Portal Frames with flexible joints

In the second of two technical articles considering the effect of allowing for joint flexibility in the analysis and design of portal frames, Richard Henderson of the SCI presents examples illustrating the effect of such joints on frame stability and structural actions.

Introduction

In the first article presented in the February edition of NSC, the theoretical development of equations similar to Kleinlogel's that allow for joint flexibility was illustrated. In the present article, example frames are considered and the variation with joint stiffness of eaves and apex bending moments, α_{cr} for the frame and eaves spread, are discussed.

Pitched portal frames

The analysis of two frames is presented to illustrate the effects of allowing for joint stiffness, one of which was taken from the example presented in SCI publication P397[1]. The characteristics of the frames examined are set out in Table 1 and features of the behaviour of the frames are discussed below. Frame I has columns and rafters formed of rolled UB sections and Frame II is made from pairs of cold-formed lipped channel sections back-to-back. Frame I is not fully representative of a conventional frame because the rafters are assumed to be uniform whereas for economy, rafters are usually haunched near the column joint.

Table 1: Frame characteristics

Item	Frame I	Frame II
Span L (m)	30.0	12.0
Eaves height h (m)	15.0	3.0
Rise r (m)	3.0	1.608
Column	914 × 305 UB 224	Pairs of lipped channels
Column I_{yy} (m^4)	3.76×10^{-3}	2.42×10^{-5}
Rafter	533 × 210 UB 101	Pairs of lipped channels
Rafter I_{yy} (m^4)	6.15×10^{-4}	2.42×10^{-5}
Uniform load (kN/m)	20.0	6.33

The frames have been analysed assuming fully rigid joints at the eaves and apex and with the base stiffnesses recommended by the SCI for different load cases:

- for frame stability, 10% of the column stiffness (i.e. 10% of $4EI/h$ Nm/radian);
- for serviceability, 20% of the column stiffness;
- for design actions, with fully pinned bases.

The results of the analysis of Frame I is shown in Table 2.

Table 2 Results for rigid joints at eaves and apex

Item	Units	Frame I
α_{cr}	-	7.11
Eaves spread	mm	124
Eaves moment	kNm	1332.1
Apex moment	kNm	-651.4
Column stiffness	MNm/radian	211
20% of column stiffness	MNm/radian	42.2

The frame has been analysed to show the effect on some of the parameters of varying the spring stiffness of the eaves joint while keeping the apex joint stiffness constant. The results have been normalized by varying the rotational stiffness of the joint from a value equal to 1% of the column stiffness to 100% for each frame. The apex joint stiffness has been fixed at 100 MNm/radian. Graphs showing the eaves moment and maximum sagging moment moments are presented in Figure 1. The bases have been assumed to be pinned for this case.

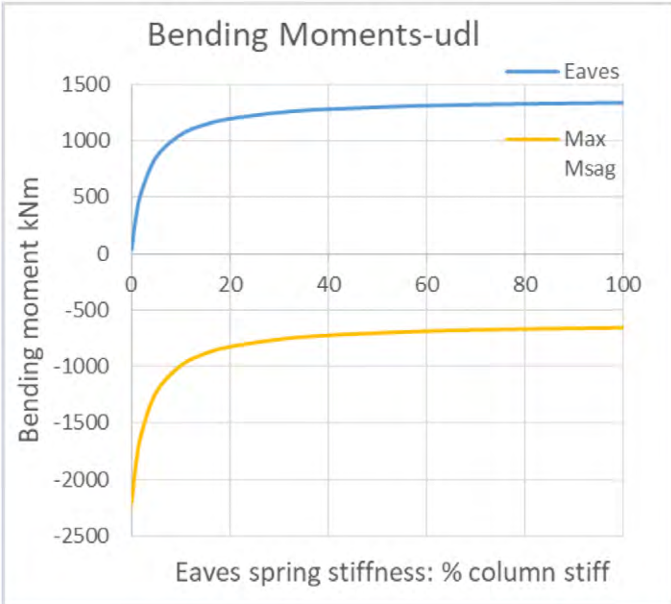

Figure 1 Eaves and maximum sagging moments: Frame I

It can be seen that the bending moments change rapidly over increases in eaves joint stiffness from 1% to 20% of the column stiffness. At 20% of the column stiffness, the eaves moment is 89% of the value at 100% and nearly 90% of the value when both joints are assumed to be rigid.

Figure 2 shows the value of α_{cr} plotted for the same range of eaves joint stiffness. A base stiffness equal to 10% of the column stiffness has been assumed in the analysis. The rafter axial force has been allowed for in calculating α_{cr} as described in Reference 1.

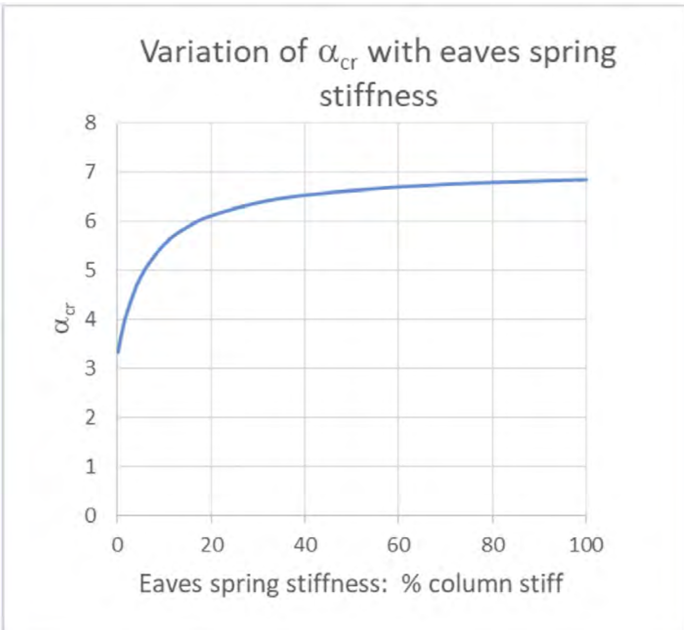

Figure 2 Elastic critical load factor: Frame I

▸26

▸24 The value of α_{cr} at 20% is 6.1 compared with values at 100% of 6.84 and for fully rigid eaves and apex joints, of 7.11. These values correspond to amplifiers of 1.2, 1.17 and 1.16 respectively.

Figure 3 shows the eaves spread for frame 1 for various eaves stiffnesses and exhibits similar characteristics to the other properties with much of the reduction in eaves spread occurring over the first 20% increase in eaves joint stiffness. The spread reduces to 146 mm for eaves joints with 100% of the column stiffness. The values presented are due to the same factored uniform load as for the other parameters, not an unfactored load corresponding to variable loads only.

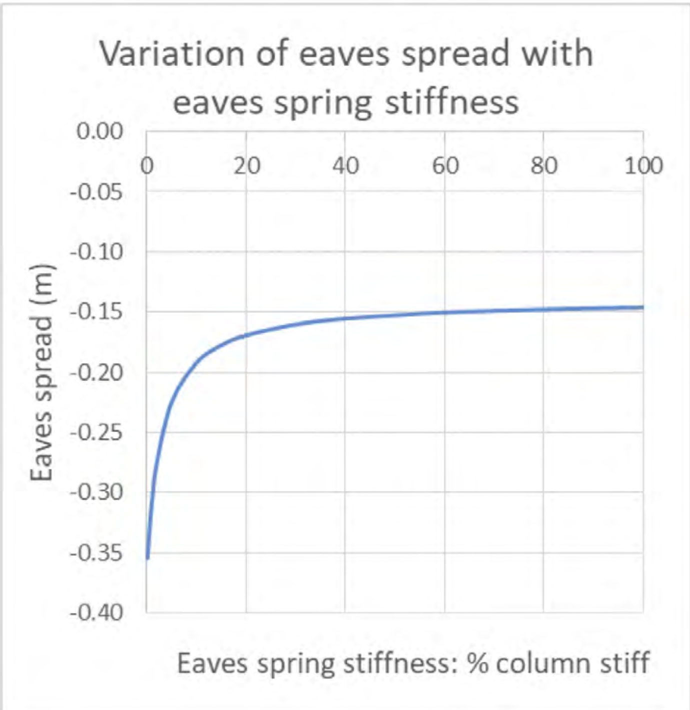

Figure 3 Eaves spread: Frame I

Constant eaves joint stiffness

A similar analysis was carried out keeping the eaves joint stiffness constant and varying the apex joint stiffness from zero to 100% of the column stiffness. This has little effect on the elastic critical load factor if determined (as here) by applying equal lateral loads to both eaves because the apex bending moment is zero. Adopting a spring stiffness at the base of 10% of the column stiffness, in accordance with SCI advice, results in α_{cr} increasing from 6.89 to 7.14. (With a pinned base to the column, the value varies from 3.54 to 3.65). The eaves and apex bending moments do vary with changes in the apex joint stiffness in the vertical load cases. The results are shown in Figure 4. The rafter moments in the vertical load case vary more slowly with changes in the apex joint stiffness than with changes in the eaves joint stiffness. The maximum sagging moment is equal to -542.6 kNm when the joint stiffness is 20% of the column stiffness. The corresponding maximum moment is

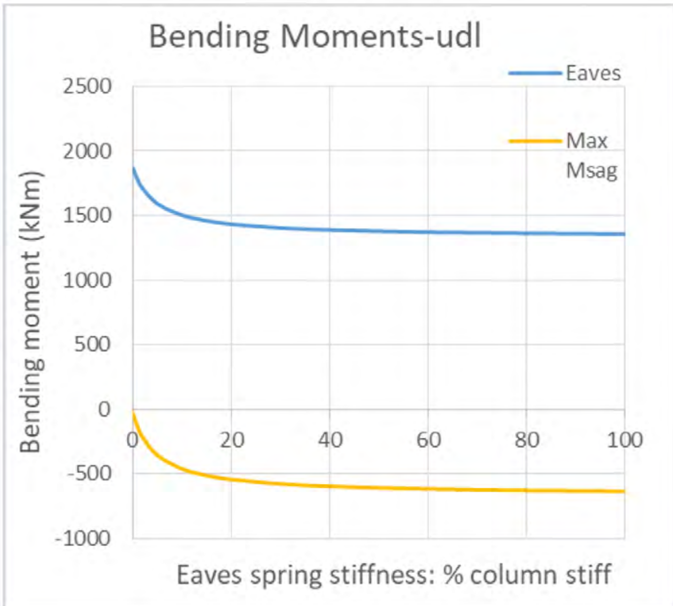

Figure 4 Eaves and maximum sagging moment

-662.0 kNm for rigid joints, an increase of 22% of the smaller value.

Joint Stiffness Estimates

The calculation of joint stiffness in reference 1 was made for a 533 × 210 UB 92, one serial size lighter than the rafter in Frame I. The joint was taken from example C.2 presented in the Green Book for moment connections[2] and the value determined was 102 MNm/radian. This value is a little under half the column stiffness for Frame I. Joints detailed "efficiently" such that the design resistance is only slightly higher than the design bending moment are subject to a reduction in stiffness to allow for plastic deformation as discussed in reference 2. If an "efficiently" detailed joint in conjunction with a relatively low joint stiffness is initially provided, iteration is likely to be necessary to achieve a suitable α_{cr} value for the frame and adequate joint resistance.

Item	Units	Frame II	
		Rigid Joints	Flexible Joints
α_{cr}	-	16.2	11.8
Eaves spread	mm	33	61
Eaves moment	kNm	56.6	54.1
Apex moment	kNm	-27.1	-30.9
Column stiffness	MNm/radian	6.77	6.77
Rafter axial load	kN	19.5	18.7
Base shear	kN	-18.9	-18.0

Table 3 Results for rigid joints at eaves and apex

Cold Formed Portal Frames

Portal frames made from cold formed members are used for smaller buildings and in the agricultural sector. Columns and rafter elements are commonly back-to-back lipped channel sections. Rafters are generally not haunched or provided with a knee brace and joints are effected using gusset plates between the pairs of channels, bolted through the channel webs. The gusset plates can also be flanged and bolted to the channel flanges. The joints in such frames are less stiff than those used for rolled sections where end-plate connections are adopted, particularly if the gusset plates are unflanged.

In Frame II, as indicated in Table 1, the same elements have been adopted for both column and rafter and take the form of lipped, back-to-back channels 261 mm deep with 76 mm wide flanges. The material thickness is 2.86 mm (2.9 mm galvanized). A similar analysis to that on Frame I has been carried out on Frame II. The joints consist of gusset plates between the channel webs connected with through bolts, with estimated stiffnesses of 2.0 MNm/radian and 1.8 MNm/radian at eaves and apex respectively. The results are shown in Table 3.

The results show that the joint stiffness can have a profound effect on the stability of the frame and on the deflections at the eaves. In the example shown, when the joint stiffness is included in the analysis, the α_{cr} value is reduced by 27% and the eaves spread is almost doubled, relative to the values for rigid joints.

Conclusions

The slope-deflection equations modified to include joint stiffness can be used effectively as a checking or investigatory tool in the design of simple frames such as goal-post or pitched portals, where joint stiffness is to be included in the design.

In the development, elements are assumed to be uniform in cross section along their length and to exhibit bending deformation only, unlike element formulations in some FE software which also include shear deformation.

In the examples considered, joint stiffnesses of at least 20% of the column stiffness produce joint moments of about 90% of the value for fully rigid joints. The α_{cr} value for the same column stiffness is also approximately 90% of the rigid joint value.

If it is possible to achieve joint stiffnesses of at least the magnitude estimated in reference 1, i.e. about 100 MNm/radian, their effect on the characteristics of conventional portal frames made from hot rolled sections should not result in significantly different element sizes or frame behaviour.

For certain types of frame and joints, such as cold formed portal frames with gusset plate joints, the inclusion of joint stiffnesses in the design calculations could have profound implications[3] ■

References

1. Koschmidder, D M, and Brown, D G, *Elastic design of single span steel portal frame buildings to Eurocode 3* (P397), SCI, 2012.
2. Joints in steel construction. *Moment-resisting joints to Eurocode 3* (P398) SCI and BCSA, 2013.
3. Brown, D G, *Design of cold-formed portal frames*, NSC, March 2015.