Structural Design of Buildings

Trussed and cut roofs

Prepared by

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Trussed and cut roofs

Modern truss roofs

Cut roofs

Roof components

Wind bracing

Roof spread

Overloading of roof members

Alterations to roof structures

Traditional timber frame building trusses

Modern rafter design

Flat roof construction

Reference :

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2. This document is intended to be used by engineers to provide guidance in designing and evaluating timber roof truss structures. Do not attempt to design a timber roof truss structure without adult supervision from a qualified professional (preferably an experienced timber engineer). The Timber Frame Engineering Council (TFEC) and the Timber Framers Guild (TFG) assume no liability for the use or misuse of this document. TFEC-4 Committee: Jim DeStefano, P.E., AIA, F.SEI chairman Ben Brungraber, Ph.D., P.E. David Connolly, P.E. Jeff Hershberger, E.I. Jaret Lynch, P.E. Leonard Morse-Fortier, Ph.D., P.E. Robin Zirnhelt, P.Eng

Illustrations by Ken Flemming and Josh Coleman

INTRODUCTION

For covering large industrial or residential areas, to protect them against rain, sun, dust or other natural vagaries, we require roofing. The material used for roofing are called roof covering, which may range from tiles, corrugated steel and asbestos sheets to light FRP covers and tarpaulins. However, these materials are not structurally strong enough to support themselves and need to be supported by steel or concrete structures. Beams are some of the more common structural elements to support roofs. But when the area and the span also to be covered become too large, beams also become too heavy and uneconomical as structural members. The next most common type of roof supporting structures are truss elements, called roof trusses. Roof trusses are composed of tension and compression members joined together by welding or riveting. Purlins are the members which carry the roof cladding directly and are subjected to bending as in . The shape of the roof trusses are determined largely by the area and space to be covered, the use under which the covered premises is put and the type of roof cover used. The truss can be visualized as beam with inclined flanges and open web

Trussed and cut roofs

Essentially there are two types of roof: trussed roofs and cut roofs. In the context of a truss roof, we are not talking about a traditional truss roof but the modern truss roof. Modern truss roofs were introduced in America in the late 1940s, but they were not introduced in the UK until after 1964. Truss roofs are constructed using fabricated structural members held together using plates nailed to the timber members. The weakest part of the truss is arguably the steel plate. Conversely, a cut roof is one where the members are all "cut" from individual timber members, screwed, nailed or bolted together.

Modern truss roofs

There are a number different types of truss used in construction, and these are manufactured by specialist companies who calculate the loadings, spacing of the trusses and member sizes. A diagram of the different types can be seen in but the most common is a fink or "W" truss.

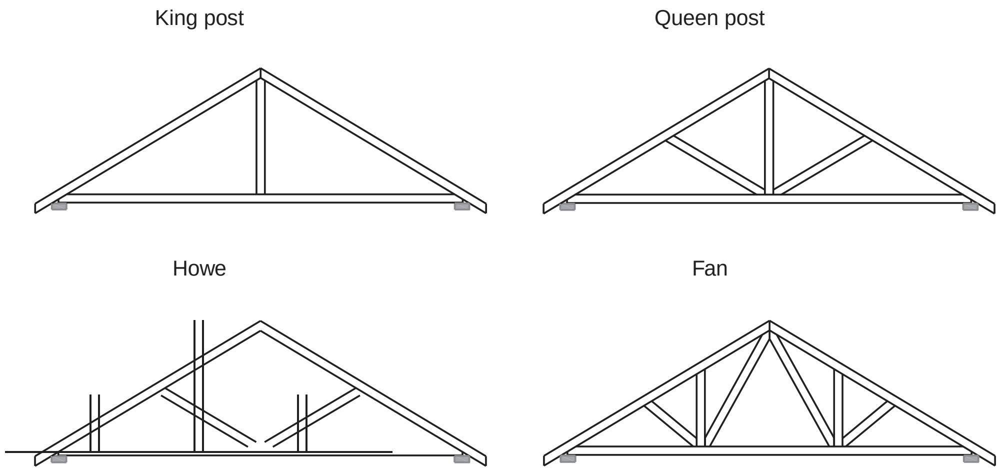
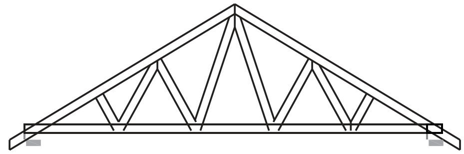
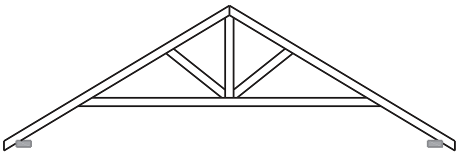


Figure.1: Different modern truss types.

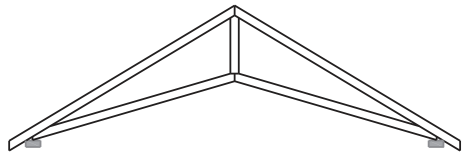
Double fink/Double W



Raised tie



Scissor



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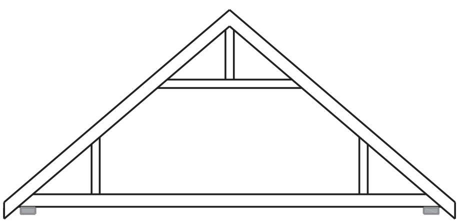
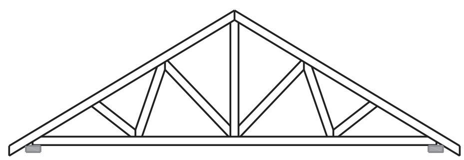
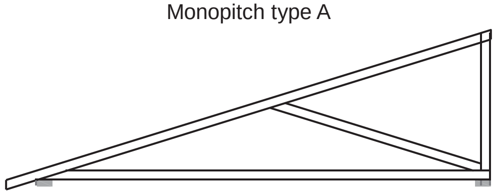


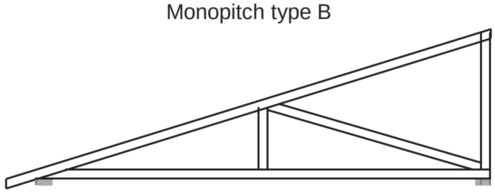
Modified queen



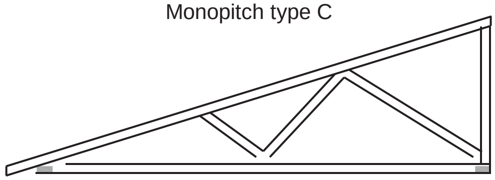
Monopitch type A



Monopitch type B



Monopitch type C



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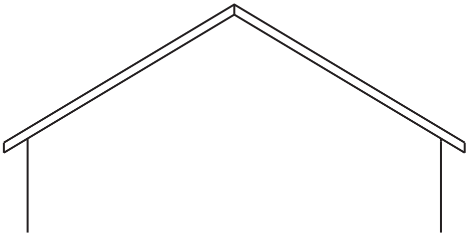
Cut roofs

There are different types of cut roofs, and diagrams of these can be seen below.

- ✓ **Coupled roof**

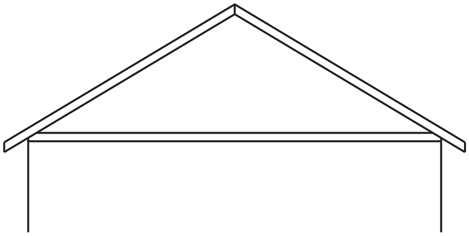
A coupled roof has two members supported by the walls.



Coupled roof.

- ✓ **Close coupled roof**

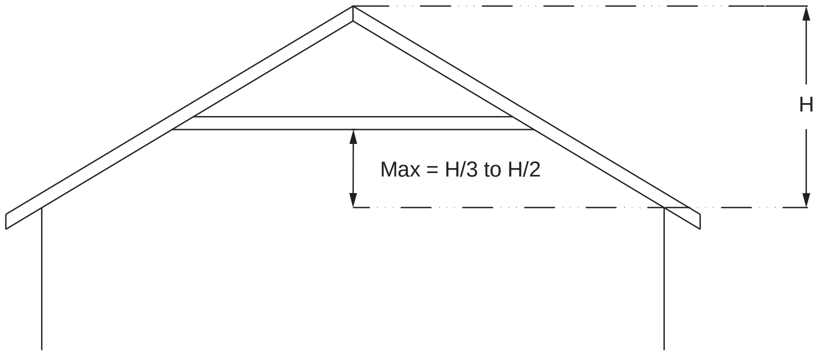
A close coupled roof has a ceiling joist ensuring triangulation of the roof frame.



Close coupled roof.

Collared roof

A collared roof has a joist but this is secured higher than the eaves and to be effective the collar is placed between a half and a third of the vertical height of the distance between the eaves and the ridge.

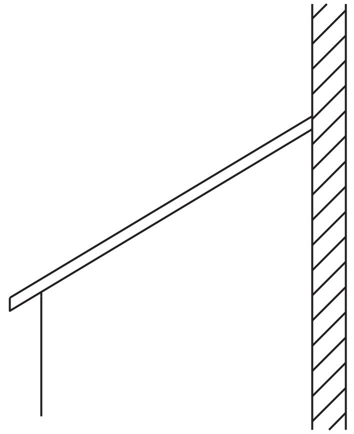


Collared roof.

Lean to roof

As the name suggests, this type of roof leans against a wall which continues above the lean to roof.

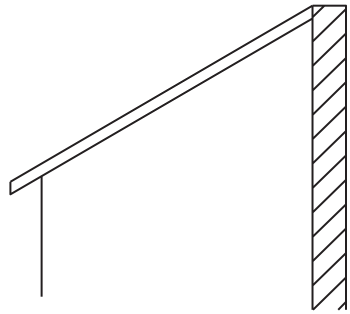
Lean to roof.



Monopitch roof

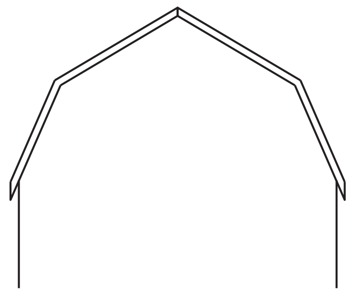
In this situation the roof slopes in one direction only and the wall at the highest slope does not continue.

Monopitch roof.



Mansard roof

This type of roof is more common in the west of the country, in such places as Cornwall and Gloucestershire, and in countries such as Holland and America. This is a cut roof and for small spans can accommodate additional rooms in the roof. This type of roof structure is also known as a Dutch or gambrel roof.



Gambrel roof.

Hipped roof

To prevent the height of a roof appearing excessive, a hip can be placed on the end or both ends of the roof. This may be necessary as a planning condition to maintain the style and character of roofs in the area, or so as not to dominate surrounding features and architecture.

The primary purpose of a roof is to ensure that moisture does not penetrate into the build- ing, but at the same time it has to be strong enough to sustain the imposed, dead and wind loads to which it is exposed.

Roof components

Rafters

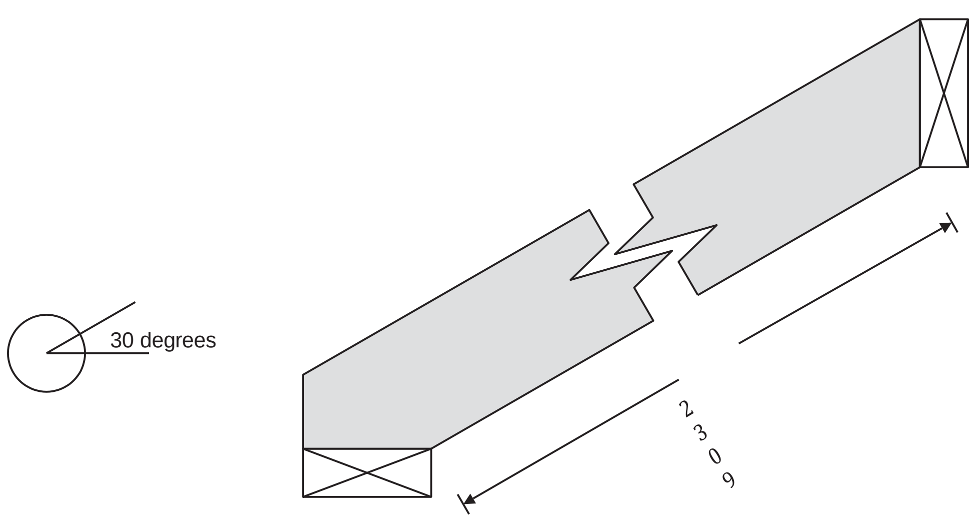
The rafters support battens to which the tiles or slates of the roof covering are attached. The rafter size will depend on the loads, and one of the first failures is deflection. Although the roof does not structurally fail, it may sustain large deflections and undulations along its length if the loading, particularly the dead load, is too heavy for the rafter section used. Rafters are subject to compressive and bending stresses and their size and spacing is important in accommodating such stresses. Care has to be taken when changing a roof covering to ensure the rafter size, span and spacing are still able to accommodate the new load.

The rafters connect to a wall plate which is secured to the wall, and the principle is to direct as much of the force vertically to the walls from the rafters as possible and minimise the horizontal force, since walls act better in compression and can sustain vertical loads far more resiliently than lateral or horizontal loads. Therefore, roofs are designed to ensure that loads are directed vertically. A steeper-pitched roof will be more efficient in directing forces vertically and minimising the horizontal thrust on walls. A bird mouth cut on the rafter where it adjoins the wall plate also tries to achieve the maximum likelihood of vertical rather than horizontal thrusts.

An example of a rafter design can be seen below. Let us consider 47 mm × 125 mm rafters at 400 mm centres with an imposed load of 0.75 kN/m^2 and a dead load as measured on the slope of 0.70 kN/m^2. The roof has a proposed slope of 30° and we will use a C16 grade structural timber.

These calculations have been undertaken using structural engineering software and we gratefully acknowledge Tekla (UK) Ltd for their approval in the use of this software.

TIMBER RAFTER DESIGN (BS 5268-2: 2002).



Rafter details

Breadth of timber sections;	$b = \mathbf{47}$ mm
Depth of timber sections;	$h = \mathbf{125}$ mm
Rafter spacing;	$s = \mathbf{400}$ mm
Rafter slope;	$\alpha = \mathbf{30.0}$ deg
Clear span of rafter on horizontal;	$L_{clh} = \mathbf{2000}$ mm
Clear span of rafter on slope;	$L_{cl} = L_{clh}/\cos(\alpha) = \mathbf{2309}$ mm
Rafter span;	**Single span**
Timber strength class;	**C16**

Section properties

Cross-sectional area of rafter;	$A = b \times h = \mathbf{5875}\ mm^2$
Section modulus;	$Z = b \times h^2/6 = \mathbf{122396}\ mm^3$
Second moment of area;	$I = b \times h^3/12 = \mathbf{7649740}\ mm^4$
Radius of gyration;	$r = \sqrt{(I / A)} = \mathbf{36.1}$ mm

Loading details

Rafter self-weight;	$F_j = b \times h \times \rho_{char} \times g_{acc} = \mathbf{0.02}$ kN/m
Dead load on slope;	$F_d = \mathbf{0.70}\ kN/m^2$
Imposed load on plan;	$F_u = \mathbf{0.75}\ kN/m^2$
Imposed point load;	$F_p = \mathbf{0.90}$ kN

Modification factors

Section depth factor;	$K_7 = (300\ mm/h)^{0.11} = \mathbf{1.10}$
Load sharing factor;	$K_8 = \mathbf{1.10}$

Consider long-term load condition

Load duration factor;	$K_3 = \mathbf{1.00}$
Total UDL perpendicular to rafter;	$F = F_d \times \cos(\alpha) \times s + F_j \times \cos(\alpha) = \mathbf{0.258}$ kN/m
Notional bearing length;	$L_b = F \times L_{cl}/[2 \times (b \times \sigma_{cp1} \times K_8 - F)] = \mathbf{3}$ mm
Effective span;	$L_{eff} = L_{cl} + L_b = \mathbf{2312}$ mm

Check bending stress

Bending stress parallel to grain;	$\sigma_m = \mathbf{5.300}\ N/mm^2$
Permissible bending stress;	$\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8 = \mathbf{6.419}\ N/mm^2$
Applied bending stress;	$\sigma_{m\_max} = F \times L_{eff}^2/(8 \times Z) = \mathbf{1.408}\ N/mm^2$

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain;	$\sigma_c = \mathbf{6.800}\ N/mm^2$
Minimum modulus of elasticity;	$E_{min} = \mathbf{5800}\ N/mm^2$
Compression member factor;	$K_{12} = \mathbf{0.63}$
Permissible compressive stress;	$\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12} = \mathbf{4.697}\ N/mm^2$
Applied compressive stress;	$\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha))/(2 \times A) = \mathbf{0.176}\ N/mm^2$

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress;	$\sigma_e = \pi^2 \times E_{min}/\lambda^2 = \mathbf{13.944}\ N/mm^2$
Euler coefficient;	$K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12}/\sigma_e) = \mathbf{0.988}$
Combined axial compression and bending check;	$\sigma_{m\_max}/(\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max}/\sigma_{c\_adm} = \mathbf{0.259}$; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain;	$\tau = \mathbf{0.670}\ N/mm^2$
Permissible shear stress;	$\tau_{adm} = \tau \times K_3 \times K_8 = \mathbf{0.737}\ N/mm^2$
Applied shear stress;	$\tau_{max} = 3 \times F \times L_{eff} / (4 \times A) = \mathbf{0.076}\ N/mm^2$

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff}$ = **6.936** mm

Bending deflection; $\delta_b = 5 \times F \times L_{eff}^4 / (384 \times E_{mean} \times I)$ = **1.426** mm

Shear deflection; $\delta_s = 12 \times F \times L_{eff}^2 / (5 \times E_{mean} \times A)$ = **0.064** mm

Total deflection; $\delta_{max} = \delta_b + \delta_s$ = **1.490** mm

PASS – Total deflection within permissible limits

Consider medium-term load condition

Load duration factor; K_3 = **1.25**

Total UDL perpendicular to rafter; $F = [F_u \times \cos(\alpha)^2 + F_d \times \cos(\alpha)] \times s + F_j \times \cos(\alpha)$ = **0.483** kN/m

Notional bearing length; $L_b = F \times L_{cl} / [2 \times (b \times \sigma_{cp1} \times K_8 - F)]$ = **5** mm

Effective span; $L_{eff} = L_{cl} + L_b$ = **2314** mm12

Check bending stress

Bending stress parallel to grain; σ_m = **5.300** N/mm^2

Permissible bending stress; $\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8$ = **8.024** N/mm^2

Applied bending stress; $\sigma_{m\_max} = F \times L_{eff}^2 / (8 \times Z)$ = 2.642 N/mm^2

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain; σ_c = **6.800** N/mm^2

Minimum modulus of elasticity; E_{min} = **5800** N/mm^2

Compression member factor; K_{12} = **0.59**

Permissible compressive stress; $\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12}$ = **5.510** N/mm^2

Applied compressive stress; $\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha)) / (2 \times A)$ = **0.330** N/mm^2

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress; $\sigma_e = \pi^2 \times E_{min} / \lambda^2$ = **13.916** N/mm^2

Euler coefficient; $K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12} / \sigma_e)$ = **0.979**

Combined axial compression and bending check; $\sigma_{m\_max} / (\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max} / \sigma_{c\_adm}$ = **0.396**; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain; τ = **0.670** N/mm^2

Permissible shear stress; $\tau_{adm} = \tau \times K_3 \times K_8$ = **0.921** N/mm^2

Applied shear stress; $\tau_{max} = 3 \times F \times L_{eff} / (4 \times A)$ = **0.143** N/mm^2

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff}$ = **6.943** mm

Bending deflection; $\delta_b = 5 \times F \times L_{eff}^4 / (384 \times E_{mean} \times I)$ = **2.680** mm

Shear deflection; $\delta_s = 12 \times F \times L_{eff}^2 / (5 \times E_{mean} \times A)$ = **0.120** mm

Total deflection; $\delta_{max} = \delta_b + \delta_s$ = **2.800** mm

PASS – Total deflection within permissible limits

Consider short-term load condition

Load duration factor; K_3 = **1.50**

Total UDL perpendicular to rafter; $F = F_d \times \cos(\alpha) \times s + F_j \times \cos(\alpha)$ = **0.258** kN/m

Notional bearing length; $L_b = [F \times L_{cl} + F_p \times \cos(\alpha)] / [2 \times (b \times \sigma_{cp1} \times K_8 - F)]$ = **6** mm

Effective span; $L_{eff} = L_{cl} + L_b$ = **2315** mm

Check bending stress

Bending stress parallel to grain; σ_m = **5.300** N/mm^2

Permissible bending stress; $\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8$ = **9.629** N/mm^2

Applied bending stress; $\sigma_{m\ max} = F \times L_{eff}^2 / (8 \times Z) + F_p \times \cos(\alpha) \times L_{eff} / (4 \times Z)$ = **5.099** N/mm^2

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain; σ_c = **6.800** N/mm^2

Minimum modulus of elasticity; E_{min} = **5800** N/mm^2

Compression member factor; K_{12} = **0.55**

Permissible compressive stress; $\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12}$ = **6.182** N/mm^2

Applied compressive stress; $\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha)) / (2 \times A) + F_p \times \sin(\alpha)/A$ = **0.253** N/mm^2

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress; $\sigma_e = \pi^2 \times E_{min} / \lambda^2$ = **13.902** N/mm^2

Euler coefficient; $K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12} / \sigma_e)$ = **0.985**

Combined axial compression and bending check; $\sigma_{m\_max} / (\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max} / \sigma_{c\_adm}$ = **0.578**; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain; τ = **0.670** N/mm^2

Permissible shear stress; $\tau_{adm} = \tau \times K_3 \times K_8$ = **1.106** N/mm^2

Applied shear stress; $\tau_{max} = 3 \times F \times L_{eff} / (4 \times A) + 3 \times F_p \times \cos(\alpha) / (2 \times A)$ = **0.275** N/mm^2

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff}$ = **6.946** mm

Bending deflection; $\delta_b = L_{eff}^3 \times (5 \times F \times L_{eff} / 384 + F_p \times \cos(\alpha)/ 48) / (E_{mean} \times I)$ = **4.429** mm

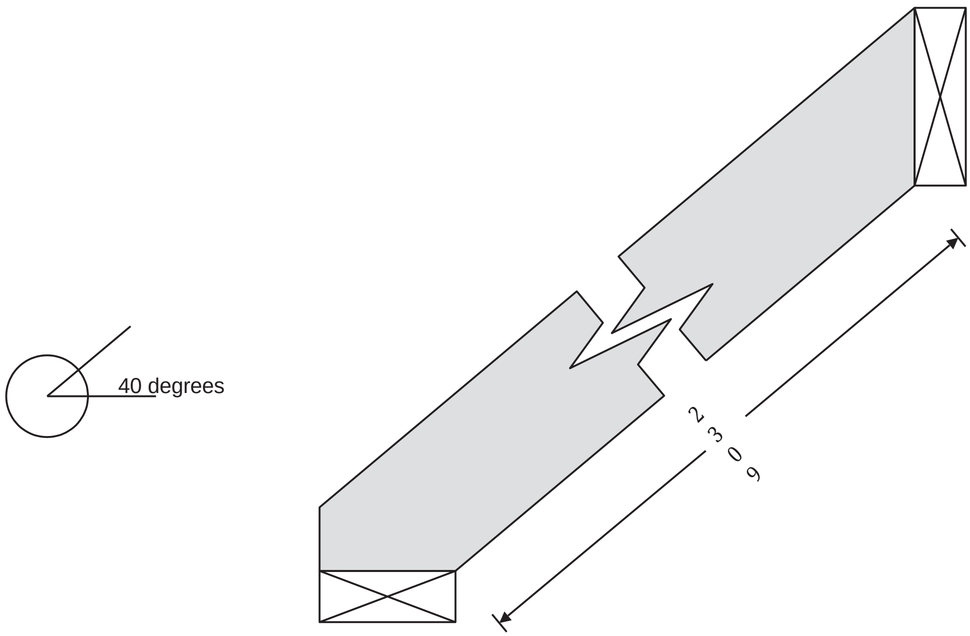
Shear deflection; $\delta_s = 12 \times L_{eff} \times (F \times L_{eff} + 2 \times F_p \times \cos(\alpha)) / (5 \times E_{mean} \times A)$ = **0.232** mm

Total deflection; $\delta_{max} = \delta_b + \delta_s$ = **4.660** mm

PASS – Total deflection within permissible limits

Let us take the same example and ascertain the effect of changing the pitch from 30° to 40°, with all other criteria remaining the same.

These calculations have been undertaken using structural engineering software and we gratefully acknowledge Tekla (UK) Ltd for their approval in the use of this software.



Rafter details

Breadth of timber sections;	b = **47** mm
Depth of timber sections;	h = **125** mm
Rafter spacing;	s = **400** mm
Rafter slope;	α = **40.0** deg
Clear span of rafter on horizontal;	L_{clh} = **1769** mm
Clear span of rafter on slope;	$L_{cl} = L_{clh}/\cos(\alpha)$ = **2309** mm
Rafter span;	**Single span**
Timber strength class;	**C16**

Section properties

Cross-sectional area of rafter;	$A = b \times h$ = **5875** mm^2
Section modulus;	$Z = b \times h^2/6$ = **122396** mm^3
Second moment of area;	$I = b \times h^3/12$ = **7649740** mm^4
Radius of gyration;	$r = \sqrt{(I / A)}$ = **36.1** mm

Loading details

Rafter self-weight;	$F_j = b \times h \times \rho_{char} \times g_{acc}$ = **0.02** kN/m
Dead load on slope;	F_d = **0.70** kN/m^2
Imposed load on plan;	F_u = **0.75** kN/m^2
Imposed point load;	F_p = **0.90** kN

Modification factors

Section depth factor;	$K_7 = (300\ mm/h)^{0.11}$ = **1.10**
Load sharing factor;	K_8 = **1.10**

Consider long-term load condition

Load duration factor;	K_3 = **1.00**
Total UDL perpendicular to rafter;	$F = F_d \times \cos(\alpha) \times s + F_j \times \cos(\alpha)$ = **0.228** kN/m
Notional bearing length;	$L_b = F \times L_{cl}/[2 \times (b \times \sigma_{cp1} \times K_8 - F)]$ = **2** mm
Effective span;	$L_{eff} = L_{cl} + L_b$ = **2312** mm

Check bending stress

Bending stress parallel to grain; σ_m = **5.300** N/mm^2

Permissible bending stress; $\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8$ = **6.419** N/mm^2

Applied bending stress; $\sigma_{m\_max} = F \times L_{eff}^2/(8 \times Z)$ = **1.245** N/mm^2

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain; σ_c = **6.800** N/mm^2

Minimum modulus of elasticity; E_{min} = **5800** N/mm^2

Compression member factor; K_{12} = **0.63**

Permissible compressive stress; $\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12}$ = **4.698** N/mm^2

Applied compressive stress; $\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha)) / (2 \times A)$ = **0.166** N/mm^2

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress; $\sigma_e = \pi^2 \times E_{min} / \lambda^2$ = **13.949** N/mm^2

Euler coefficient; $K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12} / \sigma_e)$ = **0.989**

Combined axial compression and bending check; $\sigma_{m\_max} / (\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max} / \sigma_{c\_adm}$ = **0.232**; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain; τ = **0.670** N/mm^2

Permissible shear stress; $\tau_{adm} = \tau \times K_3 \times K_8$ = **0.737** N/mm^2

Applied shear stress; $\tau_{max} = 3 \times F \times L_{eff} / (4 \times A)$ = **0.067** N/mm^2

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff}$ = **6.935** mm

Bending deflection; $\delta_b = 5 \times F \times L_{eff}^4 / (384 \times E_{mean} \times I)$ = **1.260** mm

Shear deflection; $\delta_s = 12 \times F \times L_{eff}^2 / (5 \times E_{mean} \times A)$ = **0.057** mm

Total deflection; $\delta_{max} = \delta_b + \delta_s$ = **1.317** mm

PASS – Total deflection within permissible limits

Consider medium-term load condition

Load duration factor; K_3 = **1.25**

Total UDL perpendicular to rafter; $F = [F_u \times \cos(\alpha)^2 + F_d \times \cos(\alpha)] \times s + F_j \times \cos(\alpha)$ = **0.404** kN/m

Notional bearing length; $L_b = F \times L_{cl} / [2 \times (b \times \sigma_{cp1} \times K_8 - F)]$ = **4** mm

Effective span; $L_{eff} = L_{cl} + L_b$ = **2313** mm

Check bending stress

Bending stress parallel to grain; σ_m = **5.300** N/mm^2

Permissible bending stress; $\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8$ = **8.024** N/mm^2

Applied bending stress; $\sigma_{m\_max} = F \times L_{eff}^2/(8 \times Z)$ = **2.209** N/mm^2

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain; σ_c = **6.800** N/mm^2

Minimum modulus of elasticity; E_{min} = **5800** N/mm^2

Compression member factor; K_{12} = **0.59**

Permissible compressive stress; $\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12}$ = **5.512** N/mm^2

Applied compressive stress; $\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha)) / (2 \times A)$ = **0.295** N/mm^2

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress; $\sigma_e = \pi^2 \times E_{min} / \lambda^2 = \mathbf{13.927}$ N/mm^2

Euler coefficient; $K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12} / \sigma_e) = \mathbf{0.981}$

Combined axial compression and bending check; $\sigma_{m\_max} / (\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max} / \sigma_{c\_adm} =$ **0.334**; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain; $\tau = \mathbf{0.670}$ N/mm^2

Permissible shear stress; $\tau_{adm} = \tau \times K_3 \times K_8 = \mathbf{0.921}$ N/mm^2

Applied shear stress; $\tau_{max} = 3 \times F \times L_{eff} / (4 \times A) = \mathbf{0.119}$ N/mm^2

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff} = \mathbf{6.940}$ mm

Bending deflection; $\delta_b = 5 \times F \times L_{eff}^4 / (384 \times E_{mean} \times I) = \mathbf{2.239}$ mm

Shear deflection; $\delta_s = 12 \times F \times L_{eff}^2 / (5 \times E_{mean} \times A) = \mathbf{0.100}$ mm

Total deflection; $\delta_{max} = \delta_b + \delta_s = \mathbf{2.340}$ mm

PASS – Total deflection within permissible limits

Consider short-term load condition

Load duration factor; $K_3 = \mathbf{1.50}$

Total UDL perpendicular to rafter; $F = F_d \times \cos(\alpha) \times s + F_j \times \cos(\alpha) = \mathbf{0.228}$ kN/m

Notional bearing length; $L_b = [F \times L_{cl} + F_p \times \cos(\alpha)] / [2 \times (b \times \sigma_{cp1} \times K_8 - F)]$ $= \mathbf{5}$ mm

Effective span; $L_{eff} = L_{cl} + L_b = \mathbf{2315}$ mm

Check bending stress

Bending stress parallel to grain; $\sigma_m = \mathbf{5.300}$ N/mm^2

Permissible bending stress; $\sigma_{m\_adm} = \sigma_m \times K_3 \times K_7 \times K_8 = \mathbf{9.629}$ N/mm^2

Applied bending stress; $\sigma_{m_{max}} = F \times L_{eff}^2 / (8 \times Z) + F_p \times \cos(\alpha) \times L_{eff} / (4 \times Z) = \mathbf{4.508}$ N/mm^2

PASS – Applied bending stress within permissible limits

Check compressive stress parallel to grain

Compression stress parallel to grain; $\sigma_c = \mathbf{6.800}$ N/mm^2

Minimum modulus of elasticity; $E_{min} = \mathbf{5800}$ N/mm^2

Compression member factor; $K_{12} = \mathbf{0.55}$

Permissible compressive stress; $\sigma_{c\_adm} = \sigma_c \times K_3 \times K_8 \times K_{12} = \mathbf{6.184}$ N/mm^2

Applied compressive stress; $\sigma_{c\_max} = F \times L_{eff} \times (\cot(\alpha) + 3 \times \tan(\alpha)) / (2 \times A) + F_p \times \sin(\alpha) / A = \mathbf{0.265}$ N/mm^2

PASS – Applied compressive stress within permissible limits

Check combined bending and compressive stress parallel to grain

Euler stress; $\sigma_e = \pi^2 \times E_{min} / \lambda^2 = \mathbf{13.913}$ N/mm^2

Euler coefficient; $K_{eu} = 1 - (1.5 \times \sigma_{c\_max} \times K_{12} / \sigma_e) = \mathbf{0.984}$

Combined axial compression and bending check; $\sigma_{m\_max} / (\sigma_{m\_adm} \times K_{eu}) + \sigma_{c\_max} / \sigma_{c\_adm} =$ **0.519**; **< 1**

PASS – Combined compressive and bending stresses are within permissible limits

Check shear stress

Shear stress parallel to grain; $\tau = \mathbf{0.670}$ N/mm^2

Permissible shear stress; $\tau_{adm} = \tau \times K_3 \times K_8 = \mathbf{1.106}$ N/mm^2

Applied shear stress; $\tau_{max} = 3 \times F \times L_{eff} / (4 \times A) + 3 \times F_p \times \cos(\alpha) / (2 \times A) = \mathbf{0.243}$ N/mm^2

PASS – Applied shear stress within permissible limits

Check deflection

Permissible deflection; $\delta_{adm} = 0.003 \times L_{eff}$ = **6.944** mm

Bending deflection; $\delta_b = L_{eff}^3 \times (5 \times F \times L_{eff}/384 + F_p \times \cos(\alpha)/48) / (E_{mean} \times I)$ = **3.913** mm

Shear deflection; $\delta_s = 12 \times L_{eff} \times (F \times L_{eff} + 2 \times F_p \times \cos(\alpha)) / (5 \times E_{mean} \times A)$ = **0.205** mm

Total deflection; $\delta_{max} = \delta_b + \delta_s$ = **4.118** mm

PASS – Total deflection within permissible limits

Table.1 shows a comparison of the results with short-term loading.

We can see from this simple analysis that the greater the pitch, the more efficient the timber becomes since the force is directed vertically where the timber acts more efficiently as a compression member.

Purlin

The purlin acts like a beam and is primarily to prevent deflection in the rafters by reducing the span. In older, more traditional roofs the rafters were bird-mouthed over the purlin to ensure the force was directed vertically rather than horizontally.

In traditional Victorian and Edwardian houses, where hipped roofs were fashionable, the purlin can be seen to extend along each roof and in some cases is unsupported. The theory is that the force or load from the hip and the side of the roof is equal and opposite to the force or load from the other side. Consequently, the purlin acts as a continuous beam pushing against itself, with the loads and forces equalising out.

Joists

Ceiling joists carry the ceiling, which usually comprises lath and plaster or in more modern constructions plasterboard and skim. The key to ensuring these brittle finishes do not crack is to ensure the limits on deflection as outlined under the relevant Eurocode Standards and previous British Standards are observed. The deflection can be reduced by inserting ceiling binders across the joist, which reduce the span. However, the second function of the joist is to triangulate the roof structure and ensure the roof does not spread by acting as a tie between the rafters.

Table.1: Comparison of rafter loading for different roof pitches

Structural	**Pitch at 30**	**Pitch at 40**
Shear stress (N/mm^2)	0.275	0.243
Combined axial bending and compression	0.578	0.519
Deflection (mm)	4.66	4.118

On a flat roof, joists are used to carry the roof dead and imposed loads. The dead loads will be dependent on the type of materials used and some examples include felt, fibre glass and metal sheets. The imposed loads on a flat roof will be greater than those on a pitched roof, and consideration should also be given for additional imposed loads due to access and maintenance.

Joists and collars to triangulate the forces in the roof structure

Traditionally it was recognised that to prevent roof spread at the eaves and ensure the roof did not induce horizontal forces on the wall, triangulation of the roof frame was necessary to ensure equal and opposite forces were exhibited across the frame. This was achieved by the use of a collar or a ceiling joist acting as a tie. However, a collar placed too high will not respond in the desired way by acting in tension, but act in compression – thus allowing the base of the rafter to spread. Hence there are limitations on the height at which a collar should be placed. For collars to be effective, it is normally the case that they are located at a height of one-third to one-half of the height measured from the eaves to the ridge.

Failing this, and if vaulted or open roofs are desired, the roof frame has to employ some other means of resistance to ensure the roof cannot spread and these are described below.

a couple roof does not benefit from a collar or ceiling joist providing the necessary triangulation and tie. In this situation the roof has to be sufficiently designed that the load is mainly directed vertically down the walls, hence the roof has to have a steeper pitch. The resulting horizontal load must be able to be sustained by the walls, and this will depend on the construction, thickness and stiffness of the walls. Interestingly, lateral restraint straps are added to modern houses not only to afford restraint to the wall, but also to spread the load of the lateral force at wall plate level over a deeper section of wall. In cathedrals, flying buttresses are employed for this very purpose – to direct horizontal loads from roofs and ceilings vertically to the ground.

Wind bracing

Trussed and cut roofs will need to be braced against wind loading, which is absorbed by the roof frame. For truss roofs the truss manufacturer will normally specify the bracing on the truss diagram that accompanies the trusses when they are delivered. BS 5268: Part 3 and Eurocode 5 set out the requirements for bracing of roof structures for truss and cut roofs.

Normally, a series of diagonal and longitudinal timber members (nominally 22 mm × 97 mm) will be secured to each of the rafters and ceiling joists along the length of the building. The design standards referred to above set out the lapping requirements, fixing requirements and details for the bracing depending on the wind speed, pitch and length of the roof.

Roof spread

Failure to reduce the lateral or horizontal loads can result in roof spread, whereby the wall is unable to sustain the horizontal thrust and the wall plate is forced from its original position – or worse still the wall exhibits bowing and leaning. Cracking can also occur on the gable wall, and the photograph in Figure 10.8 is an example of roof spread where the gable wall has suffered tapered cracking from being pushed out by the purlins.

In domestic buildings the following methods are usually employed to prevent roof spread if ceiling joists or collars are not used.

Ridge beam

In this scenario a beam is placed at ridge level and is designed to sustain a minimum of half the loading on the roof. The rafters and roof frame hang from the beam and in order for the roof to spread, the roof would have to drop vertically. Thus, if this vertical movement is prevented, then roof spread cannot ensue. A photograph of a typical ridge beam can be seen in Figure 10.9. The critical thing is to make sure there is a good connection of the rafters to the ridge beam, to ensure they cannot slip from the beam. Consequently, a timber plate is normally bolted to the top flange of the ridge beam and the rafters are bird-mouthed over the timber plate. The rafters are skew nailed or screwed, and a small collar

Photograph of a steel ridge beam.

placed under the beam across the rafters using a 47 mm × 100 mm timber. Ridge beams can be of steel or timber construction.

Ring beam

A ring beam is positioned at eaves level and the rafters connect firmly and securely onto the beam. As the name suggests, the beam is a ring – usually of concrete or steel although sometimes of timber – and for the roof to spread the ring beam must be pushed out. The beam and cross-members on the gable wall at the end prevent this from occurring. It can be seen that the connections at the ends of the beams on the wall plate provide the resistance to tension forces. Whether in concrete or steel, the strength of the connections is paramount.

In traditional solid brick buildings timber ties were connected across the gable walls connecting the wall plates in an attempt to offer a cross-tie to the side walls and provide some lateral restraint to the roof structure (with a similar principle to the ring beam). It is not uncommon for property developers, sometimes under instruction from warranty organisations, to request these to be removed. This is usually due to the idea that timber in a wall will be subject to wet rot and may cause a liability under the warranty. Without the introduction of another form of triangulation or lateral restraint mechanism this can compromise the structural integrity of the roof, walls or both.

Once roof spread has occurred, the impact on the remaining structure has to be considered. For example, care has to be taken to ensure the walls remain stable and that the load from the roof does not induce an excessive eccentric loading on the wall and foundation, thus making the wall unstable.

Hip beams and dragon ties

Hip beams carry the rafters on the hip of a roof and the rafters are connected to the hip beam, which carries the load to the walls. However, these beams impart a concentrated load on the corner of a building and this can result in the beam sliding over the wall plate or pushing out the corner of the building. Clearly some lateral restraint or restraint mechanism is required to overcome this lateral horizontal thrust.

One way to do this is with a dragon tie, which is a mechanism that carries the load from the hip beam in a triangular frame usually constructed of timber. The sides of the triangle rest on the wall and are at right angles to each other. Along the centre of the frame is a structural member attached to the apex of the triangle on the corner and attached at the other end to a tie.

The hip beam is attached to the central member, which pulls on the tie member, thus causing tension in the tie. The tie acting in tension transfers the load to the side members over the wall, which are then in compression. This ensures the triangulation of the forces on the corner of the wall. The forces are directed along the timbers over each wall, and where they meet on the corner the forces are horizontally equal and opposite, thus cancelling each other out with no resultant force causing a thrust on the wall.

Overloading of roof members

In some circumstances it may be found that roof members such as rafters and ceiling joist are under-sized, particularly if new roof coverings have been employed. For example, the removal of thatch at approximately 41.5 kg/m^2 and replacement with a heavier clay tile at approximately 78 kg/m^2 can make a difference of approximately 36.5 kg/m^2. This equates to an 88% increase in the load, and this type of exchange of materials was not uncommon in traditional timber frame housing; the effects in some parts of the UK can still be seen today. Figure 10.10 is a photograph of a house with a traditional thatched roof, but with part of the roof covered in a heavier clay tile. The clay tile was presumably changed later than the original thatch. If other finishes such as plasterboard and plaster are added, one can easily understand how rafters can begin to fail under the additional load if they are not strengthened. Not only does the load to the rafter increase, but some consideration of the increase in horizontal thrust at wall plate level is also required to ensure that roof spread does not result.

One way to combat this overloading is to identify the size of the rafter required and thicken the existing rafter by screwing and gluing an additional thickness of timber to the bottom.

Wind loading can cause problems to roofs and in traditional timber frame buildings which are constructed using trusses, supporting purlins and rafters, raking can occur which causes the roof to move laterally across the length of the building.

In truss roofs and modern cut roofs wind bracing is employed to comply with current-day design standards, but traditionally this was not always the case. Consideration needs to be given to wind bracing during the conversion of old barns and buildings. This can be resolved by the addition of wind bracing or ply in-fill panels between the rafters at the end of the building. However, you are advised to seek professional advice from a structural engineer if this is deemed necessary, since an assessment of the roof structure may be necessary to ensure the structural integrity has not been compromised and the wind loading will vary depending on the location and topology.

Alterations to roof structures

A roof frame is an intricate structure and alterations undertaken must be on guidance from suitably qualified persons. Trusses have a series of members that act in compression and tension, forming an integral structure. The removal or alteration of one member can distribute loads to other members that are not able to sustain these additional loads.

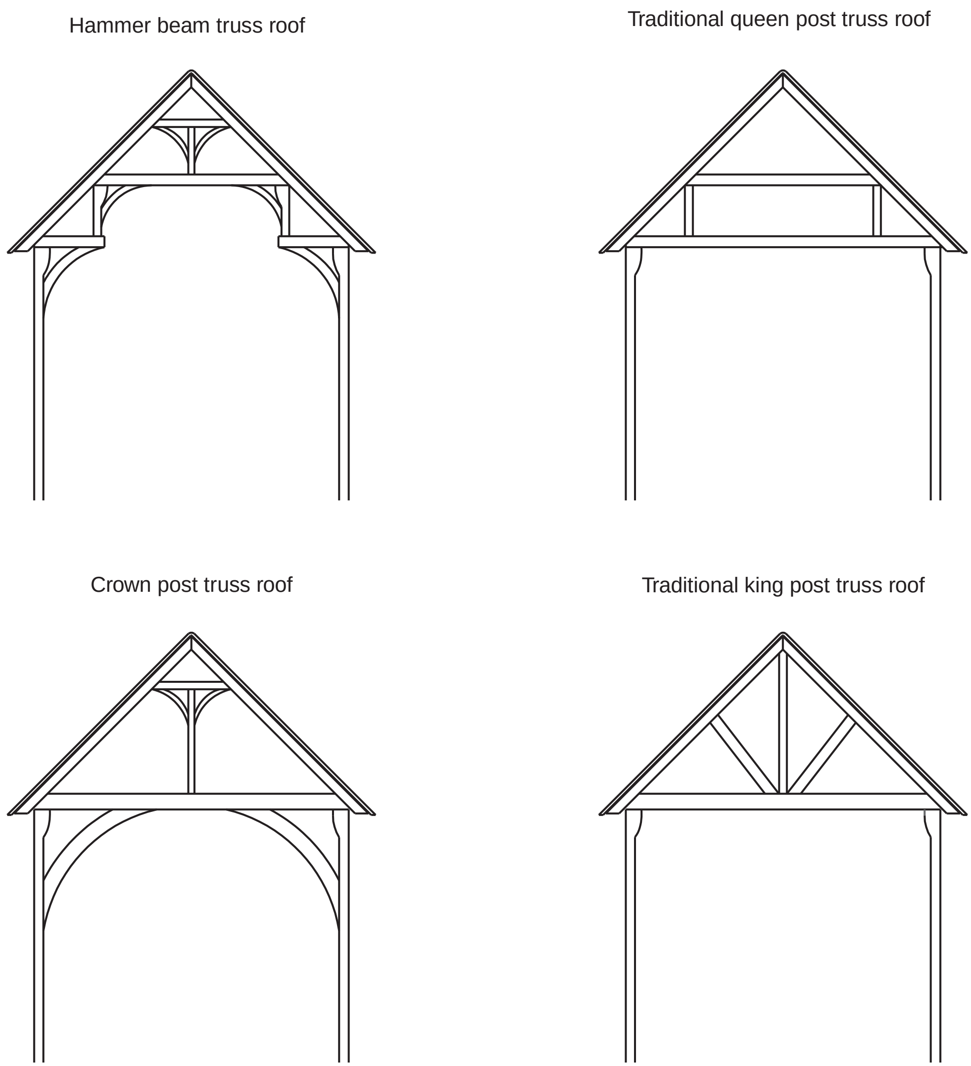
If alterations to a cut roof are being undertaken, then the order of the alterations is probably as important as the strengthening of the remaining members.

The alteration of a truss may result in a member changing from being in compression to being in tension, which can impact not only on the structure itself but also on the surrounding structure and fabric of the building.

Traditional timber frame building trusses

There are a number of types of truss found in traditional timber frame buildings, and examples and sketches of these can be seen in Figure 10.11.

There are many examples where the members have been removed to facilitate openings or access arrangements for newly constructed floors at roof level. In some circumstances these modifications have been undertaken without full knowledge and understanding of the resulting impact on the roof structure. Once the roof structure has deformed, it is very difficult and often expensive to recover the situation – even though the movement may be limited, the distortion will remain. In addition to this it is worth noting at this conjecture that the removal of such members in traditional buildings, undertaken in an attempt to accommodate modern-day living, seeks to destroy our significant architectural heritage and in listed buildings this is illegal without Listed Building Consent approvals from the Local Authority.



Traditional timber truss types.

Modern rafter design

Tables.2–.4 provide the more common sizes of rafters for a given pitch of roof with dead and imposed loadings for Grade C24 timber. The imposed snow loading will vary across the country, and the geographical position in the country and exposure will deter- mine the imposed loads to be used. In these tables an imposed load of 0.75 kN/m^2 has been used. The dead load will depend on the roof covering as well as any plasterboard or timber boarding used to line the underside of the roof. An understanding of the loads must be assumed before using the tables. These tables are for guidance only, and profes- sional advice should be sought for final designs to be implemented. The tables provide clear spans for rafters.

Rafter span for pitch of roof between 15 and 22.5 ° °
Grade C24 timber
Imposed load 0.75 kN/m^2
Point load 0.9 kN

Size of rafter: breadth × depth (mm^2)	Dead load 0.5 kN/m^2			Dead load 0.75 kN/m^2			Dead load 1.0 kN/m^2		
	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm
47 × 100	2.12	2.17	2.08	2.08	2.04	1.93	1.98	1.93	1.82
47 × 125	2.93	2.88	2.74	2.74	2.68	2.56	2.60	2.52	2.37
47 × 150	3.67	3.59	3.40	3.40	3.32	3.12	3.23	3.12	2.91
47 × 195	5.00	4.88	4.54	4.61	4.49	4.21	4.38	4.20	3.90

Table independently compiled by structural calculations undertaken by Geomex Ltd, Structural Engineers and Architectural Design.

Rafter span for pitch of roof between 22.5 and 30 ° °
Grade C24 timber
Imposed load 0.75 kN/m^2
Point load 0.9 kN

Size of rafter: breadth × depth (mm^2)	Dead load 0.5 kN/m^2			Dead load 0.75 kN/m^2			Dead load 1.0 kN/m^2		
	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm
47 × 100	2.25	2.23	2.12	2.12	2.08	1.97	2.01	1.97	1.85
47 × 125	2.99	2.93	2.79	2.79	2.73	2.57	2.64	2.57	2.81
47 × 150	3.75	3.68	3.47	3.47	3.38	3.18	3.26	3.18	2.97
47 × 195	5.09	4.98	4.64	4.69	4.57	4.27	4.39	4.27	3.97

Table independently compiled by structural calculations undertaken by Geomex Ltd, Structural Engineers and Architectural Design.

Rafter span for pitch of roof between 30 and 45 ° °
Grade C24 timber
Imposed load 0.75 kN/m^2
Point load 0.9 kN

Size of rafter breadth × depth (mm^2)	Dead load 0.5 kN/m^2			Dead load 0.75 kN/m^2			Dead load 1.0 kN/m^2		
	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm	Spacing of rafter 400 mm	Spacing of rafter 450 mm	Spacing of rafter 600 mm
47 × 100	2.32	2.28	2.18	2.18	2.14	2.02	2.07	2.02	1.91
47 × 125	3.08	3.02	2.87	2.87	2.80	2.64	2.71	2.64	2.47
47 × 150	3.84	3.77	3.56	3.56	3.47	3.26	3.35	3.26	3.04
47 × 195	5.22	5.10	4.78	4.81	4.68	4.38	4.50	4.38	4.07

Table independently compiled by structural calculations undertaken by Geomex Ltd, Structural Engineers and Architectural Design.

Flat roof construction

provides joist spans for a flat roof construction for the loads identified using Grade C16 timber.

The table has an assumed imposed load of 1.02 kN/m^2 and a concentrated load of 0.9 kN with a nominal bearing of 40 mm.

Flat joist spans using Grade C16 timber (clear spans in metres)

Size of joist: breadth × depth	Dead loads not more than 0.5 kN/m^2: spacing of joist (mm)			Dead load not more than 0.75 kN/m^2: spacing of joist (mm)			Dead load not more than 1.0 kN/m^2: spacing of joist (mm)		
	400	**450**	**600**	**400**	**450**	**600**	**400**	**450**	**600**
38 × 97	1.64	1.61	1.55	1.55	1.52	1.45	1.48	1.45	1.37
38 × 120	2.17	2.13	2.04	2.04	2.00	1.89	1.94	1.89	1.78
38 × 145	2.77	2.72	2.58	2.58	2.53	2.38	2.44	2.38	2.23
38 × 170	3.38	3.31	3.09	3.13	3.06	2.87	2.95	2.87	2.68
38 × 195	4.00	3.90	3.54	3.69	3.59	3.29	3.46	3.37	3.00
38 × 220	4.56	4.39	3.80	4.24	4.10	3.65	3.97	3.86	3.40
47 × 97	1.81	1.78	1.70	1.71	1.68	1.60	1.63	1.60	1.51
47 × 120	2.40	2.35	2.25	2.24	2.19	2.08	2.12	2.08	1.95
47 × 145	3.00	2.98	2.82	2.83	2.76	2.60	2.67	2.60	2.44
47 × 170	3.70	3.61	3.32	3.42	3.33	3.10	3.21	3.13	2.92
47 × 195	4.35	4.18	3.80	4.00	3.90	3.54	3.76	3.66	3.34
47 × 220	4.90	4.70	4.28	4.57	4.39	3.99	4.31	4.15	3.76
75 × 120	2.91	2.86	2.72	2.72	2.66	2.51	2.58	2.52	2.36
75 × 145	3.66	3.60	3.32	3.41	3.33	3.10	3.21	3.13	2.92
75 × 170	4.41	4.25	3.88	4.09	3.98	3.62	3.84	3.74	3.42
75 × 195	5.00	4.85	4.43	4.71	4.54	4.14	4.46	4.30	3.91
75 × 220	5.50	5.35	4.98	5.30	5.11	4.66	5.02	4.83	4.40

Table independently compiled by structural calculations undertaken by Geomex Ltd, Structural Engineers and Architectural Design.

The table has an assumed imposed load of 1.02 kN/m^2 and a concentrated load of 0.9 kN with a nominal bearing of 40

Advantages and types of steel roof trusses

A steel roof truss is a structural member element that adds strength and support to roofs. It comes in the form of a triangle unit. Each triangle unit is constructed with two top chords, a bottom chord, and webs, all connected at the ends by joints. All the joints in the truss members have pinned connections such that no shear or moment forces are transferred from member to member. Steel roof trusses main functions are to carry the roof load and to provide horizontal stability.

Components of steel roof trusses;

A roof truss consists of three main components namely, top chords, bottom chords and web bracing

- Top chord: it is an inclined or horizontal member used to create the upper perimeter of the roof to resist live load
- Bottom chord: is the bottom horizontal that carries combined stress from both tension and bending of the truss.
- Web bracing: there are members that enable the joining of bottom chords together in a triangular pattern

Advantages of steel roof trusses

A lightweight steel roof truss does not provide too much of a strain on elements such as walls, ceilings etc. These are used in a wide range of industrial and commercial buildings. They are the most suitable solutions for construction projects that require long spans and flexible space. Its applications include factories, airport terminals, aircraft hangers, sports stadiums, auditoriums etc.

- Lightweight and durable
- Supports and strengthens the roof framework
- Efficient in resisting external loads as the cross section of all the members is uniformly stressed
- Provides energy efficiency
- Maintains a high strength-to-weight ratio
- Reduce/prevent condensation and occurrence of mold
- Prevents damage to an exposed roof
- Offers cover and protection from outdoor elements
- Prevents UV radiation
- Fabricated under a controlled environment
- Help to improve the aesthetics of a building structure.
- Withstands natural calamities because of their sturdy construction
- It can also be used to support storage
- Easy and quick to erect
- High resistance to adverse weather conditions,
- During manufacturing, additional protective and anti-corrosive coatings are added
- Fire-resistant
- Supports long span

- Reduced deflection
- Support considerable loads.
-

Because of its functionality and advantages a roof truss is essential to the integrity of the building roof system.

Structural Design of Buildings

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