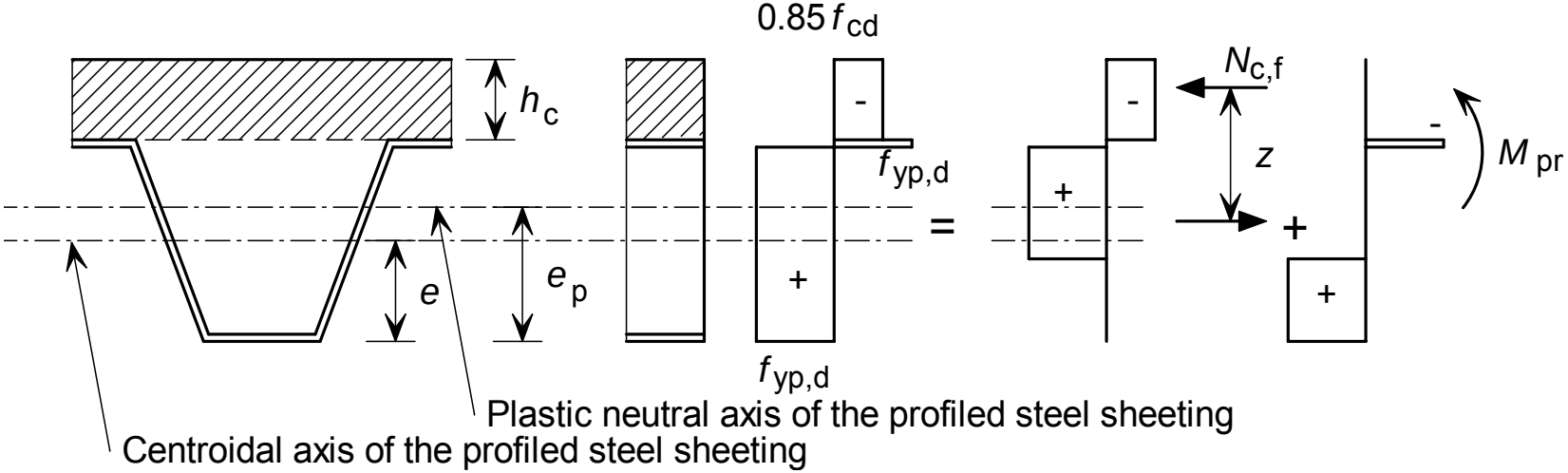
Depth of the concrete in compression

$x_{pl} = N_{c,f} / (0{,}85\, f_{cd}\, b) \leq h_c$

Design moment resistance of the composite slab in sagging bending

$M_{Rd} = N_{c,f}\ (d_p - 0{,}5\, x_{pl})$

Neutral axis within the sheeting and full shear connection ($\eta = 1$)



Design compressive normal force in the concrete flange: $N_{c,f} = 0{,}85\ f_{cd}\ b\ h_c$

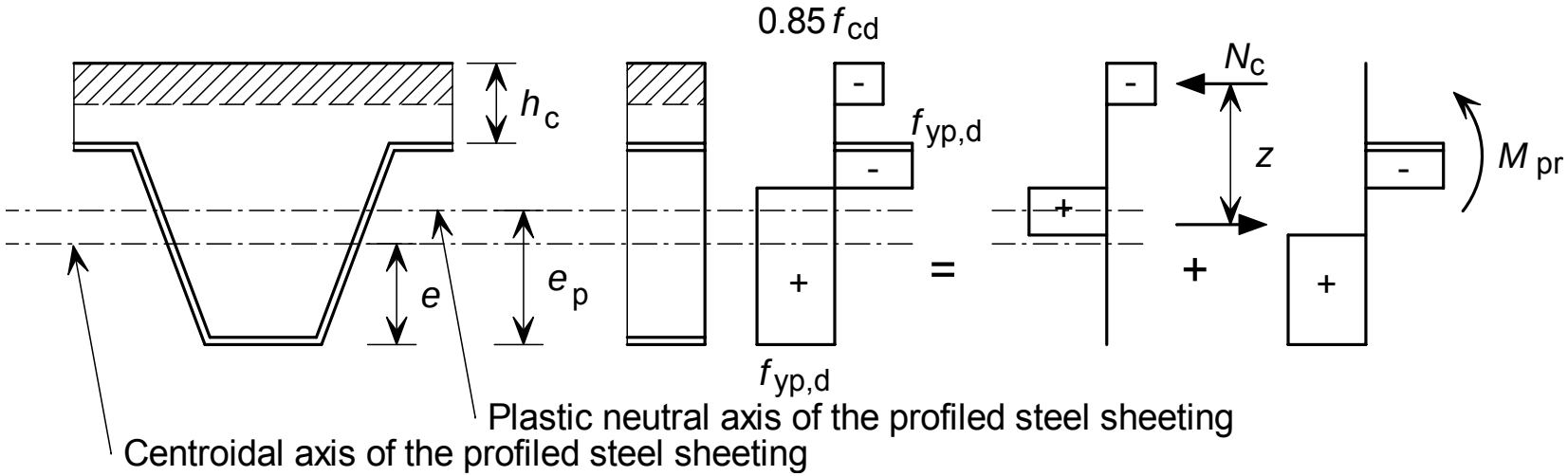
Reduced plastic moment resistance of the sheeting: $M_{pr} = 1{,}25 M_{pa}\left(1 - \frac{N_{cf}}{A_{pe} f_{yp,d}}\right)$

Lever arm: $z = h - 0{,}5h_c - e_p + \left(e_p - e\right)\frac{N_{cf}}{A_{pe} f_{yp,d}}$

Design moment resistance of the composite slab in sagging bending

$M_{Rd} = N_{c,f}\ z + M_{pr}$

Partial shear connection ($0 < \eta < 1$)



Design compressive normal force in the concrete flange: $N_c = \tau_{u,Rd}\, b\, L_x \leq N_{c,f}$

Reduced plastic moment resistance of the sheeting: $M_{pr} = 1{,}25 M_{pa}\left(1 - \dfrac{N_c}{A_{pe}\, f_{yp,d}}\right)$

Lever arm: $z = h - 0{,}5h_c - e_p + \left(e_p - e\right)\dfrac{N_c}{A_{pe}\, f_{yp,d}}$

Design moment resistance of the composite slab in sagging bending

$M_{Rd} = N_c\, z + M_{pr}$

End anchorage

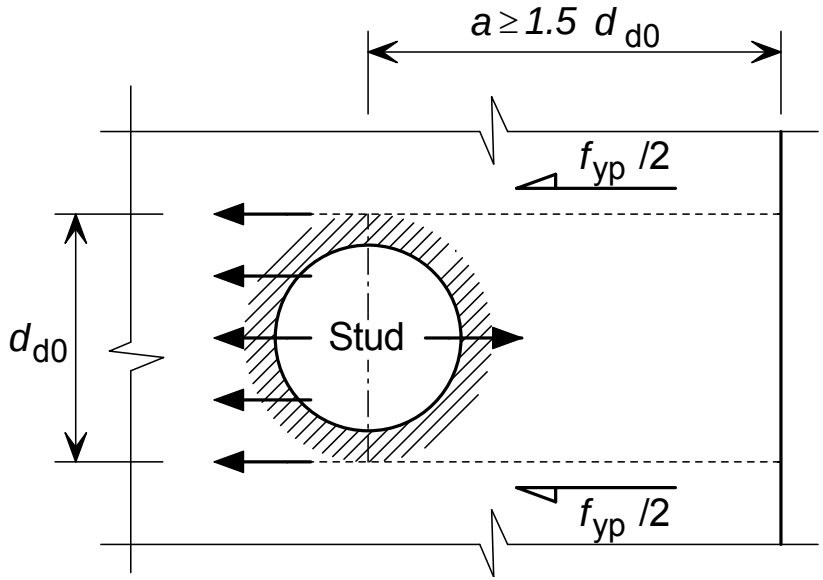
According to EN 1994-1-1, design resistance of a headed stud welded through the steel sheet used for end anchorage should be taken as the lesser of:

$P_{Rd}\ k_t$

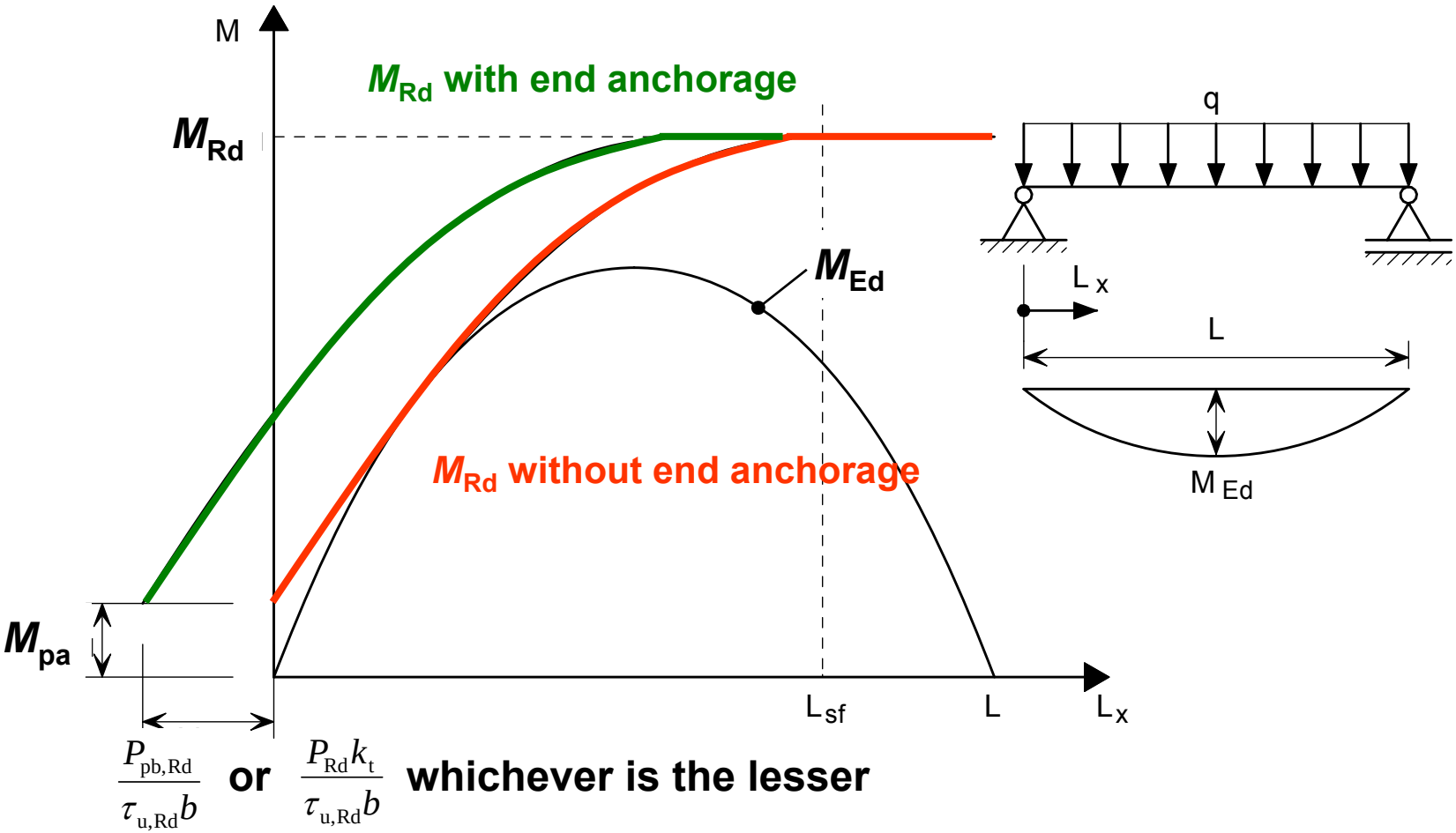
or

$P_{pb,Rd} = k_\varphi\ d_{do}\ t\ f_{yp,d}$

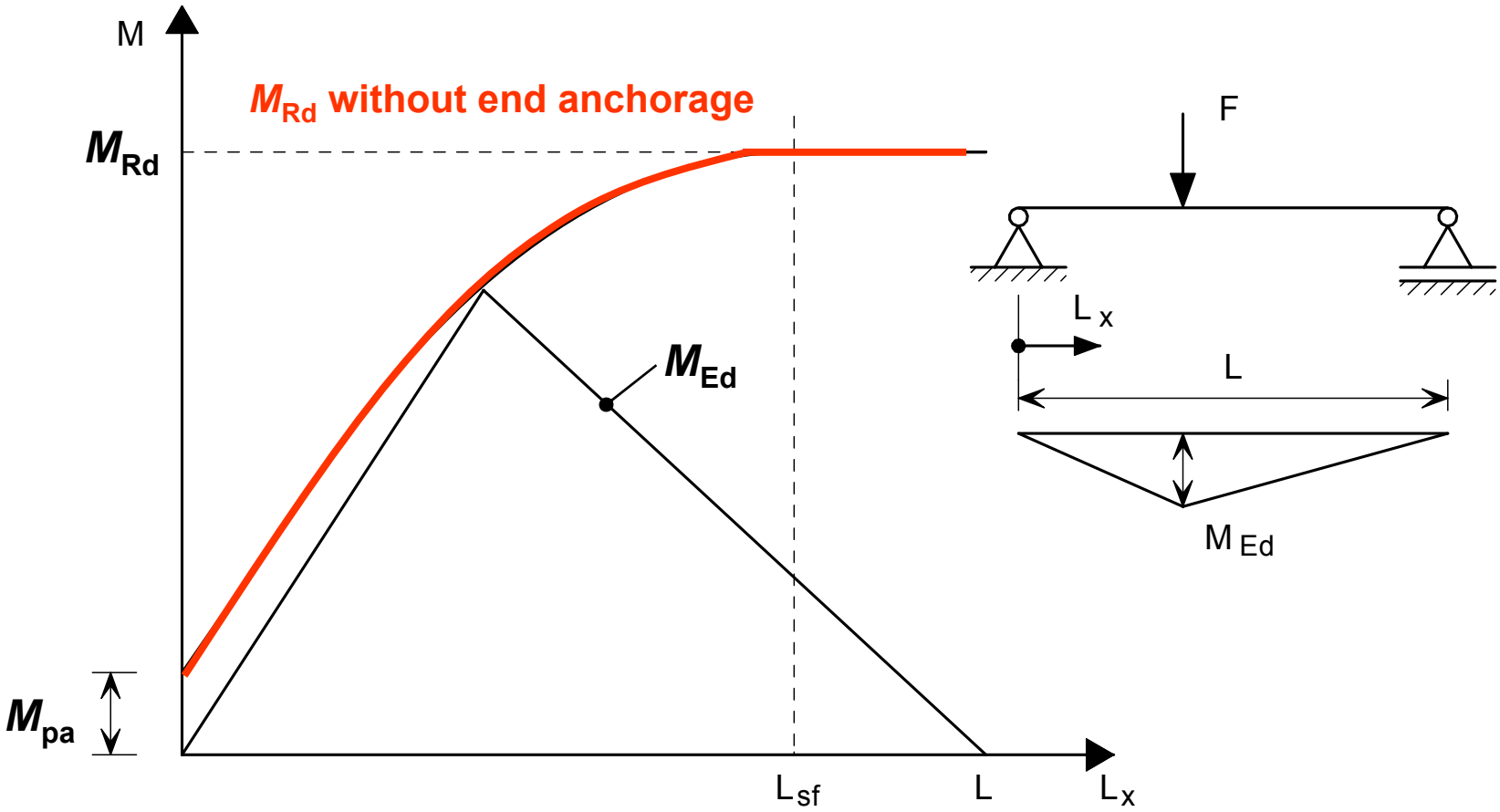
where P_{Rd} is the design resistance of a headed stud embedded in concrete, k_t is a reduction factor for deck shape, d_{do} is the diameter of the weld collar (which may be taken as 1,1 times the shank diameter), t is the sheet thickness and $k_\varphi = 1 + a / d_{do} \leq 6{,}0$



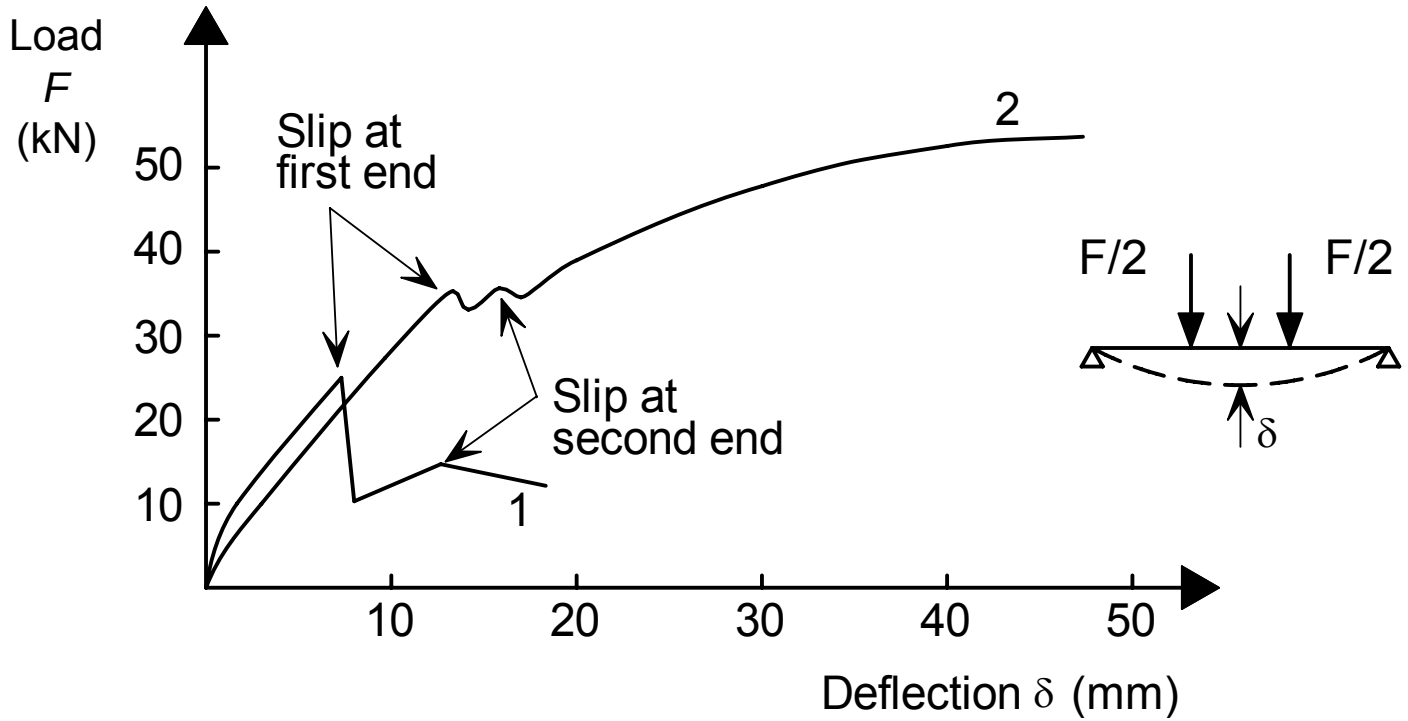
Variation of bending resistance along a span: uniform distributed load



Variation of bending resistance along a span: Point load



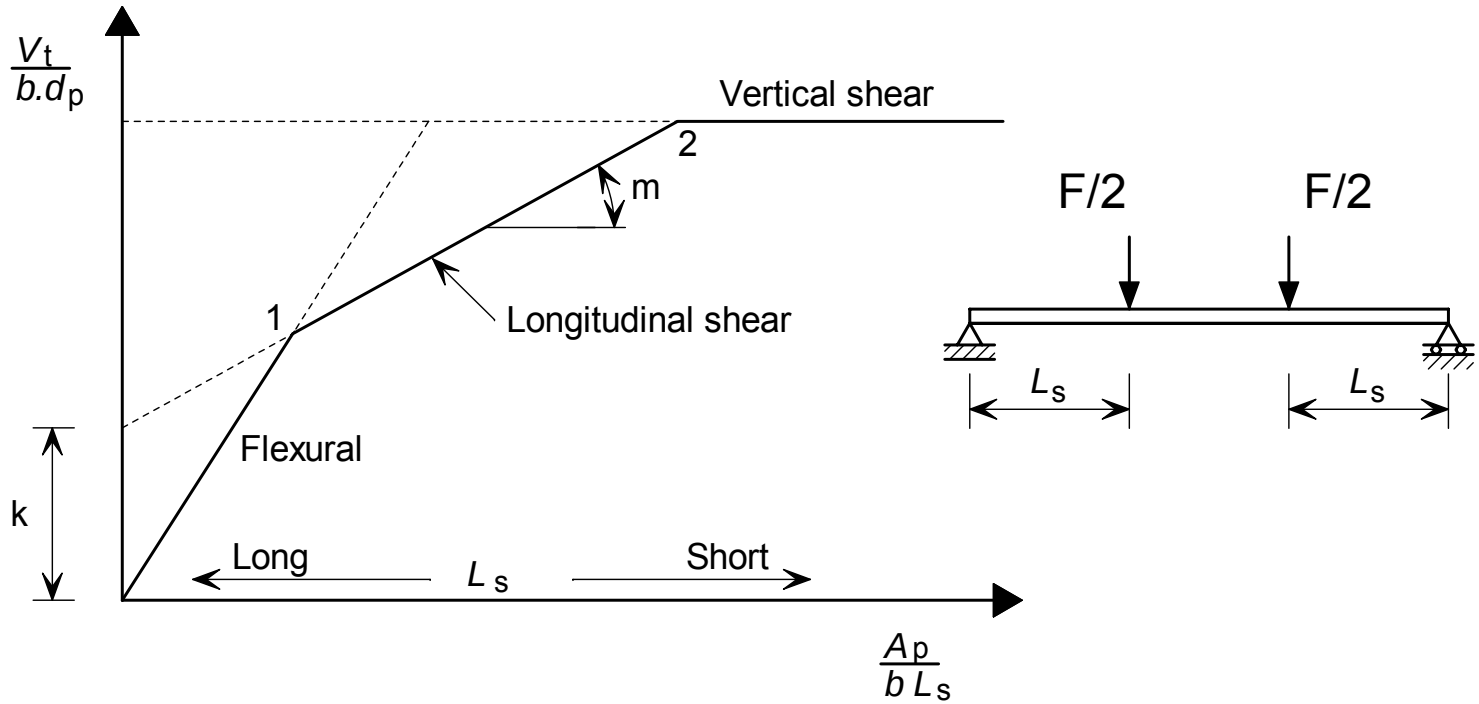
Classification of ductile or brittle behaviour



1. **Brittle behaviour**
   - *m-k* method

2. **Ductile behaviour - failure load exceeds the load causing a recorded end slip of 0,1 mm by more than 10%**
   - Partial connection method
   - *m-k* method

Determination of *m-k* values from tests

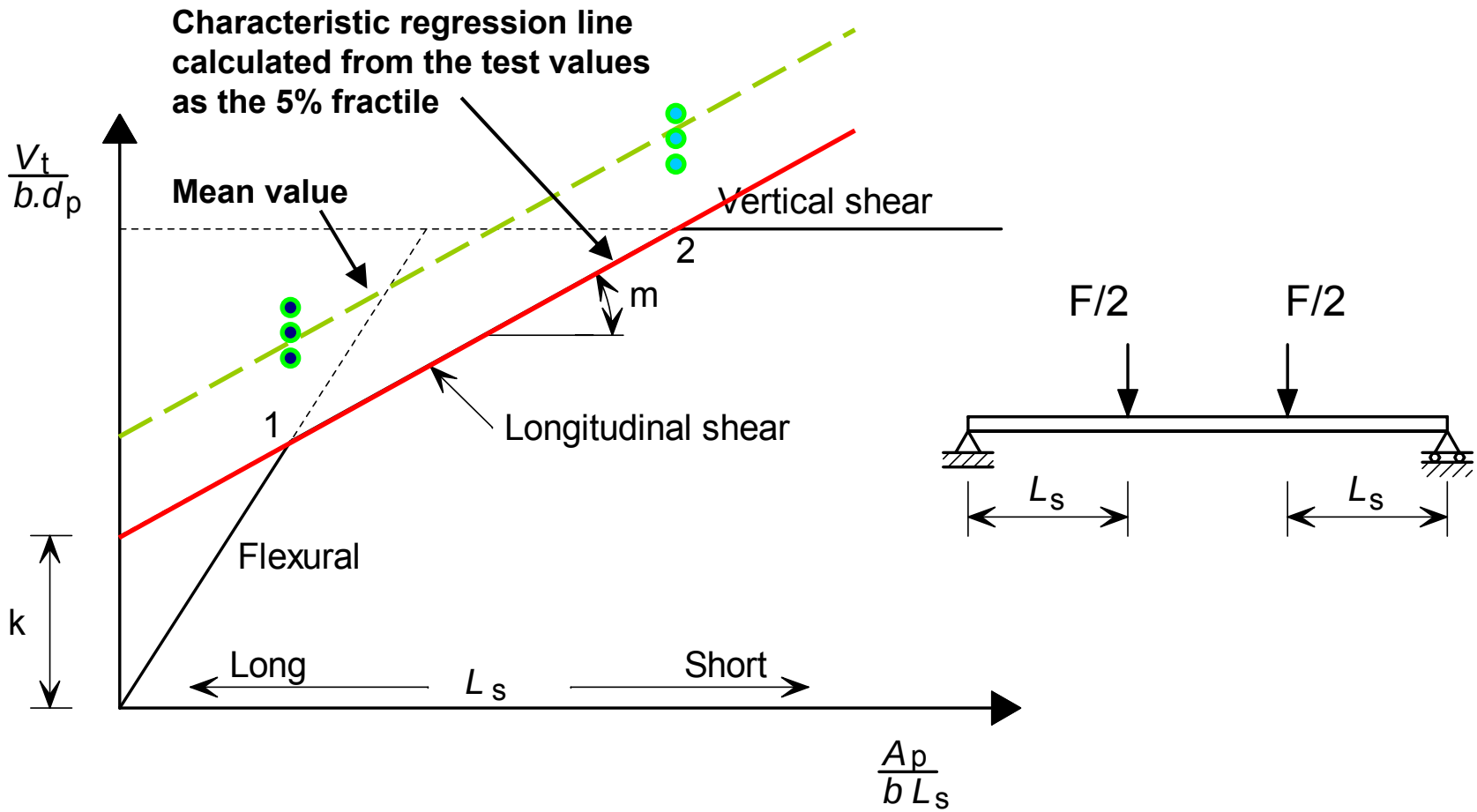


For each variable investigated:

- **3 test specimens with the shear span L_s as long as possible, whilst still providing failure in longitudinal shear.**
- **3 test specimens with the shear span L_s as short as possible (but not less than 3 × overall slab thickness), whilst still providing failure in longitudinal shear to classify the behaviour**

If behaviour brittle, $V_t = 0{,}8\ (F / 2)$

Determination of *m-k* values from tests



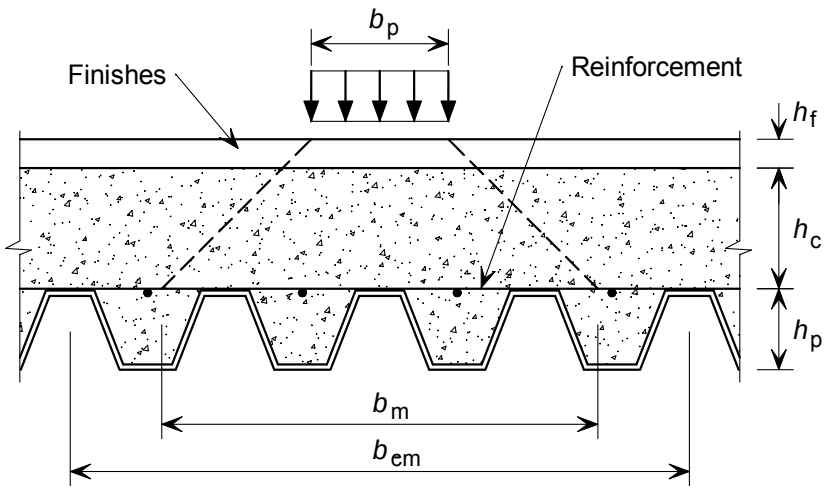
Design shear resistance

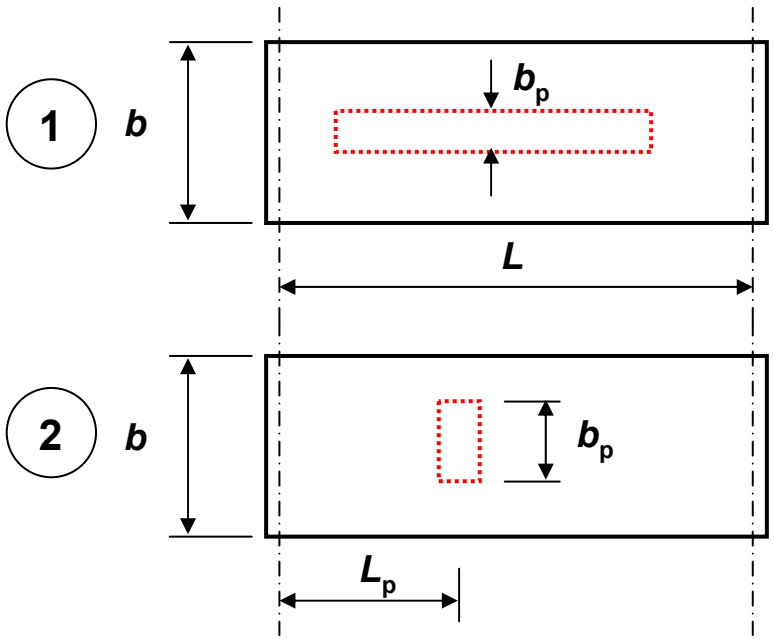
$$V_{l,Rd} = \frac{bd_p}{\gamma_{VS}}\left(\frac{mA_p}{bL_s} + k\right)$$

Disadvantages of *m-k* method

- The results contain all the influencing parameters, but are impossible to separate from one another.
- Methodology is not based on a mechanical model and is therefore less flexible than the partial connection approach (contribution from end anchorage and reinforcement need to be evaluated from additional tests).
- Other loading arrangements that differ from the test loading can be problematical.

Effective width for slabs with concentrated loads





For h_p / $h \leq 0{,}6$

For bending and longitudinal shear:
i) for simple spans and exterior spans of continuous slabs

$$b_{em} = b_m + 2L_p\left(1 - \frac{L_p}{L}\right) \leq b$$

ii) for interior spans of continuous slabs

$$b_{em} = b_m + 1{,}33L_p\left(1 - \frac{L_p}{L}\right) \leq b$$

For vertical shear

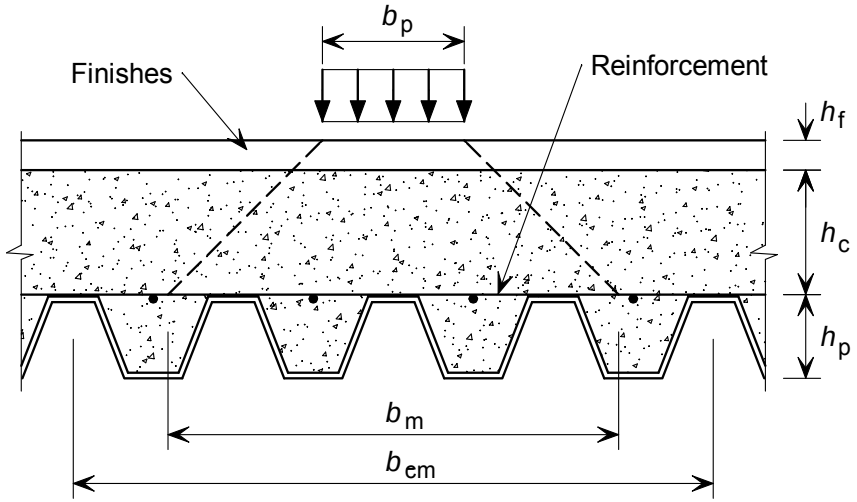
$$b_{ev} = b_m + L_p\left(1 - \frac{L_p}{L}\right) \leq b$$

Width of slab over which load is distributed

$b_m = b_p + 2\,(h_c + h_f)$

Case ① – Concentrated loads applied parallel to the span
Case ② – Concentrated loads applied perpendicular to the span

Transverse reinforcement for concentrated loads



If the characteristic imposed loads do not exceed the values given below, a nominal transverse reinforcement of not less than 0,2% of the area of concrete above the ribs of the sheet (which extends ≥ the minimum anchorage length beyond b_{em}), may be provided without any further calculation:

- **concentrated load: 7,5 kN;**
- **distributed load: 5,0 kN/m².**

For characteristic imposed loads greater than these values, the distribution of bending moments and the appropriate amount of transverse reinforcement should be evaluated according to EN 1992-1-1.

Vertical shear resistance of composite slabs

$V_{v,Rd}$ should be determined using EN 1992-1-1, 6.2.2 which gives the following:

$$V_{v,Rd} = [C_{Rd,c}\, k(100\rho_l\, f_{ck})^{1/3} + k_1\, \sigma_{cp}]\, b_s d \qquad (6.2a)$$

with a minimum of

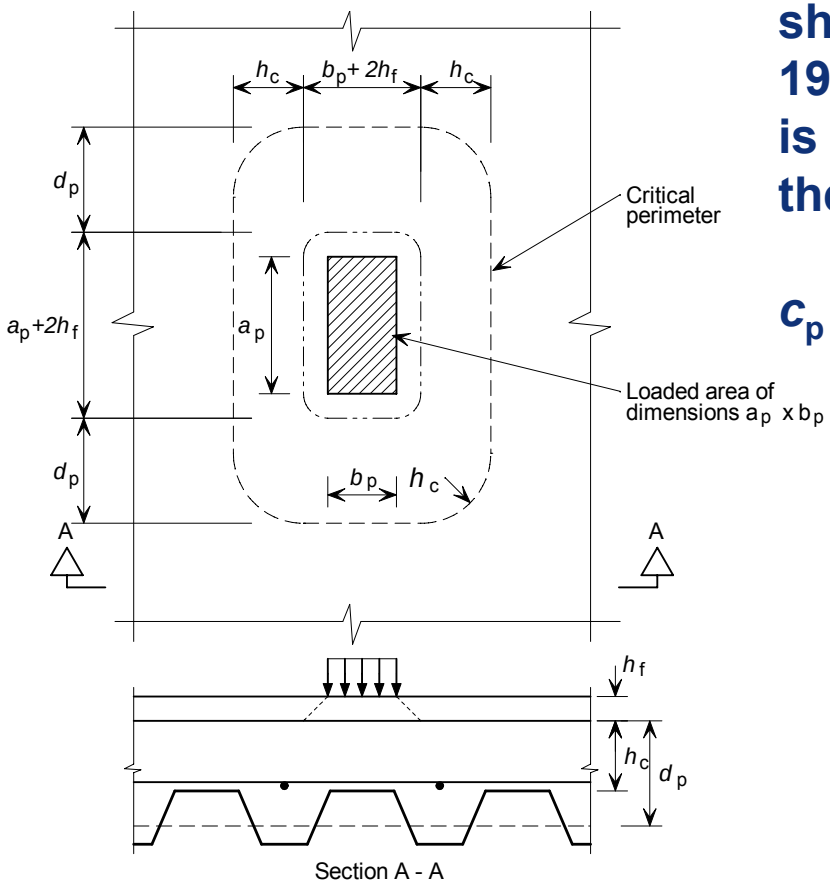
$$V_{v,Rd} = (v_{min} + k_1\, \sigma_{cp})\, b_s d \qquad (6.2b)$$

where $\rho_l = A_{sl} / b_s\, d$, A_{sl} is the area of the tensile reinforcement which extends ≥ (l_{bd} + d) beyond the section considered and other symbols are defined in EN1992-1-1.

For normal loading conditions, and the fact that the sheeting is unlikely to be fully anchored, the vertical shear resistance will commonly be based on Eq (6.2b).

For heavily loaded slabs, additional reinforcement bars may be required at the support and the vertical shear resistance based on Eq (6.2a). According to the ENV version of EN 1994-1-1, it is permitted to assume that the sheeting contributes to A_{sl} provided that it is fully anchored beyond the section considered.

Punching shear resistance



The punching shear resistance $V_{p,Rd}$ should be calculated according to EN 1992-1-1. For a loaded area $a_p \times b_p$, which is applied to a screed with a thickness h_f, the critical perimeter is given by:

$$c_p = 2\pi h_c + 2(b_p + 2h_f) + 2(a_p + 2h_f + 2d_p - 2h_c)$$

Serviceability limit states for composite slabs

Crack widths

For continuous slabs that are designed as simply-supported, the minimum cross-sectional area of the anti-crack reinforcement within the depth h_c should be:

- 0,2% of the cross-sectional area of the concrete above the ribs for unpropped construction
- 0,4% of the cross-sectional area of the concrete above the ribs for propped construction.

The above amounts do not automatically ensure that $w_{max} \leq 0,3$ mm as given in EN1992-1-1 for certain exposure classes.

If cracking needs to be controlled, the slab should be designed as continuous, and the crack widths in hogging moment regions evaluated according to EN 1992-1-1, 7.3.

Deflection

Deflections due to loading applied to the composite member should be calculated using elastic analysis, neglecting the effects of shrinkage.

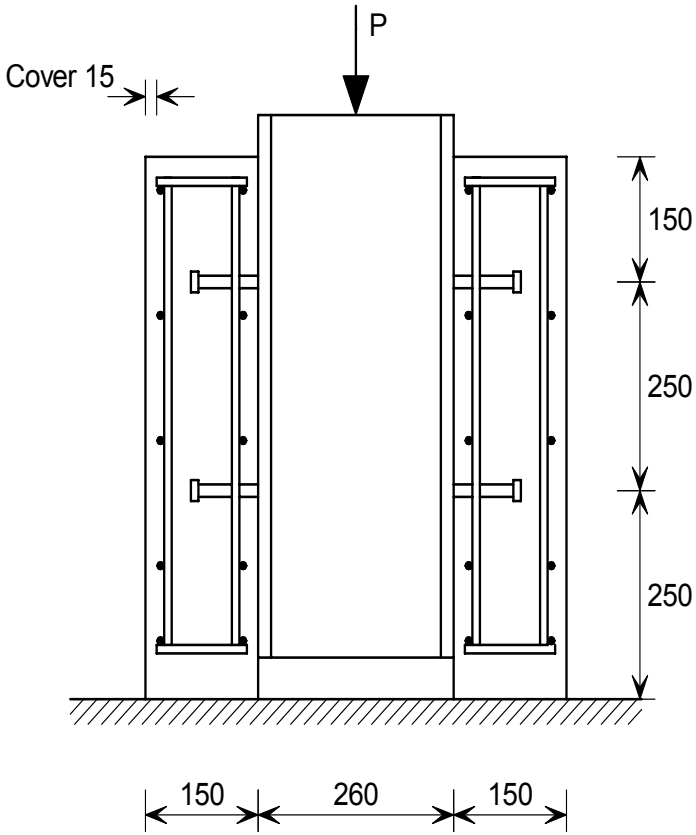
For an internal span of a continuous slab, the deflection may be estimated using the following approximation:

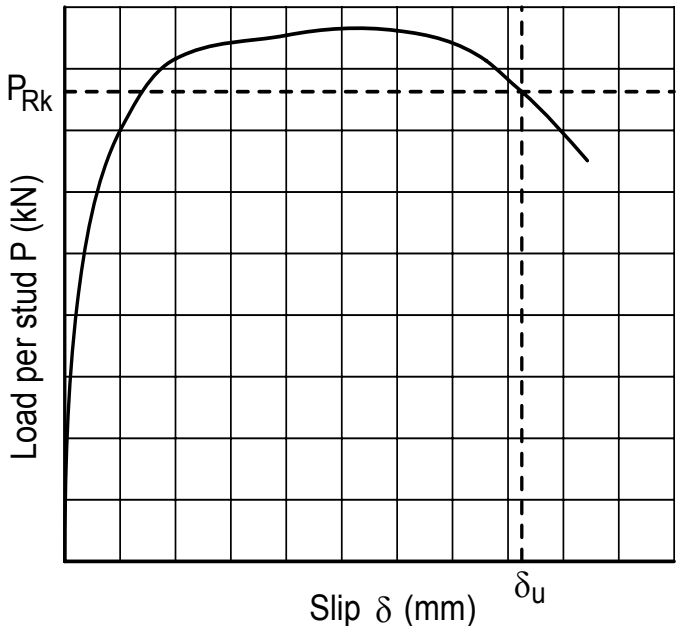
- the average value of the cracked and uncracked second moment of area may be taken.
- for the concrete, an average value of the modular ratio for long-term and short-term effects may be used.

For external, or simply supported spans, calculations of the deflection of the composite slab may be omitted if:

- the span/depth ratio of the slab does not exceed 20 for a simply-supported span and 26 for an external span of a continuous slab (corresponding to the lightly stressed concrete limits given in EN 1992-1-1; and
- the load causing an end slip of 0,5 mm in the tests on composite slabs exceeds 1,2 times the design service load.

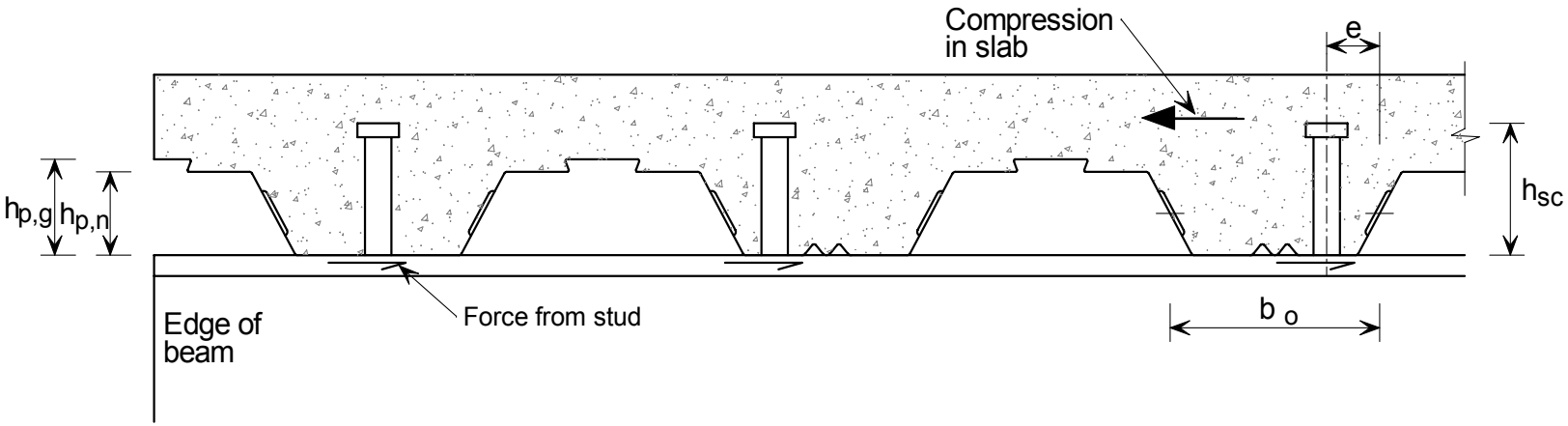
Standard push test





6 mm

Position of studs in open trough sheeting and reduction factor formula according to EN 1994-1-1

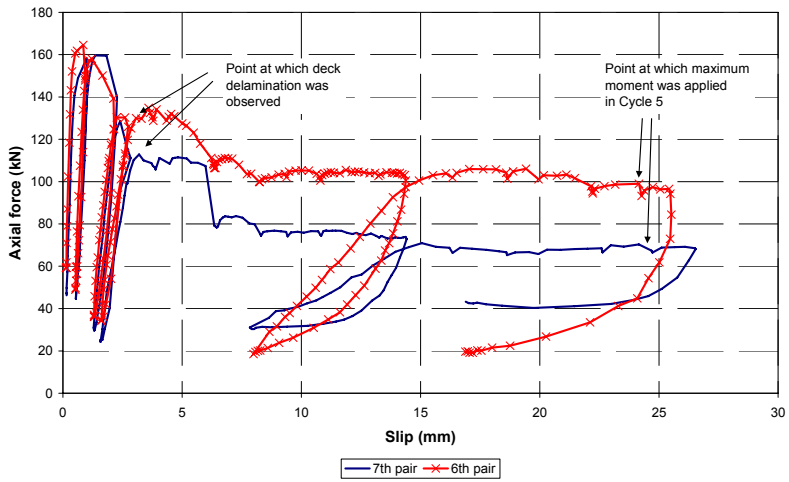


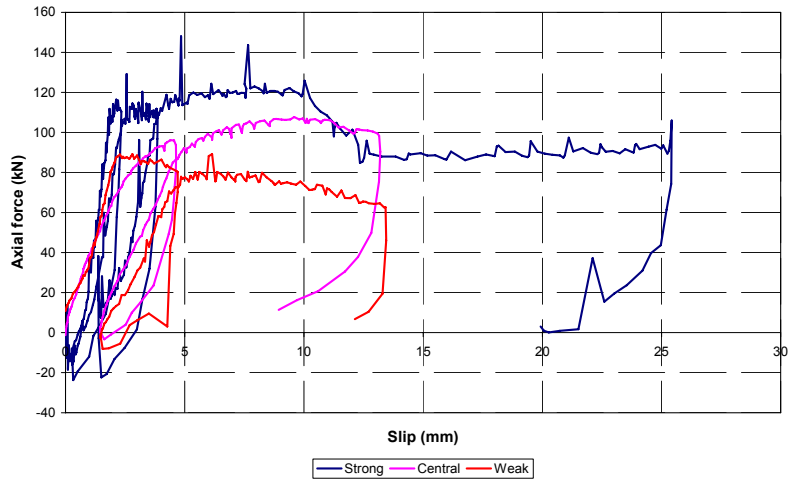
(a) Central (b) Favourable (c) Unfavourable

$$k_t = 0.85 / \sqrt{n_r}\,(b_0 / h_p)\,\{(h_{sc} / h_p) - 1\} \le k_{t,max}$$

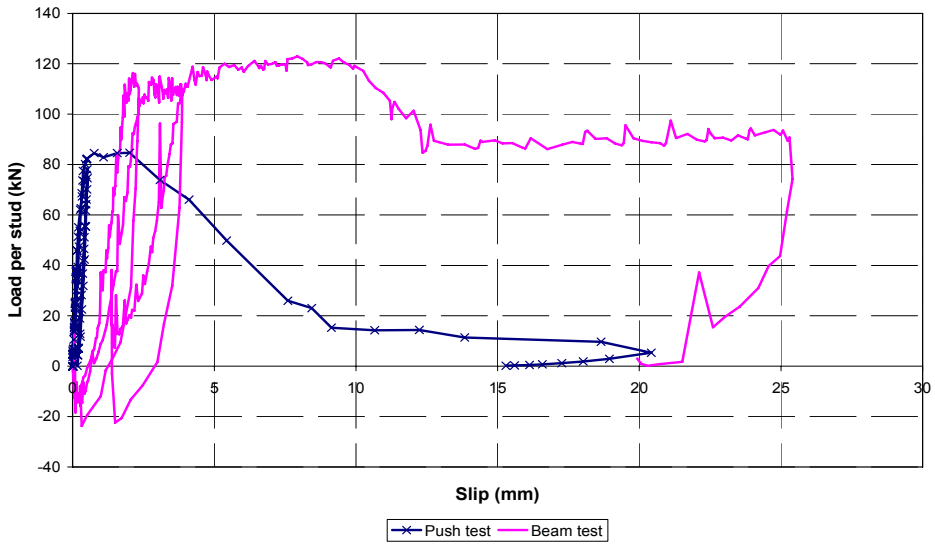
Number of stud connectors per rib	Thickness t of sheet (mm)	Studs not exceeding 20 mm in diameter and welded through profiled steel sheeting	Profiled steel sheeting with holes and studs 19 mm or 22 mm in diameter
$n_r = 1$	≤ 1,0 > 1,0	0,85 1,00	0,75 0,75
$n_r = 2$	≤ 1,0 > 1,0	0,70 0,80	0,60 0,60

Stud ductility demonstrated in full-scale composite beam tests with studs through-deck welded in open trough sheeting

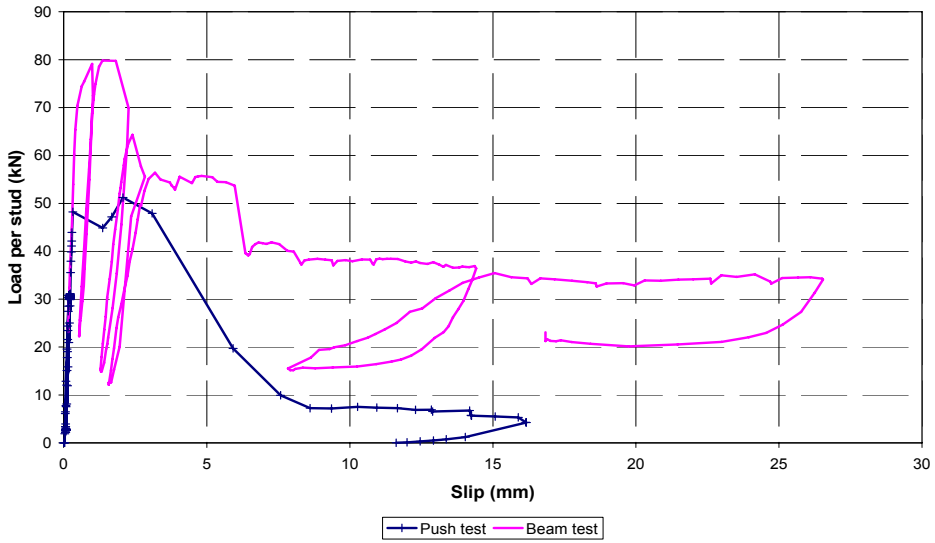




Load-slip curves for push tests cf. beam tests



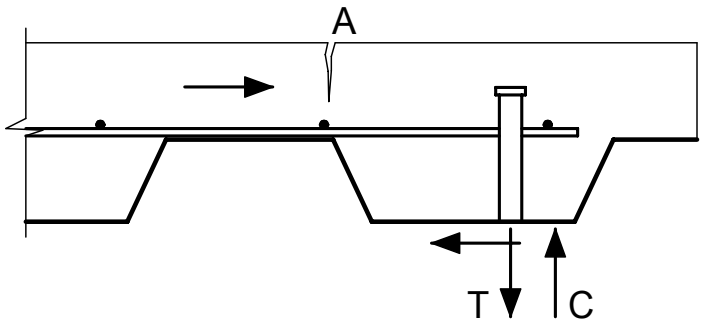
$n_r = 1$

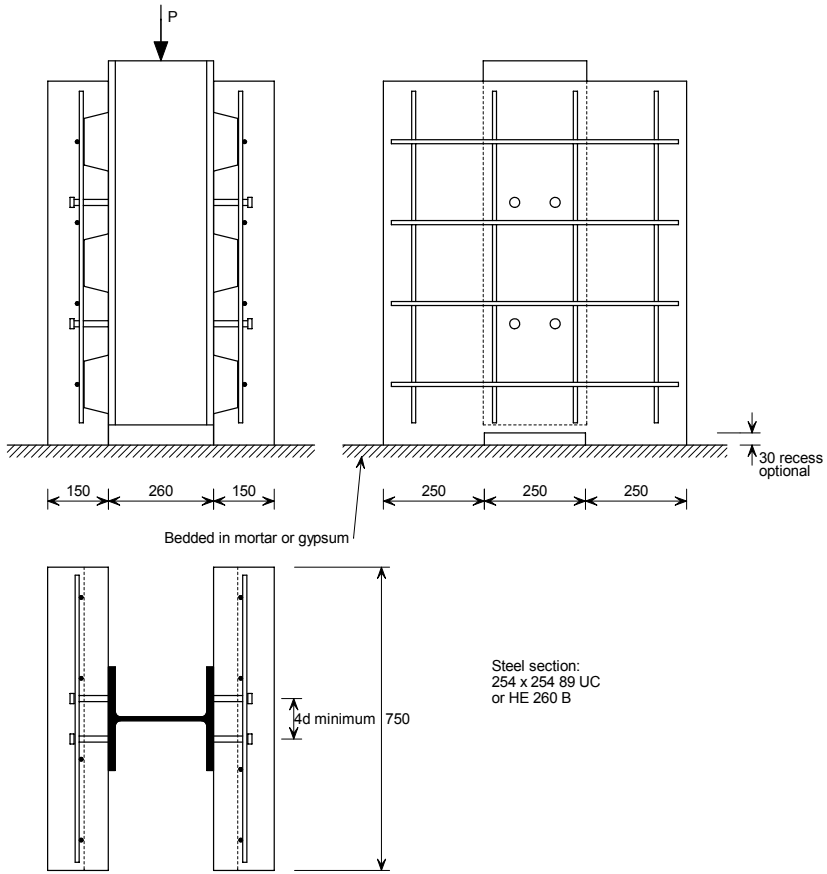


$n_r = 2$

Recommended detailing to push test with open trough profiled steel sheeting

Back-breaking failure





Where can I get further information?

http://www.access-steel.com/

s.hicks@steel-sci.com