ANNEX J

Seismic design of the slab reinforcements of composite beams in moment frames

J1 Introduction

Two different conditions have to be fulfilled to ensure that a high ductility in bending is obtained in the plastic hinges developed in the beam ends of a composite moment frame:

-early buckling of the steel part must be avoided

-early crushing of the concrete of the slab must be avoided

Each of these two conditions brings a limit of the section A of the reinforcement present in the slab of a composite T beam made of a steel section with slab.

J2 Requirement on the section A of re-bars in order to avoid premature buckling

At the negative moment side, the section is supposed to be ductile if the section is class 1, that is if the plastic neutral axis of the section is such that the slenderness of the steel walls under compression is not too high (EC4 classical approach, [4]).

Classification of section

$$A_L < A_{\text{limit class 1}} \quad \text{in the effective width } b_{eff} \tag{J.1}$$

J3 Requirements on the section A of re-bars in order to avoid premature cracking of the concrete

The Annex J-EC4 approach ensures a ductile behaviour in the slab under negative moment; it doesn't take the presence of a transverse beam into account. Developments aimed at a ductile behaviour of the slab under positive moment conclude that the plastic resistance of the full composite section cannot be developed without transverse beam.

The following presentation tries to list all the possible situations and to determine the controlled situations, meaning by that the situations for which design can be made, and the others.

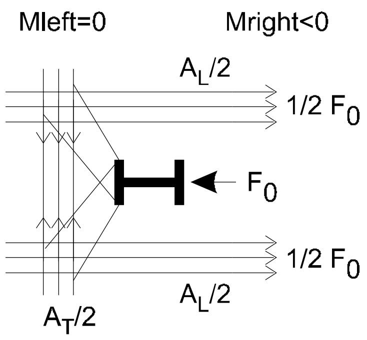
J3.1 Exterior column - bending of the column along its strong axis

J3.1.1 M<0 - no transverse element - no edge beam design possible

When no transverse beam and no edge beam are present, the transferable moment is the steel beam plastic moment only.

J3.1.2 M<0 - no transverse element - edge beam design possible

When there is an edge beam and no transverse beam, Annex J of EC4 applies.



$F_{Rd0} = 1.1\, b_c\, t_{slab}\, 0.85\, f_{cd}$

The ductility condition on the longitudinal re-bars which ensures their yielding before the crushing of concrete is:

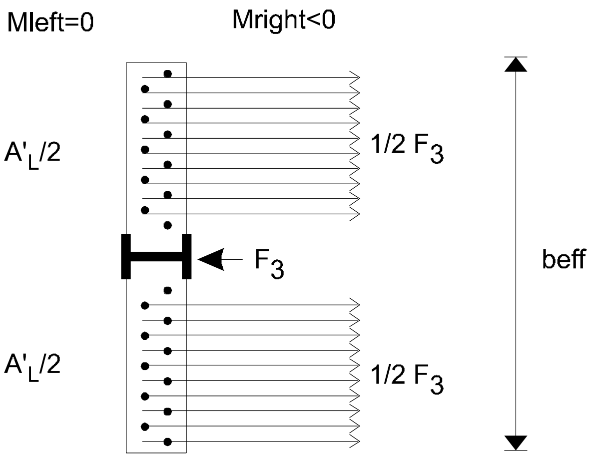
$$A_L \leq 0.94\, b_c\, t_{slab} \frac{f_{cd}}{f_{sdL}} \qquad ()$$

The condition on the transverse re-bars to exclude their failure is:

$$A_T \geq \frac{A_L}{\tan\delta} \frac{f_{sdL}}{f_{sdT}} \cong A_L \frac{f_{sdL}}{f_{sdT}}$$ with compressed struts at 45°

J3.1.3 M<0 - transverse element - no edge beam design possible

When a transverse beam is present but no edge beam, the only way to transfer the moment is to use the transverse beam to anchor the slab forces.



No limitation on the longitudinal re-bars exists.

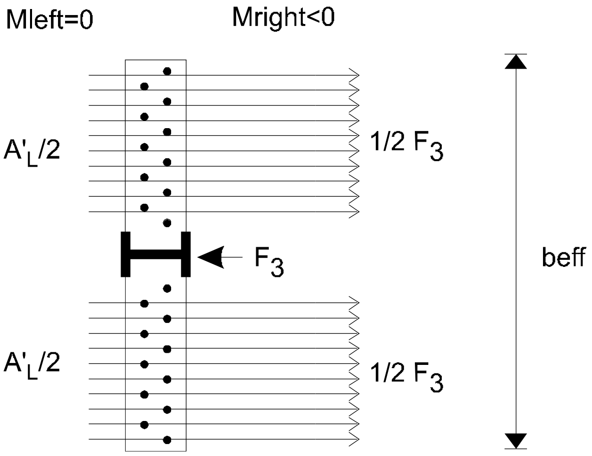
F_{Rd3} depends on the effective width.

$F_{Rd3} = n \times F_{stud}$ on the effective width

$A'_L = F_{Rd3}/f_{sdL}$

J3.1.4 M<0 - transverse element - edge beam present design possible

When both a transverse beam and an edge beam are present, two mechanisms of transfer are possible: the mechanism of EC4 annex J and the transfer through the transverse beam.



No limitation on the longitudinal re-bars exists and the maximal reinforcing section in beff is:

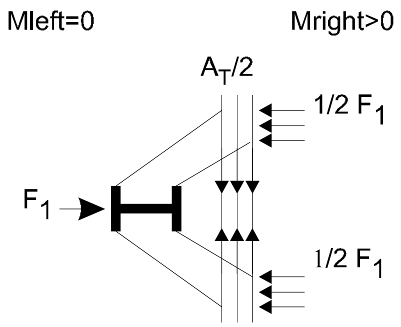
$$A_L = A_L(\text{EC4-J}) + A_L(\text{transverse beam})$$

$$= 0.94\, b_c\, t_{slab} \frac{f_{cd}}{f_{sdL}} + \frac{F_{Rd3}}{f_{sdL}}$$

J3.1.5 M>0 - no transverse element - edge beam present or not design possible

When no transverse beam is present, the transferable moment is linked with the two following mechanisms:

Mechanism 1: struts (45°) on the column sides

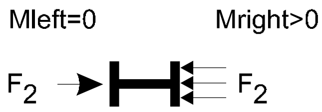


$F_{Rd1} = 0.6\ h_c\ t_{slab}\ f_{cd}$

Condition on the tension tie:

$$A_T \geq \frac{F_{Rd1}}{f_{sdT}} = 0.6 h_c t_{slab} \frac{f_{cd}}{f_{sdT}}$$

Mechanism 2: direct compression on the column



$F_{Rd2} = b_c\ t_{slab}\ 0.85\ f_{cd}$

The node is able to resist a plastic moment calculated with a maximal compression in the slab of $F_{Rd1} + F_{Rd2} = b_{eff}\ t_{slab}\ 0.85\ f_{cd}$

corresponding to a maximal effective width of:

$b^{+}_{eff\ connec} = 0.7\ h_c + b_c$

If the full composite plastic moment corresponds to the effective width $b^{+}_{eff} = 0.15\ell$, with the approximations that $b_c \cong h_c$ and $b_c \cong 0.05\ \ell$,

$b^{+}_{\text{eff connec}} \cong 1.7\ b_c \cong 0.085\ \ell \quad < \quad b^{+}_{\text{eff}} = 0.15\,\ell$

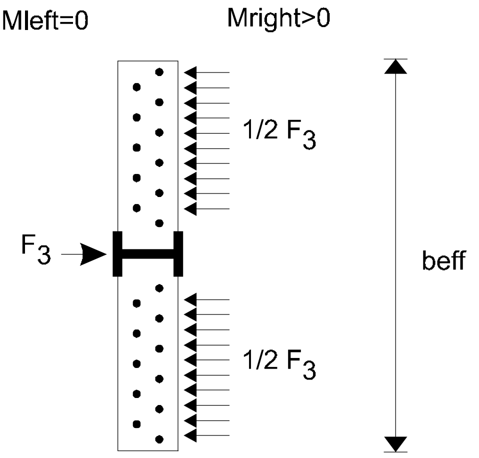
$b^{+}_{\text{eff connec}} \cong 0.5\ b^{+}_{\text{eff}}\ (\text{EC4})$

Without an additional mechanism, the full positive composite plastic moment is not transferred. Only one half of the EC4 effective width can effectively be realised.

J3.1.6 M>0 - transverse element - edge beam present or not design possible

When a transverse beam is present, a third transfer is activated through the transverse beam.

$F_{Rd3} = n \times F_{stud}$ in the effective width



The condition on the tension tie to mobilise F_{Rd1} is still:

$$A_T \geq \frac{F_{Rd1}}{f_{sdT}} = 0.6 h_c t_{slab} \frac{f_{cd}}{f_{sdT}}$$

The node is able to resist a plastic moment calculated with a maximal compression in the slab of $F_{Rd1} + F_{Rd2} + F_{Rd3} = b_{eff}\ t_{slab}\ 0.85\ f_{cd}$

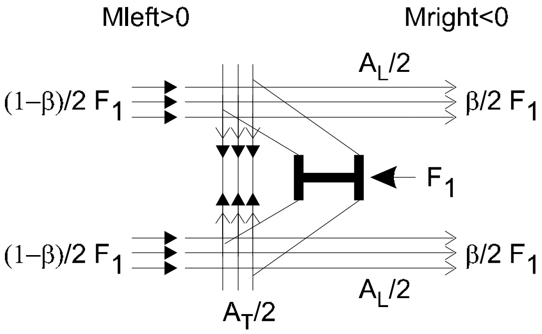
F_{Rd3} is designed in such a way that the "full" composite plastic moment is reached, i.e.:

$b^{+}_{\text{eff connec}} = b^{+}_{\text{eff}}\ (\text{EC4}) = 0.15\ \ell$

J3.2 Interior column - bending of the column along its strong axis

J3.2.1 No transverse element present - with the imposition that $A_L = A_T = A_S$ design not possible

Mechanism 1: struts (45°) on the column sides

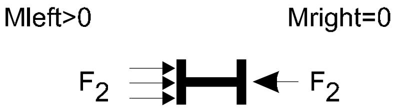


$F_{Rd1} = 0.6\ h_c\ t_{slab}\ f_{cd}$

Condition on the tension tie:

$$A_T \geq \frac{F_{Rd1}}{f_{sdT}} = 0.6\ h_c\, t_{slab}\ \frac{f_{cd}}{f_{sdT}}$$

Mechanism 2: direct compression on the column



$F_{Rd2} = b_c\ t_{slab}\ 0.85\ f_{cd}$

The resistance is at the most:

$F_{Rd1} + F_{Rd2} = (0.7\ h_c + b_c)\ t_{slab}\ 0.85\ f_{cd}$

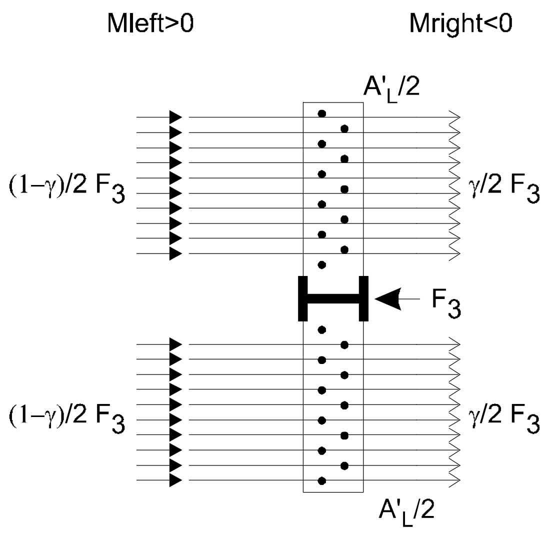
The action force is the sum of the tension coming from the re-bars at the negative moment side and the compression of the concrete at the positive moment side:

$F_{St} + F_{Sc} = As\ (\text{in } b^-_{eff})\ f_{sd} + b^+_{eff}\ t_{slab}\ 0.85\ f_{cd}$

It is impossible to transfer an action that would correspond to the effective width under positive bending moment deduced from EC4 ($b^+_{eff} = 0.15\,\ell$) at one side and to the effective width under negative bending moment at the other side, because it was already not possible for an exterior node under positive moment only. Adding a negative moment still makes the situation worse. As the real effective widths for positive and negative moments are not known, this situation is not controlled.

J3.2.2 Presence of transverse elements - with the imposition that $A_L = A_T = A_S$ design possible

Addition of mechanism 3: action of the transverse beam



The condition on the tension tie for mechanism 1 is still:

$$A_T \ge \frac{F_{Rd1}}{f_{sdT}} = 0.6\, h_c\, t_{slab} \frac{f_{cd}}{f_{sdT}}$$

The resistance is at the most:

$F_{Rd1} + F_{Rd2} + F_{Rd3} = (0.7\, h_c + b_c)\, t_{slab}\, 0.85\, f_{cd} + n\, F_{stud}$ in max (b^-_{eff}, b^+_{eff})

The applied force is the sum of the tension coming from the re-bars at the negative moment side and the compression of the concrete at the positive moment side:

$F_{St} + F_{Sc} = As$ (in b^-_{eff}) $f_{sd} + b^+_{eff}\, t_{slab}\, 0.85\, f_{cd}$

In a design option aiming at little degradation of the slab and yielding located essentially in the bottom flange of the steel section, the general design condition to fulfil is :

$1.2\, (F_{Sc} + F_{St}) \le F_{Rd1} + F_{Rd2} + F_{Rd3}$

If it is fulfilled, the situation is controlled and the transferred forces correspond to the proposed EC8 effective widths : $b^-_{eff} = 0.2\,\ell$ and $b^+_{eff} = 0.15\,\ell$.

If it is not, the situation is not controlled and the real effective widths and their repartition between positive and negative moments are not known.

Additional remarks:

Is it possible to realise a beam column joint with a ductile behaviour at the positive moment side simultaneously with a ductile behaviour at the negative moment side (meaning by this: complying to 3.2 that is avoiding early buckling of bottom flange)? It appears that it may be very difficult to develop ductile behaviours of sections at the same time at the negative moment side and the positive moment side.

The solution may be found when $F_{rdconcrete} << F_{rd\ steel\ section}$ for what concerns re-bars. But this means high neutral axis and early buckling of steel section under negative moment.