In-plane stability of portal frames

David Brown of the Steel Construction Institute offers a reminder of the guidance covering in-plane stability of this very common form of construction. Judging by recent questions received by the SCI, the topic is not as clearly understood as it should be!

The problem(s) identified

In March and April of 2020, to offer some light relief during COVID-19 lockdown, the SCI ran a number of free webinars covering the analysis, member verification and detailing of portal frames. The webinars were significantly over-subscribed, and were repeated four times. Two topics gave rise to the most questions – in-plane stability and restraints to the inside flange. Many delegates wanted to know what in-plane effective length should be used when verifying members – particularly the column. Others wanted to apply Annex E of BS 5950 to determine an in-plane effective length. There was no problem with out-of-plane lengths – no-one questioned that out-of-plane, members should be verified between restrained positions.

Perhaps the problem is highlighted if designers are using general elastic analysis software to determine the design forces and moments around the frame and then to verify the members within it. Such software expects to complete both in-plane checks and out-of-plane checks, which naturally demands an in-plane buckling length. Portal frames are a special case, with particular rules discussed in this article.

What does BS 5950 say?

Before opening the Eurocode, it is valuable to look at the particular rules for portal frames given in BS 5950. The UK would claim to have developed most of the rules for portal frame design, backed up by many decades of successful application, so one might expect definitive guidance in our previous standard.

Portal frames are one example of a continuous frame, and may be designed elastically or plastically, so we need to look carefully at the relevant clauses.

Within the "Continuous structures" section, clause 5.2.3.1 discusses plastic analysis. The second paragraph should be sufficient to clarify the in-plane verifications needed:

The in-plane stability of the members in a continuous frame designed using plastic analysis should be established by checking the in-plane stability of the frame itself, see 5.5.4.

Designers should note that according to this clause in-plane checks of individual members are not required.

Portal frames are addressed in section 5.5. Clause 5.5.2 covers elastic design:

If elastic global analysis is used for a portal frame, the cross-section capacity should be checked… and the out-of-plane buckling resistance should be checked….

For portal frames with no in-plane bracing…*the in-plane stability of the frame should be verified by checking the cross-section capacity and the out-of-plane buckling resistance of the members* (amplified if necessary)

Plastic design is covered in clause 5.5.3:

> *Plastic global analysis may be used for a portal frame provided that the conditions in 5.2.3 are satisfied* (which is a reference back to the clause previously quoted).

Checking the in-plane buckling of individual members in a portal frame is inappropriate – the frame buckles as a single entity, and therefore the standard demands that stability is verified by checking "the in-plane stability of the frame itself".

Multi-span frames

One potential exception to the preceding general rule is an internal column in a multi-span frame (Figure 1). In the so-called gravity combination, the bending moment in the internal column may be very small. The in-plane buckling of this member should be checked. P292 recommends an effective length factor of 1.0 for truly pinned bases, 0.85 for nominally pinned bases and 0.7 for nominally fixed bases.

Internal columns probably have no restraint at any level below the haunch. If the internal column is orientated in the orthodox direction (major axis in the plane of the frame) then the minor axis resistance will of course be critical, not the in-plane buckling. If the internal column was turned 90°, such that its weak axis was in the plane of the frame (Figure 2), or if the internal column was a fabricated section with a larger inertia out of the plane of the frame, then in-plane buckling could be critical, but it seems most unlikely.

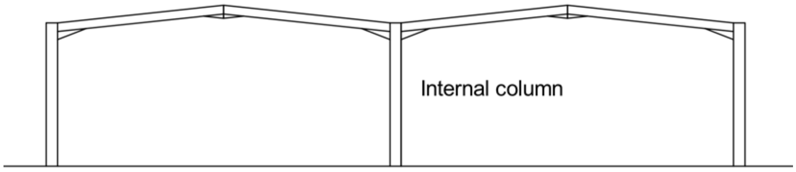

Figure 1; Multi-span portal with internal column

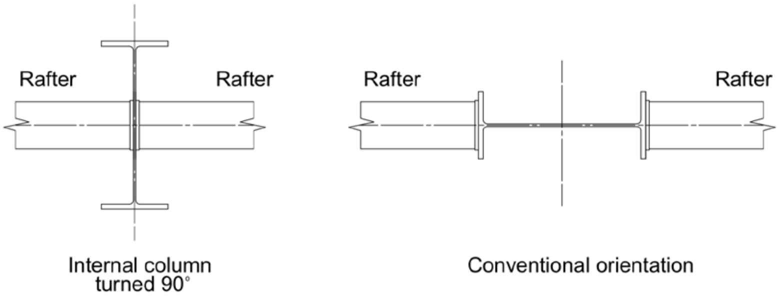

Figure 2; Orientation of internal column

In-plane buckling of the frame

According to BS 5950, in-plane stability of portal frames can be verified by three methods:

1. The sway-check method – commonly known as the *h*/1000 check, with a limited scope (and a snap-through check for multi-span frames);
2. The amplified moments method, requiring the determination of λ_{cr} and an amplifier if necessary. No amplifier is required if $\lambda_{cr} > 10$;
3. Second-order analysis.

In each method, the impact of second-order effects is considered. Satisfying the sway-check method means that second-order effects are small enough to be ignored. The amplified moments method allows for second-order effects with an amplifier unless the effects are small enough to be ignored. Second-order analysis will always allow for those effects.

Member checks in BS 5950

Having completed the in-plane buckling checks of the frame in its entirety and allowing for second-order effects if necessary, the cross section has to be checked and then out-of-plane checks completed. BS 5950 has a range of clauses covering different conditions – next to plastic hinges, with intermediate restraints to the tension flange only, tapered sections etc.

Why not Annex E?

The introduction to the Annex seems to offer opportunities for use, describing "the effective length L_E for in-plane buckling of a column or other compression member in a continuous structure with moment resisting joints should be determined using the methods given in this annex." That sounds appropriate for portals, but as one reads further, it becomes abundantly clear ▶28

▶27 that this annex is limited to columns in rectilinear multi-storey frames. The annex describes columns in multi-storey beam-and-column framed buildings with …. concrete or composite floor and roof slabs. Hardly the description of a portal frame!

Eurocode rules

One would not expect the fundamental physics to change simply because the Eurocode was introduced. On that basis alone, one should be confident that the same rules apply to orthodox portal frames – that in-plane, the stability of the entire frame as one unit is critical, followed by checks of the cross section and only out-of-plane buckling checks.

The key clause is 5.2.2(7)a in BS EN 1993-1-1:

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 according to 6.3 is necessary.

In-plane second order effects are allowed for by determining α_{cr} (directly equivalent to λ_{cr} in BS 5950), and using an amplifier in the global analysis if necessary. Frame imperfections are allowed for by always including the equivalent horizontal forces (EHF) in every combination. The only in-plane effects that are not included in the global analysis are the individual member imperfections, such as an initial lack of straightness. To consider the impact of in-plane member imperfections, colleagues at the SCI spent (very) many hours analysing a wide range of frames with and without in-plane member imperfections. Imperfections were modelled in both directions, in each member, to produce the most onerous effect. The study concluded that the value of α_{cr} changed less than 0.3%. Two conclusions can be made. Firstly that the effect of in-plane member imperfections on the stability of the frame is small enough to be ignored – or presented another way, we can say that all relevant in-plane effects have been allowed for in the global analysis. We therefore do not need an in-plane stability check of individual members. The second conclusion is that as expected, BS 5950 was correct – *"The in-plane stability of the members in a continuous frame …. should be established by checking the in-plane stability of the frame itself"*

The global analysis has not verified the out-of-plane resistance – members still must be verified between restraints, using section 6.3 of the Eurocode, aided perhaps by the guidance in Annex BB, which is simply the guidance from BS 5950 'translated' into Eurocode nomenclature.

Member verification in section 6.3 of BS EN 1993-1-1

If (and only if) the interaction factors in expressions 6.61 and 6.62 are taken from Annex B of the Eurocode (very strongly recommended by SCI), it can be concluded that expression 6.61 deals with in-plane effects and expression 6.62 deals with out-of-plane effects. Since we have concluded that no in-plane member checks are needed (other than the possible internal columns mentioned earlier), we can dispense with expression 6.61 altogether.

As there is no minor axis moment in a portal frame, expression 6.62 reduces to a rather simpler form:

$$\frac{N_{Ed}}{N_{b,z,Rd}} + k_{zy}\frac{M_{y,Ed}}{M_{b,Rd}}$$

The numerators are the design force and major axis moment. The denominators are the minor axis flexural resistance and the lateral torsional buckling resistance, which with some judicious interpolation can generally be obtained from look-up tables if required. In all cases, the lateral torsional buckling resistance depends on the shape of the bending moment diagram over the length being considered, reflected in the value of the factor C_1. Resources are readily available to determine the C_1 factor for different shapes of bending moment diagram. The interaction factor k_{zy} is painful to compute, but in portal frames is generally around 0.97 – there is not much loss in manual calculations if k_{zy} is assumed to be 1.0.

Conclusions

Portal frames are special in many ways, despite their frequent use in the UK. They are slender, have significant axial forces in the members, generally are sensitive to second-order effects, experience reversing bending moments and demand very careful restraints to otherwise unrestrained flanges. The objective of this article was to confirm one special design feature – that in-plane buckling is an concern for the frame as a whole, not for individual members.

1 King, C, M.
In-plane stability of portal frames to BS 5950-1-2000 (P292)
SCI, 2001