Bolt slip in connections

The effect of bolt slip in truss connections is an issue that is raised with SCI from time to time in various contexts. Richard Henderson discusses some of the issues.

Introduction

The deflection of a truss can be estimated using various analytical methods and often a stick finite element (FE) package will be used to determine the member forces and the deflections under the different load cases. The calculated deflection depends on the assumptions made in the analysis about the nature of the joints – whether pinned or rigid.

Truss Joint types

In BS EN 1993-1-8, three categories of bolted connection loaded in shear are identified:

- Category A: bearing connections where the bolts act in shear and bearing;

Connections made with preloaded bolts:

- Category B: slip-resistant at serviceability limit state;
- Category C: slip-resistant at ultimate limit state.

Connections in category B must also be designed for shear and bearing in the ultimate limit state and Category C for bearing and net area. Fewer bolts will be required in Category B connections than in Category C ones.

SCI recommends adopting joints made with preloaded bolts where members are spliced and deflection is of concern because this allows the deflection of a truss to be better controlled. Category B joints are usually sufficient but Category C joints maybe specified in special cases (eg with oversize or slotted holes). In theory, once the joints are made, the subsequent deflection of the structure is due only to the elastic deformation of the members.

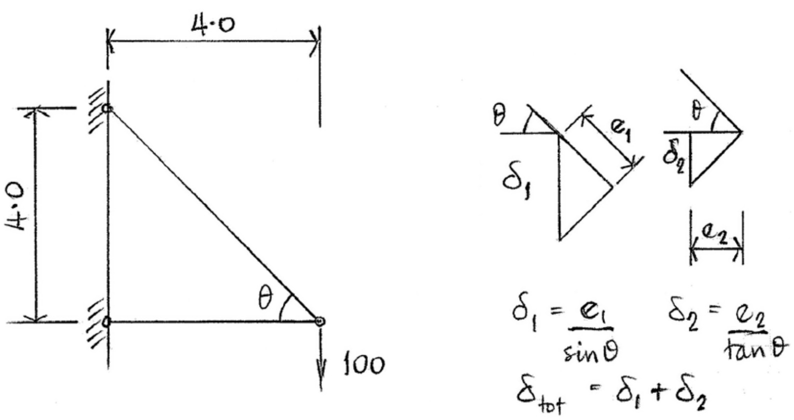

Figure 1 Bracket arrangement

Predicting deflections in trusses

As discussed in the introduction, an FE model of a truss will deliver the deflections of the structure as well as the member forces for a given load case. The actual deflection of a truss made with Category A bolted joints may well be greater than the predicted deflection, because the joints may slip when the load comes onto the structure and the bolts take up their loaded position. The deflection will be more significant if holes are oversize or slotted. This effect may be predicted by using virtual work methods which assume a pin-jointed model and adding an allowance for the slip at each bolted connection to the extension of the member due to the internal forces. This can be illustrated by example.

Example 1

Consider a two element pin-jointed bracket connected to rigid supports as shown in Figure 1. Estimate the total deflection if there is a 2 mm slip in each bolted connection.

Considering the elements separately for displacements that are small relative to the lengths of the members, if there is a change in length in the elements of 2 mm due to bolt slip, the vertical deflection in millimetres resulting from the extension of the diagonal is 2/sinθ and 2/tanθ from shortening of the horizontal member. The total deflection is therefore $2 \times (1/\sin\theta + 1/\tan\theta) = 4.8$ mm for $\theta = 45°$.

The same calculation by virtual work is given in Table 1.

Element		Diagonal	Strut	Total (mm)
Area (mm²)	A	470	667	
Length (m)	L	4√2	4	
Member forces (kN)	p_1	100√2	100	
Member forces due to unit load	p_2	√2	1	
Member flexibility (mm/kN)	L/EA	0.0573	0.0286	
Member deformation (mm)	p_1 L/EA	8.1	2.9	
Deflection due to member deformation (mm)	$p_2 p_1$ L/EA	11.5	2.9	14.4
Slip (mm)	s	2.0	2.0	
Deflection due to slip (mm)	p_2 s	2.8	2.0	4.8
Total deflection: $\Sigma p_2\,(p_1 L/AE + s)$				19.2

Table 1 Bracket deflection

Both methods give the same deflection due to bolt slip.

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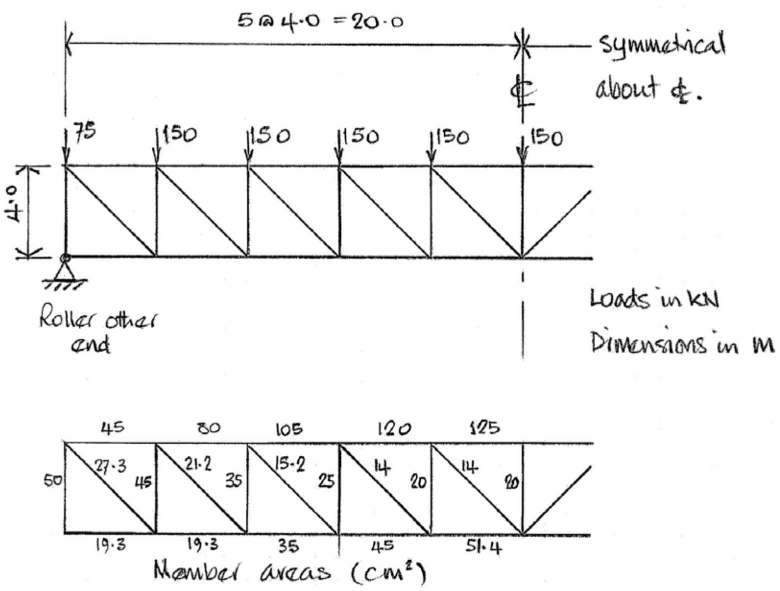

Figure 2 Truss arrangement

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Example 2

To illustrate the effect of bolt slip consider a pin jointed Pratt truss (N frame), shown in Figure 2. Member areas are based on a tensile stress of 350 MPa and 150 MPa in compression, with the area limited to a minimum value.

The deflection of the truss centre under the total design load is estimated to be 175 mm (span divided by 230), calculated by virtual work. An FE model gives a deflection of 179 mm. The deflection can be apportioned to 110 mm of bending deflection (deformation of the truss booms) and 65 mm of shear deflection, from the bracing members. Making this distinction is useful if the deflection is to be reduced because the elements making the greatest contribution to the total deflection can be identified.

In estimating the effect of bolt slip, it is assumed that with automated saw and drill lines, the accuracy of holing is such that slip can occur in all holes simultaneously. If all the members are bolted with 2 mm oversize holes and 1 mm of slip is assumed at each end of a member, a total of 2 mm per member, the deflection increases by 43% to about 250 mm. The effect on the mid-span deflection of other assumptions about which members experience slip is shown in Table 2. Possible scenarios are 1) that pipe-flange type bearing splices are effected in compression booms with no slip; 2) that both booms are effectively continuous with the bracing members bolted to them and 3) that the truss is shop-welded with bolted splices.

Condition	Deflection (mm)	% increase
No slip	175	-
All members bolted, 1 mm slip in each joint	250	43
No slip in compression boom, 1 mm slip in other joints	220	26
No slip in booms, 1 mm slip in bracing joints	200	14
1 mm slip at 2 bolted splices in booms and diagonals	190	9

Table 2 Effect of bolt slip on deflection – 2 mm slip per member

If the most unfavourable assumptions are made about the position of the bolts in their holes a slip of 4 mm at each end of a member is theoretically possible as shown in Figure 3.

The corresponding deflections are set out in Table 3. It can be seen that the theoretical increase in the mid-span deflection is very large. This is not surprising when the elastic deformations in the compression members are about 3 mm and an average of about 5 mm in the tension members.

A truss designed with joints made with preloaded bolts of Category C where the friction coefficient assumed in design is not achieved may well experience increased deflection in service. However, the magnitude of the increased deflection is uncertain. The potential percentage increases indicated in Tables 1 and 2 are unlikely to be realized for several reasons.

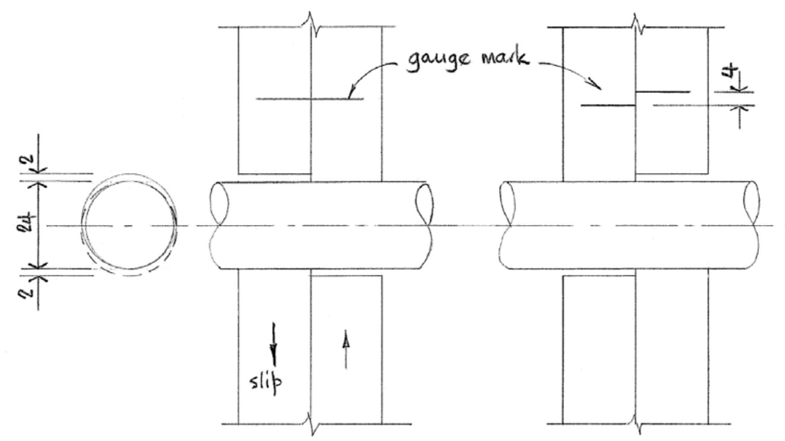

Figure 3: Worst case slip

Condition	Deflection (mm)	% increase
No slip	175	-
All members bolted, 8 mm slip in each joint	470	269
No slip in compression boom, 8 mm slip in other joint	350	200
No slip in booms, 8 mm slip in bracing joints	270	55
Slip at 2 bolted splices in booms and diagonals	242	38

Table3 Effect of bolt slip on deflection – 8 mm slip per member

Discussion and conclusion

It is almost certainly not the case that each joint in each member will slip by the same amount, because the force carried per bolt will not be uniform throughout. For example if the number of bolts required in a joint is 6.2, determined by dividing the design load by the bolt resistance, 8 bolts will be provided. This suggests that the possibility of any dynamic effects due to a sudden slip in all the joints is unlikely.

The absolute worst-case increased deflection set out in Table 3 will not occur because in practice the bolts will never be installed in every joint such that the maximum slip can occur. According to the NSSS, the maximum deviation from the intended position of a hole in a group of holes is 2 mm so it is anticipated that there will be some variation in the position of the bolt holes in a group (meaning some bolts will already be in bearing) and reduce the potential slip.

Kulak and others[1] discuss the behaviour of bolted joints and state "High strength bolts are usually placed in holes that are nominally 1/16 in. [1.6 mm] larger than the bolt diameter. Therefore the maximum slip that can occur in a joint is equal to 1/8 in [3.2 mm]. However, field practice has shown that joint movements are rarely as large as 1/8 in. and average less than 1/32 in [0.8 mm]. In many situations the joint will not slip at all under live loads because the joint is often in bearing by the time the bolts are tightened. This might be due to small misalignments inherent to the fabrication process. In addition slip may have occurred under dead load before bolts in the joint were tightened. Generally, slips under live loads are so small that they seldom have a serious effect on the structure".

In practice therefore, the maximum slip at each joint may well be no more than 1 mm.

If further reading is desired, a design guide for single storey steel buildings[2] published by Arcelor Mittal and others includes a section on estimating deflection due to bolt slip.

1. Geoffrey L Kulak, John W Fisher, John H Struik, Guide to design criteria for bolted and riveted joints, Second Edition, AISC, 2001
2. Steel buildings in Europe, Single storey steel buildings, Part 5 Detailed design of trusses Section 3.6 *https://constructalia.arcelormittal.com/en/news_center/articles/design_guides_steel_buildings_in_europe*