Undergraduate Course

COMPOSITE STRUCTURES

Introduction

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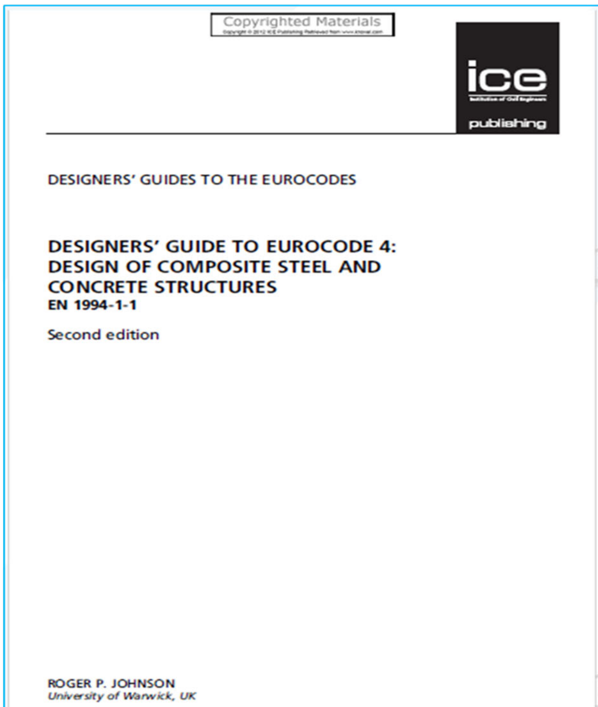
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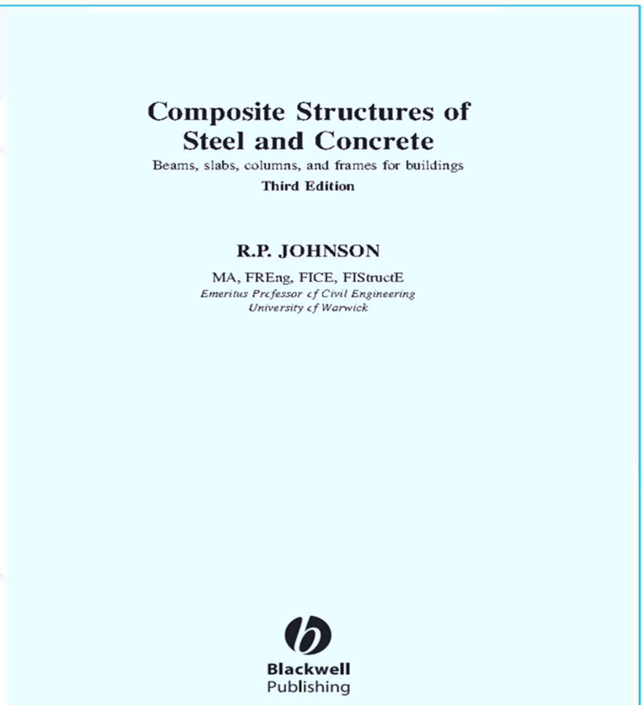
DESIGNERS' GUIDES TO THE EUROCODES

DESIGNERS' GUIDE TO EUROCODE 4: DESIGN OF COMPOSITE STEEL AND CONCRETE STRUCTURES
EN 1994-1-1

Second edition

ROGER P. JOHNSON
University of Warwick, UK

Johnson R. P. (2012), **"Designers' Guide to Eurocode 4: Design of Composite Steel and Concrete Structures EN 1994-1-1"**, *2nd Edition ICE Publishing, Thomas Telford Ltd, London, UK.*


Composite Structures of Steel and Concrete
Beams, slabs, columns, and frames for buildings
Third Edition

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Emeritus Professor of Civil Engineering
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Blackwell Publishing

Johnson R. P. (2004), **"Composite Structures of Steel and Concrete - Beams, slabs, columns, and frames for buildings"**, *3rd Edition Blackwell Publishing, Oxford, UK.*

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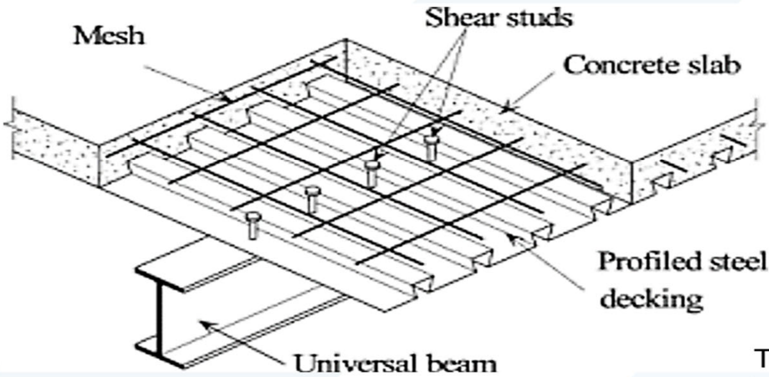
Steel-Concrete composite structure

They have an ideal combination of strengths with the concrete efficient in compression and the steel in tension and shear; concrete also gives corrosion protection and thermal insulation to the steel at elevated temperatures and additionally can restrain slender steel sections from local or lateral-torsional buckling.



Composite floor system

Typical composite multi-storey steel-framed building during execution - a factory building for the car industry in Germany

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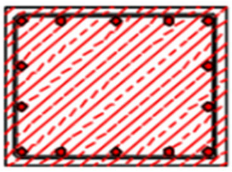
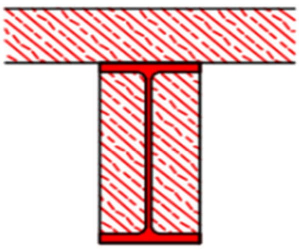
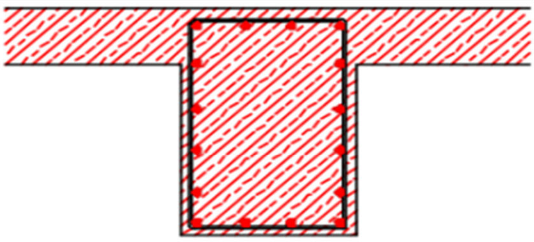
Comparison between bare reinforced concrete & composite members

	Composite	Reinforced concrete
Column		
Dimensions [cm]	70 / 70	80 / 120
Beam		
Dimensions [cm]	160 / 40	160 / 120

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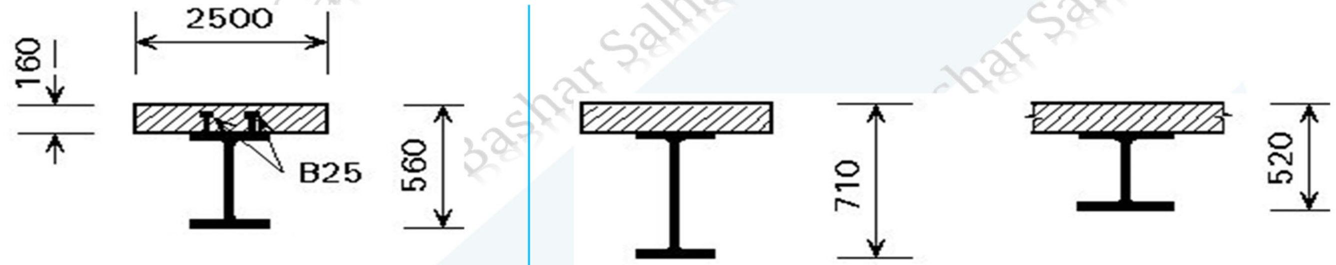
Comparison between bare steel beams & composite beams

The main advantages of using composite members are also illustrated by comparison with structures of steel and concrete used independently.



	IPE 400 composite beam	IPE 550 Steel beam without any shear connection	HE 360B Steel beam without any shear connection
Load resistance	100 %	100 %	100 %
Steel weight	100 %	159 %	214 %
Overall height	100 %	127 %	93 %

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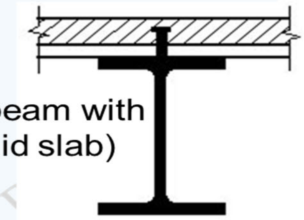
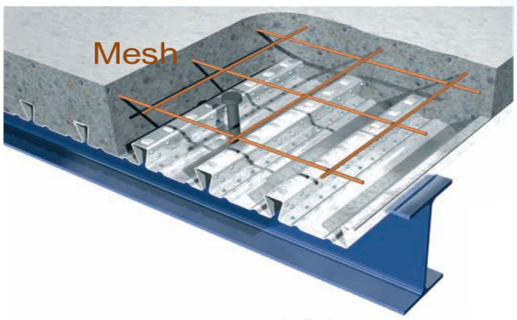
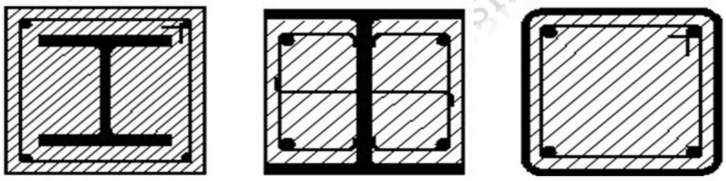
Composite elements for buildings

Composite girder (steel beam with composite slab or RC solid slab)

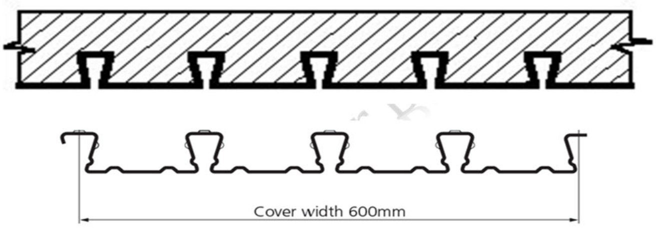




Composite column (steel profiles embedded in or filled with concrete)



Composite slab (Holorib sheeting + concrete)



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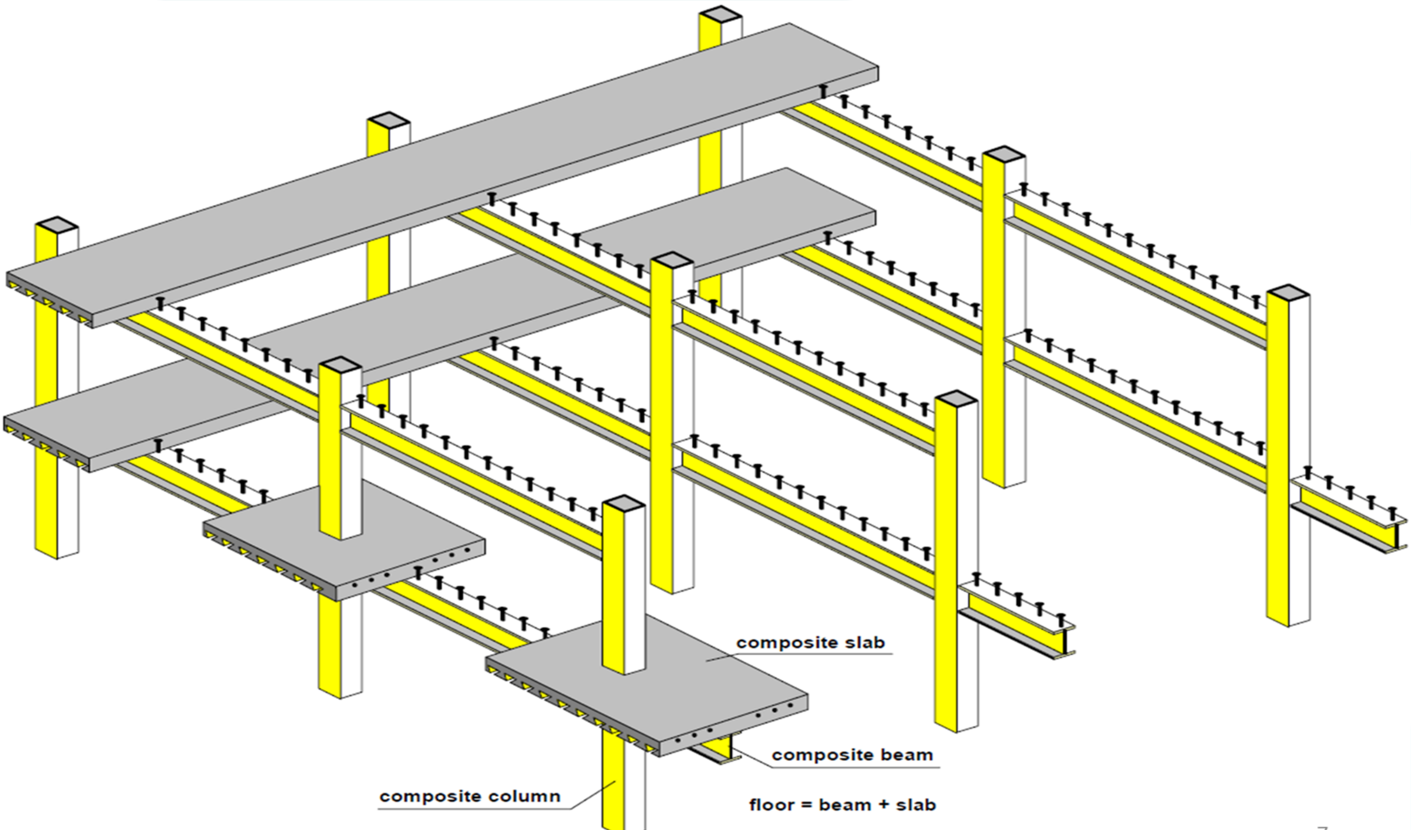
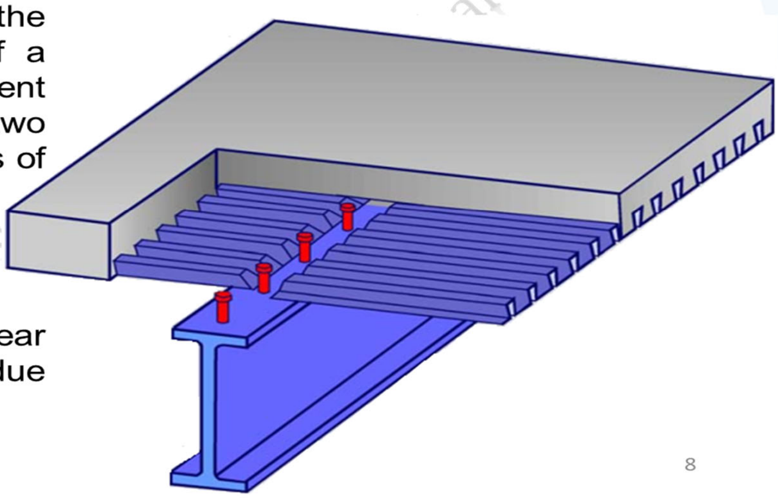


Steel-concrete composite frame

EN 1994-1-1 § 1.5.2 Definitions:

1.5.2.1 Composite member
a structural member with components of concrete and of structural or cold-formed steel, interconnected by shear connection so as to limit the longitudinal slip between concrete and steel and the separation of one component from the other.

1.5.2.2 Shear connection
an interconnection between the concrete and steel components of a composite member that has sufficient strength and stiffness to enable the two components to be designed as parts of a single structural member.



1.5.2.3 Composite behaviour
behaviour which occurs after the shear connection has become effective due to hardening of concrete.

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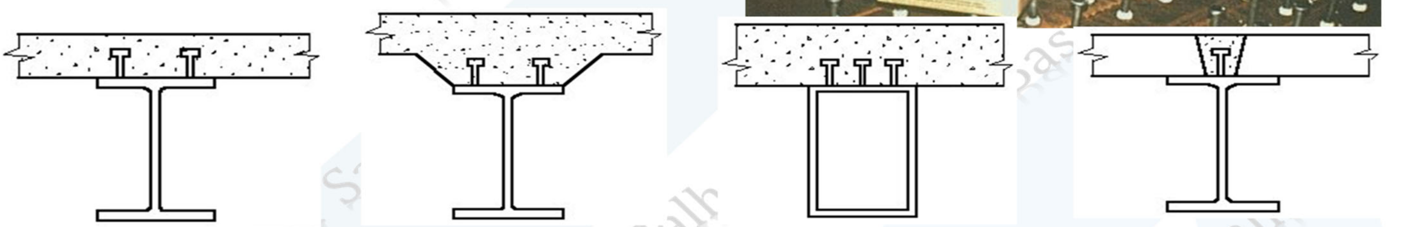
Composite action in beams

The two materials are interconnected by means of mechanical shear connectors. It is current European practice to achieve this connection by means of headed studs, semi-automatically welded to the steel flange.



T-beam | Haunched slab | Steel box girder | Precast concrete units

Composite beam cross-sections in which the wet concrete has been cast in situ on timber shuttering. For single span beams, sagging bending moments, due to applied vertical loads, cause tensile forces in the steel section and compression in the concrete deck thereby making optimum use of each material. Therefore, composite beams, even with small steel sections, have high stiffness and can carry heavy loads on long spans.

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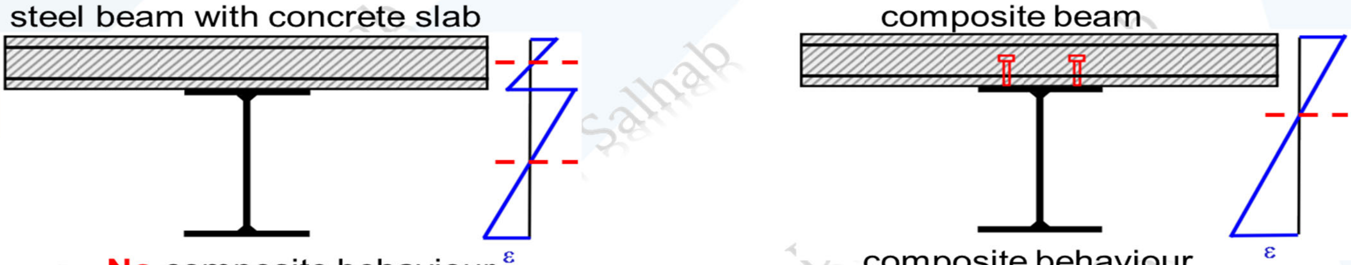
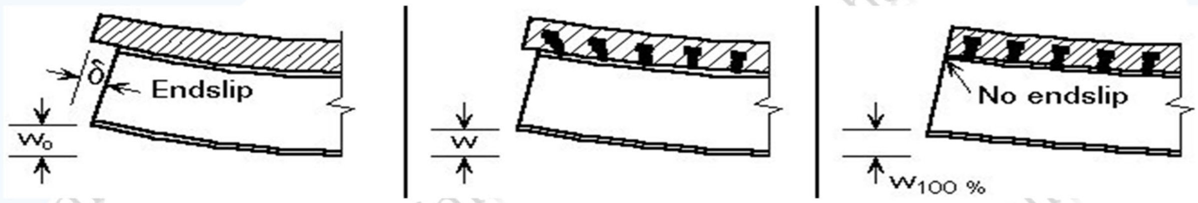
Composite behaviour

steel beam with concrete slab | composite beam

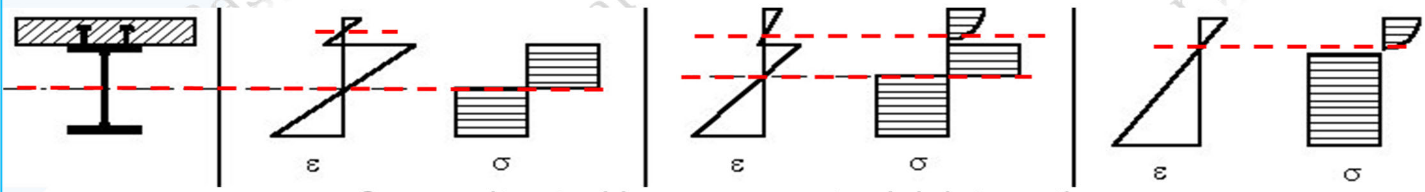


No composite behaviour acting as two individual sections

composite behaviour acting as **one** section

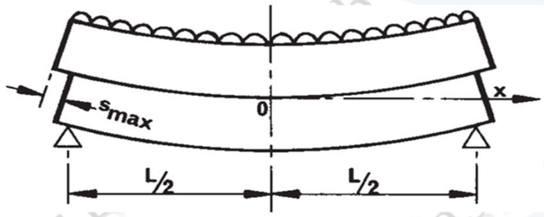


No interaction | Partial interaction | Full interaction

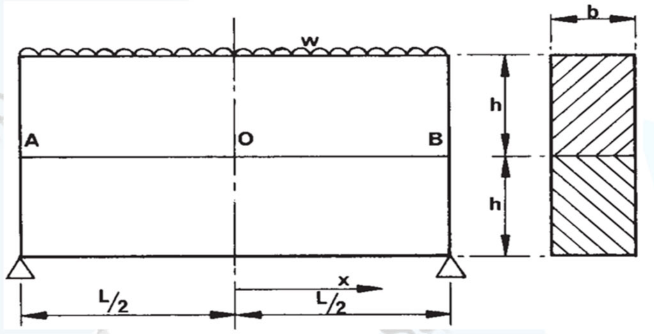


Composite steel beam-concrete slab interaction

No shear connection:



Deflected shape



$$I_{no} = \frac{bh^3}{12}$$

$$M = \left(\frac{wL^2}{8}\right)/2$$

$$\delta_{no} = \frac{5\frac{w}{2}L^4}{384EI_{no}} = \frac{wL^4}{12.8Ebh^3}$$

$$\sigma_{no} = \frac{M}{I_{no}}\frac{h}{2} = \frac{3wL^2}{8bh^2}$$

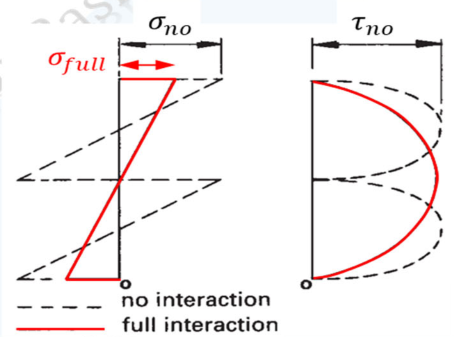
Full interaction:

$$I_{full} = \frac{b(2h)^3}{12} \qquad M = \frac{wL^2}{8}$$

$$\delta_{full} = \frac{5wL^4}{384EI_{full}} = \frac{wL^4}{51.2Ebh^3}$$

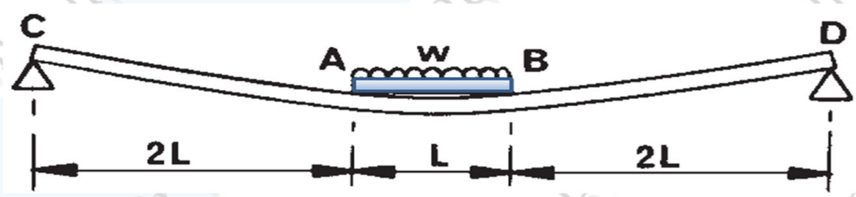
$$\sigma_{full} = \frac{M}{I_{full}}h = \frac{3wL^2}{16bh^2}$$

$$\Rightarrow \frac{\delta_{full}}{\delta_{no}} = \frac{\frac{wL^4}{51.2Ebh^3}}{\frac{wL^4}{12.8Ebh^3}} = 0.25 \qquad \frac{\sigma_{full}}{\sigma_{no}} = \frac{\frac{3wL^2}{16bh^2}}{\frac{3wL^2}{8bh^2}} = 0.5$$



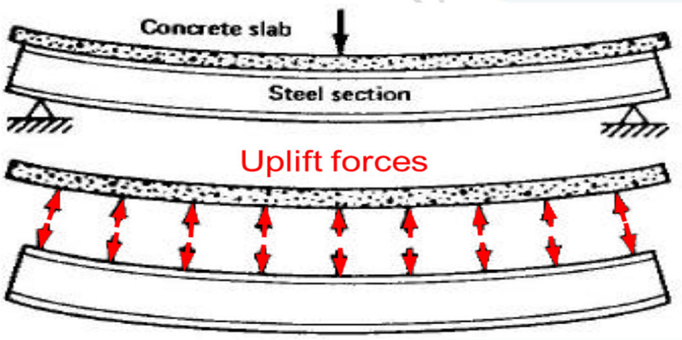
Bending stress Shear stress

Uplift

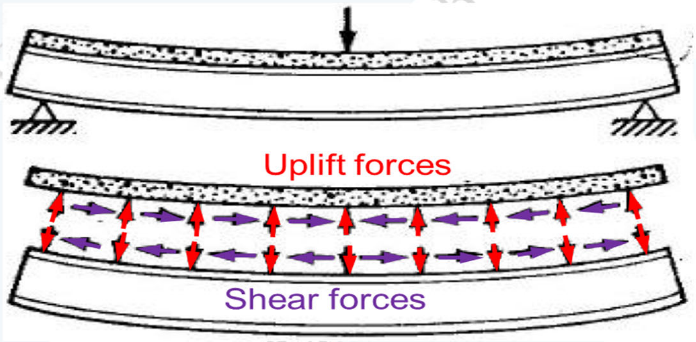


Two members without shear connection, provide a simple example. AB is supported on CD and carries distributed loading. It can easily be shown by elastic theory that if the flexural rigidity of AB exceeds about one-tenth of that CD, then the whole of the load on AB is transferred to CD at points A and B, with separation of the beams between these points. If AB were connected to CD, there would be uplift forces at mid-span.

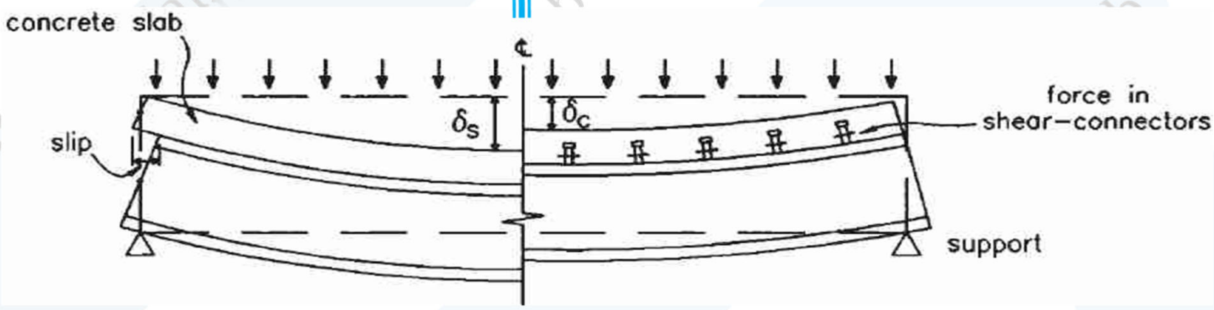
Almost all connectors used in practice are therefore so shaped that they provide resistance to uplift as well as to slip. Uplift forces are so much less than shear forces that it is not normally necessary to calculate or estimate them for design purposes, provided that connectors with some uplift resistance are used.



Deflected noncomposite beam



Deflected composite beam



EN 1994-1-1 § Section 3 Materials

3.1 Concrete

This Part of EN 1994 does not cover the design of composite structures with concrete strength classes lower than $C20/25$ and $LC20/22$ and higher than $C60/75$ and $LC60/66$

3.2 Reinforcing steel

Properties should be obtained by reference to EN 1992-1-1 § 3.2

Strength $400\ \mathrm{N/mm^2} \le f_{sk} \le 600\ \mathrm{N/mm^2}$

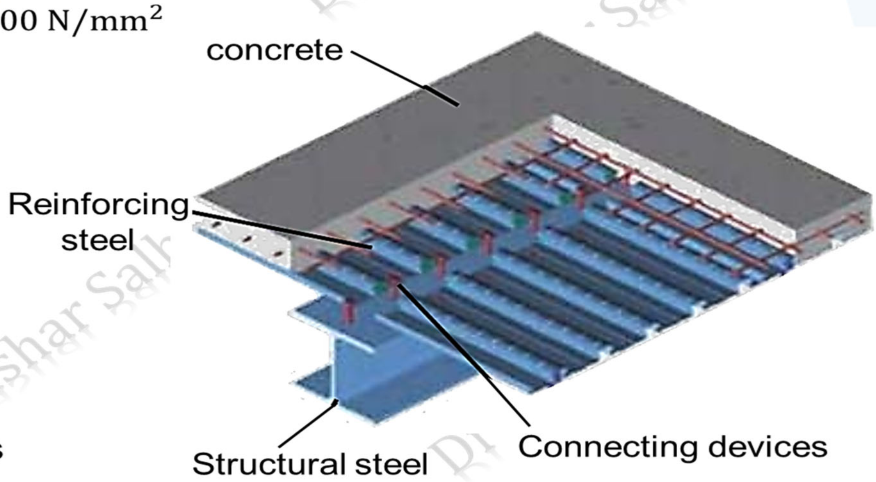
3.3 Structural steel

Properties should be obtained by reference to EN 1993-1-1 § 3.1 and 3.2

$f_{yk} \le 460\ \mathrm{N/mm^2}$

3.4 Connecting devices

Headed stud shear connectors according to EN 13918



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EN 1994-1-1 §2.4.1.2 Design values of material or product properties

EN 1992-1-1 § 3.1 for normal concrete ($\rho \approx 2400\ kg/m^3$) and to EN 1992-1-1 § 11.3 for lightweight concrete ($\rho \leq 2200\ kg/m^3$)

Ultimate Limit State $E_d \leq R_d$

The design value of a material property represents its lower characteristic value divided by its corresponding partial safety factor; the partial factors for material properties (and strengths) are:

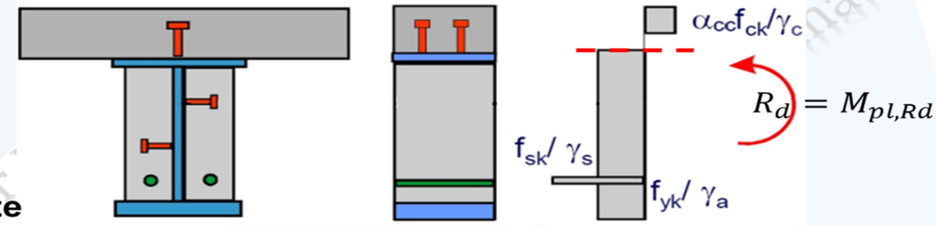
For steel reinforcement, a partial safety factor $\gamma_s = 1.15$ shall be applied according to EN 1992-1-1.

For structural steel & Profiled steel sheeting, steel sheeting and steel connecting devices, partial factor $\gamma_a = \gamma_{M0} = 1$ shall be applied. (EN 1993-1-1)

Partial safety factor for concrete $\gamma_c = 1.5$ according to EN 1992-1-1

For shear connection, a partial factor $\gamma_v = 1.25$ shall be applied.

For longitudinal shear in composite slabs for buildings, a partial factor $\gamma_{vs} = 1.25$ shall be applied.



Serviceability Limit State

under service conditions, the deflections and vibrations do not exceed allowable values and that cracking of the concrete is limited

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Partial safety factors for material (recommended values)

Ultimate limit state (STR)

design situation	structural steel	reinforcement	concrete	shear connectors (headed studs)
persistent and transient	$\gamma_{a,mo} = 1$ $\gamma_{a,m1} = 1$	$\gamma_s = 1{,}15$	$\gamma_c = 1{,}5$	$\gamma_V = 1{,}25$
accidental	$\gamma_a = 1$	$\gamma_s = 1$	$\gamma_c = 1{,}2$	$\gamma_V = 1$

$\gamma_a = 1.25$ for structural steel subjected to direct tension, bolts, plates and welds

Fatigue (FAT)

	structural steel		reinforcement	concrete	shear connection
	low consequence of failure	high consequence of failure			
damage tolerant	$\gamma_{f,a} = 1$	$\gamma_{f,a} = 1{,}15$	$\gamma_{f,s} = 1{,}15$	$\gamma_{f,c} = 1{,}5$	$\gamma_{f,V} = 1$
safe life	$\gamma_{f,a} = 1{,}15$	$\gamma_{f,a} = 1{,}35$			

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Mechanical properties of Concrete

EN 1992-1-1 § Table 3.1 Strength and deformation characterstics for concrete

	Strength classes for concrete													
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0
E_{cm} (Gpa)	27	29	30	31	32	34	35	36	37	38	39	41	42	44
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8

f_{ck} Characteristic compressive cylinder strength of concrete at 28 days

f_{cm} Mean value of concrete cylinder compressive strength $f_{cm} = f_{ck} + 8\ [N/mm^2]$

f_{ctm} Mean value of axial tensile strength of concrete

E_{cm} Secant modulus of elasticity

E_c tangent modulus of elasticity

$$E_{cm} = 22000\left(\frac{f_{cm}}{10}\right)^{0.3}\ N/mm^2$$

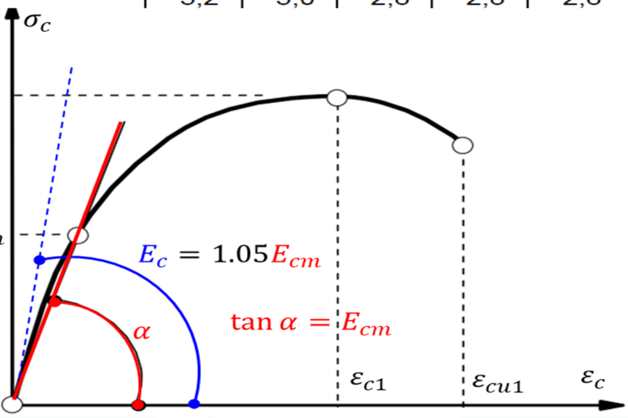

Figure 3.2 Schematic representation of the stress-strain relation for structural analysis

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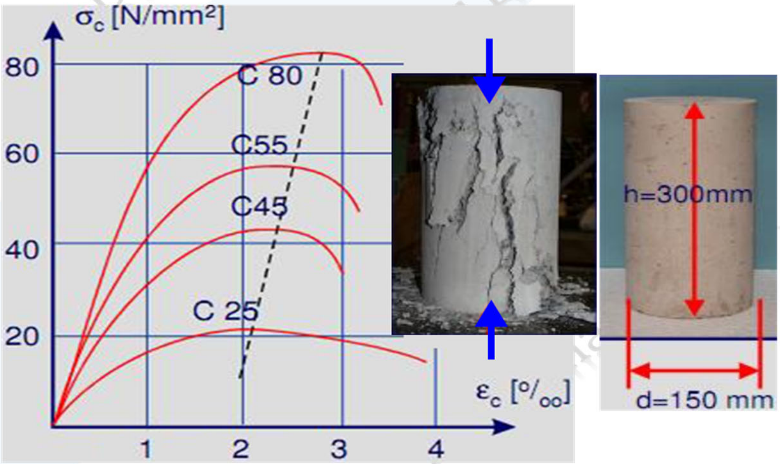
Concrete compressive strength: (Test specimen stored in water for 28 days)

Concrete strength class **C 20 / 25**

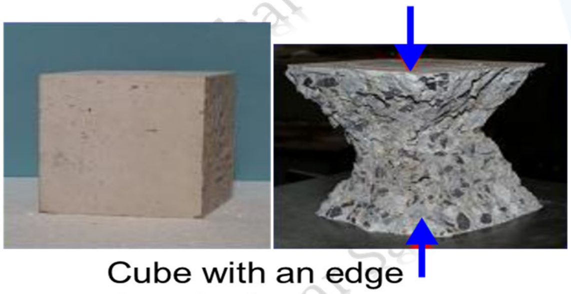
f_{ck}

Characteristic compressive cylinder strength of concrete determined at 28 days



$f_{ck,cube}$

Characteristic compressive cube strength of concrete determined at 28 days



Cube with an edge length of 150 mm

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EN 1992-1-1 § 3.1.7 Stress-strain relations for the design of cross-sections

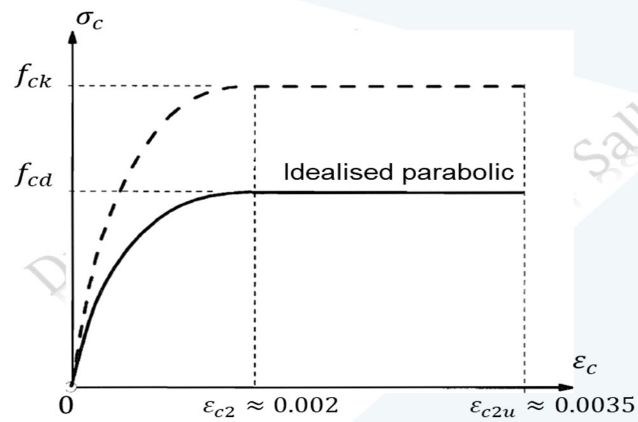

Figure 3.3: Parabola-rectangle diagram for concrete under compression

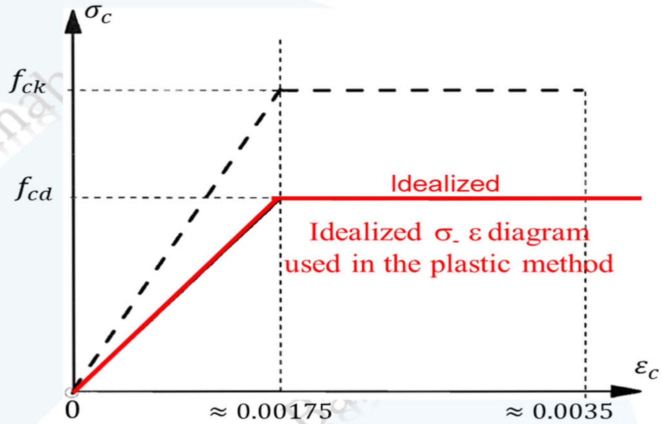

Figure 3.4: Bi-linear stress-strain relation

γ_c the partial safety factor for concrete:

Design situations	γ_C for concrete	γ_S for reinforcing steel
Persistent & Transient	1,5	1,15
Accidental	1,2	1,0

Table 2.1 N: Partial factors for materials for ultimate limit states

α_{cc} the coefficient taking account of long term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied (Concrete filled hollow sections $\alpha_{cc} = 1$, Other cases $\alpha_{cc} = 0.85$)

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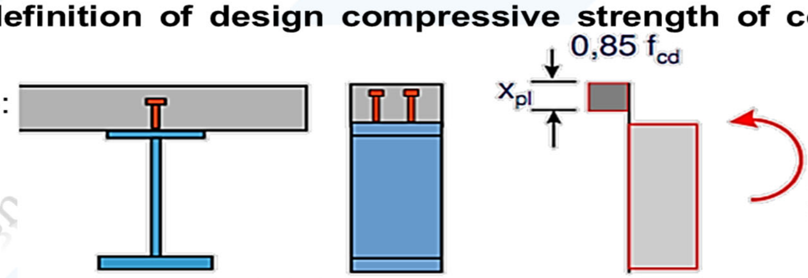
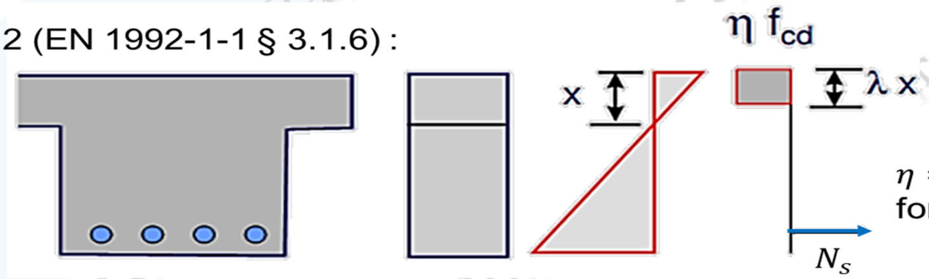
Different definition of design compressive strength of concrete f_{cd} in EC4 and EC2

Eurocode 4:



$$f_{cd} = \frac{f_{ck}}{\gamma_c}$$

Eurocode 2 (EN 1992-1-1 § 3.1.6) :



$$f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c}$$

$\eta = 1$ and $\lambda = 0.8$ for $f_{ck} \leq 50\ \mathrm{N/mm^2}$

In the strength classes for concrete in EN 1992, the ratios f_{ck}/f_{cu} range from 0.78 to 0.83, so for $\gamma_c = 1.5$, the stress $0.85 f_{cd}$ corresponds to a value between $0.44 f_{cd}$ and $0.47 f_{cd}$. This agrees closely with BS 5950, which uses $0.85 f_{cd}$ for the plastic resistance of cross-sections. The factor 0.85 takes account of several differences between a standard cylinder test and what concrete experiences in a structural member. These include the longer duration of loading in the structure, the presence of a stress gradient across the section considered, and the differences in the boundary conditions for the concrete.

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Mechanical properties of Reinforcing Steel

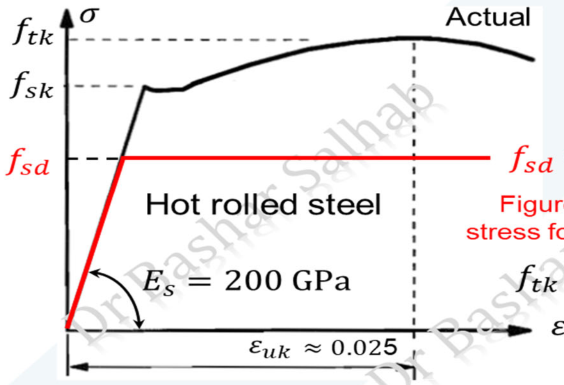
EN 1992-1-1 § 3.2.2

The application rules for design and detailing in this Eurocode are valid for a specified yield strength range, $f_{sk} (or f_{0.2k}) = 400\ to\ 600$ MPa

The surface characteristics of ribbed bars shall be such to ensure adequate bond with the concrete.

Table C.1: Properties of reinforcement

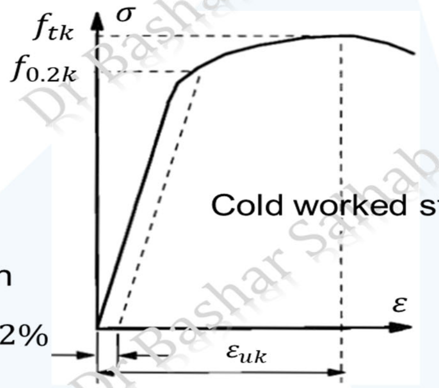
Product form	Bars and de-coiled rods		
Class	A	B	C
Characteristic yield strength f_{yk} or $f_{0,2k}$ (MPa)		400 to 600	
Minimum value of f_{tk}/f_{sk}	≥1,05	≥1,08	≥1,15 <1,35
Characteristic strain at maximum force, ε_{uk} (%)	≥2,5	≥5,0	≥7,5



$f_{sd} = \frac{f_{sk}}{\gamma_s}$ $\gamma_s = 1.15$

Figure 3.8: Idealised stress for reinforcing steel

f_{tk} the tensile strength



0.2%

Figure 3.7: Stress-strain diagrams of typical reinforcing steel

(4) The design value of the modulus of elasticity, $E_s = 200$ GPa

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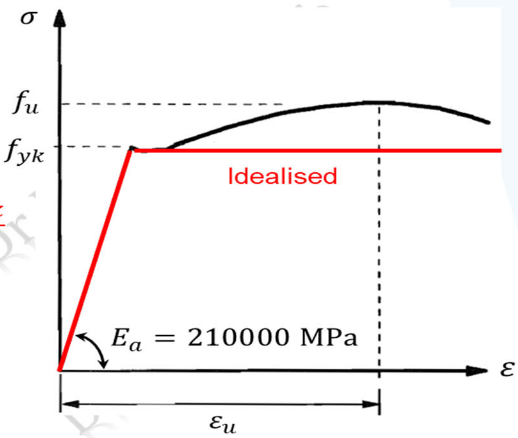
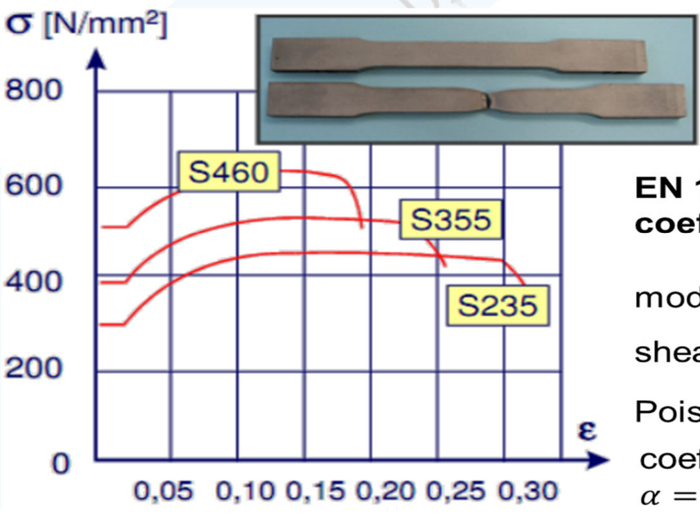
Mechanical properties of Structural Steel

The rules in EN 1994 apply to structural steel of nominal yield strength $\leq 460\ \mathrm{N/mm^2}$ (For composite structures steel grades S235, S355, S460 may be used)

According to UK Annex $\gamma_a = 1$

$f_{yd} = \frac{f_{yk}}{\gamma_a}$





EN 1993-1-1 § 3.2.6 Design values of material coefficients

unit mass $\rho_a = 7850\ \mathrm{kg/m^3}$

modulus of elasticity $E_a = 210000\ \mathrm{N/mm^2}$

shear modulus $G_a = \frac{E_a}{2(1+\upsilon)} \approx 81000\ \mathrm{N/mm^2}$

Poisson's ratio in elastic stage $\upsilon = 0.3$

coefficient of linear thermal expansion $\alpha = 1.2 \times 10^{-5}$ perK

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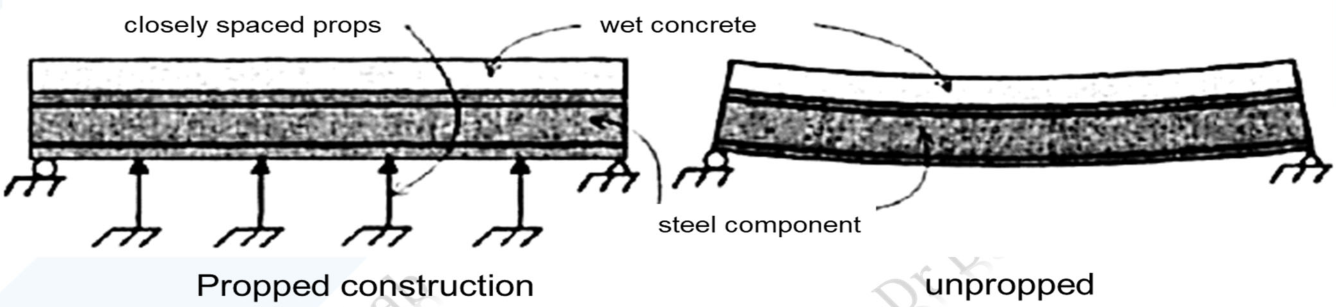
EN 1993-1-1 § Table 3.1: Nominal values of yield strength f_{yk} and ultimate tensile strength f_{uk}

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		$40 \text{ mm} < t \leq 80$ mm	
	f_{yk} [N/mm^2]	f_{uk} [N/mm^2]	f_{yk} [N/mm^2]	f_{uk} [N/mm^2]
for hot rolled structural steel:				
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	510	335	470
S 450	440	550	410	550
for structural hollow sections:				
EN 10210-1				
S 235 H	235	360	215	340
S 275 H	275	430	255	410
S 355 H	355	510	335	490

Construction methods of composite structures (Propped or unpropped)



The efficiency in structural performance will be greatest if it is possible to ensure that the concrete slab and steel member act compositely at all times. This requirement can be met by supporting the steel beam until the concrete has hardened. Such support is known as "propping".

The number of temporary supports need not be high; propping at the quarter-span points and mid-span is generally sufficient. The props are left in place until the concrete slab has developed adequate resistance.

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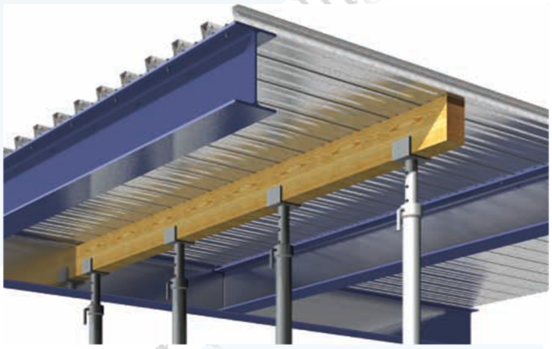
In unpropped construction: Initially the steel beam alone resists: its own weight, weight of the formwork, weight of the wet concrete, & placement loads.
Other loads are added later and so are carried by the composite member.

Propping is needed where the steel beam is not able to support the weight of a thick concrete slab during construction, or where deflection of the steel beam would otherwise be unacceptable



propped

The most economic method of construction is generally to avoid the use of temporary propping. Unpropped construction method is the only practical method in the majority of bridges. This technique is usually preferred for a building in order to reduce the time of construction.

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the advantages of composite construction

- Steel and concrete are two materials complete one another: Concrete is efficient in compression and steel in tension.
- Steel components are relatively thin and prone to buckling, concrete can restrain these against buckling.
- Concrete also gives protection against corrosion provides thermal insulation at high temperatures.
- Steel brings ductility into the structure.
- Speed of construction: The use of the decking as a working platform speeds up the construction process for other trades.

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- Safe method of construction: The decking provides a safe working platform and also acts as a safety 'canopy' to protect workers below from falling objects.

- Saving in weight: Composite construction is considerably stiffer and stronger than many other floor systems, thus the weight and size of the primary structure can be reduced. Consequently, foundation sizes can also be reduced. Saving 30% to 50%.

- Saving in transport: Decking is light and is delivered in pre-cut lengths that are tightly packed into bundles.

- Structural stability: The decking can act as an effective lateral restraint for the beams provided that the decking fixings have been designed to carry the necessary loads. The decking may also be designed to act as a large floor diaphragm to redistribute wind loads in the construction stage, and the composite slab can act as a diaphragm in the completed structure. The floor construction is robust due to the continuity achieved between the decking, reinforcement, concrete and primary structure.

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- Shallower construction: The stiffness and bending resistance of composite beams means that shallower floors can be achieved than in noncomposite construction. This may lead to smaller storey heights, more room to accommodate services in a limited ceiling to floor zone, or more storeys for the same overall height. This is especially true for slim floor construction, whereby the beam depth is contained within the slab depth.

- Easy installation of services: Cable trays and pipes can be hung from hangers that are attached using special 'dovetail' recesses rolled into the deck profile, thereby facilitating the installation of services such as electricity, telephone and information technology network cabling. These hangers also allow for convenient installation of false ceilings and ventilation equipment.