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The effect of the relative slip between plies of multiple-ply timber girder trusses subjected to single face loading

W M G Burdzik

Certain three-dimensional effects are sometimes ignored in the analysis of multiple-ply timber girder trusses that are loaded on one face of the combined truss, namely relative slip between the trusses and torsion. The effect of torsion on timber girders has been discussed in a previous paper and this paper now looks at the effect of the relative slip only. An analytical model is used and the results are compared with experimental values obtained by Enjily and Whale (1994). Their results are included in BS 5268-3:1998 for the design of nail plates and web members in multiple-ply timber girder trusses. This paper shows how their values may be obtained through using relatively simple analyses. The author goes further and warns that the distribution of the bending moment in the bottom chords of the individual plies may be greater than anticipated.

INTRODUCTION

Multiple-ply timber trusses are often used as primary support elements within a roof structure. The multiple-ply girder trusses should be assembled on flat and then hoisted into position. To assemble the trusses, the first truss is placed on a flat surface and the next truss is then nailed to it by means of 76 mm wire nails. This procedure is repeated until all the plies have been assembled. On the chord members, nails are spaced at 150 mm and on the web members at 300 mm. The plies are also bolted together by means of 12 mm bolts or threaded rods positioned close to the nodes of the girder truss (see figure 1). The assembled truss is then lifted into position and the hangers for incoming trusses are nailed or nailed and bolted to the bottom chord of the assembly. If the hangers are nailed, the nails will only penetrate the first ply and if bolted the bolts will be drilled through the full thickness of the assembly.

However, owing to a lack of on site hoisting facilities, multiple-ply trusses are often assembled in their final position and the nailing is done in the air. The nails are inclined to push out as a result of the out-of-plane flexibility of the whole system. Furthermore, small nail plates may become slightly dislodged and thin web members may crack or break. The temptation to leave out nails is great and this method of assembly should be treated with some circumspection. The industry specification for the nail size used in the nailing of multiple-ply timber trusses was recently changed from a 75 mm long, 3,5 mm diameter nail, to a 100 mm long, 4 mm diameter nail. The nails, in the first pair of trusses that are nailed together, would be clinched thereby preventing the nails from pushing out when subsequent nails are added. The method of analysis described in this paper will still be valid for the bigger nail size.

The loads from the incoming trusses are usually eccentric with regard to the centre line of the girder truss as the hangers are fixed only to the bottom chord of an outer ply. Torsion that is applied to the bottom chord of the truss assembly (Burdzik 2004) must be taken into account. Some truss
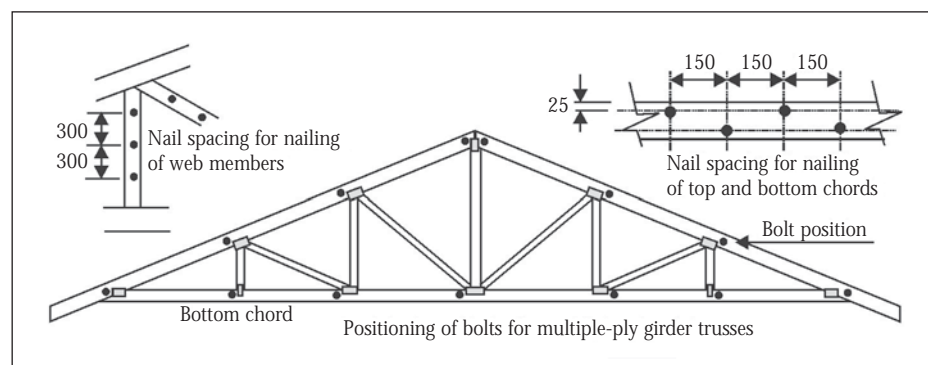

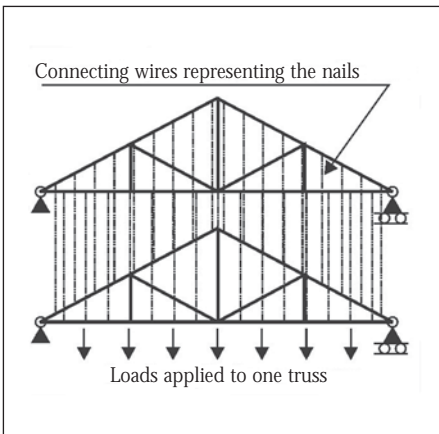Figure 1 This shows the bolting and nailing pattern for multiple-ply girder trusses (per SANS 10243, 2003)

Figure 2 This shows how the stiffness of the nails may be taken into account by means of interconnecting wires
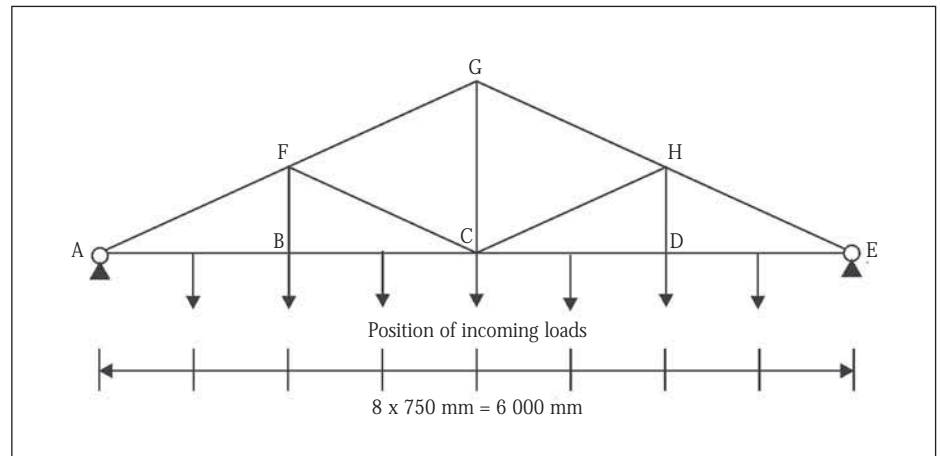

Figure 3 Truss geometry for two-ply girder truss

Table 1 Truss member sizes and loads from incoming trusses

	Two-ply	Three-ply	Four-ply
Span	6 m	9 m	12 m
Pitch of truss	25º	25º	25º
Top chord	36 x 111 mm (Grade 5)	36 x 149 mm (Grade 5)	36 x 149 mm (Grade 5)
Bottom chord	36 x 149 mm (Grade 5)	36 x 149 mm (Grade 7)	36 x 225 mm (Grade 7)
Webs	36 x 73 mm (Grade 5)	36 x 73 mm (Grade 5)	36 x 73 mm (Grade 5)
Load from incoming trusses	2,475 kN	3,713 kN	4,95 kN
Spacing of incoming trusses	750 mm	750 mm	750 mm

hangers that are used in the assembly of a roof are able to equilibrate this torsional moment so that the girder truss need only carry the vertical load. This paper investigates the effect that the slip between the trusses will have on the distribution of forces in the various plies of the girder truss.

Enjily and Whale (1994) undertook a large number of full-scale tests on two to four ply girder trusses. Their recommendations are included in BS 5268-3:1998, which gives additional load factors to be applied to nail plates and web members of multiple-ply girder trusses. They have listed issues needing further investigation, two of which are as follows:

■ Investigation should be continued as to what portion of the eccentric load is resisted by the individual plies of girders.
■ The distribution of torsion, tension, shear and bending stresses at the bottom chord nodes of girders.

ASSUMPTIONS

As the multiple-ply girder truss is loaded on one face by the truss hangers, load sharing between the trusses can only occur through the nails and bolts connecting the trusses together. Slip between the truss faces must occur prior to load sharing. It is assumed that the holes are drilled 1 mm oversize to enable the threaded rod to be placed. Slip of at least 0,5 mm must therefore occur before the bolts can transfer load from one truss to the adjacent truss. The nails are not pre-drilled and it is assumed therefore that they start transferring load between the trusses immediately.

In order to simplify the analyses and to cover from worst case to best case, the following analyses were carried out. First, it was assumed that only the nails would transfer load. This should be the worst case with truss hangers being nailed only to the outer truss. The second analysis was based on the assumption that the bolts at the nodes did not require 0,5 mm of slip but were immediately capable of transferring load. This is an optimistic analysis of the case where truss hangers are nailed to the outer truss. The final analysis was based on truss hangers that are bolted through all the plies and that no slip was required before the bolts were capable of transferring load.

The stiffness of the nailed and bolted connections was calculated using the equations given in the final draft of Eurocode 5 (1995). Bosch (2005) has found that the Eurocode equations may be on the conservative side for nails in SA pine for short-duration loading, but will be applicable to long-term loading. The equation for the stiffness of nailed connections without pre-drilling is given by:

$$k = \rho_m^{1,5} \cdot d^{0,8} / 30 \tag{1}$$

Where:
ρ_m = the density of the timber in kg/m³
D = the diameter of the fastener in mm, 3,5 mm for 75 mm long nails and 4,0 mm for 100 mm long nails.
k = the nail stiffness in N/mm or kN/m
For connectors where pre-drilling is required the stiffness is given by:

$$k = \rho_m^{1,5} \cdot d / 25 \tag{2}$$

If the density of timber is taken as 450 kg/m³ the stiffness of a 3,5 mm diameter nail will be 867 kN/m and of a 4,0 mm nail, 964 kN/m. The bolts have a much higher stiffness of 4 580 kN/m but will first have to slip the 0,5 mm due to the oversized hole. This can be taken into account in the analysis.

The author realises that the timber has a great variation in stiffness, not only between members but also in the length of the individual member. This has not been taken into account during the analysis and would require a separate investigation. All members were thus assumed to have the average stiffness for the given grade of timber.

MATRIX STIFFNESS ANALYSIS

It is possible to analyse a multiple-ply truss three dimensionally by using solid or beam elements and simulating the nail plates at joints and the nails between the trusses with springs. However, the input of coordinates becomes complicated as each nail or theoretical position of a nail will have to be defined. Coordinates can be so close together that it becomes difficult to define the solid elements.

A simpler way of analysing the slip between trusses and the effect that it has on the load distribution between the plies is to use a two-dimensional analysis and to stack the trusses vertically above one another. The nails between the trusses can then be replaced by wire elements that interconnect the trusses (see figure 2). These wires are then given an axial stiffness equal to the shear stiffness of the nails and bolts. The area of the equivalent wire is given by:

$$A = \frac{k \cdot L}{E} \tag{3}$$

Where:
A is the area of the equivalent wire in mm²
k is the shear stiffness of the nail in N/mm or kN/m
L is the length of the equivalent wire in mm
E is the modulus of elasticity of the equivalent wire in MPa

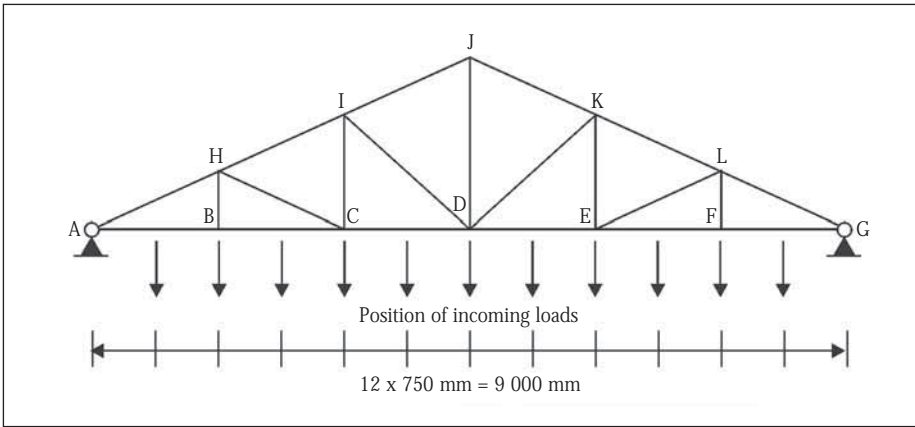Defining a slack of 0,5 mm in the wires can replicate the initial slip required by bolts

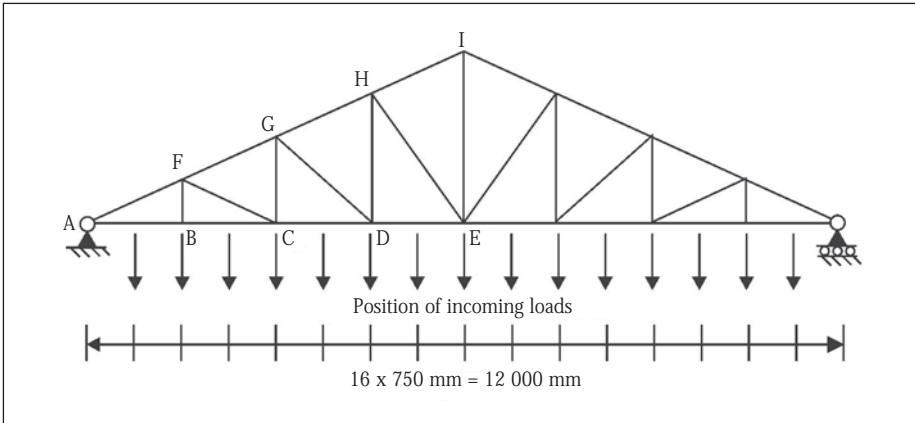*Figure 4 Truss geometry for three-ply girder truss*

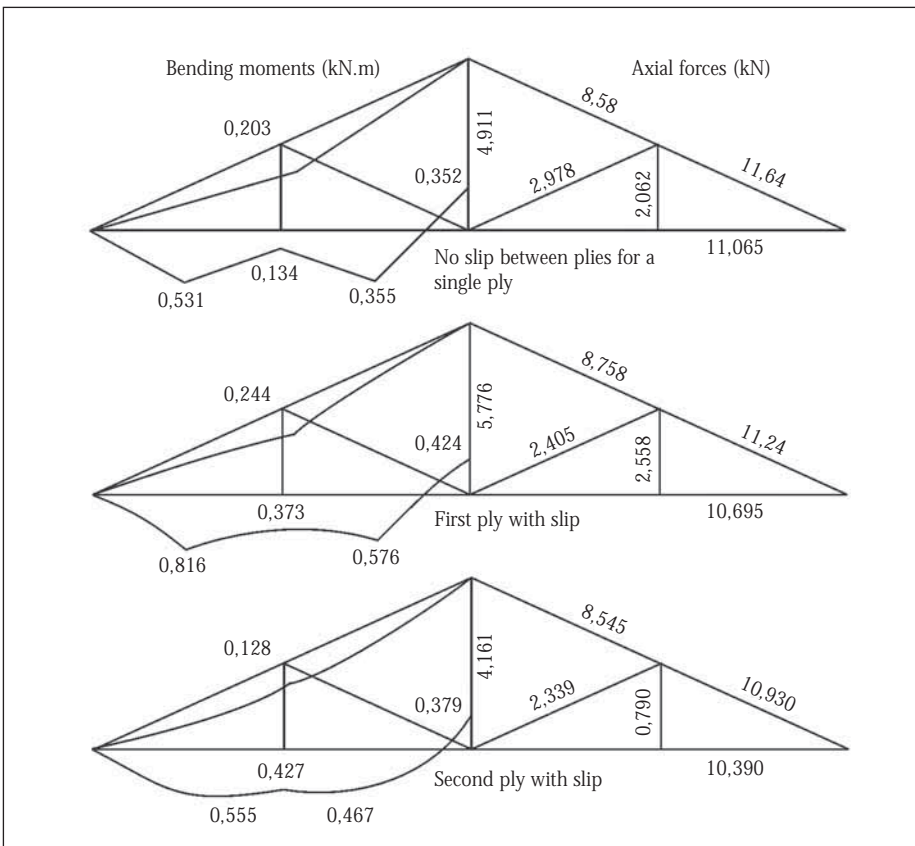*Figure 5 Truss geometry for four-ply girder truss*

Figure 6 Typical force and bending moment distribution for a two-ply girder truss with slip on the interface, pitch of truss = 17,5°

before loads may be transferred. This method simplifies the input of the truss geometry and clarifies how and where the loads are distributed between the plies. The analysis, however, does not consider the torsional effects in the bottom chord. Burdzik 2004 has covered the effect of torsion in multiple-ply girder trusses in a previous paper.

Analysis

The use of two-, three- and four-ply trusses is not unusual in South Africa. Only the most typical truss layout was considered in this analysis, although others may be found in practice. Three spans, namely 6 m, 9 m and 12 m, with two different pitches, namely 17,5° and 25°, were analysed and important differences between the forces in the plies will be highlighted. The 6 m, 9 m and 12 m spans will be analysed as two-, three- and four-ply trusses respectively. The member sizes that were used are given in table 1 on page 13.

The truss geometry that was used is given in figures 3, 4 and 5. A change in geometry would affect the distribution of the loads between the plies. It is not the author's intention to investigate all possible truss geometries and incoming loads, but rather to show how slip between trusses can influence the load distribution in the plies for a limited number of cases.

Results of the analyses

The analyses of two- and three-ply trusses have shown that the slip at the nails will be less than 0,5 mm and that the bolts will only be effective if they are placed into tight fitting holes. This is impractical and therefore the author believes that the bolt influence should be ignored. The bolts do, however, serve the purpose of keeping the plies together and should therefore not be omitted.

The testing of multiple-ply trusses, for force distribution between the trusses, may lead one to incorrectly interpret results especially if only the reactions are measured. The small difference between the reactions could lead one to believe that the forces are evenly distributed amongst the trusses. The analyses show that the difference is not in the total load that the individual truss must carry but in how the forces are distributed in that truss. The only way that experimental verification of the analyses could be achieved is by sticking strain gauges onto the nail plates and back calculating to determine the bending moments in the bottom chords.

It was found that the biggest variation between the plies occurred in the bottom chord and the axial forces in the vertical web members. The nails, throughout the truss, distribute the load from one ply to another so that the difference in axial forces of the chord members is not significant.

Two-ply girder trusses

Figure 6 shows the distribution of the bending moments and the axial forces for a two ply girder truss with a pitch of 17,5°.

The following table should be used together with figure 3 and gives the bending moments and axial forces for two- ply trusses with a pitch of 25°. The typical shape of the bending moment is given in figure 6.

Table 2 *Bending moments and axial forces in a two-ply girder truss with a pitch of 25° with only the incoming loads taken into account. Self weight and other roof loads have been ignored, as these will be evenly distributed throughout the plies*

Member	Force	No slip	1st ply with slip	2nd ply with slip
AB	Axial (kN)	−8,14	−8,10	−7,79
AF	Axial (kN)	8,93	8,96	8,63
BF	Axial (kN)	−2,46	−3,01	−1,90
GC	Axial (kN)	−5,10	−5,50	−4,64
AB	BM at B (kN.m)	0,135	0,073	0,085
	BM between A and B	−0,390	−0,530	−0,313

Table 3 *Axial forces and bending moments for a three-ply girder truss with only the incoming loads taken into account. Self weight and other roof loads have been ignored, as these will be evenly distributed throughout the plies*

Member	Force	No slip	1st ply with slip	2nd ply with slip	3rd ply with slip
AB	Axial (kN)	−12,67	−13,05 −12,84 −12,74	−12,63 −12,68 −12,67	−12,32 −12,49 −12,56
BC	Axial (kN)	−12,70	−13,06 −12,86 −12,74	−12,66 −12,71 −12,76	−12,38 −12,55 −12,63
AH	Axial (kN)	14,01	14,53 14,21 14,15	13,98 14,03 14,03	13,66 13,84 13,95
BH	Axial (kN)	−2,03	−4,15 −3,90 −2,73	−1,35 −1,61 −1,09	−1,01 −1,07 −1,67
CI	Axial (kN)	−3,47	−5,49 −5,09 −4,12	−3,15 −3,19 −3,35	−2,69 −2,74 −3,16
DJ	Axial (kN)	−7,39	−9,47 −9,11 −8,16	−7,14 −7,15 −7,29	−6,76 −6,74 −7,10
AB	BM at B (kN.m)	−0,245	−0,152 −0,057 −0,214	−0,238 −0,280 −0,225	−0,294 −0,347 −0,246
	BM between A and B	−0,558	−0,938 −0,957 −0,677	−0,462 −0,456 −0,559	−0,400 −0,402 −0,519
BC	BM at C (kN.m)	0,060	0,126 0,198 0,062	0,021 0,021 0,061	0,020 0,040 0,046
	BM between B and C	−0,541	−0,783 −0,819 −0,591	−0,439 −0,426 −0,517	−0,413 −0,404 −0,498
CD	BM at D (kN.m)	0,356	0,520 0,563 0,385	0,318 0,297 0,359	0,234 0,213 0,330
	BM between C and D	−0,254	−0,523 −0,552 −0,316	−0,150 −0,141 −0,236	−0,117 −0,108 −0,213

The first values are for truss where only the nails are active, the second when the bolts at the intersections are fully active as well and the last when bolted brackets are used and the bolts are fully active

The maximum force in the nails is in the region of 0,27 kN. This is well within the elastic range of the nail load deflection curve as the ultimate strength of a nailed connection is 0,762 kN. The slip in the nail will also only be about 0,3 mm, which is less than the clearance on a bolt in timber. It is therefore acceptable to ignore the stiffness of bolts in the truss assembly.

Three ply girder truss with a pitch of 25º
Only the girder trusses with a pitch of 25º were investigated, as it is difficult to size the truss with the flatter pitch. The bending moments and axial forces became too large for the currently available section sizes. The table should be read together with figure 4. Only the critical element forces are given in table 3.

In the case of the three-ply girder truss the bolts at the connection between A and B would have come into play, but would only have been effective between the first two plies. Thereafter the nails would have been able to transfer the loads. It is also assumed that a truss hanger with four bolts is used to transfer the loads. If the truss hangers are nailed and not bolted, the middle values in the table are an optimistic evaluation of the true conditions.

Four ply girder truss with a pitch of 25º
The table should be read together with figure 5. Only the critical element forces are given in table 4.

In a separate analysis, where a slip of 0,5 mm was assumed for the bolts to become active, only the bolts on the bottom chord underwent the required slip and then only between the first and second plies.

CONCLUSION AND RECOMMENDATIONS
The analysis of multiple-ply girder trusses hinges not only on whether rotation can be prevented at the position of loading on the bottom chord, but also on whether trusses have been connected together in accordance with some standard. If nails and bolts are not placed to some specification, it becomes virtually impossible to determine the loads carried by individual trusses. The analyses in this paper assumed that nailing and bolting were done correctly in accordance with SANS10243, 2003, using 75 mm nails, and that no torsion was applied to the bottom chord. Multiple-ply girder truss should not be analysed as a single truss, as the nails and bolts require slip before load can be transferred between the plies. This slip takes place throughout the trusses so that, in some instances, the nails in web members will be overloaded and will deform plastically even though the slip at bolt positions does not exceeded 0,5 mm. It is thus extremely difficult to set up generalised rules that will be true for all girder trusses.

In the case of two-ply girder trusses, the slip between the faces of the trusses is so low that only the nails will be active if the bolts are not placed in tight-fitting holes. In three-ply girder trusses, only the bolts in the bottom chord of the first bay will become active and then only between the first and second ply. A conservative approach to the design of the bottom chord would be to assume that only the nails are active and that the bolt holes all have a 1 mm clearance. In the case of four-ply trusses, the relative slip between trusses is greatest and as such the bolts become effective and assist in the transfer of loads between plies. A conservative approach would be to assume that bolts are inactive and that only the nails transfer loads.

The difference in the axial forces in the chords is small when considering slip versus no slip. A 5 % or 6 % difference is insignificant when considering overall analysis and assumptions made. Axial forces in the vertical webs and the bending moments in the bottom chord showed the

Table 4 Axial forces and bending moments for a four-ply girder truss with only the incoming loads taken into account.
Self weight and other roof loads have been ignored, as these will be evenly distributed throughout the plies

Member	Force	No slip	1st ply with slip	2nd ply with slip	3rd ply with slip	4th ply with slip
AB	Axial (kN)	−17,61	−18,62 −18,18 −17,87	−17,86 −17,89 −17,72	−17,19 −17,39 −17,53	−16,86 −15,17 −17,42
BC	Axial (kN)	−17,66	−18,63 −18,18 −17,91	−17,92 −17,89 −17,78	−17,27 −17,47 −17,59	−16,95 −17,23 −17,49
AF	Axial (kN)	19,50	20,75 20,20 19,87	19,78 19,75 19,63	19,04 19,26 19,41	18,68 19,01 19,29
FG	Axial (kN)	14,03	17,70 17,57 17,56	17,72 17,66 17,60	17,60 17,63 17,61	17,55 17,61 17,57
BF	Axial (kN)	−1,85	−5,45 −5,08 −3,26	−1,52 −1,42 −1,76	−0,64 −0,58 −1,35	−0,37 −0,34 −1,15
GC	Axial (kN)	−3,72	−7,27 −6,67 −4,98	−3,61 −3,63 −3,69	−2,84 −2,89 −3,36	−2,57 −2,66 −3,24
DH	Axial (kN)	−4,47	−7,95 −7,39 −5,79	−4,63 −4,63 −4,62	−4,02 −4,04 −4,36	−3,81 −3,83 −4,26
EI	Axial (kN)	−9,98	−12,80 −12,42 −11,12	−9,91 −9,88 −9,93	−9,30 −9,35 −9,62	−9,34 −9,25 −9,59
AB	BM at B (kN.m)	−0,407	−0,225 −0,087 −0,339	−0,384 −0,425 −0,372	−0,462 −0,541 −0,412	−0,502 −0,526 −0,427
	BM between A and B	−0,677	−1,281 −1,303 −0,864	−0,608 −0,597 −0,672	−0,522 −0,504 −0,500	−0,507 −0,529 −0,554
BC	BM at C (kN.m)	0,088	0,252 0,358 0,134	0,111 0,015 0,112	0,013 0,013 0,092	0,012 0,013 0,014
	BM between B and C	−0,613	−1,000 −1,049 −0,699	−0,542 −0,526 −0,586	−0,505 −0,519 −0,551	−0,502 −0,520 −0,537
CD	BM at D (kN.m)	−0,082	0,147 0,237 0,017	0,017 0,016 0,016	−0,113 −0,144 −0,052	−0,128 −0,158 −0,066
	BM between C and D	−0,445	−0,834 −0,880 −0,518	−0,318 −0,302 −0,405	−0,256 −0,239 −0,369	−0,240 −0,232 −0,354
DE	BM at E (kN.m)	0,580	0,795 0,847 0,553	0,456 0,437 0,490	0,330 0,314 0,431	0,299 0,283 0,407
	BM between D and E	−0,207	−0,678 −0,715 −0,360	−0,176 −0,168 −0,233	−0,144 −0,151 −0,188	−0,143 −0,150 −0,170

The first values are for truss where only the nails are active, the second when the bolts at the intersections are fully active as well and the last when bolted brackets are used and the bolts are fully active

Table 5 Suggested multiplication factors that should be applied to the forces of the vertical webs of the truss carrying the truss hangers in multiple-ply girder trusses

Force	Two-ply girder truss	Three-ply girder truss	Four-ply girder truss
Bending moment in first bay	1,36	1,68	1,89
Axial force in first vertical (from support)	1,22	2,04	2,95
Axial force in second vertical	1,08	1,58	1,95
Axial force in third vertical		1,28	1,78
Axial force in fourth vertical			1,28

largest variation between the plies. Table 5 gives a summary of the critical members, that is, bottom chord and vertical web members. The factor shown is the factor with which the bottom chord forces and bending moments, obtained from a no-slip analysis, must be multiplied.

It must stressed that the effect of torsion on the bottom chord plays a far bigger role on the forces that must be transferred by the nail plates. Two tables are given with suggested factors with which the nail plate forces must be increased. Table 6 is a summary of suggested factors for the eccentric loading of trusses where the torsional moment as a result of the eccentric loading has been equilibrated by the truss hanger. Table 7 is a summary of suggested factors for the eccentric loading of trusses where the torsional moment as a result of the eccentric loading has not been equilibrated by the truss hanger. The author realises that the specification for nail diameter has been changed and before of multiplication factors in tables 6, 7 and 8 are written into SANS 10163, the effect of the larger-diameter nail will have to be investigated.

The factor for the increase in the plate load as a result of the torsion is far greater than the factor for slip and shows how important it is to prevent the rotation of the bottom chord. The critical vertical web member for torsion is the shortest web member, that is, the member closest to the support. If torsion is not prevented, then the force in the critical web member in a four-ply girder truss is calculated to be in the region of 1,85 kN in tension and the design force in the outer plate $1,85/2 \times 5,6 = 5,18$ kN. If the rotation is prevented, the load will drop to $1,85/2 \times 3,0 = 2,78$ kN.

Table 8 gives suggested factors with which the bending moments of the bottom chords of the outer ply of multiple-ply girder trusses should be increased to take account of the relative slip between the trusses. These factors are not given in BS 5268-3.

Adherence to the nailing specification is vitally important in the analysis. Failure to place all the nails will increase both the nail plate forces and bending moments in the bottom chord of the outer ply in multiple-ply girder trusses to the extent that the outer ply will be overloaded and could fail.

Unless a rigorous analysis of the multiple ply girder trusses has been carried out, it is suggested that the plate forces and bending moments in the bottom chord be increased in accordance with tables 7 and 8. If rotation of the bottom chord can be prevented, tables 6 and 8 could be used. However, it must be borne in mind that very little rotation is required before the full torsional moment is applied to the bottom chord.

Table 6 Suggested multiplication factors for the increase in the force transferred by the outside nail plates of the truss in a multiple-ply girder truss that is subjected to the hanger loads where torsion on the bottom chord has been equilibrated by the truss hangers. Note the similarity between the suggested factor for slip and the BS 5268-3 value

Number of plies	Increase in load on plate	Ke – BS 5268-3
1	1,00	1,00
2	1,20	1,33
3	2,00	2,00
4	3,00	3,00

Table 7 Suggested factors for the increase in the force transferred by the outside nail plates of the truss in a multiple-ply girder truss that is subjected to the hanger loads where torsion on the bottom chord has not been equilibrated by the truss hangers

Number of plies	Increase in load on plate	Ke – BS 5268-3
1	2,6	1,00
2	4,5	1,33
3	5,5	2,00
4	5,6	3,00

Table 8 Multiplication factors for bending moment increase in the bottom chord of multiple-ply girder trusses

Number of plies	Factor for bending moment increase in the bottom chord of the truss that carries the truss hangers
1	1,0
2	1,4
3	1,7
4	1,9

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