Composite Beam Design
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Introduction

This document briefly explains the theoretical background for the design check of composite beams. Design checks to BS 5950-3.1 and EN 1994-1-1: 2004 are outlined and fire resistance checks 5950:8 and EN 1994-1-2 are also presented.
Composite beam design

Design check to BS 5950-3.1

Composite beam members may be checked for their strength, stability and stiffness in accordance with BS-5950-3.1

Checks are done at final (composite) stages and also at the construction (non-composite) stages.

**Design code:** BS 5950: Part 3: Section 3.1: 1990

**Partial safety factors:**

In accordance with the code the following default values of PSF are used for the design checks, but are user editable.

**Partial safety factors on loads:**

- Dead load : 1.40
- Live load : 1.60

**Partial safety factors for material strength:**

- Structural steelwork : 1.0
- Profiled steel sheet : 1.0
- Reinforcement steel : 1.15
- Shear connectors : 1.25
- Concrete in shear : 1.25
- Concrete in compression : 1.50

**Limiting values:**

The user is responsible for defining limiting values for span/deflection ratio at serviceability limit state. The default values are,

- For permanent loads : 240
- Variable (imposed) loads : 360
- Total load : 200

**Pre-camber:**

The program can allow for pre-camber. The user can set the pre-camber value as an absolute value (in mm) or as a proportion of span (eg L/200). Very small cambers are impractical and designers should consult fabricators or published guidance in case of doubt.

**Calculation parameters:**

The following parameters are input by the user:

- Type of concrete
- Proportion of long term loading
- Percentage of variable load included in the calculation of natural frequency based on static deflection.
- Percentage of increase in moment of inertia to allow for dynamic stiffness
- Natural frequency limit (minimum value)
- Load cases included in construction stage checks
Effective span:

The effective span of a beam is defined by clause 5.1.1 of BS 5950-3 but in the absence of relevant data, the program will adopt the member length defined in the analysis model.

Construction type:

The beam may be propped or un-propped during construction. If the beam is propped during construction, construction stage analysis and design is not necessary. All beams may be designed assuming that at the ultimate limit state the whole of the loading acts on the composite member. If the beam is un-propped, construction stage checks are necessary. Using the properties of the steel beam alone without composite action.

Slab type:

The software supports the following types of slabs:

1. Solid slabs cast in-situ
2. Haunched solid slabs cast-in-situ
3. Precast hollow core slabs
4. Composite in-situ concrete and profiled steel deck

Effective breadth of concrete flange:

The total effective breadth of concrete flange acting compositely with the steel beam is taken as the sum of the effective breadths of the portions of flange on each side of the centre line of the steel beam. The information available in clause 4.6 of BS 5950-3, can be used for effective breadth calculation and input by the user. For design checking, the effective flange widths for sagging and hogging regions are taken as user input separately, but for the purpose of analysis the effective flange width of the mid zone (sagging zone) is used throughout the span.

Shear connection:

The shear connection is assumed capable of transmitting the longitudinal shear between the concrete slab and the steel beam due to the factored loads, without causing crushing or other damage to concrete and without allowing excessive slip or separation between the concrete and steel. For the related calculations, section 5.4 described in BS 5950-3 is used.

The program supports various types of shear connectors like stud, channel, bar hoop, and Hilti, which are available in the system database, and the user can add available system data to the project data.

In accordance with clause 5.5 of BS 5950-3.1, partial shear connection is allowed in the sagging region but in hogging zones, partial shear connection is discounted and the section is either fully composite or non composite.

Spacing of shear connectors:

The spacing of shear connectors should comply with clause 5.4.8 of BS 5950-3.1 and will be checked and reported as a warning if not satisfied.

Transverse reinforcement:

Transverse reinforcement refers to the reinforcement in the concrete flange running transverse to the span of the beam. Where profiled sheets are used they may also act as transverse reinforcement.

Longitudinal reinforcement:
Longitudinal reinforcement refers to the reinforcement in the concrete flange running along the span of the beam and used to provide resistance to hogging moments if present.

**Resistance of concrete flange:**

The longitudinal shear resistance of the concrete flange is calculated in accordance with clause 5.6.3 of BS 5950-3.1

**Contribution of profiled sheeting:**

Profiled steel sheeting is assumed to contribute to the transverse reinforcement provided it is continuous or stud welded to the beam flange. Clause 5.6.4 of BS 5950-3 is used for the necessary calculation.

**Section classification:**

Section classification is determined in accordance with clause 4.5 and Appendix C of BS 5950-3.1

**Plastic moment capacity:**

The plastic moment capacity of a composite cross section is calculated as per the following:

i. Concrete is assumed to be stressed to a uniform compression of 0.45$f_{cu}$ over the full depth of concrete on the compression side of the plastic neutral axis.

ii. The structural steel member is assumed to be stressed to its design strength "$p_y$" either in tension or in compression. For a section with semi compact or slender web the effective section described in clause 4.5.3 is used.

iii. Longitudinal reinforcement is assumed to be stressed to its design strength "$f_y/\gamma_s$" where it is in tension. (i.e. under hogging moments with full shear connection).

The plastic moment capacity of the composite beam depends on the degree of shear connection. The plastic moment capacity of the composite section for sagging and hogging zones are calculated in accordance with Appendix B of BS 5950-3.1. The plastic moment capacity in hogging zones is calculated assuming the concrete is cracked.

The plastic moment capacity is reduced as per clause 5.3.4 of BS 5950-3.1 in presence of high shear force.

**Elastic moment capacity:**

The elastic moment capacity of a composite cross section is calculated based on the following:

i. The strain distribution in the effective cross section is assumed linear

ii. The stress distribution in the concrete is assumed to be linear, based on the appropriate value of the modular ratio from clause 4.1 and limited to a value of "0.5$f_{cu}$".

iii. The stress in the steel beam is limited to design strength "$p_y$" reduced as recommended in BS 5950: part 1 where the section is class 4 slender.

**Stability of compression flange:**

To prevent lateral buckling, the compression flange should be laterally restrained as recommended in BS 5950 part1. Stability checks are carried out as per the guidelines given in clause 5.3.5 of BS 5950 part 3. Lateral buckling checks are carried out for the construction stages using steel only section properties. Lateral torsional buckling checks are carried out for the hogging region both in the composite stage and in construction stage.

**Longitudinal shear resistance:**

The longitudinal force and resistance are calculated in accordance with section 5.6 of BS 5950-3.1

Design checks:

The composite beam should be checked at the construction and final stages and for the ultimate and serviceability limit states.

Construction stage: In the construction stage composite action is not considered and the program will perform the following checks using only the steel beam properties.

**SLS Checks:** At the serviceability limit state the maximum deflections are calculated and compared with the limiting values as input and the utilization ratios are reported.

**ULS checks:** The ultimate section capacities are computed for moment, shear, buckling etc and are compared with the ultimate applied effects and the utilization ratios are reported.

Final Stage: For the final stage design checks the composite section properties are computed in accordance with Appendix B of the code. For hogging moment regions cracked section properties are used. For the sagging zone, the contribution of concrete in compression within the effective flange width is considered to arrive at the resistance moment

**SLS Checks:** At the serviceability limit state the maximum stresses and deflections are calculated and compared with the limiting values as input and the utilization ratios are reported. The natural frequency of vibration is computed by making use of deflection ratios. The deflection computed is modified as per section 6.1.4 in the case of beams with partial shear connection.

**ULS checks:** The ultimate section capacities are computed for moment, shear, buckling etc and are compared with the applied effects and the utilization ratios reported.

References


Fire resistance check to BS 5950-8

The fire resistance check is performed in accordance with BS 5950-8:2003

Fire Limit state:

The structural effects of fire in a building or part of a building are considered as a fire limit state. The fire limit state should be treated as an accidental limit state.

In checking the strength and stability of the structure at fire limit state, the loads should be multiplied by partial safety factors “γf” as given in Table-5 of BS 5950-8. It is the responsibility of the user to create a ULS load combination for the fire limit state.

Partial safety factors:

The default PSF values for the material properties are taken as follows,
Steel : 1.00
Concrete : 1.10

Section factor:

The rate of temperature increase of a steel member in a fire may be assumed to be proportional to its section factor, which may be defined as the ratio of,

$$S_f = \frac{A_m}{V}$$

Where:

$A_m$ : is the exposed surface area per unit length of the member
$V$ : is the volume of the member per unit length

The section factor is calculated for 3-sides for profile/box protection in accordance with Table 6.

Calculation model:

The fire behaviour of hot finished steel members may be determined using either,

1. Limiting temperature method
2. Moment capacity method

In this software the limiting temperature method is adopted, whereby if the limiting temperature, as per Table-8 for the applicable load ratio, is not less than the design temperature given in 8.4.3 for the required period of fire resistance, the member is considered to have adequate fire resistance without protection.

When the limiting temperature is less than the design temperature given in 8.4.3 the protection thickness necessary to provide adequate fire resistance may be derived from standard fire test data. The software has a good data base of fire protection materials commonly available in the UK market, obtained from "Fire Protection for structural buildings" published by "Association for Specialist Fire Protection (ASFP)" in conjunction with "Fire Test Study Group (FTSG)" & "Steel Construction Institute (SCI)".

Load ratio:

For beams designed in accordance with BS 5950-1 with three or four sides fully exposed, the load ratio $R$ is taken as the greater of,

$$R := \frac{M_f}{M_c}$$

Or

$$R := \frac{m \cdot M_f}{M_b}$$

Where:

$M_f$ : is the applied moment at fire limit state
$M_b$ : is the buckling resistance moment
$M_c$ : is the moment capacity of the section
$M$ : is the equivalent uniform moment factor
Design temperature:

The design temperature depends on the section configuration and dimensions. For beams Table-10 is used for obtaining the design temperature.

Limiting temperature:

The limiting temperature obtained from Table-8 corresponds to the load ratio.

References

1. BS 5950-8:2003 Structural use of steel work in building Part-8: Code of practice for fire resistant design

2. Fire Protection for structural steel in building Published by, "Association for Specialist Fire Protection (ASFP)" in conjunction with "Fire Test Study Group (FTSG)" & "Steel Construction Institute (SCI)".

Design check as per EN 1994-1-1: 2004

This module checks composite beam members by preparing calculations for their strength, stability and stiffness in accordance with EN 1994-1-1: 2004.

Design code: BS EN 1994-1-1: 2004

Partial safety factors:

In accordance with the code the following default values of PSF are used for the design checks, but are user editable

Partial safety factors on loads:

<table>
<thead>
<tr>
<th>Load Type</th>
<th>PSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load</td>
<td>1.35</td>
</tr>
<tr>
<td>Live load</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Partial safety factors for material strength:

<table>
<thead>
<tr>
<th>Material Type</th>
<th>PSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural steel – resistance</td>
<td>1.0</td>
</tr>
<tr>
<td>Structural steel – buckling</td>
<td>1.0</td>
</tr>
<tr>
<td>Profiled steel sheet</td>
<td>1.0</td>
</tr>
<tr>
<td>Reinforcement steel</td>
<td>1.15</td>
</tr>
<tr>
<td>Shear connectors</td>
<td>1.25</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Limiting values:

The user is responsible for defining limiting values for span/deflection ratio at serviceability limit state. The default values are,

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>For permanent loads</td>
<td>240</td>
</tr>
<tr>
<td>Variable (imposed) loads</td>
<td>360</td>
</tr>
<tr>
<td>Total load</td>
<td>200</td>
</tr>
</tbody>
</table>

Pre-camber:

The program can allow for pre-camber. The user can set the pre-camber value as an absolute value (in mm) or as a proportion of span (eg L/200). Very small cambers are impractical and designers should consult fabricators or published guidance in case of doubt.
Calculation parameters:

The following parameters are input by the user:

Type of concrete
Proportion of long term loading
Percentage of variable load included in the calculation of natural frequency based on static deflection.
Percentage of increase in moment of inertia to allow for dynamic stiffness
Natural frequency limit (minimum value)
Load cases included in construction stage checks

Effective span:

The effective span of a beam is defined by clause 5.4.1.2 of EN 1994-1-1: 2004 but in the absence of relevant data, the program will adopt the member length defined in the analysis model.

Construction type:

The beam may be propped or un-propped during construction. If the beam is propped during construction, construction stage analysis and design is not necessary. All beams may be designed assuming that at the ultimate limit state the whole of the loading acts on the composite member. If the beam is un-propped, construction stage checks are performed using the properties of the steel beam alone without composite action.

Slab type:

The software supports the following types of slabs:

1: Solid slabs cast in-situ
2: Haunched solid slabs cast-in-situ
3: Precast hollow core slabs
4: Composite in-situ concrete and profiled steel deck

Effective breadth of concrete flange:

The total effective breadth of concrete flange acting compositely with steel beam is taken as the sum of the effective breadths of the portion of flange on each side of the centre line of the steel beam. The information available in clause 5.4.1.2 of EN 1994-1-1: 2004, can be used for effective breadth calculation and input by the user.

Shear connection:

The shear connection is assumed capable of transmitting the longitudinal shear between the concrete slab and the steel beam due to the factored loads, without causing crushing or other damage to concrete and without allowing excessive slip or separation between the concrete and steel. For the related calculations section 6.6 described in EN 1994-1-1: 2004 is used.

The program various types of shear connectors like stud, channel, bar hoop, and Hilti, which are available in the system data base, and the user can add the available system data to the project data.

In accordance with section 6.6 of EN 1994-1-1: 2004, partial shear connection is allowed in the sagging region, but in the hogging regions partial shear connection is discounted and the section is either fully composite or non composite

Spacing of shear connectors:
The spacing of shear connectors should comply with clause 6.6 of EN 1994-1-1: 2004 and this will be checked and reported as a warning if not satisfied.

**Transverse reinforcement:**

Transverse reinforcement refers to the reinforcement in the concrete flange running transverse to the span of the beam. Where profiled sheets are used they may also act as transverse reinforcement.

**Longitudinal reinforcement:**

Longitudinal reinforcement refers to the reinforcement in the concrete flange running along the span of the beam and used to provide resistance to hogging moments if present.

**Resistance of concrete flange:**

The longitudinal shear resistance of the concrete flange is calculated in accordance with clause 6.2.1.2 of EN 1994-1-1: 2004

**Contribution of profiled sheeting:**

Profiled steel sheeting is assumed to contribute to the transverse reinforcement provided it is continuous or stud welded to the beam flange. Clause 6.6.6.4 of EN 1994-1-1: 2004 is used for the necessary calculation.

**Section classification:**

Section classification is determined in accordance with section 5.5.2 of EN 1994-1-1: 2004 and table 5.2 of EN 1993-1-1.

**Plastic moment capacity:**

The plastic moment capacity of a composite cross section is calculated as per the following:

i. Concrete is assumed to be stressed to a uniform compression of fck/γc over the full depth of concrete on the compression side of the plastic neutral axis.

ii. The structural steel member is assumed to be stressed to its design strength “py” either in tension or in compression. For a section with semi compact or slender web the effective section described in clause 6.2.2.4, fig 6.3 of EN 1994-1-1: 2004 is used.

iii. Longitudinal reinforcement is assumed to be stressed to its design strength “fy/γs” where it is in tension (ie under hogging moments with full shear connection).

The plastic moment capacity of the composite beam depends on the degree of the shear connections. In the absence of specific guidance in EC4, the plastic moment capacity of the composite section for the sagging zone and hogging zone are calculated in accordance with Appendix B of BS 5950-3. The plastic moment capacity in hogging regions is calculated assuming the concrete is cracked.

The plastic moment capacity is reduced as per clause 6.2.2.4 of EN 1994-1-1: 2004 in presence of high shear force.

**Elastic moment capacity:**

The elastic moment capacity of composite cross section is calculated on the basis of the following:

i. The strain distribution in the effective cross section is assumed linear
ii. The stress distribution in the concrete may be assumed to be linear, based on the appropriate value of the modular ratio from clause 4.1 and limited to a value of “0.50fck”.

iii. The stress in the steel beam is limited to design strength “py” reduced as recommended in clause 7.1 of EN 1994-1-1: 2004 where the section is class 4 slender.

**Stability of compression flange:**

To prevent lateral-torsional buckling under hogging moment in the final condition, the compression flange may require additional lateral restraint. Stability check is carried out as per the guidelines given in clause 6.4.2 of EN 1994-1-1: 2004. Lateral torsional buckling checks are carried out in the hogging regions for the final stage using composite properties as per clause 6.4.2.

**Longitudinal shear resistance:**

The longitudinal force and resistance are calculated in accordance with section 6.6.6 of EN 1994-1-1: 2004.

**Design checks:**

Composite beam should be checked at the construction and final stages and for the ultimate and serviceability limit states.

**Construction stage:** In the construction stage the following checks has to be performed by using steel section properties.

- **SLS Checks:** At the serviceability limit state the maximum deflections are calculated and compared with the limiting values as input and the utilization ratios are reported.

- **ULS checks:** The ultimate section capacities are computed for moment, shear, buckling etc and are compared with the ultimate applied effects and the utilization ratios are reported.

At present the program can not perform construction stage checks for the composite beams but the user can still make use of the existing Esa steel check functionality to perform checks at construction stage.

**Final Stage:**

For final stages design checks the composite section properties are computed in accordance with Appendix B of BS 5950-3.1. For the hogging moment region the cracked section properties are used for the sagging zone the contribution of the concrete in compression within the effective flange width is considered to arrive at the resistance moment.

- **SLS Checks:** At the serviceability limit state the maximum stresses and deflections are calculated and compared with the limiting values as input and the utilization ratios are reported. The natural frequency of vibration is computed by making use of deflection ratios. In the absence of EC guidance the deflection computed is modified as per section 6.1.4 of BS-5950-3 in the case of beams with partial shear connection.

- **ULS checks:** The ultimate section capacities are computed for moment, shear, buckling etc and are compared with the applied effects and the utilization ratios reported.

**References**


**Fire resistance check to EC4**

The fire resistance check is performed in accordance with BS EN 1994-1-2
Fire actions / Effects:

The effects at fire limit state should be computed as per section 2.4.2 of EC4. The reduction factor “ηfi” is calculated for the load combinations using combination factors “Ψfi” in accordance with EN 1991-1-2.

The user can make use of the ULS accidental combination option available in ESA PT for creating the load combination for the fire check. Users can also create their own ULS combinations for the fire check.

Partial safety factors:

The default PSF values for the material properties are taken as 1.0 in accordance with EC4.

Temperature-time curves:

The program supports three different types of fire curves as listed below,

1. Standard temperature-time (ISO 834) curve
2. External fire curve
3. Hydro carbon curve

Standard temperature-time curve

The standard temperature-time curve can be defined by the following equation,

\[ T_g = 20 + 345 \cdot \log (8 \cdot t + 1) \]

with, coefficient of heat transfer by convection( \( \alpha_c \))

\[ \alpha_c = 25 \text{ W/m}^2\text{K} \]

External fire curve

The external fire curve can be defined by the following equation,

\[ T_g = 20 + \left[ 660 \cdot \left( 1 - 0.687 \cdot e^{-0.32t} - 0.313 \cdot e^{-3.8t} \right) \right] \]

with, coefficient of heat transfer by convection( \( \alpha_c \))

\[ \alpha_c = 25 \text{ W/m}^2\text{K} \]

Hydro carbon curve

The hydrocarbon curve can be defined by the following equation,

\[ T_g = 20 + \left[ 1080 \cdot \left( 1 - 0.325 \cdot e^{-0.167t} - 0.675 \cdot e^{-2.5t} \right) \right] \]

with, coefficient of heat transfer by convection( \( \alpha_c \))

\[ \alpha_c = 50 \text{ W/m}^2\text{K} \]

Temperature of steel beam:
The temperature increase in the steel profile depends on whether the section is protected or not.

For an unprotected section the increase in temperature ($\Delta \theta_{at}$) during the time interval ($\Delta t$) may be determined from:

$$\Delta \theta_{at} := K_{shadow} \left( \frac{1}{Ca \cdot \rho_a} \right) \cdot (Sf \cdot h_{net} \cdot \Delta t)$$

where,

$$K_{shadow} := 0.9 \left[ e_1 + e_2 + \left( \frac{b_1}{2} \right) \right] + \frac{\sqrt{\frac{h_w^2 + 1}{4} \left( \frac{b_1 - b_2}{2} \right)^2}}{\left[ \frac{h_w + b_1 + \left( \frac{b_2}{2} + e_1 + e_2 - cw \right) }{2} \right]}$$

$Ca$ : is the specific heat of steel [J/kgK]
$
\rho_a$ : is the density of steel [kg/m$^3$]
$Sf$ : is the section factor of the steel beam/part of the beam [m$^{-1}$]
$h_{net}$ : is the design value of the net heat flux per unit area [W/m$^2$]
$\Delta t$ : is the time interval, taken as 5 sec.

For a protected section the increase in temperature ($\Delta \theta_{at}$) during the time interval ($\Delta t$) may be determined from,

$$\Delta \theta_{at} := \left[ \frac{\lambda_p}{dp} \frac{( Api )}{Vi} \right] \left[ \frac{1}{1 + \frac{w}{3}} \right] \cdot ( \theta_t - 0_{at}) \cdot \Delta t - \left[ \frac{w}{\frac{10}{e_1^2} - 1} \right] \cdot \Delta \theta_{at}$$

Where:-

$$w := \left[ \frac{C_p \cdot \rho_p}{Ca \cdot \rho_a} \right] \cdot \frac{( Api )}{Vi}$$

$\lambda_p$ : is the thermal conductivity of the fire protection material [W/mK]
$\rho_a$ : is the density of steel [kg/m$^3$]
$\rho_p$ : is the density of the fire protection material [kg/m$^3$]
$dp$ : is the thickness of fire protection material [m]
$\frac{( Api )}{Vi}$ : is the section factor of the steel beam/part of the beam [m$^{-1}$]
$h_{net}$ : is the design value of the net heat flux per unit area [W/m$^2$]
$\Delta t$ : is the time interval, taken as 30 sec.
$\Delta \theta_{at}$ : is the increase of the ambient temp. during the time interval $\Delta t$ [°C]
θt : is the ambient gas temperature at time “t” [°C]
θat : is the steel temperature [°C]

Net heat flux: The net heat flux can be defined as the design value of the net heat flux per unit area in accordance with 3.1 of EN 1991-1-2

\[ h_{net} := h_{netc} + h_{netr} \]
\[ h_{netc} := \alpha_c \cdot (\theta_t - \theta_{at}) \]
\[ h_{netr} := E_m \cdot E_f \cdot \left(5.67 \cdot 10^{-8}\right) \left[\left(\theta_t + 273\right)^4 - \left(\theta_{at} + 273\right)^4\right] \]

Where:
- \( h_{netc} \) : is the convective heat flux
- \( h_{netr} \) : is the radiative heat flux
- \( E_m \) : is the surface emissivity of the member
- \( E_f \) : is the emissivity of the fire
- \( \alpha_c \) : coefficient of heat transfer by convection

Calculation model:

For the fire check calculation, the model used is the strength domain. In this model the temperature of the cross section after a given time is calculated based on the user inputs. Depending on the design temperature the reduced capacities of the cross sections are calculated and compared with the applied effects at the fire limit state in accordance with section 4 of EN 1994-1-2.

Strength reduction factors:

The strength reduction factors for concrete and steel are calculated in accordance with Table 3.3, and Table 3.2 of EC4 based on the design temperature.

Plastic neutral axis & Moment of resistance:

The plastic neutral axis and moment of resistances of the composite beam at the fire limit state is calculated in accordance with clause 4.3.1 along with Annex E of EC4.

Vertical shear resistance:

For the calculation of vertical shear resistance of the structural steel section the method given in E4 of Annex E is used.

Longitudinal shear resistance:

The longitudinal force and resistance are obtained by a similar procedure described in clause 6.6.6 of EN 1994-1-1, with reduced strength parameters.
References


