Renovation of Buildings using Steel Technologies (ROBUST)

RFCS Project RFSR-CT-2007-0043

WP 4.2
Renovation of roofs using open trusses in light steel C sections

Date: 2009
Author: Mark Lawson

SCI, Silwood Park, Ascot,
Berkshire, UK, SL5 7QN
Tel: + 44(0) 1344 636525
Fax: + 44(0) 1344 636570

Renovation of Roofs using Open Trusses in Light Steel C Sections

Introduction

Renovation of existing timber roofs to provide additional space is an important and expanding sector as it increases the building size without adding to its ‘footprint’. Existing timber trusses cannot easily be modified to provide this useable space, whereas steel open trusses can be assembled within the existing roof and the timber trusses cut away.

Light steel open roof may be of two basic forms:

- ‘A frames’ consisting of rafters and floor beams and using C sections of different depths, as shown in Figure 1. In this case, the roof truss spans between front and rear façades
- Longitudinal lattice girders that support the existing timber rafters. In this case, the longitudinal trusses span between cross-walls or gable walls, as shown in Figure 2.

This paper addresses the structural design and practical application of open roof trusses in renovation or in new building. There are opportunities to use steel and plywood compositely to create a ‘plyweb’ beam that has advantages in terms of structural performance and thermal efficiency.

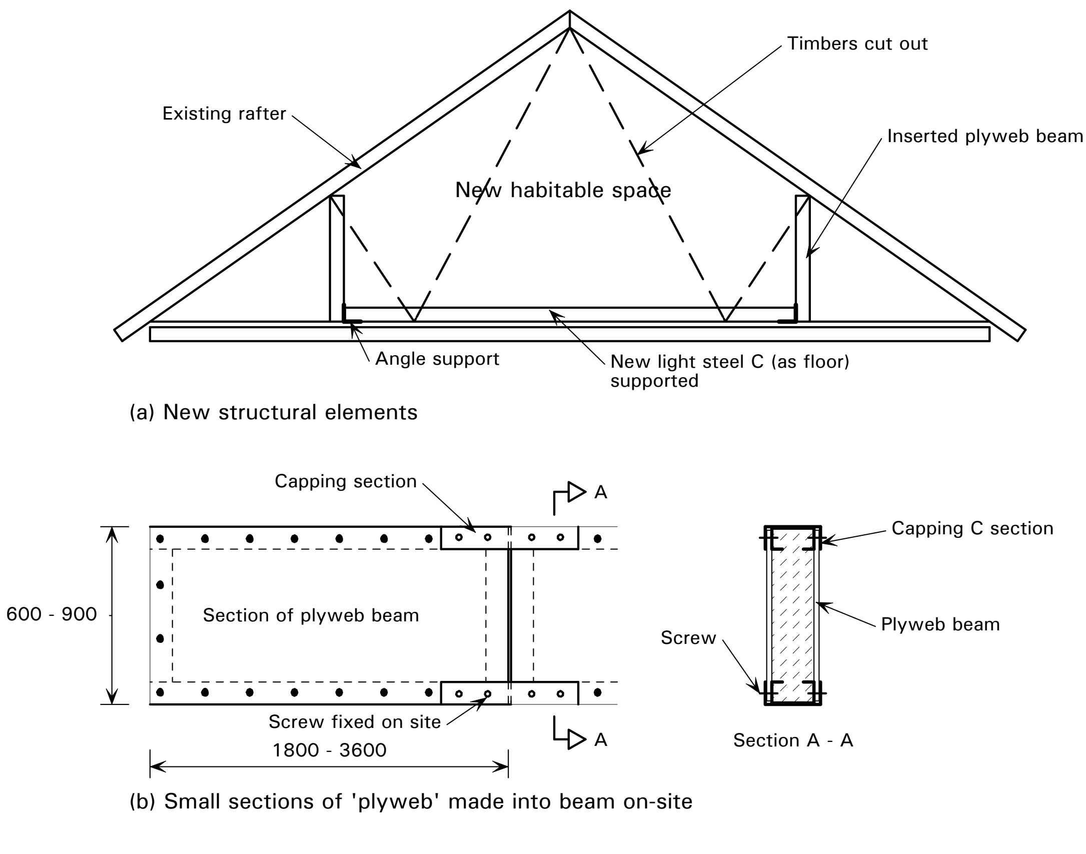


Figure 1 *Application of open roof system in renovation of existing roofs*

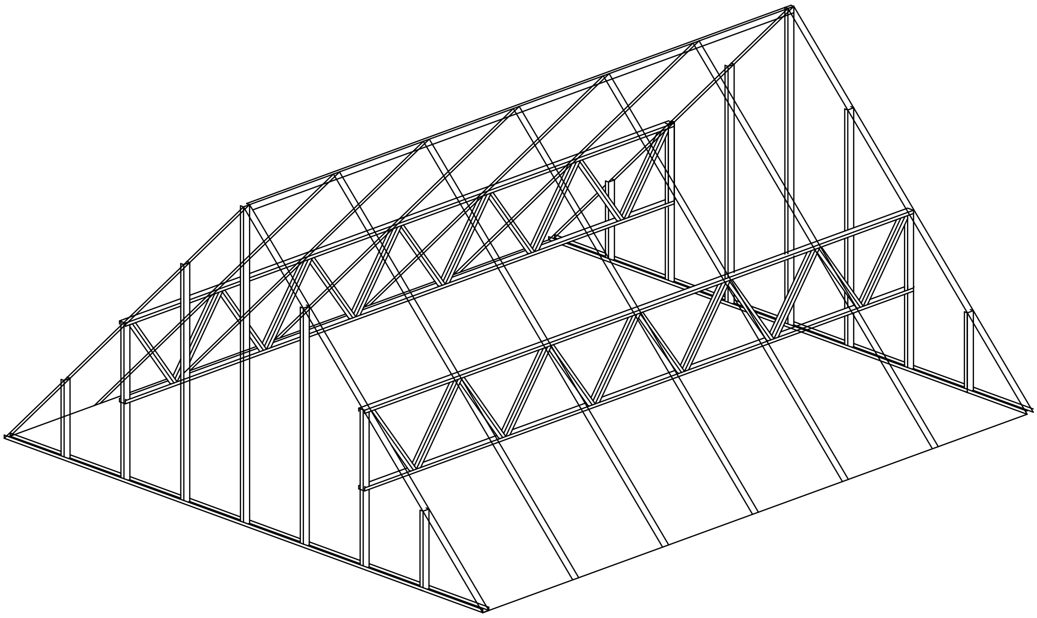


Figure 2 *Longitudinal trusses spanning between gable walls*

Open Roof Truss

The steel open roof truss is based on the use of cold formed C or Z sections and the bottom chord of the truss provides the floor to the habitable roof space. The members are easy to assemble on site by bolting (although screws would also be possible) and is self-jigging for dimensional accuracy.

The form of the roof can be easily varied to suit the required living space and window openings. The case shown is for the use of *Velux* type roof lights. Where other window forms are required, the position and height of the vertical members can be modified in manufacture.

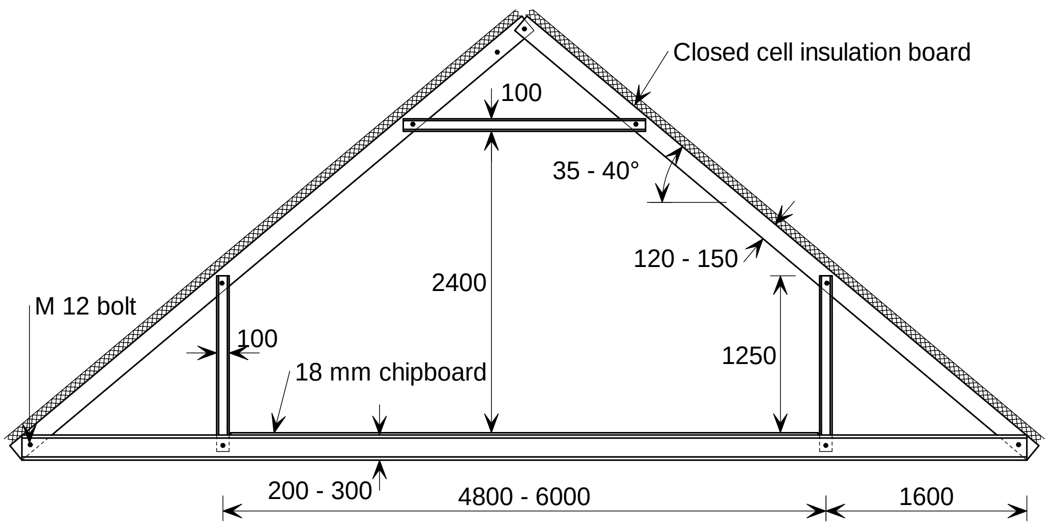


Figure 3 *Typical open roof truss using light steel C sections*

The range of application of the open roof system is:

- Spans of 6 to 10 m.
- Spacing of 400 to 1200 mm, depending on the span of the tiling battens and plasterboard supports
- Roof slope of 30 to 45°
- Habitable space of 3.5 to 6 m width between the vertical members

Roof lights may also be incorporated by increasing the spacing of the trusses locally although, economically, the system is more appropriate for wider truss spacings (say 900 mm), which reduces the number of trusses and assembly time. Dormer windows can be introduced and in this case, the minimum height of the vertical member may be taken as 900 mm.

The roof may be insulated externally by closed cell insulation board (typically 70 to 100 mm thick) to which counter-battens and battens are attached or by insulation placed between the rafters. Slotted or perforated C sections for the rafters may be advantageous when mineral wool insulation is placed between the rafters.

Structural Design

The structural design of the open roof system at the ultimate limit state is based on a modified plastic analysis, as illustrated in Figure 4, but using the elastic bending resistance of the rafters and bottom chords, which act as the floor in the roof space. The roof and floor are assumed to be loaded by line loads w_s and w_i respectively, representing the snow and imposed loading. The habitable space and hence imposed loading is confined to a length (L-2a) between the upstand members (which act as ties). Effectively, the bottom chord receives support from the shorter span and stiffer rafters.

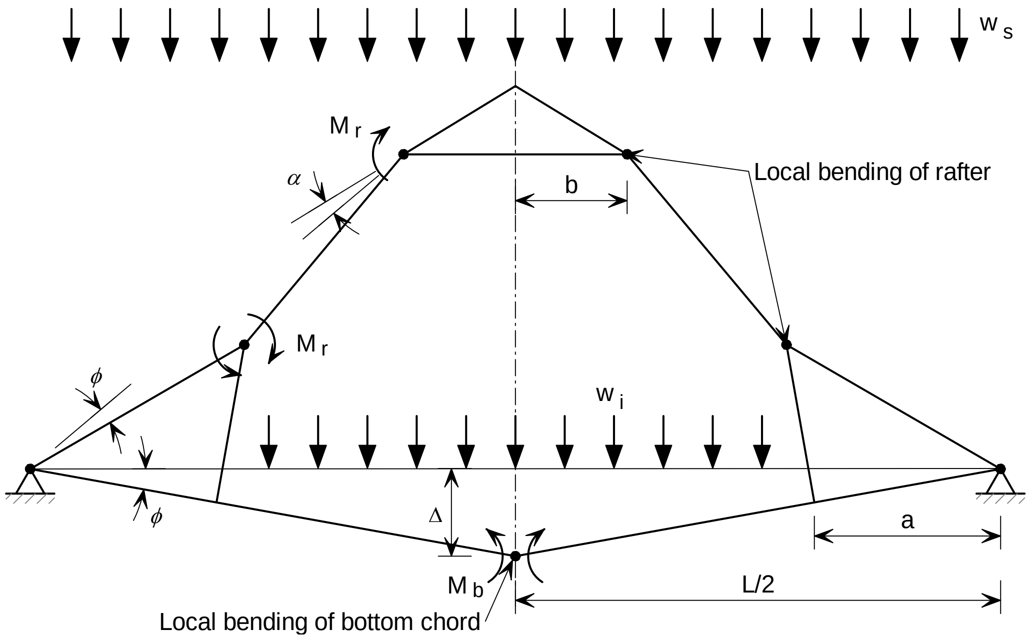


Figure 4 *Modified plastic collapse mechanism of open roof truss*

The 'failure' load of the open roof truss is obtained from the following formula, in the form of the key geometric variables. In design to Eurocode 3-1-3, partial factors of 1.5 for imposed loading and 1.35 for dead (self weight) loading are used. The bending resistances of the rafter and bottom chord M_r and M_b should satisfy the equilibrium equation:

$$1.5\left[w_{i}\left(\frac{L^{2}}{4}-a^{2}\right)+w_{s}(L/2-b)a\right]+1.35\,w_{d}\,L^{2}/4\leq 2\,M_{b}+2\,M_{r}\left(\frac{L+2a-2b}{L-2a-2b}\right)$$

where:

L is the truss span
a is the distance of the upstand tie from the support of the truss
b is half the length of the horizontal strut at the ridge
M_b is the elastic bending resistance of the bottom chord
M_r is the elastic bending resistance of the rafter in the presence of axial compression
w_i is the line load per unit length due to the imposed occupancy loading along the bottom chord
w_s is the line load per unit length due to snow loading acting vertically along the rafters
w_d is the self weight per unit length of the roof taken as acting uniformly along the rafters

The roof slope may be varied between 35 and 45^0 in order to optimise the habitable space and positions of window openings. Floor boarding is attached directly to the bottom chord and tiling battens are attached to the top chord of the rafters, which prevent lateral-torsional buckling of the C sections, and means that the elastic bending resistance of the members can be developed. Plasterboard is attached directly to the underside of the rafters, and to vertical and ceiling members of the room space.

For serviceability conditions, partial fixity at the ends of the bottom chord may be considered in the calculation of deflections. It is necessary to introduce the relatively strict deflection limits for habitable floors given in SCI P–301 when designing open roof systems.

The imposed load deflection due to load applied to the bottom chord may be calculated from the approximate formula:

$$\delta_i = \frac{3\,w_i\,(L-2a)^4}{384\,EI_{xx}}$$

where

I_{xx} is the second moment of area of the bottom chord

The coefficient of 3/384 takes account of partial fixity at the ends of the bottom chord and (L – 2a) is the length of the bottom chord between the vertical ties. However, when snow loading acting on the rafters is considered, the coefficient should be increased to 5/384 because partial fixity due to the stiffening effect of the rafters is much reduced.

In order to control deflections and acceptable floor movements, the Steel Construction Institute publication P-301 gives proposed deflection limits for floors, which may be applied as follows for the habitable roof system:

Imposed load deflection (due to loading on the floors):

$\delta_i \quad \leq (L - 2a) / 450$

Total deflection (due to self weight imposed and snow load):

$\delta_{tot} \quad \leq (L - 2a) / 350$ but $\delta_{tot} \leq 15$ mm

The imposed load case ensures adequate stiffness when the roof space is occupied. The total deflection limit ensures that the floor is stiff, so that its natural frequency of the floor exceeds 8Hz. The total deflection limit of 15mm tends to controls the design.

Typical Truss Designs

Typical designs may be made for open roof trusses placed at 600 mm centres, based on typical loadings given in Table 1:

Table 1 *Summary of loads used in roof analyses*

Loads	Bottom chord	Rafter
Imposed load on occupied floor	1.5 kN/m^2	–
Snow load	–	0.6 kN/m^2
Self weight of component	0.6 kN/m^2	1.0 kN/m^2 (inc. tiles)
Factored loading (0.6 m spacing)	1.94 kN/m	1.42 kN/m

The recommended minimum sizes of the C sections are presented in Table 2 to create the room sizes corresponding to at a minimum room height of 2.4 m. The roof is assumed to be clad with clay tiles. Roofs using composite panels or shear lightweight systems could lead to lighter C sections. The optimum design of the open roof truss is for an 8 m span, which is appropriate for a typical 3 or 4 bedroom house. In all cases, the vertical and horizontal tie members use 100 × 1.6 mm or 1.2 mm C sections and connections are made using 12 or 16 mm diameter bolts located in pre-punched holes.

Table 2 *Typical chord and rafter sizes for the open roof system*

Span (m)	Roof Slope	Room Width (between verticals	Member Sizes		Approximate Steel Weight (kg/m^2)
			Bottom chord	Rafter	
6	45^0	3.6 m	150 × 1.2C	100 × 1.2C	16
8	40^0	4.4 m	180 × 1.6C	125 × 1.6C	18
10	35^0	6.0 m	250 × 2.0C	150 × 1.6 C	24

Steel weight is expressed as relative to the plan area of the roof

In all cases, the components can be lifted into position manually within the roof space and can be bolted together. Bearing on the masonry or light steel wall is through the bottom chord of the C section which may be stiffened locally by an insert. The existing timber rafters or projecting timber pieces may be screw-fixed at eaves level to support the flashings and reduce 'cold-bridging'.

Frame Analyses of Open Roof Trusses

The elastic deflections and internal forces were analysed using the finite element programme LUSAS, based on the section properties of the light steel components listed in Table 3. The analyses were carried out for: imposed load on the floor, imposed load and dead load, and total loading of imposed load, dead load and snow load using the loads given in Table 1.

The results are presented in terms of deflections and moment and forces for these unfactored load cases for the case of an 8 m span open roof truss, and are given in Table 4. The Unity Factors show that the critical member is the rafter in combined compression and bending.

Table 3 *Section properties of members used in an 8 m span open roof truss*

Property	Rafter	Bottom Chord	Struts/Ties
Section size	125 × 55 × 1.6 C (S350 steel)	180 × 65 × 1.6 C (S350 steel)	100 × 55 × 1.2 C (S350 steel)
Bending resistance	$M_{e\ell}$ = 4.7 kNm	$M_{e\ell}$ = 8.5 kNm	$M_{e\ell}$ = 2.8 kNm
Second moment of area	I_{xx} = 83 × 10^4mm^4	I_{xx} = 226 × 10^4mm^4	I_{xx} = 44 × 10^4mm^4
Effective area	A_{eff} = 326 mm^2	A = 510 mm^2 (tension)	A_{eff} = 213 mm^2
Slenderness	λ = *58*	Member in tension	λ_x = 54
Axial resistance	P_c = 84 kN (compression)	P_t = 178 kN (tension)	P_c = 30 kN (compression)

Table 4 *Results from LUSAS analysis for 8 m span open roof truss*

Analysis Output	Rafter	Bottom Chord	Struts
Max. bending moment at ULS	3.8 kNm	4.9 kNm	NA
Max. axial force at ULS	14 kN	−1.0 kN	15 kN
Unity Factor to BS 5950-5	0.89	0.58	0.51
Deflection at working loads			
– imposed load	5.5 mm	5.9 mm	NA
– imposed load + dead loads	8.8 mm	6.5 mm	NA
– Imposed load + dead loads + snow load	13.6 mm	11.0 mm	NA

ULS = factored loading

The deflected shape of the open roof truss under imposed and dead loads is illustrated in Figure 5, which shows how the rafter tends to provide support to the bottom chord. Deflections are compared with simple calculations and with the proposed deflection limits in Table 5. The moments acting on the open roof truss at the ultimate limit state are presented in Figure 6. It can be seen that the effective points of support of the bottom chord are at the strut positions, leading to an effective span of (*L*-2a). The moments in the rafters are combined with compression.

Table 5 *Compression of theoretical deflections and measured deflections of bottom chord at working loads*

Load case (Working loads)	Deflections		
	LUSAS Analysis	Calculated	Limit (L−2a)/350
Imposed load only	5.9 mm	5.8 mm	10.6 mm
Imposed load + dead load	8.8 mm	8.1 mm	13.7 mm
Imposed load + dead load + snow load	13.6 mm	9.7mm	13.7 mm

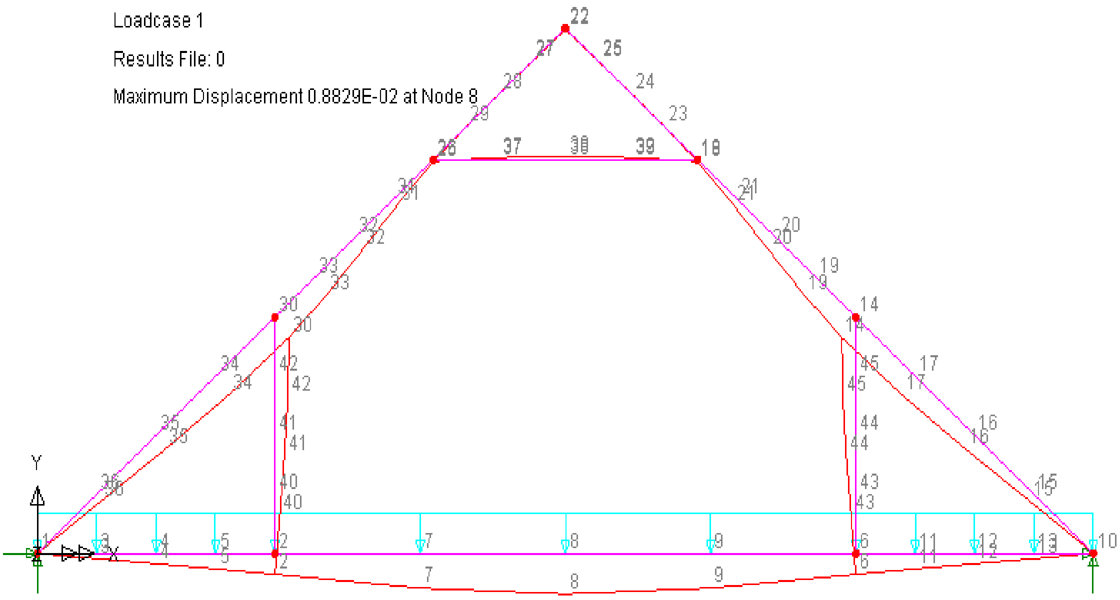


Figure 5 *Deflection shape of an 8 m span open roof truss under imposed and dead load applied to the floor*

The same analyses may be repeated for other spans, but it is generally found that deflections of the bottom chord will control the selection of the member sizes. In housing, a truss span of 7 to 9 m is most commonly used, which is within the range of application of this system.

It is concluded that the open-roof system using light steel C sections is a simple and viable alternative to create habitable space in a roof without changing its basic form

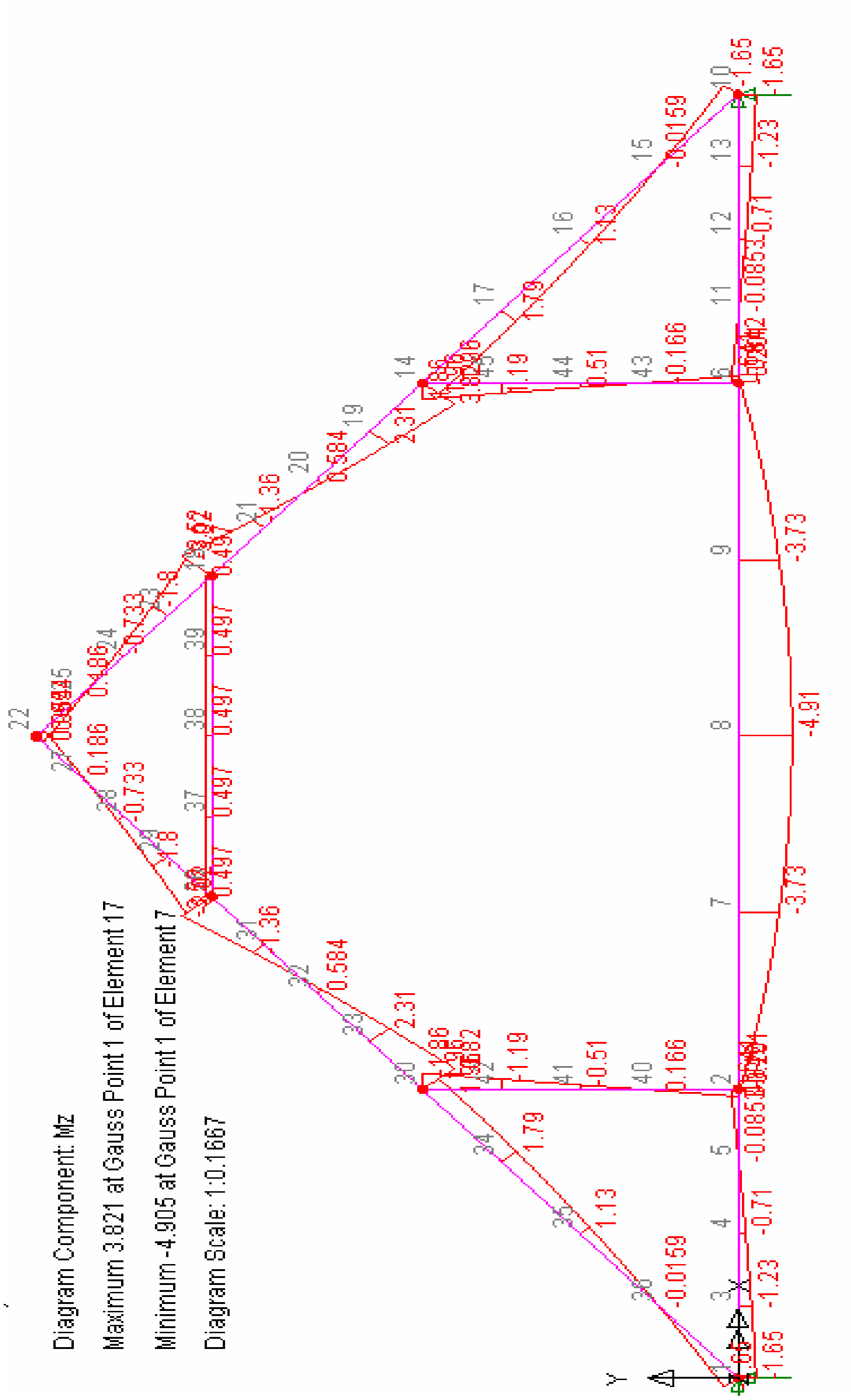
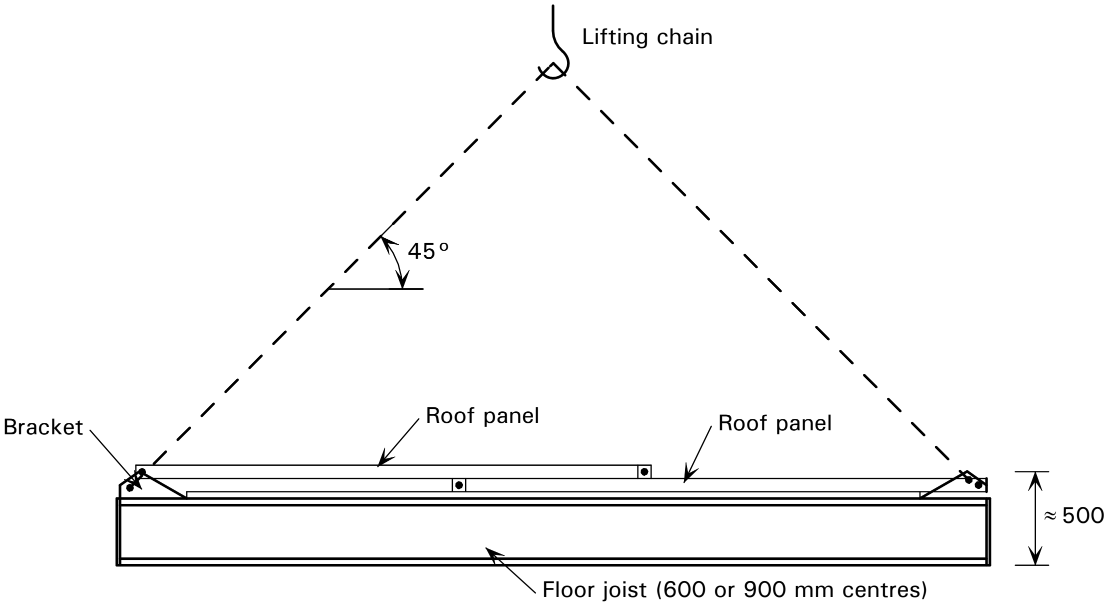


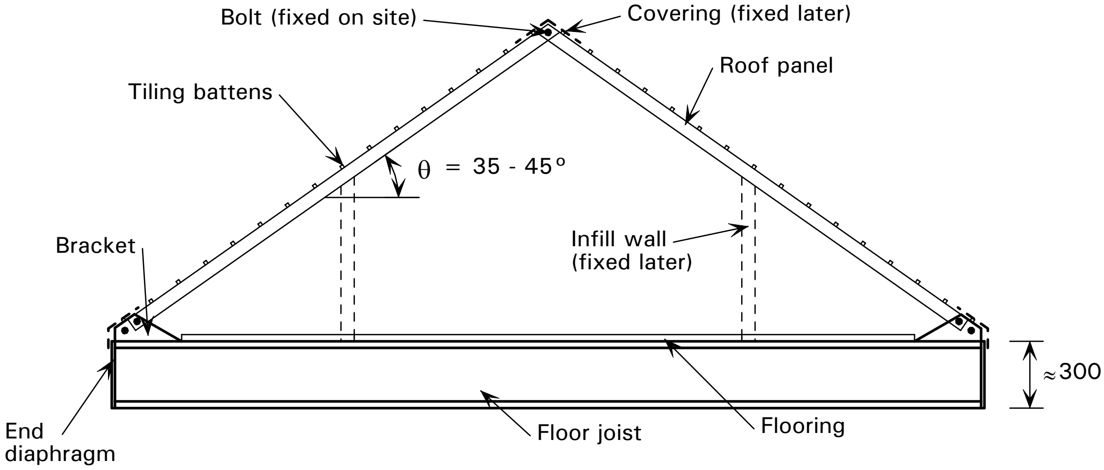
Figure 6 *Moments acting on an 8 m span open roof truss at the ultimate limit state (see loads in Table 1)*

Prefabricated open roof system

A possible extension of this technique is to create a collapsible open roof system that can be installed by crane. The connections of the rafters to floor joists are articulated, as shown in the following details (see Figure 7). It is assumed that all loads are transferred to the bottom chord in this case.



(a) Flat pack roof (2.4 or 2.7 m wide)



(b) Completed roof (roof panels rotated into position)

Figure 7 *Collapsible open roof system*

An alternative approach is to use a plyweb composite section in which the connections between the rafters and floor joists are made rigid by plywood inserts, as shown in Figure 8. The plyweb beam consists of C section flanges and 12mm plywood webs . The space between the webs can be filled with insulation for improved acoustic performance the ratio of span :depth of the plyweb beam is typically 20.

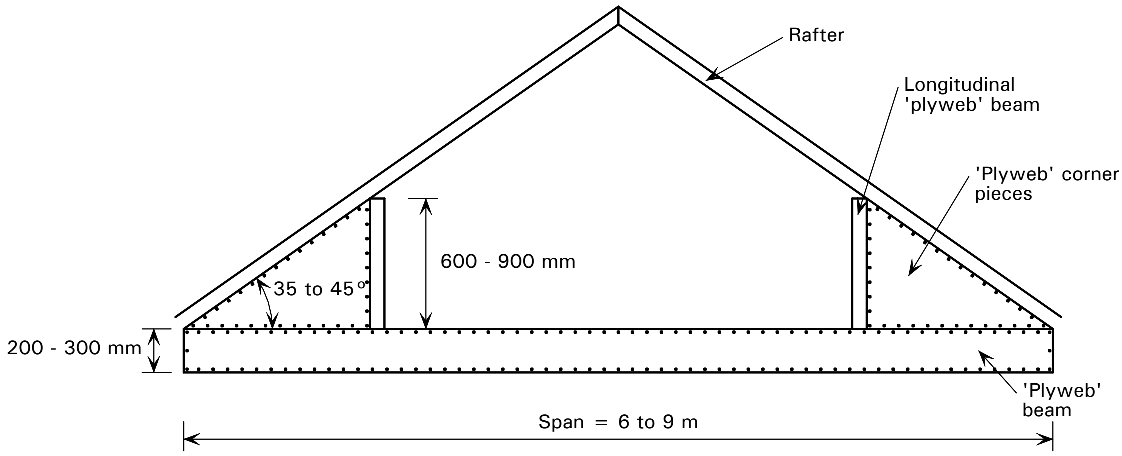


Figure 8 *'Plyweb' open roof system*