Proposed changes to assessment of frame stability

In this second article looking at the forthcoming revisions to EN 1993-1-1, David Brown of the SCI considers the proposed guidance on frame stability with some disappointment that the requirements can be easily misunderstood. Experienced designers will no doubt use the correct approach, but those looking at the standard for the first time could be misled.

Once, there was BS 449

Designers of a certain age might comment that the first time that assessment of frame stability was highlighted occurred with the introduction of BS 5950. That is not true – BS 449 required sway stability to be considered, but gave no advice on how this was to be carried out. Clause 10c of BS 449 required that all structures "shall be adequately strong and stiff to resist sway". There was no advice on what was considered to be adequately stiff.

In the same clause, BS 449 introduced notional horizontal forces to allow for "practical imperfections such as a lack of verticality", which were only applied in combination with vertical loads, and not when wind or other horizontal loads were applied.

Frame stability in BS 5950

With the introduction of BS 5950, the need for structures to have adequate stiffness against sway was highlighted, but in the early versions there was still little guidance on what assessment should be completed. In the 1990 version, clause 2.4.2.3 required that to ensure adequate stiffness against sway "a separate check should be carried out for notional horizontal loads". In the author's opinion, confusion was introduced by this rather loose requirement in the standard, which has remained ever since.

In BS 5950, the notional horizontal forces (NHF) are used to allow for imperfections such as a lack of verticality. They appear in the load combinations with only vertical loads but, according to BS 5950, not when real lateral loads are applied. The confusion arises because in later versions of the standard, the very same notional horizontal forces are used entirely independently as part of the assessment of frame stability. With the benefit of hindsight, perhaps having some entirely different forces used in the assessment of frame stability – also with a different name – might have demonstrated the difference.

With the issue of the 2000 version of BS 5950 further clarity was added. In clause 2.4.2.4 the NHF are described as allowing for imperfections such as a lack of verticality (one wonders why "out of plumb" was not used). Separately, in clause 2.4.2.5, the need for sway stiffness is described and that secondary forces and moments must be allowed for in design if they are significant. These secondary forces and moments are described as "second order" and "PΔ". This emphasis on "significance" is entirely correct – second order effects are always present, but may not be significant.

BS 5950 also included a measure of significance, λ_{cr}, which will be familiar to pre-Eurocode designers. The value of λ_{cr} is to be calculated for each storey in a structure, and is given by:

$$\lambda_{cr} = \left(\frac{h}{200\delta}\right)$$

where h is the storey height and δ is the horizontal displacement over the storey, due to the NHF (only) applied to the frame. BS 5950 clarifies that the deflection δ is due to "horizontal forces equal to 0.5% of the factored vertical dead, imposed and crane loads applied to the frame at each storey level". Thus differently loaded storeys would have different horizontal loads, in proportion to the factored vertical load on the storey.

The value of 200 appearing in the denominator is inextricably linked to the definition of the NHF being 0.5% (or 1/200) of the factored vertical loads applied at that level. As will be seen later, the measure of frame stability (or, the significance of second order effects) can be determined using any consistent set of forces and complementary expression for frame stability. Using a set of forces distinctly different from the NHF would perhaps have reduced the confusion referred to earlier.

One point to note is that the BS 5950 approach demanded a separate loadcase to be analysed, with only the NHF applied. This loadcase was only used to determine λ_{cr}

2005 and BS EN 1993-1-1 arrives

The Eurocodes were available for use from 2005 – it is not surprising that revisions are being developed over 15 years later. Within the Eurocode, "PΔ" effects become the "Effects of deformed geometry of the structure" in clause 5.2.1 and the measure of frame stability becomes α_{cr}.

The value of α_{cr} is again calculated for each storey and is given by:

$$\alpha_{cr} = \left(\frac{H_{Ed}}{V_{Ed}}\right)\left(\frac{h}{\delta_{H,Ed}}\right)$$

The value of H_{Ed} is the horizontal shear at the base of the storey and is equal to the summation of the horizontal loads applied to the structure above that level. In general, the horizontal loads are typically wind loads, plus the equivalent horizontal forces (EHF). Unlike BS 5950, the Eurocode requires that the EHF are always applied (unless the externally applied loads are very large).

The Eurocode defines $\delta_{H,Ed}$ as the relative displacement when the frame is "loaded with horizontal loads (e.g. wind) and *fictitious* horizontal loads which are applied at each level". Practice has assumed that these fictitious horizontal loads are the EHF elsewhere described in the standard. Use of the EHF is ideal, since they are based on a proportion of the factored vertical load applied at that level.

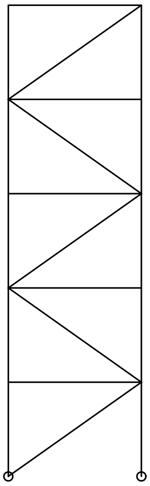
The EHF are based on the sway imperfection given in 5.3.2, which is 1/200 of the factored vertical loads, with optional fudge factors. Thus the value of H_{Ed} can be considered to be $\left(\frac{V_{Ed}}{200} + \text{wind}\right)$, which is quite the same as BS 5950 if one chooses to ignore the wind. Towards the base of an orthodox multi-storey building, the value of $\frac{V_{Ed}}{200}$ is large, and the contribution of the wind loads comparatively small.

Neglecting the relatively small influence of the wind, and neglecting the optional fudge factors in the determination of the EHF, the expression for α_{cr} becomes:

$$\alpha_{cr} = \left(\frac{V_{Ed}/200}{V_{Ed}}\right)\left(\frac{h}{\delta_{H,Ed}}\right) = \frac{h}{200\delta}$$, or the same as BS 5950.

The advantage of completing the analysis of the frame using the "actual" loads of H_{Ed} and V_{Ed} was said to be that designers would have that load combination modelled as a matter of course, and that an additional, separate loadcase with just the EHF was inconvenient. Of course, it does not matter what forces are being used in the current Eurocode (and hence the use of the word fictional) since under an elastic analysis, the lateral deflection is proportional to the applied lateral loads – the ratio $\frac{H_{Ed}}{\delta_{H,Ed}}$ is a constant.

An analysis of a simple bracing system demonstrating the equivalence of BS 5950 and EN 1993-1-1 is shown in Table 1 (over). In the example the braced bay has been extracted from the structure for simplicity (the rest of the structure is of "simple construction" and does not contribute to the lateral stability). ▸26



	Storey	Storey height (m)	Factored load on level (kN)	BS 5950 NHF (kN)	EN 1993 ΣH_{Ed} (kN)	EN 1993 ΣV_{Ed} (kN)	Lateral movement (mm)	δ (mm)	BS 5950 λ_{cr} $\frac{h}{200\delta}$	EN 1993 α_{cr} $\frac{H_{Ed}}{V_{Ed}}\frac{h}{\delta}$
Roof			3200	16			13.72			
	5	3.5						1.48	11.9	11.9
Floor			10200	51	16	3200	12.24			
	4	3.5						2.02	8.7	8.7
Floor			10200	51	67	13400	10.22			
	3	3.5						2.81	6.2	6.2
Floor			10200	51	118	23600	7.41			
	2	3.5						3.17	5.5	5.5
Floor			10200	51	169	33800	4.25			
	1	4						4.25	4.7	4.7
Ground					220	44000	0.00			

Table 1: Frame stability according to BS 5950 and BS EN 1993-1-1

▸25

Looking to the future

As has been noted in earlier articles, the draft of EN 1993-1-1 is mature – significant changes are not anticipated.

The proposed measure of frame stability is called $\alpha_{cr,sw}$ (the subscript "sw" indicates "sway") and is given by:

$$\alpha_{cr,sw} = \frac{K_{st}H_{st}}{\Sigma N_{Ed,i}}$$ (the subscripts "st" indicate "storey")

K_{st} is the lateral rigidity of the storey and is given by:

$$K_{st} = \frac{H_f}{\Delta_f}$$

where

H_f is a fictitious horizontal force applied at the top of the columns of the storey;

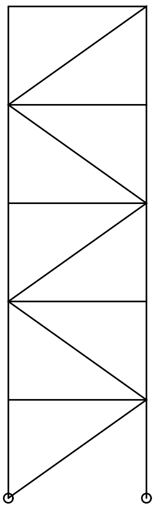
Δ_f is the horizontal displacement at the top of the storey due to H_f relative to the bottom of the storey;

$\Sigma N_{Ed,i}$ is the sum of axial forces within the columns under consideration;

H_{st} is the height of the storey.

For Eurocode designers, the formula for $\alpha_{cr,sw}$ looks like a simple rearrangement of the current expression for α_{cr}, but care must be taken when evaluating K_{st}. The draft seems to imply that the lateral rigidity of a multi-storey frame can assessed by considering each storey in isolation. Designers may be tempted to do just that and model single storeys, in isolation, with some arbitrary load applied at the top of the storey.

The correct deflections over a storey can only be determined from including the full height of the building in one analysis and calculating the differential deflections over the storey under consideration. Figure 5.1 of the current standard helpfully shows the assessment of one storey as part of a larger model – indicating that the entire stability system should be modelled, not storeys in isolation. In addition, the draft does not clarify that the fictitious load applied at the top of the columns at each storey must be consistent throughout the model. The fictitious load must be some fixed proportion of the factored vertical load applied at that level.



	Storey	Storey height (m)	Factored load on level (kN)	Fictitious force (2%)	Lateral movement (mm)	δ (mm)	$\alpha_{cr,sw}$ $\frac{H_{st}}{50\delta}$
Roof			3200	64	54.56		
	5	3.5				5.81	12.0
Floor			10200	204	48.74		
	4	3.5				8.02	8.7
Floor			10200	204	40.72		
	3	3.5				11.17	6.3
Floor			10200	204	29.55		
	2	3.5				12.61	5.6
Floor			10200	204	16.94		
	1	4				16.94	4.7
Ground					0.00		

Table 2: 2% fictitious lateral loads, and resulting values of $\alpha_{cr,sw}$

Although one might feel disappointment with the proposed rules, they are not significantly different to the current standard – which similarly does not clarify the need for the lateral loads to be a fixed proportion of the vertical loads. Previous practice with BS 5950 (and the general use of the EHF to determine frame stability) has probably meant designers "knew" what was required, rather than being left uncertain by the standard.

Recommended approach

Every storey should be modelled in one analysis, exactly as was done in BS 5950 and the current version of the Eurocode. The fictional lateral loads applied at each level should be the same proportion of the factored vertical load at that level. To avoid confusion with the NHF of BS 5950 and the EHF of the Eurocode, perhaps these fictitious loads, used only to establish the measure of frame stability, could be 2% of the factored vertical load at that level. The final calculation becomes a convenient expression:

$$\alpha_{cr,sw} = \frac{H_{st}}{50\delta}$$

This equation may look different to the Eurocode, but yields the same result, as demonstrated in Table 2. The deflections are of course larger, but the end result is the same – allowing for some loss of precision.

Conclusions

The proposed clause will hopefully go a long way to clarify the confusion between the use of notional/equivalent/fictitious horizontal forces to assess frame stability, and separately the use of notional/equivalent horizontal forces to allow for a lack of verticality. The wording of the clause could be improved, in particular to advise that the fictitious forces should be a fixed proportion of the loads applied at each level. Using a fixed absolute force at each level will yield the wrong result (unless the vertical loads at each level are identical), as will attempting to model single storeys in isolation. ■