

Design of steel portal frame buildings to Eurocode 3

Dr Richard Henderson examines SCI's publication P399 on portal frame design.

In 2012, SCI published P397: Elastic design of single-span portal frame buildings. The summary included a statement to the effect that the determination of the flexural buckling length in the major axis was a key uncertainty in the application of expression 6.61 of BS EN 1993-1-1. This equation deals with the justification of members subject to combined bending and axial load when considering major axis buckling.

As interim advice, P397 recommended that for **in-plane stability**, when considering the column, the system length when applying 6.61 should be the actual length of the column. For the rafter, the system length should be the developed length from eaves to apex (ie the true length of the rafter).

In plane, the **portal frame** is continuous and it is economical to choose different sections in different parts of the frame, corresponding to the bending moments in the elements. However, the positional or directional restraints at the ends of members are not easily determined and the sections are continually varying in some places (haunches) or much less frequently where production processes allow fabricated elements to be manufactured (eg tapered columns). The effective length of the members is in fact not clear.

Second-order analysis is a means of getting round this difficulty and this approach is described in P399. Clause 5.2.2(7) of BS EN 1993-1-1 states that "if **second order effects** in individual members and relevant member imperfections are totally accounted for in the global analysis of the structure, no individual stability check for the members ... is necessary." If the frame is considered as a whole, an overall analysis which takes into account frame imperfections, $P-\Delta$ effects (increased actions due to frame deflections), $P-\delta$ effects (increased actions due to deflections in the members) and member imperfections, requires

only a cross-section check to ensure the members are adequate to resist the actions determined.

$P-\Delta$ effects increase the bending moments in the frame because the axial loads in the columns act at an eccentricity to the column centreline at the foundations due to the sway under lateral loads or spread of the frame under symmetrical loading. $P-\delta$ effects increase the bending moments in members carrying axial loads because the bending moments equal to the axial load times the deflection in the span of the member (due to the lateral loads) result in moments which are additional to those due to the lateral loads.

Frame imperfections are allowed for by applying equivalent horizontal forces (EHF) as set out in clause 5.3.2 of BS EN 1993-1-1. $P-\Delta$ and $P-\delta$ effects are taken into account by using analysis software which calculates the effects of deformations directly. For certain types of frame, this can be done by taking the results of a first order analysis and amplifying the results to allow for the second order effects. This approach follows that described by Lim et al^[1]. The deflections are illustrated in Figure 1.

Research involving an extensive programme of finite element analysis has been carried out by the SCI. A wide range of portal frames was examined using second order analysis with member imperfections in senses the same as and opposite to the member deflections. The work showed that member imperfections in plane only affect α_{cr} (the factor by which the design loading would have to be increased to cause elastic instability in a global mode) by 0.3%. Member imperfections can therefore be ignored. This work confirms UK practice embodied in BS 5950.

When considering the stability of members out of plane, the end conditions are in general well defined because in portal frame structures, the direction perpendicular to the span of the portal frame is often **braced** with diagonal bracing in the plane of the walls of the building, from column foot to eaves. Together with an eaves beam, this arrangement provides lateral support at the eaves of the building to each portal frame. Purlins and sheeting rails provide points of intermediate lateral restraint to the outside flanges of rafters and columns respectively. P397 only dealt with **elastic design**. Plastic design of portal frames is covered in BS EN 1993-1-1 thanks to strenuous efforts from the UK representatives when the **Eurocode** was being drafted. **Plastic design** is regularly carried out in the UK. It is a strength design method which involves the formation of plastic hinges at points of maximum bending moment and the occurrence of plastic rotation at constant load (assuming the plastic hinge is adequately restrained out of plane). This redistributes load to other parts of the frame, thus making more efficient use of it. The presence of plastic hinges in members naturally entails the highest possible bending moments for the section and steep

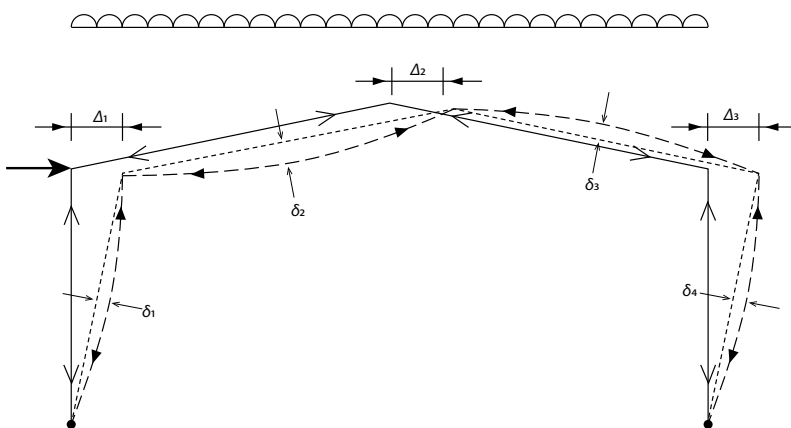


Figure 1 Sway-mode deflections under EHF and vertical loads

bending moment gradients. Effective restraint of members out of plane is fundamental to allow these moments to be carried and rotations to occur without causing lateral instability. The design approach is essentially determining the disposition of lateral restraints to prevent lateral instability from occurring. P399 is intended to provide guidance to allow the development of design software based on the current code.

The code approach to the justification of the members next to plastic hinges is to determine the stable length L_s of the segment. This is the longest length for which buckling does not occur out of plane, assuming the bending moment varies from the plastic moment to a lower value at the other end of the segment. A torsional restraint is provided at this point. Intermediate restraints are also required. The elements may be of varying section as haunches are commonly provided to carry the very large bending moments which occur at the connection of the portal frame rafters to the columns. The **out of plane stability** of these segments of members entails the determination of the buckling resistance moment of non-prismatic elements and the interaction of bending and axial load.

Work carried out in the UK by Horne and others in the late 1960s and early 1970s^[2] showed how sheeting rails connected to the outside flange of columns enhanced the load carrying capacity of the column by altering its buckling mode from **flexural buckling** to torsional buckling. The use of tension flange restraint in this way has been a common approach in portal frame design in the UK for many years.

Design checks of member segments with varying section properties along their lengths and subject to varying bending moments between points of **torsional restraint** have been put forward in examples in P399. Where a segment is subject to tension flange restraint and is tapering, there is no guidance in BS EN 1993-1-1 as to what design approach can be adopted. An approach is put forward in P399 based on UK practice which involves satisfying an interaction equation at points along the member.

Between points of **lateral restraint**, a segment of a member may also be subject to bending and axial load and may also be

tapering. There is no guidance in BS EN 1993-1-1 for a check of **lateral-torsional buckling** in this circumstance and an approach to the elastic check of this arrangement is also put forward.

3-D structural analysis software packages are widely available and can be used to design portal frame buildings. The whole building can be **modelled** using this type of software and this is common in current practice to allow BIM to be exploited. Specialist 2-D portal frame design software is also widely used based on BS 5950 code requirements. It is anticipated that 2-D software will now be updated to follow BS EN 1993-1-1 requirements.

Hit and miss frames are a common arrangement in multi-bay portal frame buildings where internal columns in alternate frames are omitted to increase the utility of the enclosed volume (Figure 2). This arrangement results in adjacent frames of different lateral stiffness and the need to provide bracing to transfer load between adjacent frames to even out the lateral deflection. A step by step procedure for achieving this has been put forward for use where hit and miss frames are designed separately, each in 2-D. This process is unnecessary when modelling the whole building because bracing loads are determined as a matter of course.

It is hoped that SCI publication P399 will assist designers in understanding the behaviour of portal frames and will also provide a means of checking the results of 2-D and 3-D analyses.

SCI Publication P399 is freely available to SCI and BCSA members on www.steelconstruction.info, or may be purchased from the SCI Shop at <http://shop.steel-sci.com>

References

- [1] Lim, J B P; King, C M; Rathbone, A J; Davies, J M and Edmondson, V. Eurocode 3 and the in-plane stability of portal frames. *The Structural Engineer*, Vol. 83 No. 21, November 2005
- [2] Horne, M R and Ajmani, J L. Stability of columns supported laterally by side-rails. *Int. J. Mech. Sci.*, Vol. 11, Issue 2, pp159-174,



Figure 2
Hit and miss frames