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Comparison between bracing requirements using various codes and a proposed new set of bracing criteria

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The notable increase in problems related to the bracing of timber roofs clearly indicates that the time is ripe to seriously consider amended rules governing the design of such bracing. Burdzik et al have proposed a set of amended rules which are founded on considering the stiffness of the bracing system as a primary criterion. These proposed amended rules are compared with the existing bracing requirements of SABS 0163 (1994) as well as with the requirements of the Eurocode, EC 5 (1992). As the proposed revised bracing rules have a stiffness and strength criterion, the strength and stiffness of nailed joints become an important component of the bracing system, which required further investigation. Despite the limited number of test results used to determine the impact of the stiffness criterion, the findings of this paper were confirmed by observations in the field.

INTRODUCTION

To appreciate the fundamentals of bracing design, it is necessary to distinguish between the two types of bracing, ie bracing required to provide overall stability to a structure (figure 1) and bracing provided to reduce the effective length of compression or flexural members (figure 2). The design and sizing of the former type of bracing are determined by the magnitude of external forces such as wind loading, while the design of the latter type is governed by a complex interaction between the bracing system and the member it is intended to restrain. The proposed bracing rules are aimed at improving the performance of the bracing that is used to reduce the effective length of compression members.

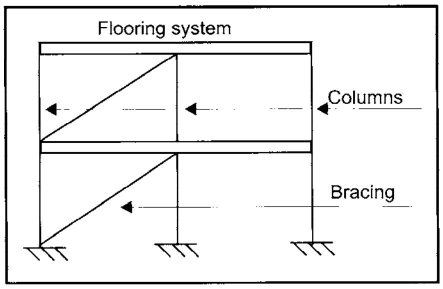


Figure 1 Bracing that is used to provide overall stability to a structure

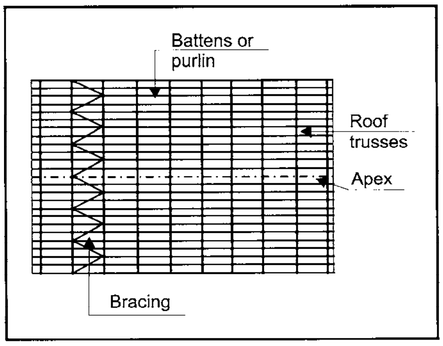


Figure 2 Bracing used to reduce the effective length of the compression members

The effective length of a compression or flexural member may be reduced by providing intermediate restraints at discrete intervals, or by providing a continuous elastic brace. In both instances the resistance of the member to axial compressive forces will be increased. When a compression member is rigidly braced at discrete intervals, the buckled shape is clearly defined and the capacity of the member may be derived by the common effective length method. When a continuous brace is employed, however, various buckled shapes are possible. The buckled shape depends on the stiffness of the lateral support and the length of the member. The two types of bracing systems discussed above are shown in figure 3, bracing at discrete intervals, and figure 4, continuous bracing system.

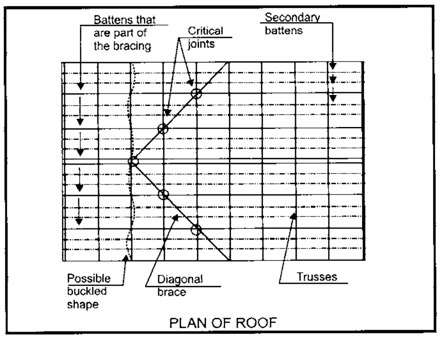


Figure 3 A trussed roof that is braced at discrete intervals

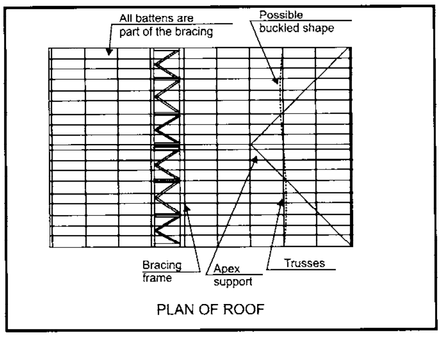
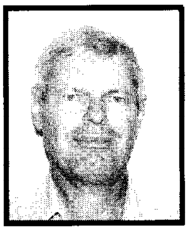
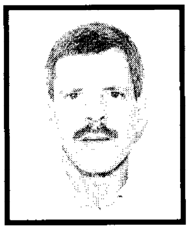


Figure 4 A trussed roof provided with a continuous bracing system



WALTER BURDZIK received the degrees BSc Eng (Civil), BEng Hons, MEng and PhD from the University of Pretoria. He spent three years working for consulting engineers before returning as a senior lecturer to the University of Pretoria, where he was later promoted to Professor of Structural Engineering. Together with Ben van Rensburg he started the timber engineering research at the university, and the two of them have expanded it to the extent that it is now one of the few recognised timber testing facilities in South Africa. Walter has been intimately involved in the committees charged with writing the timber design codes and has undertaken numerous research projects as a result of this work.



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NEW AND EXISTING BRACING CRITERIA

Proposed new set of bracing criteria (after Burdzik *et al* 1999)

In a previous paper by Burdzik *et al* (1999) the requirements for the two bracing systems were discussed. New bracing rules were proposed in this paper and they may be summarised as follows:

Case 1 Design criteria for the individual braces to compression members that are braced at discrete intervals

Stiffness criterion for bracing member:

$$k_{req} = \frac{4\,k_s\,P}{L} \tag{1}$$

Where: $k_s = 2(1+\cos(\pi/m))$

m = number of equal bays of length, L, between apex and eaves for pitched roofs, where apex is held in position or for mono-pitched roofs, from support to support

P = axial load in compression member, at the lateral support, due to dead load only

Force criterion for bracing member:

P_b = lateral force perpendicular to the compression member
= 3% of the average axial load, P, in the compression member (multiple lateral supports to a compression member)

P_b = 1,5% of the axial load, P, in the compression member (single lateral brace)

Case 2 Compression members continuously braced by a membrane or bracing frame

Stiffness criterion for bracing member:

$$\beta_{req} = \frac{5{,}921 m^2 \pi^2 P_e}{L^2}\left(\frac{P_{cr}}{P_e} - m^2\right) \tag{2}$$

Where: β_{req} = required stiffness modulus of the bracing membrane or bracing frame. Where the compression members are part of the frame, case 1 should be applied.

$m = 1$ for $\sqrt{\frac{P_e}{P_{cr}}} \geq 0{,}443$

Buckling in half sine wave

$= 2$ for $0{,}443 > \sqrt{\frac{P_e}{P_{cr}}} \geq 0{,}227$

Buckling in full sine wave

$= 3$ for $0{,}227 > \sqrt{\frac{P_e}{P_{cr}}} \geq 0{,}200$

Buckling in one and a half sine waves

$= 4$ for $0{,}200 > \sqrt{\frac{P_e}{P_{cr}}}$

Buckling in a double sine wave

P_{cr} = axial load in member due to dead load only

P_e = Euler buckling load

$$= \frac{\pi^2 E_{0,05} I}{L^2} \tag{3}$$

L = distance between eaves and apex, if apex is held in position
= distance between supports for a flat roof

$E_{0,05}$ = fifth percentile modulus of elasticity

Force criterion:

The maximum load on the bracing system is achieved in the case where the buckled shape of the strut assumes a half-sine wave and the proposed force criterion is therefore based on the most conservative case.

$$q = \frac{0{,}06\,P}{L} \tag{4}$$

Where:

q = uniformly distributed load induced in the bracing membrane or frame

P = axial force in member due to dead load alone

L = length of beam or distance from eaves to apex of truss

Bracing requirements using EC 5 Part 1-1:1992

EC 5 (1992), by comparison, stipulates the stiffness and strength criteria as follows:

Case 1 Bracing at discrete intervals in accordance with EC 5 (1992)

Stiffness criterion:

$$C = k_s \pi^2 EI / a^3$$

Where: C = the spring constant

EI = the stiffness of the compression member, based on the fifth percentile modulus of elasticity

$k_s = 2(1 + \cos\pi/m)$

m = the number of bays with length a

a = distance between lateral supports

Force criterion in accordance with EC 5 (1992):

The design resistance, F_d, is based on the mean design force N_d, which is dependent on the final curvature of the strut. As EC 5 (1992) is based on a more stringent curvature limit than that assumed in the South African Code, the force in the brace is less than the proposed force for the South African design code.

F_d = 2% of N_d for solid timber and 1,25% for laminated timber

Case 2 Continuous elastic bracing system in accordance with EC 5 (1992)

Stiffness criterion:

For a continuous brace the stiffness is governed by a deflection limit of Span/700 and the force is given by:

$$q_d = k_l \frac{n\,N_d}{30\,l}$$

Where: q_d = force induced in the bracing membrane or bracing frame

n = number of members that are being supported

N_d = the design axial force in the compression member

l = span of a beam or the distance from the eaves support to the apex of a truss

k_l = minimum of 1 or $\sqrt{15/l}$

Bracing requirements using SABS 0163-1:1994

The South African timber design code, SABS 0163 (1994), only has a load requirement which is given by:

$$P_B = 0{,}1\,n^{0{,}7}\frac{P_A}{N+1}$$

Where: P_B = force in the brace

n = number of members supported by the bracing system

P_A = average force in the compression member due to dead load

N = number of lateral restraints between eaves support and apex of truss

Comparison between bracing requirements using various codes and a proposed new set of bracing criteria

To illustrate the influence of the proposed amended rules on the bracing of timber structures, it is useful to compare the proposed rules with current codes.

Table 1 Comparison between various stiffness and strength criteria

Code	Stiffness criterion	Force criterion
SABS 0163 (1994) (discrete as well as continuous supports)		$P_B = 0{,}1\,n^{0{,}7}\frac{P_A}{N+1}$
Proposed (discrete support)	$k_{req} = \frac{4\,k_s P}{L}$	P_B = 1,5% of P_A (single supports) P_B = 3% of P_A (many supports)
EC 5 (1992) (discrete supports)	$C = k_s\pi^2 EI / a^3$	F_d = 2% of N_d (any number)
Proposed (continuous support)	$\beta_{req} = \frac{5{,}921 m^2\pi^2 P_e}{L^2}\left(\frac{P_{cr}}{P_e} - m^2\right)$	$q = \frac{0{,}06\,P}{L}$
EC 5(1992) (continuous support)	$\delta \leq \frac{L}{700}$ due to q_d	$q_d = k_l\frac{n\,N_d}{30\,l}$

The most common tiled timber roof type used in South Africa is a double-pitch truss with slopes varying between 17,5° and 25°. The comparison is based on a tiled roof with trusses spaced at 0,76 m using various values of pitch and span. Trusses were assumed to have diagonal bracing @ 45° when viewed in plan. It can then be assumed that lateral support is at discrete intervals, namely spacing/cosine (pitch). The number of lateral braces is obtained by dividing the half span by the spacing of 0,76 m. The following loads were used for the investigation:

- Tile weight 0,56 kN/m^2
- Spacing 0,76 m

The axial compressive forces in the top chord caused by these loads are given in table 2:

Table 2 Estimated compressive force at eaves joint in top chord of double-pitch trusses for dead load only

Pitch of roof	17,5°	20,0°	22,5°	25,0°
Span (m)	Estimated force in the top chord at eaves joint (kN)			
6	4,45	3,97	3,61	3,33
8	5,94	5,30	4,82	4,44
10	7,42	6,62	6,02	5,56
12	8,90	7,95	7,22	6,67
14	10,39	9,27	8,43	7,78
16	11,87	10,59	9,63	8,89

Tables 3, 4 and 5 give the bracing force and stiffness requirements for discrete point bracing of the top chord, using the various codes and the top chord loads given in table 2. Tables 6, 7 and 8 give the bracing force and stiffness requirements for continuous bracing of the top chord for the loads given in table 2.

Table 3 EC 5: Part 1-1:1992 Bracing stiffness and strength requirements for a single truss braced at discrete intervals

Pitch	17,5°	20,0°	22,5°	25,0°	17,5°	20,0°	22,5°	25,0°
Span (m)	Required stiffness of the brace (N/mm)				Force induced in the brace, P_b (kN)			
6	53,48	46,64	41,29	37,06	0,134	0,119	0,108	0,100
8	75,56	65,90	58,34	52,36	0,178	0,159	0,144	0,133
10	99,25	86,57	76,63	68,78	0,223	0,199	0,181	0,167
12	120,54	105,13	93,07	83,53	0,267	0,238	0,217	0,200
14	141,78	123,66	109,47	98,26	0,312	0,278	0,253	0,233
16	163,69	142,77	126,39	113,44	0,356	0,318	0,289	0,267

Note that the axial load is for the total load and not the dead load component only. The loads in table 2 should be multiplied by 1,5 to obtain the total load.

Table 4 Load in lateral brace in accordance with SABS 0163 requirement for a single truss that is laterally supported at discrete intervals

Pitch	17,5°	20,0°	22,5°	25,0°
Span (m)	Force induced in the brace, P_b (kN)			
6	0,111	0,099	0,090	0,083
8	0,118	0,106	0,096	0,089
10	0,106	0,095	0,086	0,079
12	0,111	0,099	0,090	0,083
14	0,115	0,103	0,094	0,086
16	0,108	0,096	0,088	0,081

Table 6 EC 5: Part 1-1: 1992 Force requirement for continuous support to a single compression member in a braced system

Pitch of roof	17,5°	20,0°	22,5°	25,0°
Span (m)	Force induced in bracing membrane or frame, q_d (kN/m)			
6	0,074	0,066	0,060	0,056
8	0,074	0,066	0,060	0,056
10	0,074	0,066	0,060	0,056
12	0,074	0,066	0,060	0,056
14	0,074	0,066	0,060	0,056
16	0,074	0,066	0,060	0,056

Table 5 Stiffness and strength criteria for dead load component of the top chord load for a single truss braced at discrete intervals using the proposed new bracing criteria

Pitch	17,5°	20,0°	22,5°	25,0°	17,5°	20,0°	22,5°	25,0°
Span (m)	Required stiffness (N/mm)				Force induced in the brace, P_b (kN)			
6	76,30	67,08	59,95	54,29	0,134	0,119	0,108	0,100
8	107,81	94,78	84,71	76,71	0,178	0,158	0,144	0,133
10	141,61	124,50	111,27	100,76	0,223	0,199	0,181	0,167
12	171,98	151,20	135,13	122,37	0,267	0,238	0,217	0,200
14	202,29	177,85	158,95	143,93	0,312	0,278	0,253	0,233
16	233,54	205,33	183,52	166,17	0,356	0,318	0,289	0,267

In the case of trusses with a continuous elastic lateral support to the compression chord, the following tables will be used to illustrate differences between current codes and the proposed amended rules:

Table 7 SABS 0163 force requirement for continuous support to a single compression member in a braced system

Pitch	17,5°	20,0°	22,5°	25,0°
Span (m)	Force induced in bracing membrane or frame, q_B (kN/m)			
6	0,148	0,132	0,120	0,111
8	0,148	0,132	0,120	0,111
10	0,148	0,132	0,120	0,111
12	0,148	0,132	0,120	0,111
14	0,148	0,132	0,120	0,111
16	0,148	0,132	0,120	0,111

The force, q_B, can be calculated by using the following equation:

$$q_B = \left(0{,}1 \cdot n^{0{,}7}\,\frac{P_A}{N+1}\right) \Big/ \left(\frac{span}{2}\right)$$

Where: $n = 1$
$N = 0$

Table 8 Stiffness and strength criteria for a single compression member that is continuously braced using the proposed new bracing criteria

Pitch	17,5°	20,0°	22,5°	25,0°	17,5°	20,0°	22,5°	25,0°
Span (m)	Required stiffness, β (kN/m/m)				Induced force in bracing membrane or frame, q (kN/m)			
6	**13,07**	**10,32**	**8,37**	**7,00**	**0,089**	**0,079**	**0,072**	**0,067**
8	**15,54**	**13,14**	**11,32**	**9,92**	**0,089**	**0,079**	**0,072**	**0,067**
10	*35,69*	*28,83*	*23,89*	*20,31*	*0,089*	*0,079*	*0,072*	*0,067*
12	*34,84*	*28,83*	*24,40*	*21,09*	*0,089*	*0,079*	*0,072*	*0,067*
14	*35,50*	*30,02*	*25,88*	*22,67*	*0,089*	*0,079*	*0,072*	*0,067*
16	***67,92***	***52,00***	***42,52***	***36,82***	***0,089***	***0,079***	***0,072***	***0,067***

Note: Values given in bold script are for buckling in single curvature. Values given in italic script are for buckling in S curvature and values in bold italic are for buckling in double S curvature.

It is important to note that the force criterion of SABS 0163 (1994) is more stringent than that of EC 5: Part 1-1:1992 or the proposed amended rule. If, however, the cumulative effect is taken into account, the resultant total force to be resisted by the bracing will be very similar.

The stiffness requirement of EC 5: Part 1-1:1992, which is based on a lateral deflection limit of span/700, will ensure double curvature or greater in the compression chords, so reducing the resultant load on the bracing system. It is therefore sensible to limit the net resultant force as given by EC 5: Part 1-1:1992.

The limits of current practice provide a useful benchmark in evaluating the potential impact of revised bracing rules. If, however, the limits of the much-favoured diagonal brace were to be investigated, the stiffness and strength of the connections between the compression member and the brace should be known.

Battens are usually nailed to the compression chord of timber trusses using a single 75 mm long round wire nail. The nail penetrates the compression chord to a depth of approximately 38 mm. Load transfer through such a connection is achieved by means of shear but only the top of the compression chord is directly restrained. In the case of a bracing frame, the load transfer is fairly direct, as the bracing frame is fixed to the underside of the battens and is therefore in line with the chords. Any attempt at quantifying the overall efficiency of the diagonal brace must include some allowance for the influence of the nailed connection.

Stiffness of nailed connections

The important connection in a bracing system is the one between the batten that completes the triangulation with the truss and the diagonal brace, or alternatively the batten that is connected to the bracing frame. This connection is generally achieved by driving one 75 mm wire nail straight through the batten into the top chord of the truss. As no published values for this type of connection are available in South Africa, a preliminary study was undertaken at the University of Pretoria by the authors to establish the order of magnitude of the nail stiffness. Sixteen connectors, placed in timber varying in density from 350 kg/m^3 to 550 kg/m^3, were tested for stiffness and strength.

These relationships were obtained from a series of tests where the batten is axially loaded and the deflection is measured at the connector (see figure 5). Typical load-slip relationships of nailed connections are shown in graphs 1 and 2. Assuming a Weibull distribution for the stiffness of the connectors, a fifth percentile value of 600 N/mm resulted. If a normal distribution is assumed, the mean is 1 452 N/mm with a standard deviation of 477 N/mm and a fifth percentile stiffness of 750 N/mm. Although the number of tests was limited, the test results serve to illustrate the influence of the stiffness of the nailed joint on the bracing system.

The distribution of the nail stiffness should be taken into account in calculating the combined stiffness of two joints. In order to quantify the spring constant for a bracing system that consists of battens that are nailed to the top chord of the trusses, the stiffness of the batten must also be taken into account. The stiffness of the batten can vary along its length and the stiffness can differ from batten to batten. The battens may also be spliced along their length. Such splices can also lead to a large loss in stiffness, as the overall stiffness of a single brace may now be influenced by as many as six nails.

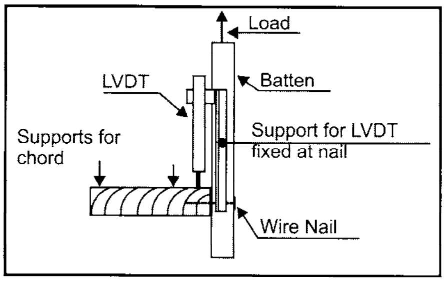
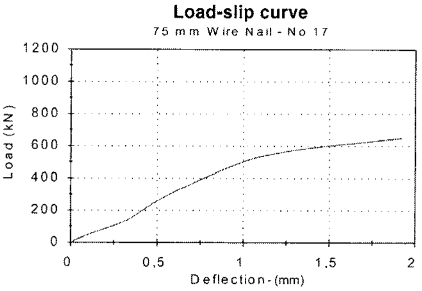
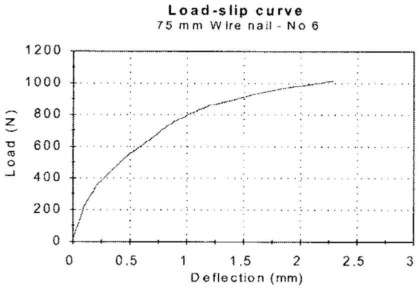


Figure 5 Schematic drawing of test setup used to determine the load-deflection curve for nailed joints

Graph 1 shows the load-slip curve for a nailed connection at the lower end of the stiffness scale and graph 2 the load-slip curve on the upper end. A nail driven into low-density timber could have stiffness as low as 513 N/mm and a nail in a high-density timber as high as 2 084 N/mm. The loading imposed by the tiles on the batten would not increase the stiffness of the connection but could increase the resistance μR, where R is the load due to the tiles and μ the coefficient of friction between the batten and the top chord.



Graph 1 Load-slip curve for nailed joint into lower-density timber



Graph 2 Load-slip curve for nailed joint in higher-density timber

Three parameters were used to determine the allowable load on the nailed connection, *viz* the mean divided by 3,0, the fifth percentile divided by 2,22 and the mean strength at a slip of 0,76 mm divided by 1,6. The allowable loads were 293 N, 229 N and 390 N respectively. These values are in keeping with SABS 0163-2. The characteristic strength of the nailed connection is therefore 229 N multiplied by 2,22, which is equal to 508 N. Adding the friction effect of the tiles would increase the permissible load by about 70 N. The maximum safe load on a single nailed connection can then be taken as about 300 N.

The cumulative effect on the strength of nailed joints can be ascertained by applying a Monte Carlo simulation (Hart 1982). A normal distribution is assumed and computer-generated numbers are used to simulate the stiffness distribution. The individual spring values may be added together by considering the stiffness of a number of springs in series. The combined stiffness of springs in series is given by:

$$\frac{1}{k_{sum}} = \sum_{i=1}^{n} \frac{1}{k_i}$$

Where: k_{sum} = the sum of the spring stiffnesses
k_i = the individual spring stiffness
n = number of springs

Using the Monte Carlo method and the values of spring stiffness as obtained from the tests to generate 100 theoretical stiffnesses, the values as given in table 9 were obtained. As the simulation is based on a limited number of tests, these values reflect at best an estimate of the actual stiffness.

Table 9 Stiffness of connection, for springs in series with assumed normal distribution in stiffness

Stiffness of connection (N/mm)				
No of springs	2	3	4	5
Mean stiffness	683	447	331	260
5th percentile stiffness	457	308	238	201

CURRENT PRACTICE AND THE INFLUENCE OF THE PROPOSED AMENDMENTS

For members braced by a diagonal brace only, the cumulative effect for a number of trusses that are braced by the same system is given in SABS 0163 (1994) by:

$$\text{Factor} = n^{0,7}$$

Where: n = the number of members supported by the same bracing system

If the same argument is used for the stiffness, it is possible to determine the number of trusses that can be braced at discrete points by a diagonal brace.

Consider the proposed stiffness and strength criteria as well as the EC 5: Part 1-1:1992 bracing criteria as a basis for calculating the bracing stiffness and strength. Assuming that there are no splices in the critical battens, that there are only two nailed connections involved in the bracing and that the batten has infinite stiffness, then the maximum number of trusses that can be braced by such a system is given in table 10. Table 10 assumes that the force and stiffness provided by the friction between the tiles cannot be defined and will under certain circumstances be negligible. Furthermore, the fifth percentile stiffness of 457 N/mm of the nailed connections must be reduced by a factor of 0,67 to allow for the long-term creep in the connection. The long-term stiffness of two connections = 306 N/mm.

Table 10 Maximum number of trusses that can be braced by a diagonal brace only, using strength and stiffness criteria of EC 5 and the proposed criteria shown in brackets

Pitch	17,5°	20,0°	22,5°	25,0°	17,5°	20,0°	22,5°	25,0°
Span (m)	Number of trusses using EC 5 stiffness criterion and (proposed)				Number of trusses using the strength criterion EC 5 and (proposed)			
6	5 (7)	6 (9)	7 (10)	8 (12)	2 (3)	3 (4)	3 (4)	3 (5)
8	4 (4)	5 (5)	5 (6)	6 (7)	2 (2)	2 (2)	2 (3)	2 (3)
10	3 (3)	3 (4)	4 (4)	4 (5)	1 (2)	2 (1)	2 (2)	2 (2)
12	2 (2)	3 (3)	3 (3)	4 (4)	1 (1)	1 (1)	1 (2)	1 (2)
14	2 (2)	2 (2)	3 (2)	3 (3)	1 (1)	1 (1)	1 (1)	1 (1)
16	2 (1)	2 (2)	2 (2)	3 (2)	1 (1)	1 (1)	1 (1)	1 (1)

Considering strength as a criterion, it is obvious that the diagonal bracing used at present in South Africa is totally inadequate, even for short-span roofs. Correct application of SABS 0163 (1994) leads to a similar conclusion. Table 10 shows that up to a span of about 8 m the stiffness of the bracing should be adequate. Given that under ultimate circumstances the average strength of the nailed connection could be as high as 900 N, with a stiffness of about 700 N/mm, it would explain why no failures have been reported for short-span roofs, having only diagonal bracing. Table 11 illustrates the possible number of trusses that could be carried under ultimate conditions. If two springs are used in series, the ultimate stiffness would be about 350 N/mm. Allowing for long-term creep, the stiffness can be reduced to about 235 N/mm.

Table 11 Maximum number of trusses that can be braced by diagonal bracing under ultimate conditions

Pitch	17,5°	20,0°	22,5°	25,0°	17,5°	20,0°	22,5°	25,0°
Span (m)	Number of trusses using proposed stiffness criterion				Number of trusses using the proposed strength criterion			
6	5	6	7	8	15	18	20	23
8	3	4	4	5	10	12	14	15
10	2	2	3	3	7	9	10	11
12	2	2	2	3	6	7	8	9
14	1	2	2	2	5	5	6	7
16	1	1	1	2	4	4	5	6

Although the diagonal bracing seems to work under ultimate conditions, the authors do not recommend that this be adopted as the standard. The authors accept that the argument will be used that diagonal bracing has been used to, supposedly, safely brace spans of up to 10 m. The history of such roofs is short, however, and the possibility of future problems cannot be eliminated. When-ever roofs are inspected only a few years after construction, a buckling problem, especially in the more highly stressed first rafter panel, will invariably be noticed. This is caused by the failure of the bracing system. Additional stabilising factors such as the shape of the roof can greatly enhance the strength and stiffness. These effects, however, are not readily quantifiable and should be ignored until further research has been undertaken.

CONCLUSION

It is evident that the current South African practice of bracing timber roofs with spans of up to 10,5 m by means of diagonal bracing only runs contrary to modern thinking and should not be permitted for roofs with a span greater than 8 m. Diagonal bracing stabilises the roof as a whole, but does not provide enough strength or stiffness to ensure that the assumed buckling length is obtained. Where only diagonal bracing is used to brace 8 m gable to gable roofs, the diagonal braces should be continuous over the full length of the roof, as in figure 6.

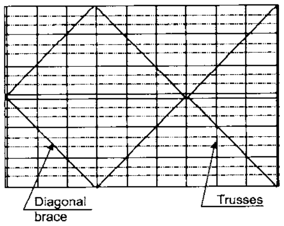


Figure 6 Continuous diagonal bracing of short-span roofs up to a maximum span of 8 m

For pitched roof trusses with spans in excess of 8 m, a set of diagonal braces to keep the apex in position, together with a bracing frame, should be used.

The bracing frame could consist of a single member that is fixed to the battens at a rafter. At all times the brace must have the required stiffness and strength. The stiffness of the bracing frame should be large enough to ensure that the midspan deflection under dead load conditions (between apex and eaves) is less than span/500. Alternatively the frame must have the required bracing stiffness as proposed. To simplify construction requirements on site, a set of practical details, for various spans and loadings, should be devised based on the proposed design parameters. These could be included in SABS 0243 (1992). It is recommended that SABS 0163 (1994) be revised to facilitate the introduction of the proposals.

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