Theory

Composite column design

Scia Engineer
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Introduction

This document describes the theoretical background involving composite column design check in accordance with EN 1994-1-1:2004. The topics listed below are discussed in the subsequent parts:

1. Types of composite column sections supported for design check.
2. Design checks carried out for ultimate limit state.
3. Methods of analysis and member imperfections.
4. Design checks for columns subjected to fire exposure.
Composite Column Sections

Design checks can be carried out for the following **six** types of composite sections as illustrated in the figure below:

a) Fully concrete encased section.
b) Partially concrete encased section.
c) Partially concrete encased with crossed I sections.
d) Concrete filled rectangular hollow sections.
e) Concrete filled circular hollow sections.
f) Concrete filled circular hollow section incorporating an I section.

![Types of composite column sections](image)

**Fig.1 Types of composite column sections supported for design check.**

It may be noted that a rolled or welded structural steel section may be selected corresponding to sections (a), (b), (d), (e) and (f) whereas for section (c) as illustrated above, only a rolled section has to be selected.

Composite design checks can be carried out both for a linear combination as well as a non linear combination. The parameters involved in the check which are unique to linear / non-linear combination are discussed below:

**Linear combination:**

**Second order effects**

The applicability of the second order effects is checked in accordance to clause 5.2.1(3). If applicable, these are incorporated in accordance with clause 6.7.3.4(5). The equivalent moment factor \( \beta \) is calculated as per Table 6.4.
Member imperfection moments

The imperfection is the lateral departure at the mid-height of the column of its axis of symmetry from the line joining the centres of symmetry at the ends of the column. The curved shape assumed in the calculation model is that of a circular arc. The influence of geometrical and structural imperfections is accounted through the equivalent member imperfections as per Table 6.5. The same process is followed about both the principal axes.

Modified moment

The moments obtained following static linear analysis are modified based on the second order moments and imperfection moments calculated as stated above.

Non linear combination

Second order effects

Second order effects are not accounted for; if analysis is carried out for a non-linear combination.

Member imperfections

If the non-linear functionality is selected; then an option is available to consider / not consider the imperfections.

If the non-linear analysis is carried out without considering the imperfections in the analysis then these imperfections are accounted for in the design check in accordance with Table 6.5; else if the non-linear analysis is carried out considering the imperfections then these imperfections do not form a part of the design check.

Modified moment

The moments obtained following the non-linear analysis are modified by adding the imperfection moments if the same are not incorporated in the analysis.

Axial check

It must be noted that in case of axial check for non linear combination; no separate buckling check is carried out. That is; axial resistance is taken as the plastic moment of resistance of the composite section (obtained as described in section 4.1.1 below) and the corresponding utilization is defined as the ratio of axial force at the section to the plastic resistance to compression.

Note: All clause numbers stated in this section refer to EN 1994-1-1:2004 unless otherwise specified

The design checks for composite column sections are based on the simplified method of design which is applicable to prismatic column sections with doubly symmetric sections. Further, limits of applicability of this method are described in clause 6.7.3.1. The design checks carried out are briefly discussed below:
Resistance of members in axial compression

Following computations are carried out in order to determine resistance of the column member in axial compression:

Plastic resistance to compression of the composite section

1. Plastic resistance of an encased steel section or a concrete filled hollow square/rectangular section is calculated as per clause 6.7.3.2; equation 6.30.
2. For concrete filled circular hollow sections the increase in resistance of concrete due to the confining effect of the circular hollow section is accounted as per clause 6.7.3.2; equations 6.32 through 6.37.

Elastic critical normal force

Composite Columns may fail in buckling and one of the important parameters in the design of composite columns is the computation of the elastic critical normal force $N_{cr}$ which is calculated with the effective stiffness computed as described below.

Effective flexural stiffness

Effective flexural stiffness of a cross section is calculated as per clause 6.7.3.3 (3); equation 6.40

Influence of long-term effects

In order to account for the influence of long term effects on the effective elastic flexural stiffness the modulus of elasticity of concrete $E_{cm}$ is reduced to a value $E_{c,eff}$ as stipulated in clause 6.7.3.3(4); equation 6.41

It may be noted that; the ratio of the permanent load to the total normal force is obtained as input from the user as part of the set up data.

European Buckling Curves: Background

An idealised buckling curve may be represented as indicated below:

![Figure 2: Effect of slenderness on plastic resistance to axial compression](image)

In the figure the horizontal line represents $N_{pl}$ the plastic resistance to compression of the composite section while the curve represents $N_{cr}$ which is a function of the column slenderness. These are the boundaries of the compressive resistance of the column. In the figure below the buckling resistance of the column may be expressed as a function of the plastic resistance to compression $N_{pl}$ thereby non-dimensionalising the vertical axis. Similarly, the horizontal axis may be non-dimensionalised as indicated in the figure 3:
By incorporating the effect of residual stresses and geometric imperfections the European Buckling curves may be drawn as indicated in the figure below:

![Buckling curves](image)

**Figure 3: Effect of slenderness (Non- dimensionalised)**

Non dimensional slenderness
The non-dimensional slenderness is computed as per clause 6.7.3.3 (2); equation 6.39

Buckling resistance to compression
Once, the non-dimensional slenderness is established the buckling resistance to compression is evaluated. In accordance to clause 6.7.3.5 equation 6.44; the buckling resistance is obtained by multiplying the plastic resistance to compression with the reduction factor for the relevant buckling as given in EN 1993-1-1; clause 6.3.1.2. The buckling curves used are as per to Table 6.5

Utilisation ratio for the resistance in axial compression

The utilization ratio for the resistance in axial compression is calculated as the ratio of the axial force at the section to the buckling resistance or the ratio of the axial force at the section to the plastic resistance to compression, depending on the method of analysis as described in section-3.
Combined compression and uniaxial bending

Interaction curve:

In accordance with clause 6.7.3.6 the resistance of a member to combined compression and uniaxial bending is evaluated by means of an interaction curve. The Interaction curve for a composite section is evaluated by taking several positions of the neutral axis and computing the moment of resistance and axial force carrying capacity corresponding to each level of neutral axis.

Salient points on the interaction curve:

The salient points on the interaction curve are illustrated and explained below:

Note, in the diagram below, axis “N” denotes the axial resistance and axis “M” denotes the moment of resistance.

![Diagram of interaction curve](image)

**Figure 5: Typical interaction curve**

i. **Point A** marks the plastic resistance to compression of the cross section

   At point A:
   
   \[N_a = N_{pl,Rd}\]
   \[M_a = 0\]

ii. **Point B** represents the plastic moment of resistance of the cross-section.

   At point B:
   
   \[N_b = 0\]
   \[M_b = M_{pl,Rd}\]

iii. At **point C** the compressive resistance and the moment of resistance of the column are given by:

   \[N_c = N_{pm,Rd}\]
   \[M_c = M_{pl,Rd}\]
The compression area of the concrete at point B is equal to the tension area of the concrete at point C. The moment of resistance at point B is equal to the moment of resistance at point C.

iv. At point D the neutral axis coincides with the centroid of the cross-section and the resulting force is half that of point C.

**Stress distribution corresponding to the salient points**

The stress distribution corresponding to points A, B, C and D above is illustrated in the figure below.

![Stress Distribution](image)

**Figure 6: Stress Distribution for the salient points on the Interaction Curve.**

**Utilisation ratio**

The ratio of the bending moment at the section *(modified as stated in section 3.1.3 above)* to the plastic bending resistance is evaluated taking into account the normal force. The plastic bending resistance taking into account the normal force is calculated from the interaction curve by suitably interpolating between two successive points. This ratio in turn is divided by the factor \( \alpha_m \) which in accordance with clause 6.7.3.6(1) is 0.9 for steel grades S 235 and S355 and 0.8 for steel grades S 420 and S 460. The above check is carried out about both the principal axes.

**Combined compression and biaxial bending**

The resistance of the section under combined compression and biaxial bending is evaluated according to clause 6.7.3.7 equation 6.47. The bending moment at the section is modified as stated in section 4.1.3 below. The bending resistance about each principal axis taking into account the normal force is evaluated through the interaction curve as stated above.
Utilisation ratio:

The utilization ratio in this case is taken in accordance to clause 6.7.3.7 (2); equation 6.47.

Influence of transverse shear on resistance to bending

The influence of transverse shear forces on the resistance to bending and normal force is considered when determining the interaction curve as per clause 6.7.3.2(3)
The distribution of the shear force on the structural steel section and the reinforced concrete section is considered in accordance with clause 6.7.3.2(4); equation 6.31
The design shear resistance of the structural steel section is taken in accordance to clause 6.2.2.2 which in turn refers to EN 1993-1-1; clause 6.2.6

Shear resistance

Longitudinal shear at the interface between concrete and steel is verified in accordance with clause 6.7.4.3. Clause 6.7.4.3(2) permits the use of elastic analysis and the calculation model is taken in accordance to the example provided given in the Designers Guide to EN 1994-1-1 (Example 6.11; page 118).

Utilisation ratio:

Utilisation ratio is expressed as the ratio of the shear force at the section to the resistance calculated in accordance to the clauses mentioned above. The check is carried out about both the principal axes.
Design checks: Fire exposure

Note: All clauses, tables mentioned in this section refer to EN 1994-1-2:2005 unless otherwise specified.

Following are the calculation models used to check the resistance of a column in a fire situation:

- **Fully concrete encased sections**: Check in accordance to with the Tabulated data in Table 4.4
- **Partially concrete encased sections**: Balanced summation model as described in Annex G.
- **Concrete filled circular hollow sections and concrete filled rectangular (or square) hollow sections**: Generalised design method as described in clause 4.3.5.1 as well as the alternative design method described in Annex-H

**Fully concrete encased sections**

In case of fully concrete encased sections the dimensions viz. width of concrete encased, depth of concrete encased, cover to the structural steel and axis distance of the reinforcing bars are checked against the minimum dimensions as stated in Table 4.4.

The utilisation is expressed as the ratio of minimum dimension to the dimension provided.

**Partially concrete encased section: Balanced summation model described in Annex G**

This calculation model is meant for the computation of the fire resistance of composite columns with partially encased steel sections, for bending around the weaker axis (z axis), exposed to fire all around the column according to the standard temperature time curve.

As per this method, for calculating the plastic resistance to axial compression under fire situation \([N_{fiiplRd}]\) and the effective flexural stiffness in the fire situation, the cross section is divided into 4 components:

- flanges of the steel profile
- web of the steel profile
- concrete contained by the steel profile
- Reinforcing bars.

Each component is evaluated on the basis of a reduced characteristic strength, reduced modulus of elasticity and reduced effective flexural stiffness of the cross section

The reduced strength, reduced modulus of elasticity and effective flexural stiffness depend on the period of fire exposure i.e. R30, R60, R90, R120

Having computed the reduced stiffness, the elastic critical normal force is evaluated as described in section 3.1.2 and the non-dimensional slenderness and the buckling resistance are evaluated as described in sections 4.1.6 and 4.1.7 respectively.

Utilisation ratio:
The utilisation ratio is expressed as the ratio of axial force at the section to the buckling resistance as evaluated above.

Note: It may be noted that the code does not describe any check with regard to the combined axial plus uniaxial bending, combined axial plus biaxial bending and shear check in the balanced summation model.

Concrete filled circular hollow / concrete filled rectangular (or square) hollow sections: Generalised design method

To compute the axial resistance of the section using this approach; first and foremost the composite cross section is divided into various parts/layers, i.e. the structural steel may be divided into “j” layers, reinforcing steel into “k” layers and concrete into “m” layers.

For each layer the following properties are evaluated which are required to calculate the resistances:

- Layer dimensions
- Area of the layer
- Second moment of area of the layer about major axis
- Second moment of area of the layer about minor axis.
- Layer temperature
- Reduced strength of the material of the layer
- Reduced elastic modulus of the material of the layer.

Temperature distribution in the composite section:

For simplicity, the approximate method of Lawson and Newman is used. The steel shell is treated as one layer of uniform temperature. To account for the steep temperature gradient at the outer layers of the concrete core, each of the layers of concrete is taken to be of 10 mm thickness. Assuming an ambient temperature of 20º C, the approximate method of Lawson and Newman gives the temperature in every layer.

Composite cross-section properties

At elevated temperatures; the reduced effective yield strength and modulus of elasticity of steel, the reduced design strength and secant modulus of concrete are obtained from Table 3.2 and the reduced factor for concrete strength and the reduced factor for maximum strain in concrete are taken in accordance with Table 3.3.

Having computed the geometric and material properties in each of the layers we sum up the axial resistances of various layers of concrete, structural steel and reinforcing. For computing the flexural stiffness' the products of reduced elastic modulus and the second moment of area about the relevant axis are summed up.

The relative slenderness and the buckling resistance are computed as stated above in sections 4.1.6 and 4.1.7 respectively.
Concrete filled circular hollow / concrete filled rectangular (or square) hollow sections: Annex H method

Even for computing the axial resistance of the section using the Annex H method the section is divided into layers of concrete, structural steel and reinforcing steel. When using the Annex-H method a step by step approach is followed, with the strain in the column increasing until the design compressive resistance of the axial loading is obtained. At each step the plastic resistance and the Euler buckling load are evaluated. The plastic resistance of the column is calculated differently from that in the general calculation method. It is calculated as the sum of the area of each component of the column times its stress. Here the stress is taken from the stress-strain material property at the column strain of the current of the current step. Therefore as the strain increases, the plastic resistance of the column increases. Also, the tangent modulus of concrete decreases with increasing strain, hence the Euler buckling load too decreases with increasing strain. When the two resistances, that is, the Euler buckling resistance and the plastic resistance of the column are equal, it denotes the design compressive strength of the composite column section.

Limitations of fire check:

Fire check cannot be carried out for composite sections type c and f in Figure 1 (Partially concrete encased with crossed I and Concrete filled circular hollow sections incorporating an I section) because determination of temperature distribution within these sections required a 2-D transient thermal analysis and the facility was not available during the development of this module. Nevertheless, the same will be incorporated in the consequent release(s) of SCIA Engineer.
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