Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 8 (24): 4533-4542, 2008
ISSN 1812-5654

A Simplified Design Method for Semi-Continuous Composite Beams

[1]M. Titoum, [1]B. Achour, [2]M. Tehami and [1]A. Benanane
[1]Department of Civil Engineering, Mostaganem University, Algeria
[2]Department of Civil Engineering, UST Oran, Algeria

Abstract: This study presents a simplified method for the design of semi-continuous composite beams in braced frames taking into account the effects of partial shear connection and the semi-rigid/partial strength nature of the composite joints. The proposed method evaluates the load carrying capacity of the semi-continuous composite beam at the Ultimate Limit State (ULS) and its deflection at the Serviceability Limit State (SLS). A worked example was proposed to show the design procedure. Through this example, the potential benefits of accounting for strength and stiffness of composite joints have been demonstrated. Also the use of partial shear connection in composite beams resulted in a small reduction in strength but with a significant benefit in ductility. The proposed method is shown to be simple and can be implemented using hand calculation or spreadsheet.

Key words: Semi-continuous, composite beam, composite joint, partial shear connection, load capacity, deflection

INTRODUCTION

In the traditional design of composite frames, the behaviour of beam-to-column joints is idealized as being either pinned or as rigid. In the case of pinned joints no continuity is assumed, the composite beams are designed as simply supported between columns. With rigid joints, full continuity is assumed and the composite beams are designed as continuous. However, as it is evident from experimental observation, most types of composite joints used in practice possess some stiffness that falls between the two extreme cases of pinned and rigid. Thus, the true behaviour of composite joints should be treated as semi-rigid. Consequently, when composite beams are attached to columns by semi-rigid and partial strength joints, they are considered as semi-continuous. This new type of composite beams was adopted by the Eurocode 4 (CEN, 2004) but without providing detailed guidance on how this may be undertaken.

Most of the work done in the past focused mainly on the study of simply supported and continuous composite beams. However, few practical methods have been developed for the design of semi-continuous composite beams. Nethercot (1995) proposed a quasi-plastic design method for semi-continuous composite beams in braced frames, based on several research studies on the behaviour of composite joints and moment redistribution. Wong *et al*. (1996) proposed a simplified method for the design of beam deflection in braced composite frames under vertical loads, which allows for the effect of the variation of composite beam stiffness in the hogging and sagging moment regions. Couchman (1997) proposed a method of analysis and design which permits semi-continuous braced steel frames to be designed by hand. Kattner and Crisinel (2000) proposed an elasto-plastic approach for the design of semi-continuous composite beams in braced frames with semi-rigid and partial strength composite joints. Liew and Looi (2001) proposed a simplified method for the elastic design of semi-continuous composite beams in braced frames incorporating the effects of joint rotational stiffness and the non-prismatic properties of a cracked steel-concrete beam. Recently, Wang and Li (2008) proposed a new design method for semi-rigid composite frames under vertical loads. The accuracy of the proposed method is verified by a pair of tests carried out on full-scale semi-rigid composite frames.

Because of the complexity of the previous design methods, a simplified method is proposed herein for the design of semi-continuous composite beams in braced frames incorporating the concept of partial shear connection at the steel-concrete interface and the semi-rigid/partial strength nature of the composite joints. The proposed method can evaluate the load capacity of the semi-continuous composite beam at the Ultimate Limit State (ULS) and its deflection at the Serviceability Limit State (SLS). A design example is used to demonstrate the application of the proposed design method.

Corresponding Author: Messaoud Titoum, Department of Civil Engineering, Mostaganem University, Algeria
Tel: +213 7 73 78 15 53 Fax: +213 45 21 10 18

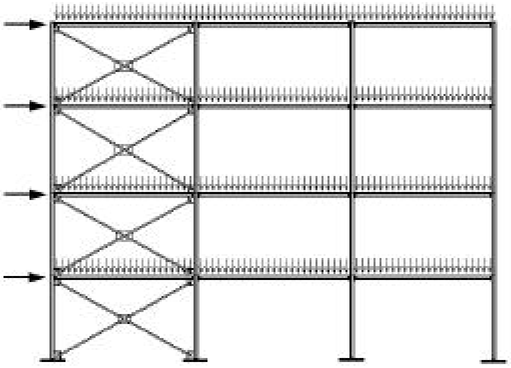

Fig. 1: Example of braced building frame

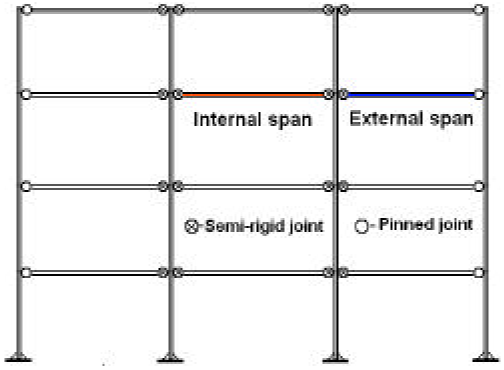

Fig. 2: Composite joint modelling in a braced frame

The analysis presented herein is limited to the following design rules:

- The proposed method is limited to composite beams of braced frames. The lateral loads are resisted by a system of diagonal cross bracings as shown in Fig. 1 Therefore only vertical loads are taken into account
- The choice of the column and beam sections is based on the concept of strong column/weak beam i.e., failure takes place in the beams instead of the columns to avoid the collapse of the entire structure
- Steel beam and steel column sections of class 1 or class 2 are used to prevent local buckling. The lateral torsional buckling of the composite beams is prevented by the concrete slab
- Identical composite beams must be used on both sides of the steel column
- The beams must be temporarily propped during construction
- Semi-rigid/partial strength composite joints are considered only in the internal columns. Due to anchorage difficulty of reinforcement at the slab edge, pinned joints are assumed to the external columns
- Partial shear connection is considered in both sagging and hogging moment regions of the semi-continuous composite beam

DESIGN PRINCIPLES OF SEMI-CONTINUOUS COMPOSITE BEAMS

The design of semi-continuous composite beams by the proposed method consists to:

- Determine the composite joint characteristics to be introduced into the calculation
- Calculate the load capacity of the semi-continuous composite beam at the ultimate limit state
- Calculate the deflection at the serviceability limit state

To illustrate this method, an example of a three span frame is considered (Fig. 2). The composite joints are modelled by rotational springs in the internal columns and by articulations in the external columns. There are therefore two types of spans to be considered in the design: internal and external spans.

Characteristics of the composite joints: The three characteristics of composite joints needed for the design of semi-continuous composite beams are:

- Initial rotational stiffness $S_{j,ini}$
- Moment resistance $M_{j,Rd}$
- Rotation capacity ϕ_{Cd}

These properties are obtained from the moment-rotation curve, typically shown in Fig. 3.

The study presented herein is limited to the case of composite endplate joints. Although, other forms such as cleated and finplate arrangements can be used. For the determination of the three main proprieties of this form of composite joint, the method suggested by Anderson and Najafi (1994) is adopted with appropriate modifications to consider the effects of partial shear connection in the hogging moment regions. Figure 4 shows a cruciform arrangement of composite endplate joint where a steel column is connected on both sides to two identical composite beams. This is to simulate the internal beam-to-column joints in a composite braced frame. No shear deformation is assumed in the column web panel by considering either a strong column with a stiffened web panel or a joint situation where loading is quasi-

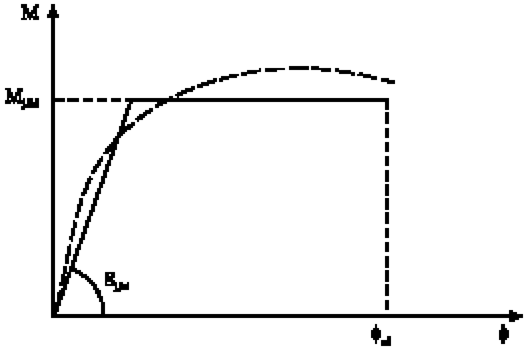

Fig. 3: Typical moment-rotation curve of composite joint

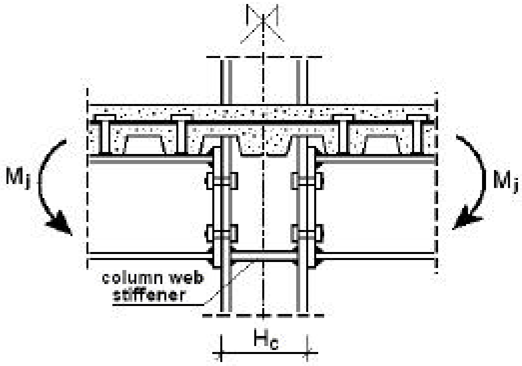

Fig. 4: Configuration of composite endplate joint

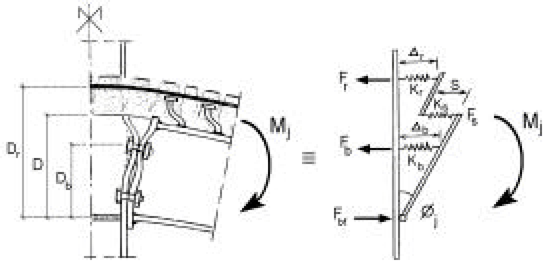

Fig. 5: Spring model for composite endplate joint

symmetric. Also, the steel column is stiffened with transverse stiffeners welded to the web at the level of the bottom beam flange to prevent local buckling of the column. Consequently, it will be assumed that the centre of rotation is located at the centreline of the lower beam flange.

Initial rotational stiffness ($S_{j,ini}$): The initial stiffness of the composite joint is determined on the basis of the spring model shown in Fig. 5.

The use of equilibrium and compatibility conditions, coupled with considerations of stiffness and deformation of the individual components to produce an expression for the initial rotational stiffness is fully described in the reference (Anderson and Najafi, 1994). The resulting expression is:

$$S_{j\,ini} = \frac{D \cdot D_r}{\left(\frac{1}{K_r} + \frac{1}{K_s}\right)} + K_b \cdot D_b^2 \qquad (1)$$

where, D is the distance from the steel-concrete interface to the centreline of the lower flange of the beam, D_r is the distance from the reinforcement centre to the centreline of the lower flange of the beam, D_b is the distance from the centre of top bolt row to the centreline of the lower flange of the beam and K_r, K_s and K_b are the stiffnesses of the reinforcement, shear connectors and bolts, respectively.

- The stiffness of the reinforcement K_r is derived assuming that the reinforcement obeys Hooke's law:

$$K_r = \frac{E_r \cdot A_r}{L_r} \qquad (2)$$

where, E_r is the elastic modulus of the reinforcement, A_r is the area of the reinforcing bars and L_r is the length of reinforcing bars taken as the distance from the centreline of the column to the centre of the first row of shear connectors.

- The stiffness of the shear connectors K_s may be calculated as:

$$K_s = N^- \cdot k_{s1} \qquad (3)$$

where, N^- is the number of shear connectors in the hogging moment region (which may be taken approximately as 15% of span length for semi-continuous composite beams in braced frame) and k_{s1} is the initial stiffness of a single shear connector taken equal to 100.10^3 kN m^{-1} for a stud connector as given in Eurocode 4 (CEN, 2004).

- Stiffness of the bolts K_b: According to Eurocode 3 (CEN, 2005), the stiffness at the level of the top bolt row is given by:

$$K_b = \frac{1}{\left(\frac{1}{K_3} + \frac{1}{K_4} + \frac{1}{K_5} + \frac{1}{K_{10}}\right)} \qquad (4)$$

where, K_3, K_4, K_5 and K_{10} are the stiffness of the components located at the level of the top bolt row which

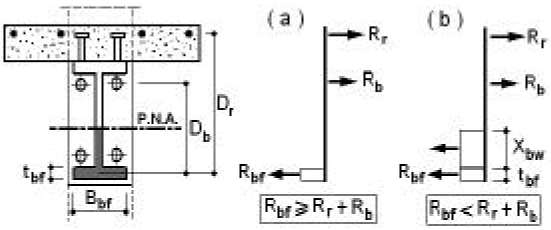

Fig. 6: Calculation of moment resistance of composite endplate joint

are the column web in tension, the column flange in bending, the endplate in bending and bolts in tension, respectively.

Moment resistance ($M_{j,Rd}$): The moment resistance of the composite endplate joint can be predicted using the conventional rigid-plastic analysis approach which considers stress blocs acting on each of the joint components as shown in Fig. 6.

R_r is the tensile resistance of the reinforcement, R_b is the tensile resistance of the bolts and R_{bf} is the compressive resistance of the lower beam flange (Fig. 6).

The moment resistance of composite joint is predicted using the following steps:

- Calculate the tensile and compressive resistances of the active joint components
- Locate the position of the plastic neutral axis
- Calculate the moment resistance of composite endplate joint

Resistance of component

Tensile resistance of the reinforcement (R_r): When the composite joint is designed using full shear connection in the hogging moment region of composite beam, the reinforcement in the slab is treated to be fully effective and its strength is attained under its yield stress. However, for partial shear connection in the hogging moment region, the strength of the reinforcement is limited by the strength of the shear connection (Aribert, 1996). Thus,

$$R_r = \min\left(A_r f_{yr}; N^{-}.P_{Rd}\right) \tag{5}$$

Where:

A_r = Section area of reinforcing bars
f_{yr} = Yield strength of reinforcing bars
N^{-} = No. of shear connectors in hogging moment region
P_{rd} = Design shear resistance of a single connector

Tensile resistance of bolts (R_b): The effective tensile resistance at the level of the tensile bolts is determined from Eurocode 3 (CEN, 2005) using the following expression:

$$R_b = \min(F_{t,wc,Rd}, F_{t,fc,Rd}, F_{t,p,Rd}, F_{t,wb,Rd}, F_{t,B,Rd}) \tag{6}$$

Where:

$F_{t,wc,Rd}$ = Resistance of column web in tension
$F_{t,fc,Rd}$ = Resistance of column flange in bending
$F_{t,p,Rd}$ = Resistance of endplate in bending
$F_{t,wb,Rd}$ = Resistance of beam web in tension
$F_{t,B,Rd}$ = Resistance of bolts in tension

Compressive resistance of the lower beam flange (R_{bf}): This resistance is given by:

$$R_{bf} = B_{bf}.t_{bf}.f_{yb} \tag{7}$$

Where:

B_{bf} = Width of the lower beam flange
t_{bf} = Thickness of the lower beam flange
f_{yb} = Yield strength of steel beam

Location of Plastic Neutral Axis (PNA): Knowledge of tensile and compressive resistances permits the location of the neutral axis. There are two possibilities for its location:

- If $R_{bf} \geq R_r + R_b$, the plastic neutral axis is located in the lower beam flange, i.e., only the resistance of compressive beam flange is needed to equilibrate the tensile force
- If $R_{bf} > R_r + R_b$, the plastic neutral axis is located in the beam web, below the top row of bolts in tension, i.e., part of the beam web is needed together with the lower beam flange to equilibrate the tensile force. The depth of the beam web in compression necessary for equilibrium is:

$$X_{bw} = \frac{\left(R_r + R_b - R_{bf}\right)}{t_{bw} \cdot f_{yb}} \tag{8}$$

Calculation of moment resistance of the composite joint: Knowing the position of the neutral axis, the moment resistance $M_{j,Rd}$ may be determined by multiplying the forces with the respective lever arms:

- If $R_{bf} \geq R_r + R_b$, the moment resistance of composite endplate joint is given by:

$$M_{j,Rd} = R_r D_r + R_b D_b \tag{9}$$

- If $R_{bf}<R_r+R_b$, the moment resistance is:

$$M_{j,Rd}=R_r.D_r+R_b.D_b-(R_r+R_b-R_{bf})\left(\frac{X_{bw}+t_{bf}}{2}\right) \tag{10}$$

Rotation capacity ϕ_{cd}: The rotation capacity of composite endplate joint ϕ_{cd} can be predicted using the simplified formula proposed by Anderson *et al*. (2000), which is a result of the elongation of the reinforcement and the slip of the shear connection near the joint. The rotation capacity is then determined as:

$$\phi_{cd}=\frac{\Delta_{u,r}}{D_r}+\frac{S}{D} \tag{11}$$

Where:

$\Delta_{u,r}$ = Ultimate elongation of the steel reinforcement

S = Slip at the end of the steel-concrete interface

The detailed procedures and equations involved in the calculation for $\Delta_{u,r}$ and S are presented in the reference (Anderson *et al*., 2000).

Design of semi-continuous composite beam at ULS

Load capacity (q_{Rd}): The plastic analysis of composite beams with semi-rigid/partial strength joints can be done by considering only one composite beam on which a load is uniformly distributed (this type of load is commonly found in buildings). Under the action of this loading, the composite joints reach their moment resistance $M_{ji,Rd}$ before the composite beam attains its sagging moment resistance $M^{+}_{pl.Rd}$ at mid-span. The collapse of the semi-continuous composite beam will occur then by the formation of a three hinge mechanism as shown in Fig. 7. This requires a sufficient rotation of the beam axis at the joint level, called required rotation ϕ_{req}.

Using the collapse mechanism of Fig. 7, the load capacity q_{Rd} of the composite beam can be determined by the following expressions:

- For an internal span (Fig. 8a):

$$\begin{aligned} q_{Rd}\frac{L_b^2}{8}&=\left(\frac{M_{j1.Rd}+M_{j2.Rd}}{2}\right)+\mu_p\cdot M^{+}_{pl.Rd}\\ \Rightarrow q_{Rd}&=\frac{8}{L_b^2}\left[\left(\frac{M_{j1.Rd}+M_{j2.Rd}}{2}\right)+\mu_p\cdot M^{+}_{pl.Rd}\right] \end{aligned} \tag{12}$$

- For an external span (Fig. 8b):

$$\begin{aligned} q_{Rd}\frac{L_b^2}{8}&=\frac{M_{j3.Rd}}{2}+\mu_p\cdot M^{+}_{pl.Rd}\\ \Rightarrow q_{Rd}&=\frac{8}{L_b^2}\left[\frac{M_{j3.Rd}}{2}+\mu_p\cdot M^{+}_{pl.Rd}\right] \end{aligned} \tag{13}$$

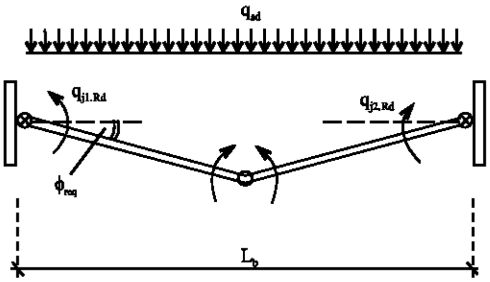

Fig. 7: Collapse mechanism of a semi-continuous composite beam

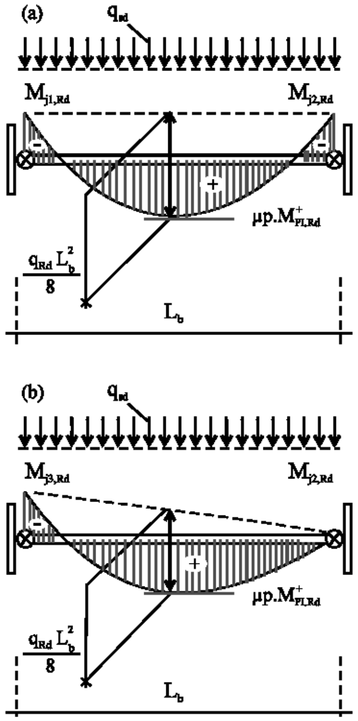

Fig. 8: Load capacity determination (a) Internal and (b) External span

Where:

$M_{ji.Rd}$ = Moment résistance of composite joint, $M_{ji.Rd}<M^{-}_{pl.Rd}$

$M^{+}_{pl.Rd}$ = Plastic moment resistance of composite beam in sagging bending

$M^{-}_{pl.Rd}$ = Plastic moment résistance of composite beam in hogging bending

μ_p = Degree of plastification of composite beam, $\mu_p\leq 1$

The résistance checking of the composite beam is done by comparing its load capacity q_{Rd} with the applied loading q_{Sd}.

$$q_{Sd} \leq q_{Rd} \tag{14}$$

When the shear connection of the composite beam is partial, the moment resistance in sagging bending should be reduced to a value $M^{red}_{pl.Rd} < M^{+}_{pl.Rd}$. According to Eurocode 4 (CEN, 2004), the moment resistance of composite beam with a partial shear connection can be calculated by an interpolation method as:

$$M^{red}_{pl} = M_{pl,a,Rd} + \eta\left(M^{+}_{pl,Rd} - M_{pl,a,Rd}\right) \tag{15}$$

where, η is the degree of shear connection defined as $\eta = N/N_f$ with N is the actual number of shear connectors and N_f is the number of shear connectors corresponding to a full shear connection, $M_{pl,\,a,\,Rd}$ is the plastic moment resistance of the steel beam and $M^{+}_{pl,\,Rd}$ is the plastic moment resistance of composite beam with a full shear connection.

Required rotation (ϕ_{req}): The available rotation capacity ϕ_{cd} of the composite joint must match or exceed the required rotation ϕ_{req} to develop the mid-span plastic hinge in the composite beam. Nethercot *et al.* (1995) considered the required rotation as a function of the steel grade, the span to overall depth ratio, the ratio of support to span moments, the design sagging moment and the loading arrangement. For the case of Uniformly Distributed Load (UDL), the required rotation was determined through the use of the following semi-empirical equations:

- For an internal span, $M_{j1} = M_{j2} = M_j$

$$\phi_{req} = \left[\begin{matrix} 0.344 - 0.212\dfrac{M_j}{M_t} \\ +0.561\left(\dfrac{M_t - M^{+}_{el}}{M^{+}_{pl} - M^{+}_{el}}\right)^2 \cdot \dfrac{1}{\sqrt{1+\dfrac{M_j}{M_t}}} \end{matrix}\right] \cdot \frac{M_t \cdot L_b}{E \cdot I_b} \tag{16}$$

- For an external span, $M_{j3} = M_j \neq 0$, $M_{j4} = 0$

$$\phi_{req} = \left[\begin{matrix} 0.344 - 0.225\dfrac{M_j}{M_t} \\ +0.566\left(\dfrac{M_t - M^{+}_{el}}{M^{+}_{pl} - M^{+}_{el}}\right)^2 \cdot \dfrac{1}{\sqrt{1+\dfrac{M_j}{M_t}}} \end{matrix}\right] \cdot \frac{M_t \cdot L_b}{E \cdot I_b} \tag{17}$$

Where:

M_j = Moment resistance of composite joint

M^{+}_{el} = Elastic moment of composite beam at mid-span

m_t = Maximum design bending moment at mid-span

Table 1: Values of the degree of plastification, μ_p

Construction mode	Steel grade	Span/depth ratio: L_b/H_t 15-22	23-30
Propped beam	S 235	1.00	0.90
	S 355	0.95	0.85
Unpropped beam	S 235	0.95	0.85
	S 355	0.90	0.80

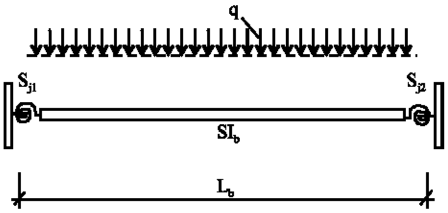

Fig. 9: Steel beam model for deflection

M^{+}_{pl} = Plastic moment resistance of composite beam at mid-span

Ei_b = Flexural stiffness of composite beam

L_b = Span length of composite beam

Degree of plastification (μ_p): If the available rotation capacity of the composite joint ϕ_{cd} matches or exceeds the required rotation ϕ_{req}, the total plastic moment resistance at mid-span of the composite beam is fully attained. Otherwise, only a proportion of the plastic moment resistance is reached. This proportion is expressed in term of the degree of plastification, μ_p. Kattner and Crisinel (2000) gave the degree of plastification values in Table 1. as a function of the construction mode, the steel grade and depth/overall span ratios for a uniformly distributed load.

Design of semi-continuous composite beam at SLS

Deflection: For calculating deflections, beams should be regarded as being rotationally restrained at the supports by springs (Fig. 9). The spring stiffness represents the stiffness of the joint itself. Therefore, the beam behaviour lies between built in and simply supported.

Couchman (1997) proposed a simplified method for calculating deflections at mid-span of semi-continuous steel beams assuming a constant flexural stiffness EI_b throughout the span length L_b. According to this method, the reduction of the deflection compared to the simply supported case, depends mainly on the ratio of the joint stiffness over that of the attached beam. This ratio is expressed by a constant K defined by the following expression:

$$K = \frac{S_j \cdot L_b}{EI_b} \tag{18}$$

with

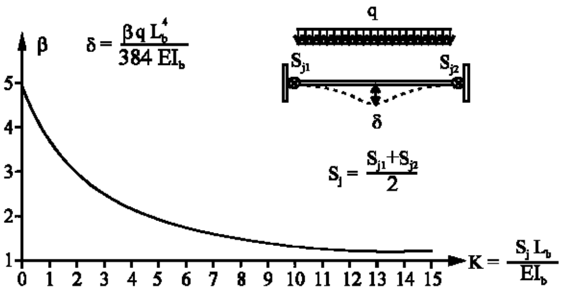

Fig. 10: Deflection as a function of joint/beam stiffness

$$S_j = \frac{S_{j1}+S_{j2}}{2} \tag{19}$$

where, S_{j1} and S_{j2} are the nominal stiffness of the joints at the left and right hand sides of the beam, respectively.

Figure 10 shows the deflection coefficient β as a function of K, for an internal span subject to Uniformly Distributed Load (UDL).

Zero joint stiffness represents the case of a simply supported beam. This corresponds to a value of β = 5 and $\delta = 5.qL_b^4/384EI_b$. As the relative joint/beam stiffness increases and the beam tends towards being built-in, the curve approaches a horizontal asymptote at β = 1 and $\delta = 1.qL_b^4/384EI_b$.

Effect of cracked concrete: In the case of semi-continuous composite beams, the flexural stiffness is no longer constant due to the cracking of the slab concrete in the hogging moment regions. The cracked flexural stiffness EI_b^- is used within 15% of the span length on each side of the internal composite joint and the uncracked flexural stiffness EI_b^+ is used in the other part of the span (Liew and Looi, 2001). To facilitate the design procedure, the two stiffnesses are combined together to give one equivalent stiffness called effective stiffness $EI_{b,eff}$ which can be approximated as follows:

- For an internal span (Fig. 11a):

$$EI_{b,eff} = 0.30EI_b^- + 0.70EI_b^+ \tag{20}$$

- For an external span (Fig. 11b):

$$EI_{b,eff} = 0.15EI_b^- + 0.85EI_b^+ \tag{21}$$

Effect of partial shear connection on deflection: The degree of partial shear connection has a significant influence on the vertical deflection of a composite beam due to the reduction of its flexural stiffness (Grant *et al*., 1977). The reduced effective stiffness can be evaluated by the following expression:

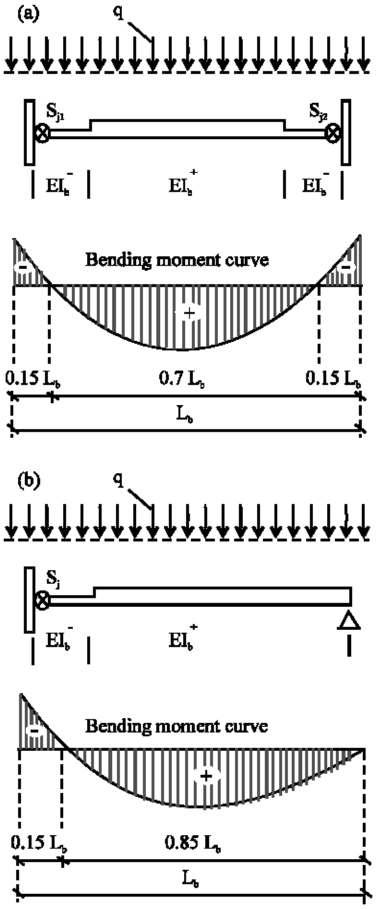

Fig. 11: Composite beam model for deflection (a) Internal and (b) External span

$$EI_{beff}^* = EI_a + \frac{N}{N_f}(EI_{beff} - EI_a) \tag{22}$$

Where:

EI_a = Flexural stiffness of the steel beam

N/N_f = Degree of partial shear connection

Deflection equations: Taking now into account the semi-rigidity of the composite joint, the cracked concrete and the partial shear connection, it is possible to determine deflections by applying the following formula:

- For an internal span:

$$\delta^{sc} = \left(\frac{K+10}{K+2}\right)\frac{q \cdot L_b^4}{384 \cdot EI_{beff}^*} \tag{23}$$

- For an external span:

$$\delta^{sc} = \left(\frac{2K+15}{K+3}\right)\frac{q \cdot L_b^4}{384 \cdot EL_{beff}^*} \tag{24}$$

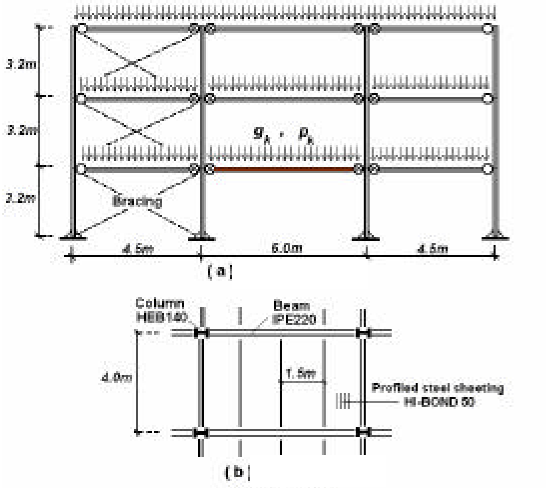

Fig. 12: Example frame (a) Elevation view and (b) Plan view

Where:

$$K = \frac{S_j \cdot L_b}{E \cdot I^{+}_{beff}}$$

Finally, the check of the deflection of semi-continuous composite beams at the serviceability limit state for composite floors is specified by Eurocode 4 (CEN, 2005) as:

$$\delta^{*} \le \frac{L_b}{300} \tag{25}$$

Design example: A design example is presented to demonstrate the application of the design procedure. A three-storey, three-bay braced frame with dimensions and sectional properties shown in Fig. 12 is studied.

Data: The uniform loads acting on the composite beams are 16 and 12 kN m^{-1} for dead and live loads, respectively, including the partial safety factors equal to 1.35 and 1.5, respectively.

The properties of the structural members are:

Columns

- HEB 140 in steel grade S235

Beams

- IPE220 in steel grade S235
- Propped during construction
- Span length, L_b = 6 m

Composite slab

- Profiled steel sheeting HI-BOND50
- Overall depth is 0.130 m
- Concrete grade is C20/25
- (f_{ck} = 20 MPa, E_{cm} = 29000 MPa)
- Slab effective width is 1.050 m for sagging moment regions and 0.650 m for hogging moment regions

Reinforcement

- 4ϕ 10 bars in steel grade S460
- (f_{sk} = 460 MPa, E_{sm} = 200000 MPa)

Shear connectors

- Welded headed studs, d = 0.019 m, h = 0.100 m
- Design shear resistance of a stud, P_{Rd} = 63.784 kN
- No. of studs located throughout the beam span is N = 20 studs
- Required number of studs for full shear connection is N = 27 studs
- No. of studs located in the hogging moment region is N = 3 studs
- Distance from the first stud to column face is 0.150 m

Endplate and bolts

- The steel beams are connected to the column flange by means of endplates 0.015 m in thickness and two rows of M16 grade 8.8 bolts.

Characteristics of the composite beam: The characteristics of the composite beam are established in accordance with Eurocode 4 (CEN, 2004):

- Plastic moment resistance of composite beam in sagging bending

$$M^{+}_{pl\,Rd} = 1479.71\ \text{kN m}$$

- Plastic moment résistance of composite beam with partial shear connection:

$$M^{red}_{pl,Rd} = 127.525\ \text{kN m}$$

- Second moment of area of the cracked composite beam:

$I^{+}_{b} = 1.37577 \times 10^{-4}\ m^4$ (for sagging moment regions)
$I^{-}_{b} = 0.3920 \times 10^{-4}\ m^4$ (for hogging moment regions)

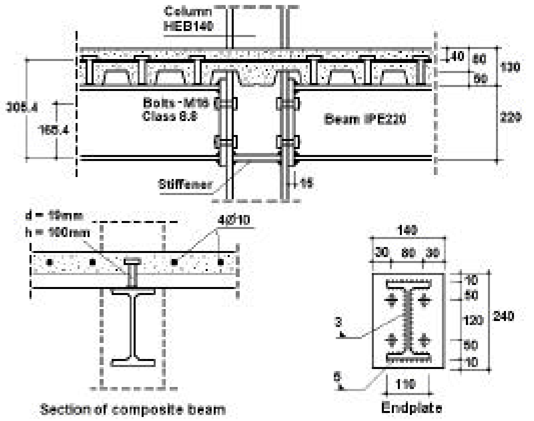

Fig. 13: Example of a composite endplate joint

Characteristics of the composite joint: The characteristics of the composite endplate joint shown in Fig. 13 can be determined using the method earlier described.

Initial stiffness $S_{j,ini}$

$$S_{j,ini} = \frac{215.4\times 305.4}{\left[\frac{1}{285.455}+\frac{1}{300}\right]} + 470.82\times 165.4^2$$

$$S_{j,ini} = 22503 \text{ kN m rad}^{-1}$$

- Nominal stiffness S_j

$S_j = S_{j,ini/2}$ (Eurocode 4 (CEN, 2004)

$S_j = 11251.5 \text{ kN m rad}^{-1}$

Moment resistance $M_{j,Rd}$

$$M_{j,Rd} = 125.6\times 305.4 + 134.55\times 165.4 - (125.6 + 134.55 - 216.2)\left(\frac{28.82+9.2}{2}\right)$$

$$M_{j,Rd} = 59.777 \text{ kN m}$$

Rotation capacity ϕ_{cd}

$$\phi_{cd} = \frac{6.6}{305.4} + \frac{4.5}{215.4} = 42.5\times 10^{-1} \text{ rad}$$

Classification of composite joint: According to Eurocode 4 (CEN, 2004), this composite joint is classified as semi-rigid and partial strength because:

$$0.5\frac{E_b I_b^+}{L_b} < S_{j,ini} < 8\frac{E_b I_b^+}{L_b}$$

and

$$0.25M^-_{pl,Rd} < M_{j,Rd} < M^-_{pl,Rd}$$

Where:

$0.5\frac{E_b I_b^+}{L_b} = 2408 \text{ kN m rad}^{-1}$

$8\frac{E_b I_b^+}{L_b} = 38522 \text{ kN m rad}^{-1}$

$0.25M^-_{pl,Rd} = 20.741 \text{ kN m}$

$M^-_{pl,Rd} = 82.963 \text{ kN m}$

Design of semi-continuous composite beam at ULS: In this example, the critical span is the internal one.

- The ultimate load carrying capacity corresponding to the formation of the three plastic hinges is calculated as:

$$q_{Rd} = \frac{8}{L_b^2}\left[\frac{M_{j1,Rd}+M_{j2,Rd}}{2} + \mu_b M^{mid}_{pl,Rd}\right]$$

Where:

$M_{j1,Rd} = M_{j2,Rd} = 59.777 \text{ kN m}$

$M^{mid}_{pl,Rd} = 127.525 \text{ kN m}$

$\mu_b = 1$ (Table 1)

$L_b = 6 \text{ m}$

$\rightarrow q_{Rd} = 41.62 \text{ kN m}^{-1}$

- In this example, it is then possible to increase the load carrying capacity of the composite beam by 46% taking into account the partial strength of the composite joint.
- The required rotation ϕ_{req} is determined using Eq. 16:

$$\phi_{req} = 29.31\times 10^{-3} \text{ rad}$$

The rotation capacity of the composite joint ϕ_{cd} exceeds the required rotation ϕ_{req}.

Design of semi-continuous composite beam at SLS: The deflection of the internal semi-continuous beam with semi-rigid composite joints has been determined using Eq. 23.

$$\delta^{*} = \left(\frac{3.654+10}{3.654+2}\right)\frac{28\times 6^4}{384\times 18475.38} = 12.35\times 10^{-3} \text{ m}$$

Whereas the deflection of simply supported composite beam with partial shear connection is 24.45×10^{-3} m.

By taking into account the stiffness of the composite joints, the deflection is therefore reduced by roughly 50%.

CONCLUSION

A simplified method for the design of semi-continuous composite beams in braced frame taking into account the partial shear connection at the steel-concrete interface and the semi-rigid/partial strength nature of the composite joint has been presented. This has been preceded by procedures to calculate associated characteristics of the composite joints needed for the design, i.e., moment resistance, rotation capacity and initial stiffness.

The used design example has shown the potential benefits of accounting for strength and stiffness of composite joints. Increases in the ultimate carrying capacity of the composite beams occur as a result of the partial strength characteristics of composite joints. Significant reductions in deflections occurring at the serviceability limit state are evident when composite beams are considered as semi-continuous rather than as simply supported. The use of partial shear connection in composite beams results in a small reduction in the moment resistance but has a significant benefit in ductility. Finally, the proposed method is shown to be simple and can be implemented using hand calculation or spreadsheet.

REFERENCES

Anderson, D. and A. Najafi, 1994. Performance of composite connections-major axis endplate joints. J. Const. Steel Res., 31: 31-57.

Anderson, D., J.M. Aribert, H. Bode and H.J. Kronenburger, 2000. Design rotation capacity of composite joints. Struct. Eng., 78: 25-29.

Aribert, J.M., 1996. Influence of slip of the shear connection on composite joint behaviour. Third International Workshop on Connections in Steel Structures, (IWCSS'96), Trento, Italy, pp: 11-22.

CEN., 2004. Eurocode 4: Design of composite steel and concrete structures-Part 1-1: General rules and rules for buildings. CEN, ENV 1994-1-1, Brussels.

CEN., 2005. Eurocode 3: Design of steel structures-Part 1-8: Design of joints. ENV 1993-1-8, Brussels.

Couchman, G.H., 1997. Design of Semi-Continuous Braced Frames. 1st Edn., Specialist Design Guides, Publication 183, Steel Construction Institute, Ascot, UK., ISBN: 1859420591.

Grant, J.A., J.W. Fisher and R.G. Slutter, 1977. Composite beams with formed steel deck. AISC Eng. J., 14: 24-43.

Kattner, M. and M. Crisinel, 2000. A design method for braced steel frames comprising partial strength composite joints. Proceedings of the Engineering Foundation Conferences Composite Construction IV, 2000, Banff, Alberta, Canada, pp: 686-698.

Liew, J.Y.R. and K.L. Looi, 2001. Practical design guidelines for semi-continuous composite braced frames. Steel Compos. Struct., 1: 213-230.

Nethercot, D.A., 1995. Semi-rigid joint action and the design of non-sway composite frames. Eng. Struct., 17: 554-567.

Nethercot, D.A., T.Q. Li and B.S. Choo, 1995. Required rotations and moment redistribution for composite frames and continuous beams. J. Const. Steel Res., 35: 121-164.

Wang, J.F. and G.Q. Li, 2008. A practical design method for semi-rigid composite frames under vertical loads. J. Construct. Steel Res., 64: 176-189.

Wong, Y.L., S.L. Chan and D.A. Nethercot, 1996. A simplified design method for non-sway composite frames with semi-rigid connections. Struct. Eng. J. Instit. Struct. Eng., 74: 23--28.