Structural modelling for analysis: Section 7 in BS EN 1993-1-1:2022

The updated version of EN 1993-1-1, BS EN 1993-1-1:2022, has been finalized and is being considered by the team draughting the UK National Annex. Adoption of an updated version of BS EN 1993-1-1 is likely to be in 2028. According to a paper by Marcus Knobloch *et al* [1], Section 5 of EN 1993-1-1 led to many questions and misunderstandings attributed to the different understanding of engineers in different countries, often due to different traditional approaches. The corresponding section in BS EN 1993-1-1:2022 has been completely restructured and rewritten as a result. The section is also renumbered. Richard Henderson of the SCI considers some of the changes.

Introduction

Effect of joints

Section 7 of the code addresses structural analysis and begins by discussing joint modelling in para. 7.1.2. This paragraph indicates that the effects of joint behaviour only need to be taken into account in the analysis where they significantly affect the distribution of internal forces and moments in the structure. The assumption of simple (pinned) and continuous (rigid) joints does not need any specific treatment in the analysis.

Consideration of second order effects

Second order effects are considered in para. 7.2.1. The code gives the same requirements as BS EN 1993-1-1:2005 and states that the effects of the deformed geometry should be considered if they increase the action effects or modify the structural behaviour significantly. Two conditions are provided which determine if second order analysis is required. The first (equation 7.1 in the code) indicates whether second order effects due to member buckling may be neglected in the global analysis. If:

$$\alpha_{cr,ns} = \frac{F_{cr,ns}}{F_d} \geq k_0$$

where the recommended value of k_0 is 25, second order effects due to in-plane or out-of-plane non-sway buckling (see Figure 1.1) may be neglected for the global analysis. $F_{cr,ns}$ is the minimum elastic critical flexural buckling load of the structure and F_d is the design load. (The value of k_0 is to be given in the National Annex).

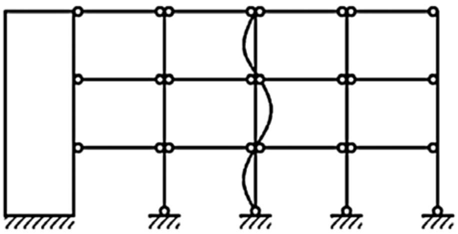

Figure 1.1: Non-Sway Buckling (Figure 7.1 BS EN 1993-1-1:2022)

This condition means that if the design load in the structure is less than 1/25 or 0.04 times the minimum elastic critical flexural buckling load, member buckling may be neglected. The non-dimensional slenderness $\bar{\lambda}$ falls on the buckling curve plateau if:

$\bar{\lambda} \leq 0.2$

so that the buckling reduction factor $\chi = 1.0$: see Figure 1.2

The condition in equation 7.1 can be demonstrated by considering buckling of an individual member as indicated:

$$(\bar{\lambda})^2 = \frac{Af_y}{N_{cr}} \geq 0.04$$

$$N_{ed} = Af_y \Rightarrow \frac{N_{cr}}{N_{ed}} \geq 25$$

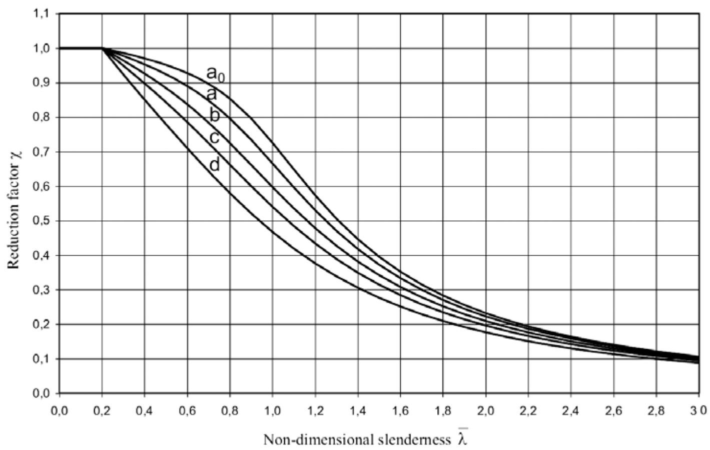

Figure 1.2: Buckling Curves

Where the condition is not met, splices in compressed members must be designed for the strut moment resulting from the member imperfection.

The second condition (equation 7.2 in the code) indicates whether second order effects due to global in-plane sway (see Figure 1.3) may be neglected in the global analysis.

$$\alpha_{cr,sw} = \frac{F_{cr,sw}}{F_d} \geq 10$$

This is the familiar condition from BS EN 1993-1-1:2005 para. 5.2.1 which indicates that second order effects due to sway may be ignored where the design vertical load on the structure is no more than 10% of the critical load for global buckling. The condition is aimed at ensuring that the increase in the internal forces and moments due to sway second order effects is no more than 10% of the internal forces and moments according to first order theory.

Consideration of lateral torsional buckling may be neglected only when the section is not susceptible to this behaviour. This applies to:

- most hollow sections;
- when bending is about one cross sectional axis but the second moment of area is larger in the other axis;
- when the member is sufficiently restrained that lateral torsional buckling cannot occur.

Para. 7.2.1(10)B indicates that $\alpha_{cr,sw}$ may be calculated for a storey using equation 7.3, provided the axial compression in the beams is not significant:

$$\alpha_{cr,sw} = \frac{K_{st}H_{st}}{\sum N_{ed,i}}; K_{st} = \frac{H_f}{\Delta_f}$$

K_{st} is the lateral rigidity of the storey of height H_{st} given by a horizontal force H_f applied at the top of the storey divided by the corresponding lateral displacement Δ_f. The denominator is the sum of the design axial forces of all the columns in the storey. The minimum value of $\alpha_{cr,sw}$ in any storey is adopted for ▸26

▸24 the whole building. The value of K_{st} must be determined from an analysis model where equivalent fictitious loads are applied to every storey in the structure, in proportion to the design vertical loads applied at that storey. Alternatively a buckling analysis of the whole structure may be carried out for a vertical load case where $\alpha_{cr,sw}$ is the eigenvalue for the first global lateral buckling mode for the structure.

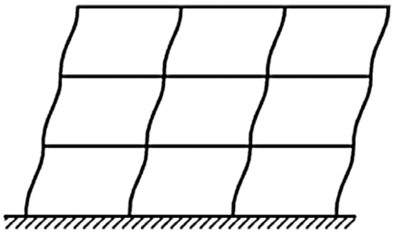

Figure 1.3: Figure 7.1 BS EN 1993-1-1:2022 Sway Buckling

Methods of analysis for ultimate limit state checks

Para. 7.2.2 identifies three approaches to dealing with second order effects:

- entirely in the global analysis;
- partially in the global analysis and partially by verification of the buckling resistance of individual members;
- by verification of the buckling resistance of "Equivalent Members" using appropriate buckling lengths in accordance with the global buckling modes of the structure.

Methods of analysis that may be used for ultimate limit state design checks are labelled M0, M1, M2, M3, M4, M5 and EM in order of increasing complexity. These methods are set out in Figure 7.3 of the code which gives a flow chart for determining the circumstances in which a given analysis method is suitable. For ease of understanding, the methods of analysis described should be considered with the analysis of rigid frames in mind, where the major axis bending of beams and columns provide the resistance to lateral loads on the frame. They are discussed in turn below.

Method M0

Details are given in para. 7.2.2(4). Method M0 applies if equations 7.1 and 7.2 are satisfied i.e.

- Compression members are not susceptible to flexural buckling;
- Second order effects due to sway can be ignored because the structure is laterally stiff;
- In addition, members are not prone to lateral-torsional buckling.

Imperfections do not need to be included in the global analysis and a cross-section check is sufficient. Excluding imperfections from the global analysis means that no equivalent horizontal forces (EHFs) need to be applied.

The elements in structures satisfying these criteria are stocky, making the structures extraordinarily stiff and strong. Such structures would only be adopted in very particular circumstances.

Method M1

Details are given in para.7.2.2(5). Method M1 is similar to M0 except that members are prone to lateral-torsional buckling because of their shape, orientation, degree of restraint or slenderness (see para. 7.2.1(6)). No global imperfection is considered because of the strength and stiffness of the structure. A cross section check based on first order internal forces and moments is sufficient. Verification of the lateral-torsional buckling resistance of beam members is required, based on first order internal forces and moments. Note that no reduction of member resistance due to flexural buckling is applicable because equation 7.1 is satisfied.

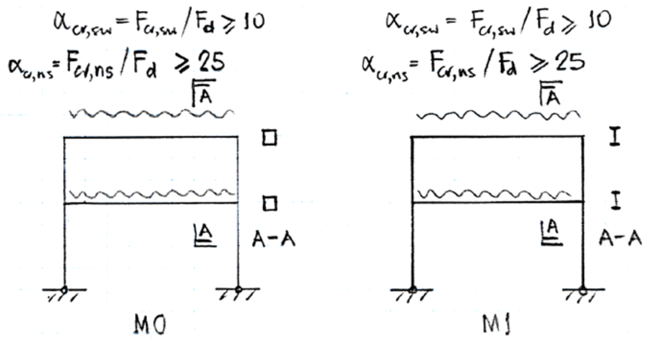

Figure 2.1: Methods M0 and M1

Method M2

Details are given in para. 7.2.2(6). In this case, equation 7.1 is not satisfied and the non-dimensional slenderness of compression members does not lie on the buckling curve plateau. The resistance of members to in-plane and out-of-plane flexural buckling must therefore be verified. Equation 7.2 is satisfied so global second order effects do not result in significant increases in internal forces and moments. However, global imperfections are considered so global EHFs are applied to allow for an out-of-plumb structure.

Cross section checks are based on first order internal forces and moments. In-plane and out-of-plane buckling checks are required based on first order internal forces and moments, considering appropriate buckling lengths for the non-sway mode (effective length factors of 1.0 or less) and corresponding bending moments.

Method M3

Details are given in para. 7.2.2(7)a). In this case, neither equation 7.1 nor equation 7.2 is satisfied. Global imperfections are included in the analysis.

Member imperfections may be neglected in the global analysis where the axial load in compressed members that contribute to the sway stiffness of the structure is less than one quarter of the critical buckling load about the major axis. Internal forces and moments should be determined from a second order global analysis. (An approximate method is to use factor k_{amp} to amplify first-order values). Cross section checks are carried out using the partial factor γ_{M1} instead of γ_{M0}, contrary to section 8.2. In-plane and out-of-plane flexural buckling checks are carried out using internal forces and moments from the second order global analysis. The checks are carried out considering appropriate buckling lengths for the non-sway mode (effective length factors of 1.0 or less).

Columns and beams are designed conventionally and member imperfections are allowed for in the buckling checks – section 8.3 in the code.

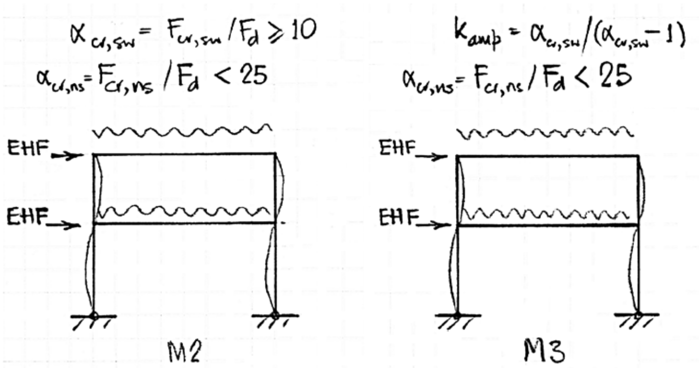

Figure 2.2: Methods M2 and M3

Method M4

Details are given in para. 7.2.2(7)b). As for method M3, neither equation 7.1 nor equation 7.2 is satisfied. Internal forces and moments are determined from a second order global analysis. The effect of member imperfections in compressed members is to reduce the stiffness of the frame and further increase the internal load effects. All in-plane second order effects (including the effects of residual stresses are allowed for in the global analysis and therefore the in-plane member buckling checks may be omitted. Members are subject to a cross-section check using the partial factor γ_{M1}. Out-of-plane buckling checks are carried out using the usual method.

Method M5

Details are given in para.7.2.2(8). In method M5, neither equation 7.1 nor 7.2 is satisfied. Global and member second order effects are included in the global analysis for both in-plane and out-of-plane effects, including torsional effects.

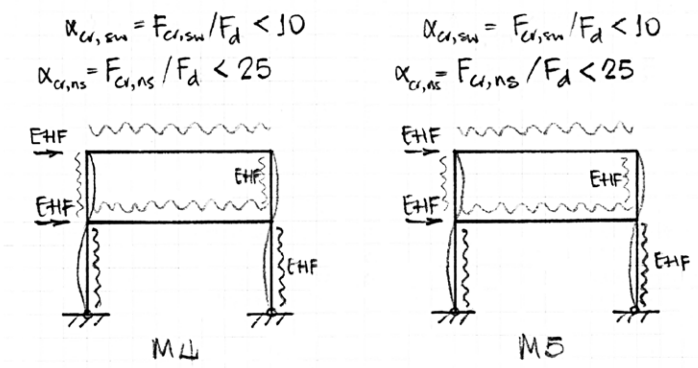

Figure 2.3: Methods M4 and M5

As the global analysis allows for all second order effects in the behaviour of members, verification of the buckling resistance of members is not necessary and a cross section check using the partial factor γ_{M1} should be applied.

Method EM

Details are given in para. 7.2.2(9). In method EM, either equation 7.1 or equation 7.2 is not satisfied or both are not satisfied. Imperfections do not need to be included in the global analysis. The Equivalent Member method includes verification of the cross-sectional resistance based on first order internal forces and moments. The effective length of each individual member for buckling checks is determined using the stiffnesses of the members coincident at the joints of the member being considered. Second order effects are neglected in this method and the implications of doing so must be considered. For accuracy, they should be included and this renders use of this method inappropriate.

Conclusion

Many different structural analysis packages are available and they deal with second order effects in different ways. The structural engineer must be aware of the capability of the analysis package used for a particular project so that the analysis results can be applied appropriately and the necessary member design checks can be carried out. It is expected that methods M2 and M3 will be most commonly used for building structures. ■

References

1. Marcus Knobloch et al, *Structural member stability verification in the new Part 1-1 of the second generation of Eurocode 3 - Part 1: Evolution of Eurocodes, background to partial factors, cross-section classification and structural analysis*, Steel Construction 13(2), May 2020