Cross-braced lateral load-resisting systems

Cross bracing is a traditional means of providing lateral stability to structures. Richard Henderson of the SCI discusses some of the features of this structural system.

As structural engineers of a certain age will recall from their student days a cross-braced panel is a statically indeterminate (or hyperstatic) structural system: the forces in the members cannot be determined simply by invoking equilibrium at the joints. Determining the forces used to be an exercise in the application of virtual work to structural problems.

When cross bracing is used to resist lateral loads, the bracing members are usually designed as tension only and the designer assumes that the element which forms the compression member buckles elastically as the frame deforms so as to shorten the relevant diagonal. This approach is favoured when analysing and designing structures by hand as determining the buckling resistance of the member is avoided. Crossed flats were traditionally used for this purpose although angle bracing could be used so the bracing members had some out of plane stiffness to make handling easier. Cautionary tales regarding finishes being pushed off by bowing bracing are told, leading to the adoption of different bracing arrangements.

Flat bar bracing

A flat bar tension only bracing member in a 4 m × 6 m pin-jointed braced panel (say a 130 mm × 10 mm flat), bolted to the opposing diagonal member at the centre, has a system length of √13 m, assuming the tension diagonal provides a point of restraint at the centre connection. (For a detailed assessment see BS EN 1993-2 Annex D). The out of plane second moment of area is 1.083×10^4 mm^4 giving an Euler buckling load:

$$N_{cr} = \frac{\pi^2 \times 210 \times 1.0833 \times 10^4}{13 \times 10^6} = 1.73\text{kN}$$

The buckling resistance of the member $N_{b,Rd}$ is very close to the Euler load because of the high out of plane slenderness and has a value of 1.69 kN, assuming S355 material. A compression force of this magnitude is unlikely to have any effect on a bracing connection designed for a tension force of 450 kN and is usually safely ignored.

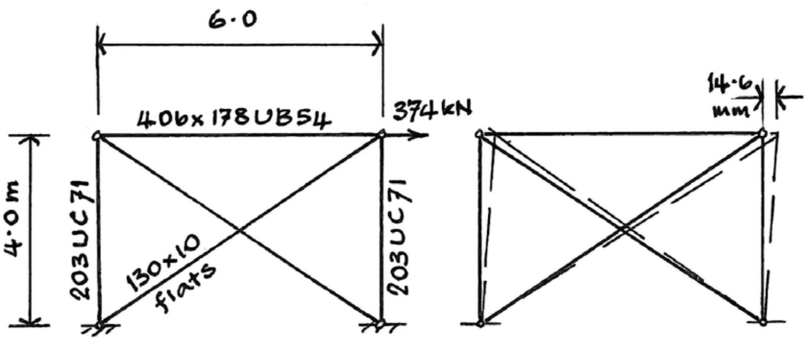

Figure 1: Braced panel

An estimate of the bow in the compression member which is making no contribution to the lateral resistance of the braced panel can be made if the panel members are known, assuming the member buckles into a circular arc. As an example, assume 203 UC 71 columns and a 406 × 178 UB 54 beam framing the 130 ×10 flat cross bracing (Figure 1), with a horizontal design load of 374 kN applied to the braced panel.

The horizontal displacement of the top of the panel relative to the bottom is 16.2 mm or 14.6 mm depending on at which end of the beam the force is applied and the displacement calculated. The extension of the bracing is about 12.1 mm (taking the smaller displacement). If the shortening of the opposing diagonal is taken as the same value, the bow is about 94 mm (neglecting the elastic shortening of the bracing member under the axial load). If the flat is unrestrained in the middle, the bow is about 180 mm. Clearly, such a bow could be sufficient to push dry lining off a wall concealing the braced panel. The low Euler load indicates clearly that the member buckles elastically and will behave satisfactorily when the loads are reversed.

An elastic stick finite element analysis that includes all the members without somehow allowing for the buckling behaviour of the bracing will produce a diagonal load in the compression member which corresponds to its axial stiffness. In such an analysis, the tension and compression diagonals share the load and carry a force which is close to half the force in the member assuming tension-only.

Tubes used as tension only bracing

An alternative form of bracing member consisting of RHS tubes, also assumed to behave as tension-only, is sometimes adopted. Consider 90 × 50 × 5 RHS tubes with centrelines in the same plane with a welded joint in the middle. Assume for the purpose of this example that the middle joint is pinned and behaves in a similar way to the crossed flats in providing a point of restraint in the middle of the compression member. The minor axis buckling resistance of the RHS for a length of √13 m is 71.6 kN by calculation. The compression member therefore carries a force of at least 71.6 kN which the connections must be able to sustain. The maximum theoretical load on the connection is equal to the Euler load and is equal to 78.4 kN, about 9.5% higher. If the connection (perhaps a gusset) is designed for tension only, it is possible that a load equal to the compression resistance is sufficient to deform the gusset permanently, compromising its ability to resist tension when the bracing load is reversed.

The amplified bow in the bracing member that corresponds to the buckling resistance can be found from back calculation. The assumed initial bow e_0 is given by:

$$e_0 = \frac{W_e}{A}\alpha(\bar{\lambda} - 0.2)$$

▶26

▶24

where $\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{1270 \times 355}{78420}} = 2.4$, and the imperfection factor for an RHS = 0.21.
Substituting values in the formula for the initial bow gives:

$$e_0 = \frac{19.7 \times 10^3}{1270} \times 0.21 \times (2.4 - 0.2) = 7.16\text{mm}$$

The amplified bow at failure is

$$\frac{N_{cr}}{N_{cr} - N_{b,Rd}} e_0 = 11.48 \times 7.16 \approx 82\text{mm}$$

This is the bow at which the extreme fibre at the point of maximum bow (and bending moment) reaches yield stress due to combined axial load and bending. The bow is about 15% less than that in the flat bar. As the frame deflects and load on the member is increased, the bow increases, the member shortens more and more quickly and the stiffness of the compression member decreases as shown in Figure 2. The member reaches its buckling load as the frame reaches its maximum sway deflection of 14.6 mm.

Column shortening

If a cross-braced panel with bracing that is intended to behave as tension-only has significant axial loads in the columns, the bracing will develop axial loads which may confuse the unwary. An elastic stick finite element analysis which includes all the elements in the model with pinned connections and which

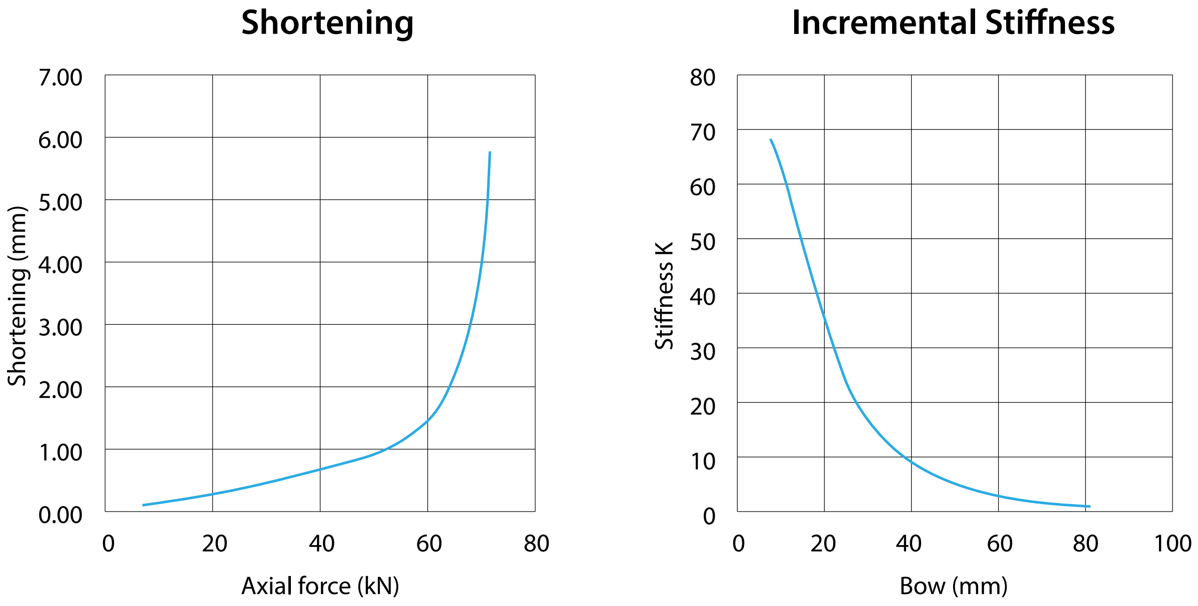

Figure 2: Member shortening and incremental stiffness

makes no provision for members intended to buckle when in compression, will exhibit compression forces in the bracing and a tension force in the beams: see Figure 3. The forces may or may not be sufficient to cause the bracing members to buckle, depending on the magnitude of the applied forces and the bracing section chosen.

If the braced panel is modelled with pinned joints and only the tension element present and if only vertical loads are applied, no axial forces will be developed in the bracing member or beams. The braced panel will deflect sideways however, to accommodate the bracing member which remains at its original length.

Lateral stiffness

It is advantageous to mobilise both tension-only bracing members in a cross-braced panel if this can be achieved, because the increased stiffness is beneficial to the overall stability of the building. The contribution of the bracing members to the lateral stiffness is of course doubled and the magnitude of the α_{cr} value for the building increased, thereby reducing any amplifier on the lateral loads. A cross bracing system formed of rods, perhaps adopted for architectural reasons, can be pre-tensioned to prevent the rod forming the compression diagonal from going slack. In this case, the bracing members in both diagonals will be effective as the tension force in the member in the shortening diagonal will be reduced as the bracing resists a lateral load. There are proprietary systems of rods, rod-ends, turnbuckles and connecting rings which are designed to achieve this effect [1].

Tensioned bracing is more difficult to achieve when the bracing members are a different geometry from rods. In the past it has been standard practice in some drawing offices to detail the holes in cross bracing members such that the length of the diagonal is 5 mm "short". This required the erection team to lean the columns when making the connections for the first bracing member to be erected. Installing the second member was much more difficult as it involved tensioning the first diagonal so as to shorten the opposing diagonal by enough to make the final connection.

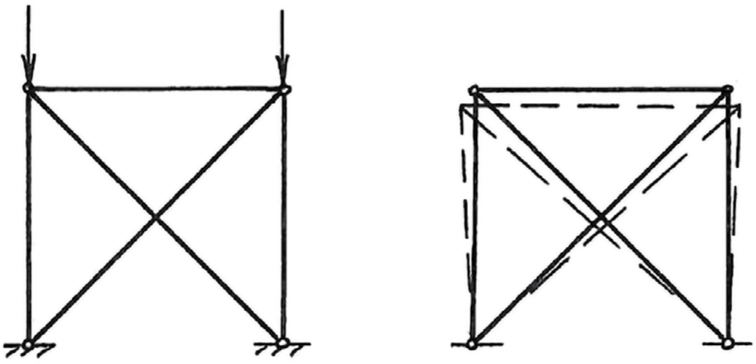

Figure 3: Deflection under vertical loads

Conclusion

Tension-only bracing members provide a simple means of resisting lateral loads on a structure but certain features of the behaviour of the bracing need to be considered:

1) The slack member of flat bar cross bracing can bow significantly which could possibly damage finishes.
2) If using tubes as cross bracing, the connections must be capable of resisting a compression force at least equal to the buckling resistance of the member.
3) A simple stick finite element analysis model of a frame with cross-bracing will develop compression forces in both bracing members unless steps are taken in the analysis to avoid this.
4) Mobilising both bracing members (eg by pre-tensioning) increases the α_{cr} value of the frame and is therefore beneficial.

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[1] Round bar cross bracing, p21 NSC, September 2015