Performance of Nailed Gusset Joints in Ridged Timber Portals

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ABSTRACT

The structural behaviour and performance of nailed plywood gusset knee joints of timber portal frames are investigated. An analytical study has shown, and experimental study has confirmed, that the behaviour of the joints in terms of strength and stiffness, distribution of stresses, and rotation of nail groups within the gusset haunches, is directly related to the joint's component arrangements, plywood grain orientation and the dowel action of the nails.

An empirical method is presented which permits calculation of the short-term ultimate strength of plywood gusset plates, for various component arrangements of the knee joints, based on the strain distribution along the critical section of the haunched gussets. It is shown that a considerable gain in ultimate strength and performance can be achieved if a correct joint configuration is used.

Key words: *nailed joints, plywood gussets, timber frames.*

INTRODUCTION

For many years timber portal frames with nailed haunched knee joints have been used extensively in farm and industrial buildings, as they provide economical buildings that can be easily constructed by semi-skilled labour. The use of timber as a cost effective alternative to other materials such as steel and concrete, depends to a significant extent on the structural efficiency of the joints, the cost of the components and the ease and speed of fabrication.

Joints have generally been the weakest link in timber structures which has necessitated research into the various types of mechanical connectors. The performance of the joints, in general, is determined by the material properties of the timber and connector, the joint configuration and the loading conditions.

General research studies by Bryant et al [5], Mack [8,9], Morris [10,11,12], Moss and Walford [13], and Smith et al [15,16] on nailed timber joints have developed theoretical and experimental understanding of the strength and stiffness of simple nailed joints subjected to short term loading. The effect of loading condition, moisture content, nail diameter and length, and timber species on simple nailed joints have been examined. Emphasis so far, by most investigators, has been placed on the more general aspects of the nailed joint behaviour rather than on the applied research studies, which for the purpose of the present investigation refers to the moment carrying haunched knee joints in timber frames.

Limited studies carried out so far, have mainly been concerned with the development of simple design methods for nailed plywood gusset knee joints. Two significantly different methods have evolved from studies at Timber Research And Development Association, UK [6] and American Plywood Association[14] which have been successfully used in design and construction of timber portal frames for more than two decades.

The method developed at TRADA assumes that the gusset strut acts as a prop to support the shear forces on the rafter and leg members, producing triangular tensile stress distributions in the plywood gussets. APA's method is based on an idealised strain distribution curve, obtained from test results, along the centre line of the haunch plates. In this method the gusset strut serves only to stiffen the compressive edge of gusset plates against buckling. Batchelar and Cavanagh [1] and Batchelar[2] have also made a study of nail jointed timber portals using laminated timber sections and reported similar conclusions to those of the APA.

In the last two decades only limited attempts have been made to investigate the real structural behaviour of the nailed plywood gusset knee joints for timber portal frames. What investigations have been carried out have been mainly concerned with the development of design procedures. The exami-

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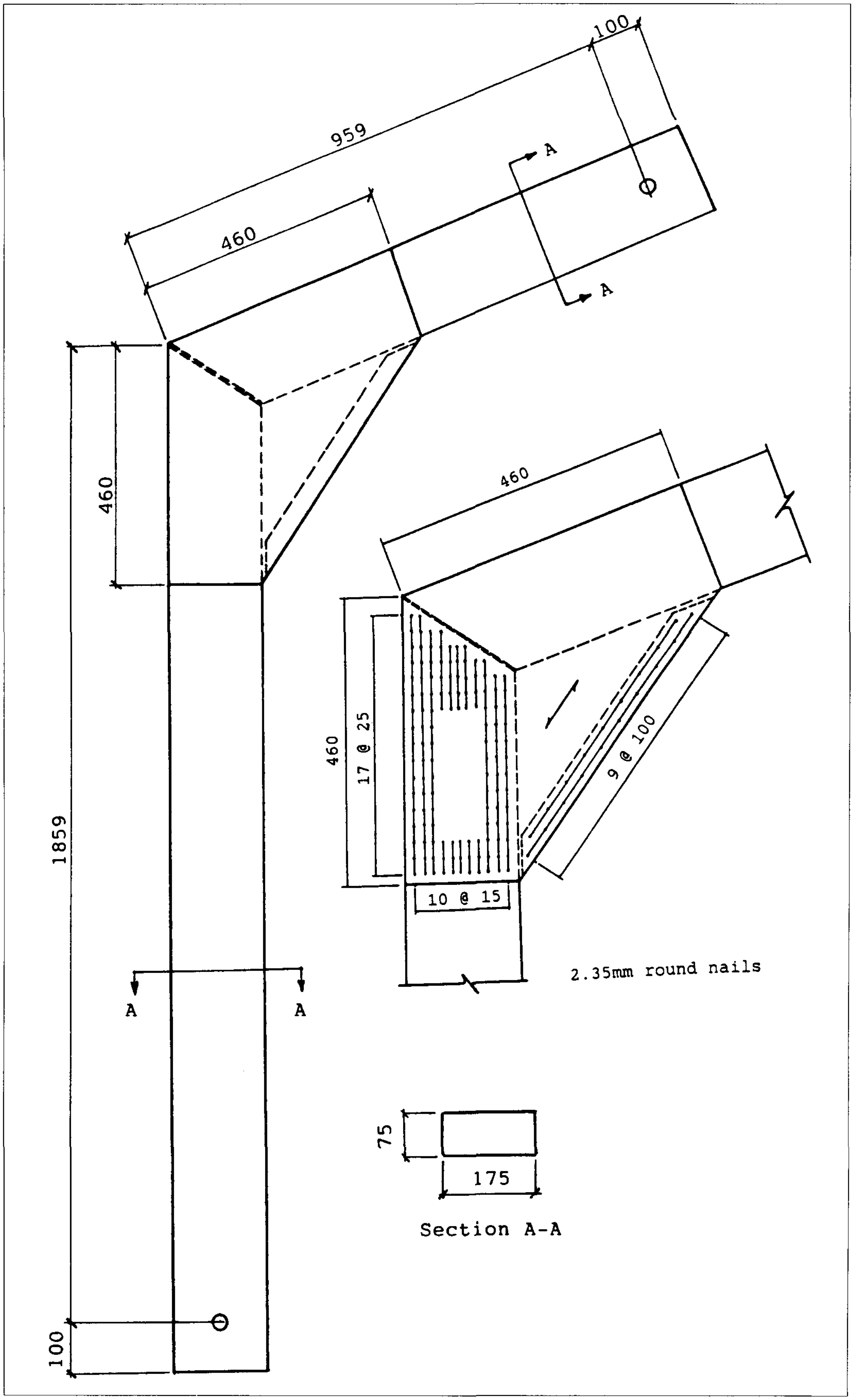
Figure 1: Details of a typical knee joint.



nation of the present design methods shows discrepancy between the methods and the assumed and real behaviour of these structures. The performance of the stiffener strut in the knee joints is not yet fully established and differs between the design methods. The effect of plywood gusset grain direction on the distribution of stresses and on the strength and stiffness of the haunched knee joints has been neglected, and so far no attempt has been made to determine the effects of member arrangements on the structural behaviour of haunched joints to justify the preference of one joint's member arrangement to another.

In this paper results of the experimental work on a set of nailed plywood gusset knee joints are described and compared with those of finite element analysis. Also an empirical formulation for the prediction of the short-term ultimate strength of the plywood gussets of the knee joints is presented.

DESCRIPTION OF TEST JOINTS

The joints were designed as a part (knee joint) of a half scaled 12m span timber portal frame with hinged feet, in accordance with BS 5268 [3]. The height of the frame from floor to eave was 3.6m and to apex was 6.0m. The dimensions of a typical knee joint of the twelve specimens tested are shown in Figure 1. The effective leg lengths shown were chosen in order to produce, when loaded, a correct combination of forces and moments as those produced in the actual portal knee joints. This was due to the fact that joints with equal leg lengths, as tested by previous investigators (1, 2, 14), were considered to be an unlikely representation of the actual frame behaviour.

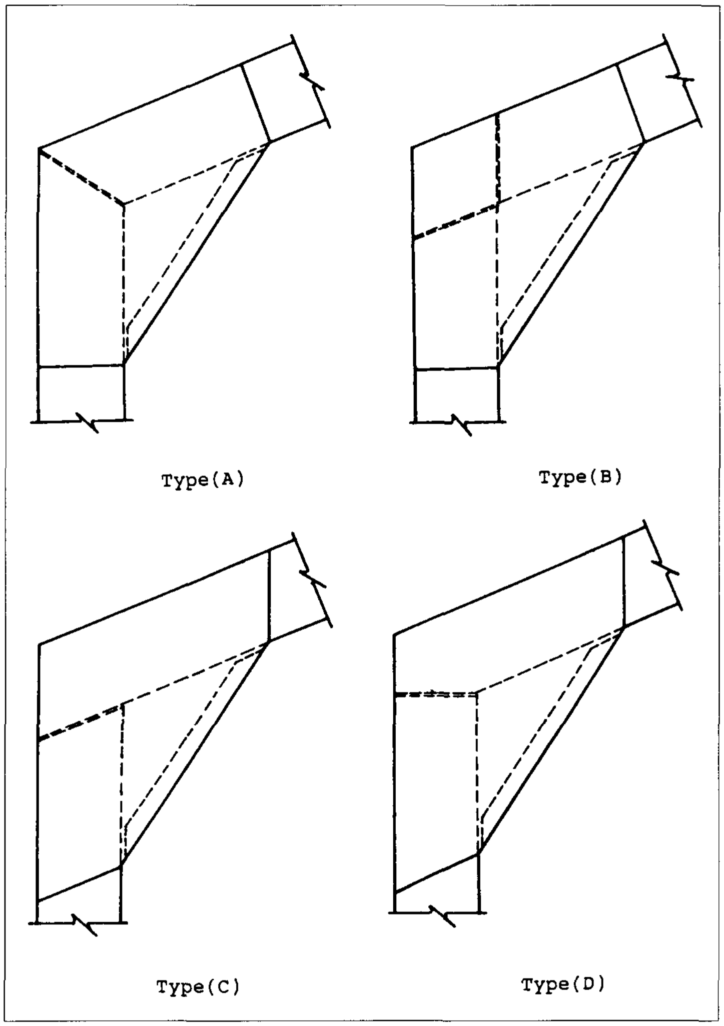


Figure 2. Knee joint types.

Classification of the joints

The joints were classified on the basis of their component arrangements, see Figure 2, into the following types :

Type(A): Joints with mitred timber legs along the centre line of the gusset plates.
Type(B): Joints with timber legs being alternately lapped over eachother.
Type(C): Joints with rafter leg passing over the column leg.
Type(D): Joints with rafter leg resting over the column leg and the touching ends being perpendicular to the column leg.

Materials

TIMBER: The timber members were cut from British grown Douglas fir grade SS, 75 x 250mm sections. The timber sections were air-dried and allowed to come to equilibrium moisture content in the laboratory before fabrication and were then tested within 72 hours. The moisture content at the time of testing was around 14 ± 2%.

PLYWOOD: With the exception of joint A1 for which 9mm 5-ply Finnish conifer plywood was used, 6.5mm 5-ply sanded Finnish birch- faced plywood was used for the gusset plates of all joints. A total of 145 specimens, based on BS 5412 [4], were made and

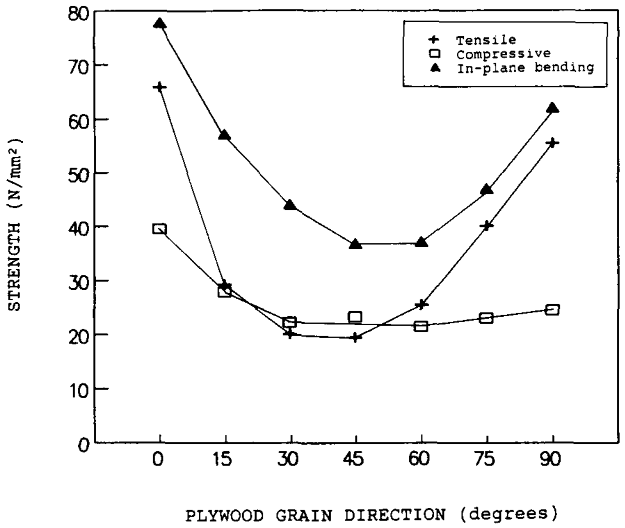


Figure 3. Effect of grain direction on strength of the plywood.

the tensile, compressive, and in-plane static bending strengths of the plywoods with respect to their grain directions were determined. In Figure 3 the significant effects of grain orientation on the strengths of Finnish birch-faced (6.5mm, 5-ply) plywood are shown.

NAILS: 2.35mm diameter, 40mm long round wire nails were used for all joints. The gusset plate nailing pattern was arrived at by assuming a pattern and then determining its moment, thrust, and shear resistance. By trial and error it was possible to arrive at a nail pattern in which the load on the average nail did not exceed the safe lateral strength, for the size used, as specified in BS 5268 [3]. A typical nailing pattern for the tested joints is shown in Figure 1.

FINITE ELEMENT MODELLING OF THE HAUNCHED JOINTS

The anticipated joint behaviours were investigated with a commercially available finite element computer programme, PAFEC. The plywood gussets were analysed as multi-layer laminated plates and timber sections as three-dimensional elements. Details of the finite element modelling of the joints are given elsewhere [7]. The analytical modelling was carried out in the following two stages.

i. The members and gusset plates of the joints were assumed to be homogeneous and isotropic. In this analysis the elastic and linear behaviour of the joints were examined and the effects of the plywood grain directions were ignored. This was to determine areas of high stress concentrations, and the magnitude and direction of the principal stresses developed during elastic loading on the plywood gusset plates irrespective of grain direction effects. The results of these analyses were then used in experimental work for the correct positioning of the strain gauges on the plywood gussets. Also the effects of various joint component arrangements on the distribution of the stresses on the gusset plates were examined. In Figure 4, the stress vectors on the plywood gussets of joints Type (A) with and without the stiffener strut in position are shown.

ii. The members and gusset plates of the joints were considered to be homogeneous and orthotropic. The structural properties of the materials and load-slip characteristics of nailed-joints were determined from the tests and used in the analysis [7]. In this analysis the non-linear behaviour of the joints was examined and the effects of the plywood grain directions were considered. In Figure 5, the effects of the plywood grain direction on the stress distribution within the plywood gussets of joints Type (A) are compared.

EXPERIMENTAL VERIFICATION

Twelve moment resisting portal knee joints were constructed and tested. Details of the joints are summarised in Table 1. The data acquired during the joint tests consisted of the following:

a. The hydraulic pressure in the tension ram, applied by a hand pump, measured by means of a pre-calibrated proving ring. The Design Load for the joints tested was equivalent to 4.82kN load produced in the tension ram.

b. Deflections of the joints, and the relative movements between plywood gussets and timber members were recorded in x and y directions, at pre-determined points, by displacement transducers.

c. Strain distribution in plywood gusset plates and timber members was measured using strain gauges (TML-PL10), a data logger, micro computer, and a printer. A total of 26 strain gauges were connected to each joint, measuring strains along the principal axes of the plywood gussets.

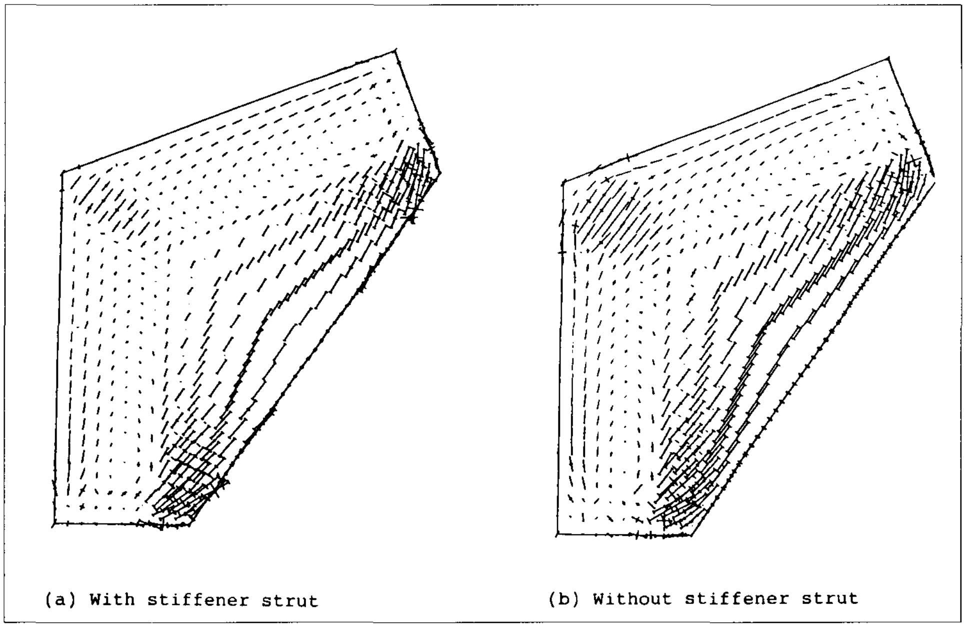


Figure 4. Stress vectors on the plywood gussets of joints Type (A).

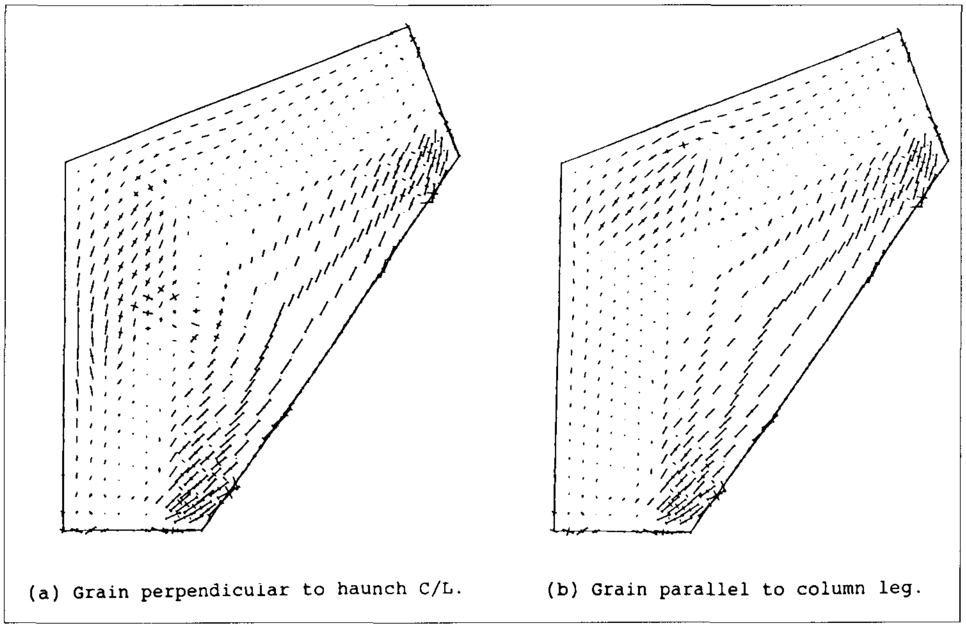


Figure 5. Effect of grain direction on stress vectors of joints Type (A).

d. The testing procedure was designed to satisfy the recommendations of BS 5268 [3]. These included the pre-load, the 24 hour deflection, and the strength tests.

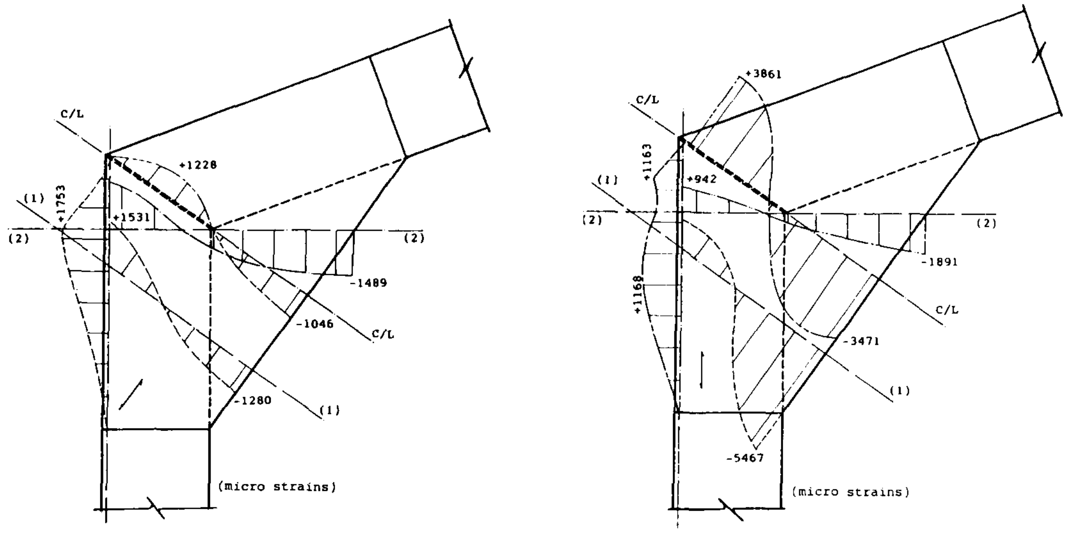
The load was applied in equal increments (10% of the Design Load). Time taken to measure and record the data at each loading interval was five minutes.

Discussion

Three series of tests were carried out on the knee joints. At first a preliminary joint of Type(A), (ie. joint A1), was constructed and tested. This was to establish a testing method and draw guidelines for the subsequent tests.

In the second series, the effects of member arrangements and the plywood face grain orientation on the behaviour, stiffness, and ultimate strength of the described joint Types were investigated.

In Figure 6 strain distribution along various axes of the plywood gusset of joints Type(A) with the plywood grain direction perpendicular to the haunch



(a) Grain perpendicular to haunch C/L (joints A1 and A2).

(b) Grain parallel to column leg (joint A3).

Figure 6. Strain distribution in joints Type (A).

centre line, and parallel to the column leg at a load of 2 x Design Load are shown.

With plywood grain direction perpendicular to the gusset centre line, up to the load level of 90% of the Design Load, the behaviour of joints Type (A) was similar to those described by APA [14]; in which the critical strain distribution was assumed to occur along the gusset centre line, see Figure 7. With an increase in load, the tensile strain along the gusset's outer edge at a position with the shortest distance from the inner mitred edges of the timber legs, increased rapidly, see Figure 8. This phenomenon indicated that the critical strain distribution, at and above working load levels, occurs along an axis perpendicular to the column leg and passes through the point of intersection of the inner edges of the mitred legs. The failure loads for joints A1 and A2 were 5.7 and 5.6 x Design Load respectively and occurred by tearing of the plywood along the gusset edge near the crown which in turn buckled the compressive edge of the gusset.

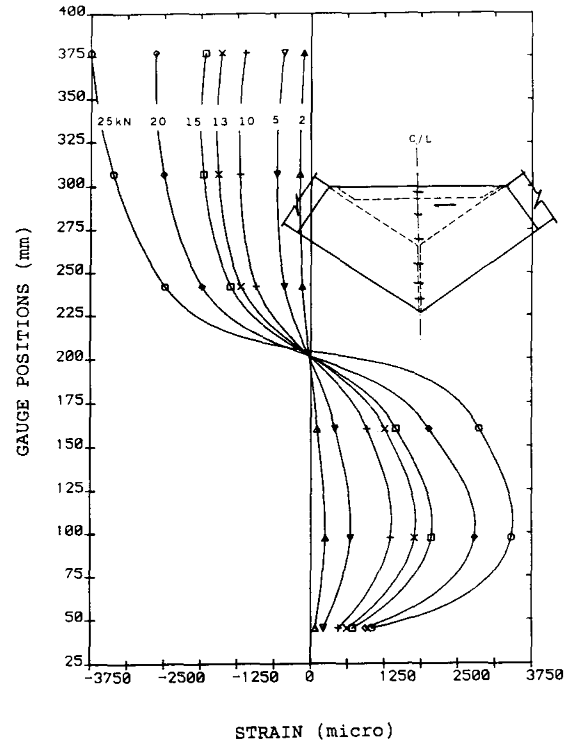


Figure 7. Strain distribution on the C/L of plywood gussets of joint Type (A).

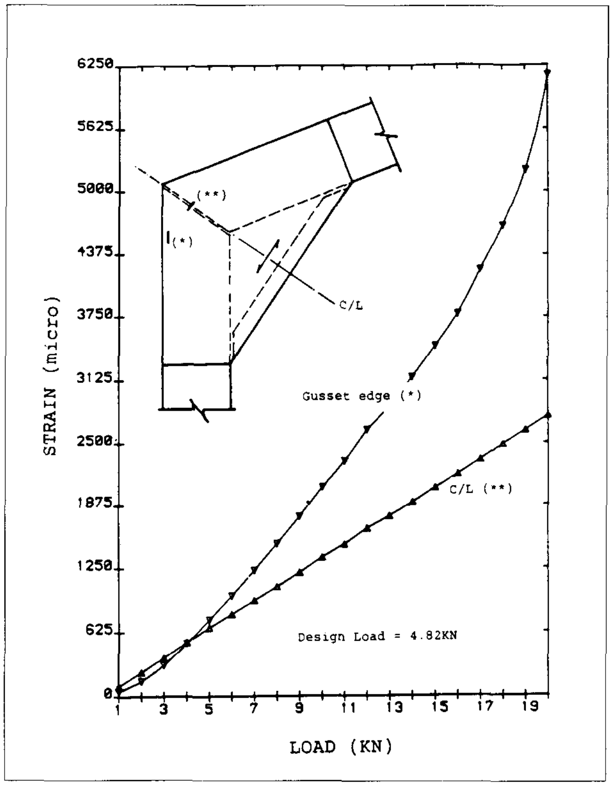
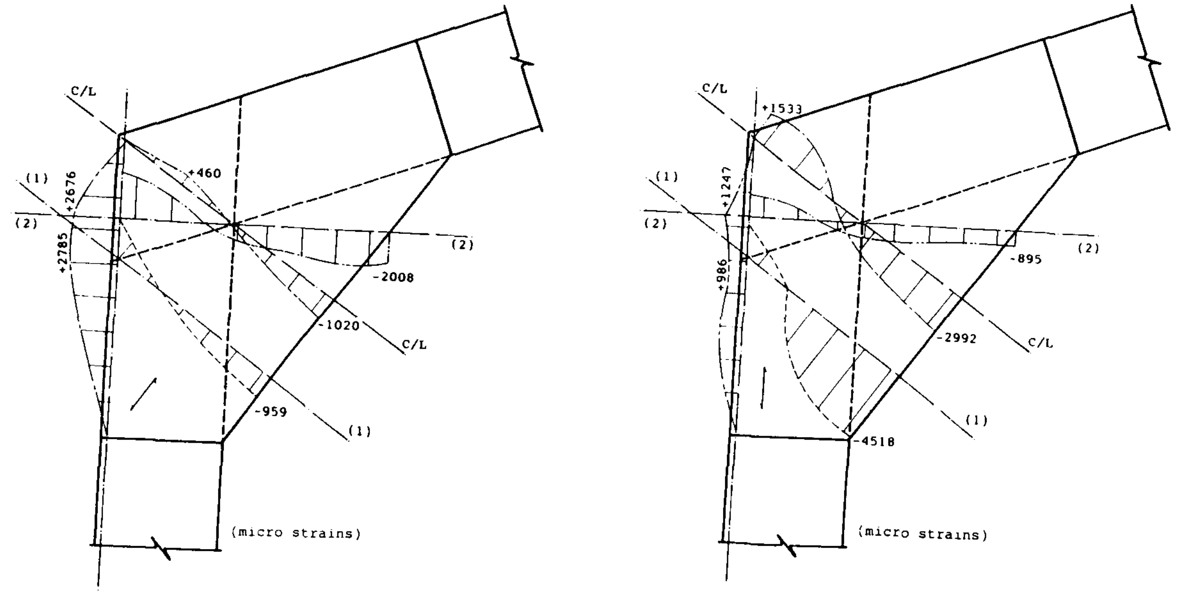


Figure 8. Maximum tensile strains along the gusset C/L and its outer edge, joint Type (A).

The effect of the plywood grain direction being parallel to the column leg on the behaviour and ultimate strength of the joints Type(A) was examined by joint A3. On average the strain magnitudes recorded for this joint were over 3 times those recorded for joints A1 and A2. At 2.8 x Design Load joint A3 failed by splitting of the plywood gussets along grain direction which in turn caused the buckling of the stiffener strut near the column leg.

In Figures 9, 10, and 11, the strain distributions on the plywood gussets of joints B1 and B2, C1 and C2, and D1 of Types (B), (C), and (D) along various axes for a load equal to 2 x Design Load are shown respectively. A summary of the results is given in Table 1.

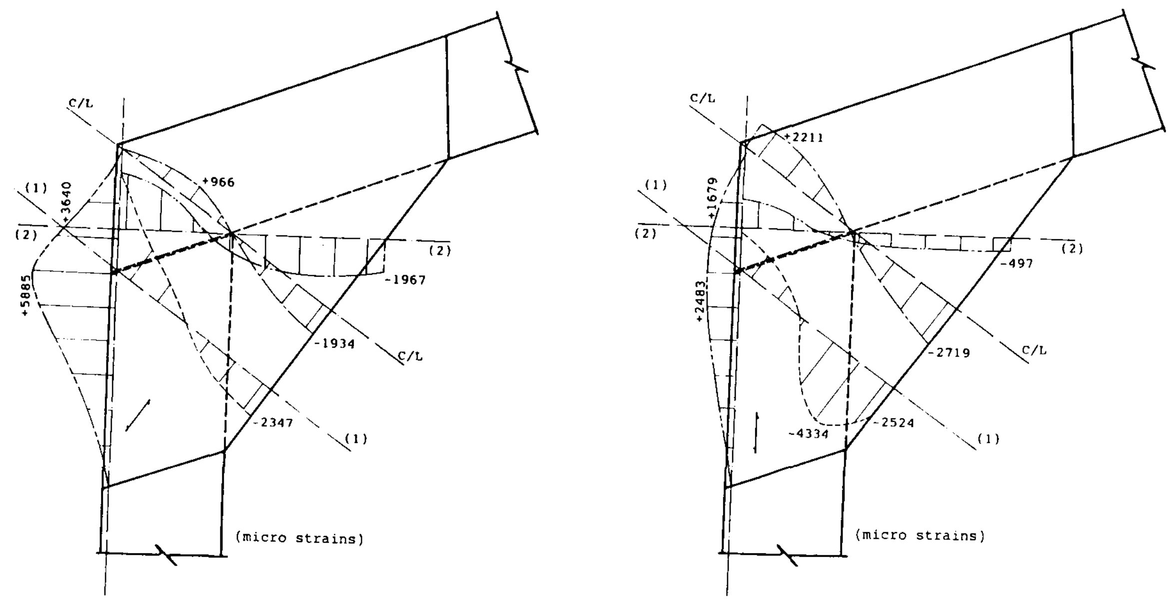
From a comparison of the results of the second test series, it became evident that the joints of Type(A) with the plywood gusset grain direction perpendicular to the haunch centre line were by far the best performed joints in terms of stiffness and short-term ultimate strength. Hence, this joint type was chosen for the third series of tests to examine the effects of the contact between the rafter and column legs, the stiffener strut ends bearing, reduction in number of nails, and the thickness/strength of the plywood



(a) Grain perpendicular to haunch C/L (joint B1).

(b) Grain parallel to column leg (joint B2).

Figure 9. Strain distribution in joints Type (B).



(a) Grain perpendicular to haunch C/L (joint C1).

(b) Grain parallel to column leg (joint C2).

Figure 10. Strain distrubition in joints Type (C).

gussets on the behaviour and ultimate strength of the joints.

Effect of gap between rafter and column leg

With all joints reported above there was full contact between rafter and column legs which caused pivoting of the members during loading. In order to examine the possible effects of the elimination of pivoting, the touching ends of the legs of joint A4 were tapered to provide a gap of 20mm between the inner edges of the mitred ends.

Although the strain distribution pattern recorded for this joint was similar to those of joints A1 and A2, a reduction of up to 15% in strain magnitudes at high stress concentration areas was noted; whereas strains at less critical areas had increased by varying magnitudes. This indicated that the stresses were being transferred into the plywood gussets more evenly and through more nails.

As the load increased above the Design Load the plywood gussets gradually started to move inwards

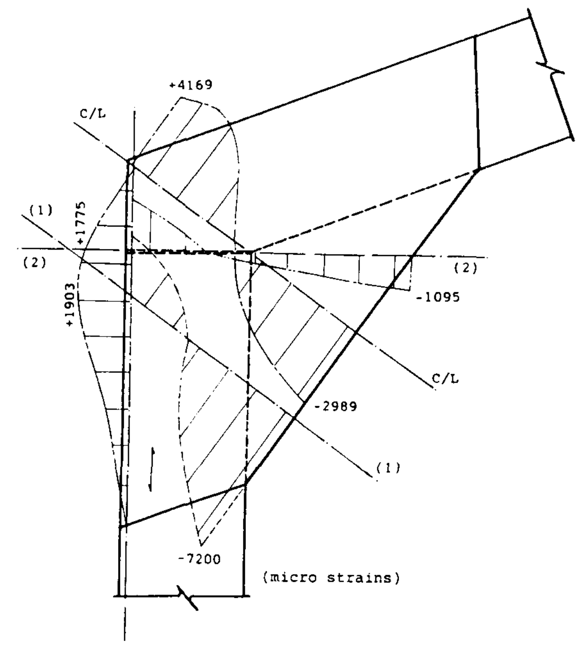


Figure 11. Strain distribution in joint D1 with grain parallel to column leg.

away from the joint crown, preventing the stiffener strut ends from contacting joint legs and hence joint failed, at 5.2 x Design Load, by buckling of the compressive edge of the gusset plates.

Effect of stiffener strut ends bearing

The ends of the stiffener strut in joint A5 were glued and screwed onto the joint legs prior to the nailing of the plywood gussets onto the joint legs. Up to 3.5 x Design Load the behaviour of this joint was similar to the joints with a gap between strut ends and timber legs; except that the neutral axes and the position of the maximum tensile strains had moved down away from the joint crown, and the compressive strains along the inner gusset edges were on average 10% greater than those in the former joints. With increase in load, the compressive stress in the stiffener strut increased transferring the load to the inner edges of the gusset plates; until the joint failed in compression at 5.4 x Design Load.

Effect of nailing density

The observation of the deformation, rotation of nail groups, and slip between plywood and timber members of the tested joints showed that the magnitude of the load carried by a nail depended on the position of the nail and therefore its distance from the geometric centre of the nail group. The magnitude of nail deformation reduced as its distance became closer to the geometric centre of the nail group. The failure of the plywood gussets in all joints also suggested the possible over-nailing of the joints. Hence, the effects of reduction in number of nails were examined by elimination of the nails closest to their geometric centre. Joint A6 was constructed with 33% less nails in which the inner ring of nails, shown in Figure 1, was eliminated.

The overall behaviour of this joint, up to 4 x Design Load, was similar to the joints with initial nailing pattern. Above this load level the rotation of the gusset plates with respect to timber legs increased considerably. This behaviour caused the gussets to move inwards, away from the crown, and in turn prevented the stiffener strut ends from contacting joint legs. At 5.2 x Design Load, the joint failed by buckling of the stiffener strut.

Effect of plywood gusset thickness/strength

The effects of plywood gusset thickness/strength were examined by joint A7 which was constructed with four plywood gussets (two on each side) glue laminated together prior to nailing. The face grain direction of all four plywood plates was perpendicular to the haunch centre line. The strain distribution pattern, as it was expected, was similar to the joints Type (A), but the magnitude of strains recorded along any axis was almost halved. The joint failed at 6.1 x Design Load of the previous joints. The failure occurred in the timber (column) leg below the gusset plates.

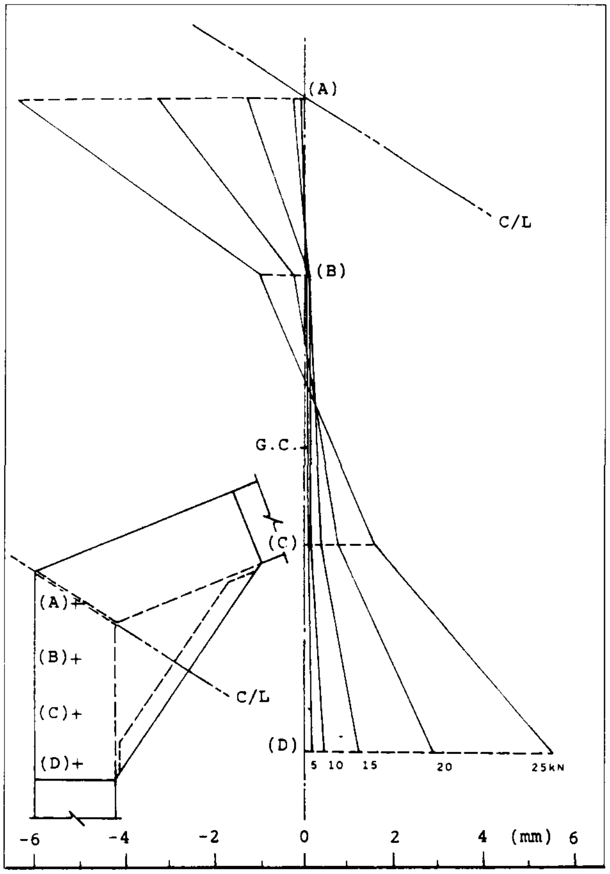


Figure 12. Rotation/slip of the nail group on the plywood gussets of joints Type (A), with respect to column leg.

Deformation and rotation of the joints

In Figure 12 the rotation/slip of the plywood gusset, with respect to leg member, in a direction perpendicular to the leg of joint Type (A) is shown. The slip of plywood in a parallel direction to the leg was negligible.

At low stress levels, the shear in the haunch was carried mainly by friction between the gusset plates and the joint legs. With increase in load, slip began to

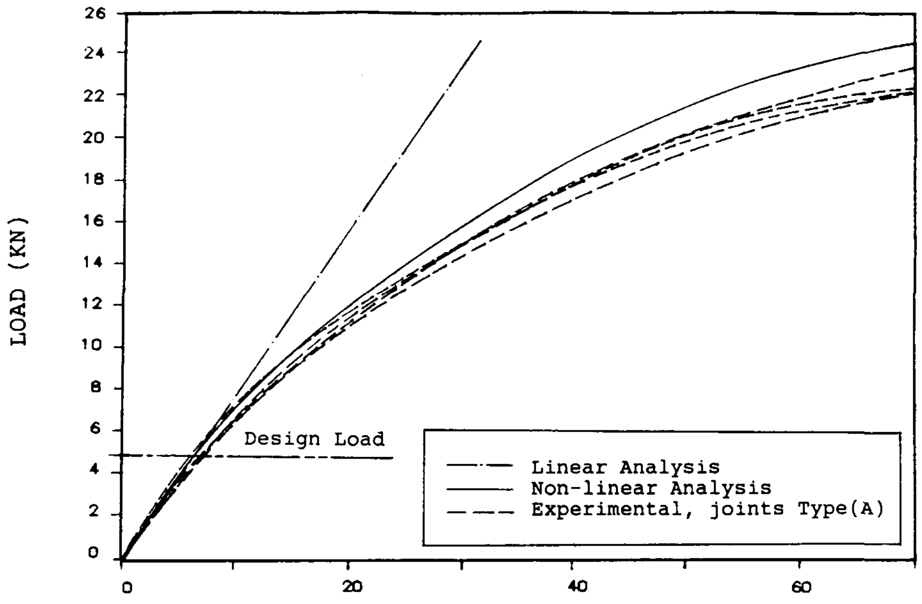


Figure 13. Deformation of joints Type (A).

take place until the nails came into bearing. At this point, as frictional resistance was overcome and nails started to bear, rotation started to take place with its centre near the centre line of the joint. As the load increased the centre of rotation moved downwards away from the haunch centre line towards the geometric centre of the nail group.

This behaviour was recorded for rotation of the nails on both legs of joints Type (A); whereas the centre of rotation on rafter legs of other joint Types remained close to the centre line of the gussets at all load levels.

At Design Load, the maximum relative motion recorded between the load points of the joints'legs was 9.1mm which occurred in joint B2. The creep during the 24 hour deflection tests was insignificant and the joints recovered over 88% of their deformation when loads were removed.

Finite element analysis

With the linear analysis and assuming isotropic plywood and timber materials, the stress magnitudes obtained compared well with the experimental results for up to 90% of the Design Load. But with increase in load the load-deformation characteristics of the joints became non-linear. Hence, the linear analysis were no longer relevant in estimating the deformation and stress distributions of the joints.

With the non-linear analysis and considering homogeneous and orthotropic materials, the relative motion calculated between the load points of the joint legs compared well with the experimental results. In Figure 13 the experimental and analytical deformation of the joints of Type (A) are compared.

The comparison of the analytical stress magnitudes with the experimental ones showed up to 30% discrepancy at 5 x Design Load. The explanation for a greater proportion of this error lies with the errors induced in the conversion of the stresses into strains. The determination of an appropriate Modulus of Elasticity to cater for the effects of both non-uniform combined stresses and plywood grain direction effects involves completely different problems and merits a separate study.

Failure modes

With increase in load above the Design Load, the nails furthest away from their geometric centre started to deform.These nails increased in effectiveness until they reached their ultimates; from that point on they continued to deform more or less under constant load. Hence, the increased load was carried by the adjacent nails until they too reached their ultimates. This behaviour simultaneous with increase in recorded strains, continued until the plywood gussets reached their ultimate tensile/ compressive strength depending on the joints'

Table 1. Details of the tested joints.

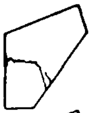
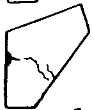
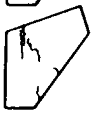
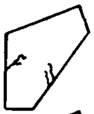
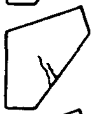
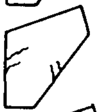
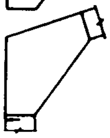
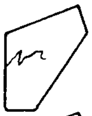
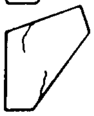
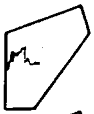
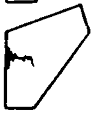
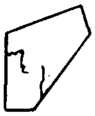
Joint Type	Joint Ref.	Plywood grain-direction	Ultimate Load (KN)	Strength Factor	Failure mode	Remarks
A	A1	⊥ to C/L	27.5	5.7		preliminary test
	A2	⊥ to C/L	27.0	5.6		
	A3	∥ to leg	13.5	2.8		grain ∥ to leg
	A4	⊥ to C/L	25.0	5.2		gap between mitred ends
	A5	⊥ to C/L	26.0	5.4		stiffener ends bearing
	A6	⊥ to C/L	25.0	5.2		33% nail reduction
	A7	⊥ to C/L	29.5	6.1		double gussets
B	B1	⊥ to C/L	20.0	4.1		
	B2	∥ to leg	19.5	4.0		
C	C1	⊥ to C/L	14.0	2.9		
	C2	∥ to leg	20.5	4.2		
D	D1	∥ to leg	15.0	3.1		

Table 2. Calculated and experimental Ultimate Loads.

Joint Type	Grain Direc.	Critical Axis	Critical Stress	RELATIONSHIP	Calc.Load P_u, (KN)	Exp.Load P_u, (KN)
A	⊥ to C/L	(2-2)	Tension	$M.P_t + P.L(0.136\ P_b - 0.304\ P_t) - 0.2726\ t.L^2.P_b.P_t = 0$	18.0	25.75
	,,	(2-2)	Comp.	$M.P_c + P.L(0.250\ P_b - 0.054\ P_c) - 0.5075\ t.L^2.P_b.P_c = 0$	27.0	,,
	‖ to leg	(1-1)	Tension	$M.P_t + P.\ L(0.167\ P_b - 0.208\ P_t) - 0.333\ t.L^2.P_b.P_t = 0$	11.8	13.5
	,,	(1-1)	Comp.	$M.P_c + P.\ L(0.250\ P_b) - 0.50\ t.L^2.P_b.P_c = 0$	16.6	,,
B	⊥ to C/L	(2-2)	Tension	$M.P_t + P.L(0.152\ P_b - 0.280\ P_t) - 0.305\ t.L^2.P_b.P_t = 0$	20.0	20.0
	,,	(2-2)	Comp.	$M.P_c + P.L(0.212\ P_b + 0.008\ P_c) - 0.424\ t.L^2.P_b.P_c = 0$	24.3	,,
	‖ to leg	(C/L)	Tension	$M.P_t + P.\ D(0.168\ P_b - 0.170\ P_t) - 0.336\ t.D^2.P_b.P_t = 0$	20.3	19.5
	,,	(C/L)	Comp.	$M.P_c + P.\ D(0.216\ P_b + 0.046\ P_c) - 0.432\ t.D^2.P_b.P_c = 0$	23.8	,,
C	⊥ to C/L	(3-3)	Tension	$M.P_t + P.L(0.149\ P_b - 0.271\ P_t) - 0.298\ t.L^2.P_b.P_t = 0$	12.4	14.0
	,,	(3-3)	Comp.	$M.P_c + P.L(0.242\ P_b - 0.024\ P_c) - 0.484\ t.L^2.P_b.P_c = 0$	18.1	,,
	‖ to leg	(C/L)	Tension	$M.P_t + P.\ D(0.161\ P_b - 0.162\ P_t) - 0.322\ t.D^2.P_b.P_t = 0$	19.5	20.5
	,,	(C/L)	Comp.	$M.P_c + P.\ D(0.179\ P_b + 0.111\ P_c) - 0.357\ t.D^2.P_b.P_c = 0$	19.9	,,
D	‖ to leg	(1-1)	Tension	$M.P_t + P.\ L(0.162\ P_b - 0.224\ P_t) - 0.324\ t.L^2.P_b.P_t = 0$	11.9	15.0
	,,	(1-1)	Comp.	$M.P_c + P.\ L(0.284\ P_b - 0.031\ P_c) - 0.569\ t.L^2.P_b.P_c = 0$	16.7	,,

member arrangement and plywood grain orientation. As anticipated, failure was initiated at areas recorded of having high stress concentration and continued along the critical axis of the gussets. The failure modes are illustrated in Table 1.

EMPIRICAL STUDY

One of the significant results obtained from the experimental work was the location of the strain distribution along the critical axis/section of the gussets. It was shown that the location of the line of critical strain depends on the joint component arrangements and grain direction of the plywood gusset plates.

In order to develop an empirical method for calculation of the strength of the plywood haunched joints, the strain distribution through the critical section of the gusset was idealised for each joint type. The forces contained in the stress blocks (ie. tensile and compressive stresses) were balanced with respect to the neutral axis of the line of critical strain, enabling the moments of resistance of the sections to be determined.

As a typical example, the analysis for a joint of Type(A) with plywood gussets' grain direction perpendicular to the centre line of the joint is given, and results of the analyses for the remaining joint types are shown in Table 2.

Consider the strain distribution along the critical axis (2-2) shown in Figure 14.

$$T = (2/3).2t.f_t.(0.32\ L) = 0.426\ t\ .\ L\ .\ f_t \tag{1(a)}$$

$$C = (7/12).2t.f_c.(0.68\ L) = 0.793\ t\ .\ L.\ f_c \tag{1(b)}$$

where ,

$$f_t = \sigma_t - (\ P/A\ )$$

$$f_c = \sigma_c + (\ P/A\ )$$

$$A = 2t\ .\ L$$

where, σ_c and σ_t are the maximum bending stresses on the compressive and tensile sides of the neutral axis respectively.

Assuming that the Interaction Equation can be applied, hence:

$$((\ P/A\ )\ /\ P_{c/t}\ ) + (\ \sigma_{c/t}\ /\ P_b\ ) = 1$$

ie. $\sigma_t = P_b.\ (\ 1 - P\ /\ (\ A\ .\ P_t\ ))$

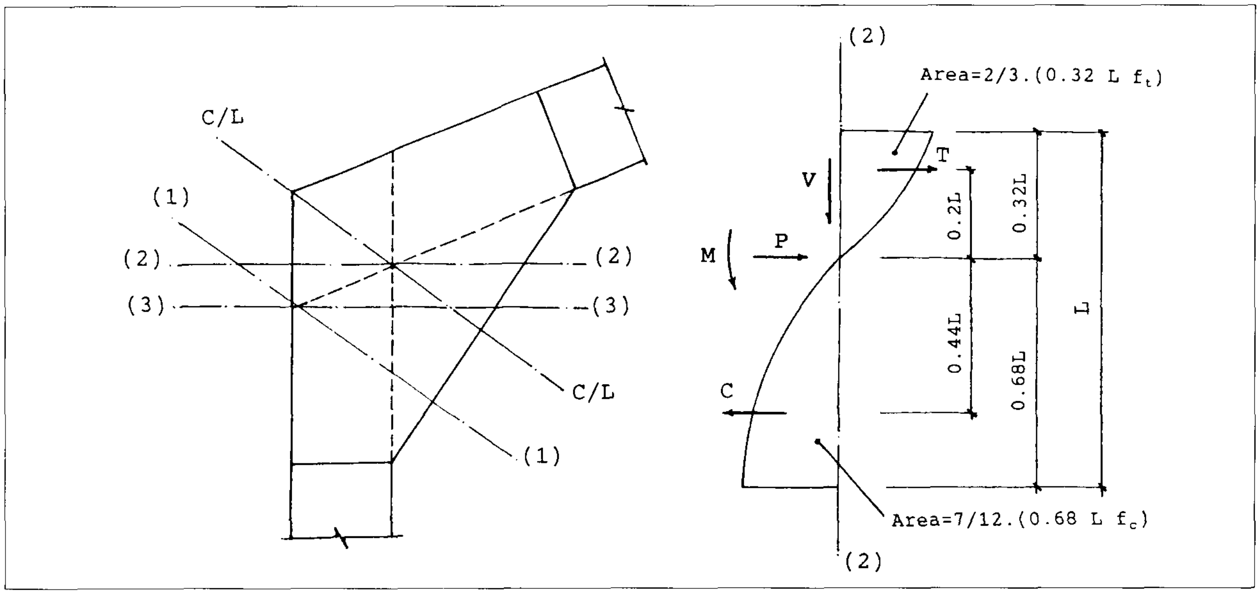


Figure 14. Strain distribution along the critical axis.

and $\sigma_c = P_b . (1 - P / (A . P_c))$

thus, by substituting for σ_t and σ_c in (i) & (ii)

ie. $f_t = P_b (1 - P / (A . P_t)) - P/A$
and $f_c = P_b (1 - P / (A . P_c)) + P/A$

Substitute f_t and f_c in 1(a) and 1(b) respectively,

$$T = 0.462\, t . L . (P_b (1 - P / (A . P_t)) - P/A) \qquad 2(a)$$

$$C = 0.793\, t . L .(P_b (1 - P / (A . P_c)) + P/A) \qquad 2(b)$$

From Figure 14

$$T + P = C \qquad 3(a)$$

Also by summing of the moments about N.A.

$$M - 0.2\, L . T - 0.44\, L . C = 0 \qquad 3(b)$$

Therefore,

$$T = (M - 0.44\, L . P) / 0.64\, L \qquad 4(a)$$

$$C = (M + 0.20\, L . P) / 0.64\, L \qquad 4(b)$$

By equating 4(a) to 2(a) and 4(b) to 2(b), equations 5(a) and 5(b) were obtained. They relate the load carrying capacity of the plywood gusset to its tensile and compressive strengths along axis (2-2), respectively.

$$M. Pt + P. L .(0.136\, P_b - 0.304\, P_t) - 0.2726\, t. L^2. P_t.P_b = 0 \qquad 5(a)$$

$$M. P_c + P. L .(0.25\, P_b - 0.0541\, P_c) - 0.5075\, t. L^2. P_c.P_b = 0 \qquad 5(b)$$

P and M are definable in terms of the applied load. If P_b, P_t, and P_c express the permissible in-plane bending, tensile, and compressive stresses in the plywood gussets in the direction perpendicular to axis (2-2); from equations 5(a) and 5(b) the minimum thickness of the plywood gussets (t) required to carry the applied load for an arbitrary haunch size (L) can be determined.

Alternatively, for a known haunch gusset size and thickness, if P_b, P_t, and P_c express the ultimate stresses in the plywood gussets in the direction perpendicular to axis (2-2), it is possible to calculate the minimum load carrying capacity of the plywood gussets.

The analysis presented here is applicable to the joints with the geometrical proportions and nailing pattern described and tested. For joints of different geometrical proportions or loaded so as to "open" the knee joint, a modified form of the proposed method could be applied.

CONCLUSIONS

The investigation has shown that the structural behaviour of the nailed plywood gusset knee joints depends entirely upon the member arrangements in the joints, and the grain orientation of the plywood gusset plates. The effects of these factors on the ultimate strength and stiffness of the joints were significant and are summarised below. These conclusions relate to situations where the moment is closing the knee joints.

1. Of all possible knee joint component arrangements tested, joints with timber legs mitred at the haunch centre line and with plywood gussets' grain direction perpendicular to the haunch centre line were found to produce the best joint performance as defined by their ultimate strength. They were on average over 25% stronger than the joints with rafter member passing over the column member, and over 28% stronger than the joints with alternately lapped members.

2. The effect of the plywood gussets' grain direction was well pronounced in joints with legs mitred at the haunch centre line. The ultimate strength of these joints was reduced by 47% when the plywood face grain direction changed from perpendicular to the haunch centre line, to parallel to the column leg.

3. The stiffener strut ends bearing on timber legs had little or no effect upon the strain distribution or the ultimate strength of the joints. It functioned only as a stiffener for the inside edges of the gusset plates against buckling.

4. It was shown that it is possible to approximately predict the short term ultimate strength of the haunched plywood gusset plates, for various component arrangements of the knee joints, based on the strain distribution along the line of critical axis of the haunched gussets.

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Nomenclature

P_b, P_t, P_c : Permissible/ultimate plywood stresses in bending, tensile, and compression in the direction appropriate to the line of critical strain axis.

L : Depth of plywood gussets along the line of critical strain axis.

D : Depth of plywood gusset at C/L.

M : Applied moment at the N.A. of the critical section.

P : Applied force perpendicular to the critical section at N.A.

t : Thickness of the plywood gusset.

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APPENDIX

1. Example of Design

Consider the design of the plywood gusset plates for the knee joints of the pinned-feet timber portal frame shown in Figure 15.

If the frame is loaded via (say) 13 equally spaced purlin points; using a standard plane-frame computer program, the reactions at each base are found as:

V = 18.0 kN, H = 6.7 kN.

150 x 350mm (Douglas fir, grade SS) sections for both rafter and leg members were found to satisfy the requirements of BS 5268 [3].

Assume gusset depth at C/L of 2.3 times the depth of leg members, ie. d = 2.3 x 350 = 805mm, hence: L = 795mm.

For Finnish birch-faced (6.5mm, 5-ply) plywood, for medium-term loading, the permissible stresses given by BS 5268 are:

P_c = 7.53 x 1.25 = 9.41 N/mm2
P_t = 9.67 x 1.25 = 12.1 N/mm2
P_b = 9.67 x 1.25 = 12.1 N/mm2

The value in tension, with face grain parallel to the span, is used for the grade plywood stress in bending, because the material is being bent in plane, rather than as a flat plate.

M = 6.7 x 103 (3600-214) - 18 x 103 (246-175)
= 21.4 x 106 Nmm P = 18.0 x 103 N

Substituting for M, P, P_c, P_t, P_b in Eqns.5(a) and 5(b) and solving for t, therefore:

If tensile strength is critical, from Eqn.5(a)
t = 9.01mm
If compressive strength is critical, from Eqn.5(b)
t = 6.45mm

Hence, the minimum required plywood thickness is: t = 9mm

2. Ultimate Strength

In the knee joints of the above portal, the plywood grain direction is perpendicular to the haunch C/L which makes an angle of 34° with axis(2-2),

Figure 16. The ultimate strengths of the Finnish birch-faced plywood obtained from the test results, Figure 3, are as follows:

$P_b =$ 41.0 N/mm2
$P_c =$ 20.4 N/mm2
$P_t =$ 18.6 N/mm2

P and M are both directly proportional to the applied load. To express M in terms of P, where the M/P ratio at N.A. of the axis (2-2) is 21.4x106/18x103, then: M = 1180 P.

If two 6.5mm thick gussets are used on each side (t=13mm); by substituting for M, t, P_b, P_t, P_c in Eqns. 5(a) and 5(b), hence:

From Eqn.5(a) P_u = 78.0 kN (if tension is critical)

From Eqn.5(b) P_u = 111.3 kN (if compression is critical)

Hence, the ratio of Ultimate/Design Load (P_u/P), based on the tensile strength = 78.0/18 = 4.3 based on the compressive strength = 111.3/18 = 6.1

Therefore, the gussets should have a minimum short-term strength ratio of 4.3.