Trusses made from glulam and solid timber

STEP lecture E7
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Objectives

To describe the design considerations and analysis of trusses and to present two design examples.

Summary

As a common construction method, the general design of trusses will be briefly explained. The numerous considerations in design and the working steps for the computation of the structure will be briefly presented. By means of two examples, the design and computation of trusses consisting of glulam or solid timber will be detailed using the rules in section 5.4.1 of EC5.

Introduction

In timber structures, trusses are a wide-spread construction form taking full the potential advantage of the wood and the benefits of mechanical connections. Trusses find applications in wide spans, frame constructions, and as roof and wall bracing and are for example used in hangar constructions.

The top chord of the truss usually is adapted to the shape of the roof and the profile of the bottom chord is governed by clearance, ceiling and construction height requirements. For simply supported trusses the top chord is stressed in compression and also in bending in the case of load distribution between the nodes. The internal members (diagonal and vertical) are arranged in such a way that a triangulated web is generated. In order to reduce the number of joints and with it the production costs, widely triangulated systems are preferred. In addition to the common triangular, trapezoidal and parallel chord shapes, a variety of special forms are possible for trusses. A selection of such trusses is recorded in STEP lecture B12, which also deals with the possibilities and constraints of three-dimensional systems. A number of design considerations forms the basis for the selection of the appropriate system, the material of the web members, and the fasteners in the truss joints. Then, the computation of the structure, the design of the joints and the internal members follows. The accurate transformation of the computational results into complete and detailed construction and working drawings represents the last but very important stage of work in order to achieve correct fabrication and erection of the truss.

Design considerations

Depending on the use of the building, the following items have first to be clarified:

- ground plan
- elevation
- protection from heat and moisture
- fire protection
- illumination
- openings
- roof drainage
- installation.

In order to select an adequate type of truss the following data are required:

- minimum clearance
- slope of the roof
- height of the eaves and of the ridge
- span
- truss spacing
- roof loads.

Trusses spanning up to 30 *m* can be made of solid timber members. Members consisting of glulam, laminated veneer lumber (see STEP lecture E6) or parallam (see STEP lecture A9) may be used for wide-spanning systems or structures, whose wooden surfaces usually are to be free of cracks. Glulam is also preferred for truss members when large cross-sections are required. Cross-sections of spaced glulam members may be used for heavily loaded trusses of long span. The member forces can typically be transmitted by dowels and steel plates.

Trusses make it possible to adapt the construction height, and also the cross-sectional area and the quality of material, to the bending moment. Unlike thin webbed beams, installations and components can easily be run transverse to the plane of the truss. The selection of the fasteners (see also STEP lectures D1 and D2) is governed by the magnitude of the forces and the extent of the connecting areas, however it is also important to consider if steel plates and fasteners need to be hidden for reasons of aesthetics or fire protection.

Joints, which can be industrially produced using machinery to a large extent, should be preferred to mainly hand made joints with higher labour costs. The design appraisal should also consider transportation and erection of the trusses (see STEP lecture D7), as these factors influence the arrangement and position of the chord connections.

Computation of the structure

The system drawing, containing axial dimensions, numbers of members and nodes, joints and conditions of support, is required for the preparation of the structural calculations. According to EC5 the computation is classified into a simplified analysis and into a general analysis (see STEP lecture B12).

EC5: Part 1-1: 5.4.1

Simplified analysis

- determination of the axial member forces on the basis of a model where all nodes are pinned
- dimensioning of members and joints
- calculation of the deflection
  - taking into account the elastic straining of the members and the displacement stiffness of the joints, or
  - taking into account only the elastic straining of the members. In this case it is expedient to halve the deflection limit values recommended in EC5.

General analysis

- initial calculation of the truss as a frame structure on the basis of estimated cross-sections of the members and, eventually, on estimated displacement stiffnesses

- dimensioning of the members and joints
- improved computation of the internal forces and moments leading to improved cross-sectional areas and numbers of fasteners
- computation of the deflection.

Example of a truss consisting of solid timber

Provided that either the truss construction is hidden or, if exposed, flawless surfaces are not required, trusses consisting of solid timber are quite common for intermediate spans up to 30 *m*.

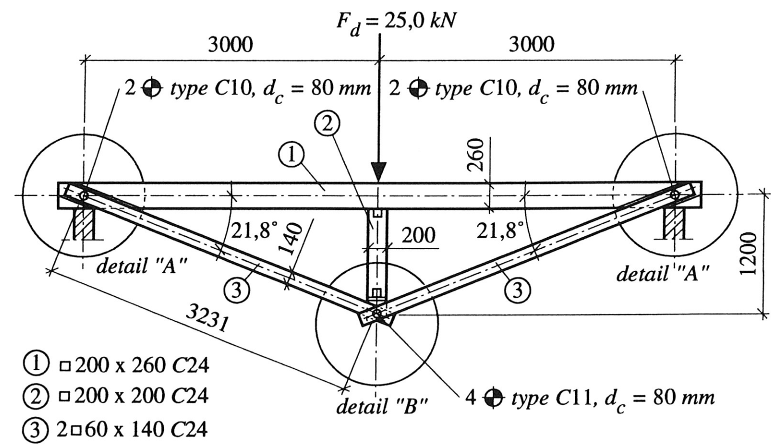

Figure 1 *Kingpost truss made from solid timber.*

EC5: Part 1-1: 5.4.1.3(1)

A simplified analysis for the kingpost truss shown in Figure 1 is not permitted, because the condition $H > 10\ h_{chord,max}$ is not fulfilled since $H = 1200\ mm$ and $10\ h_{chord,max} = 2600\ mm$.

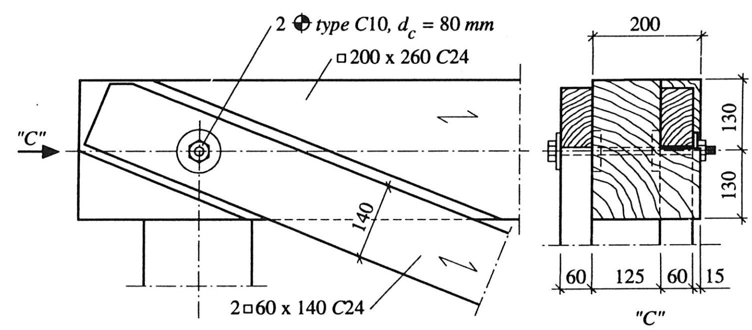

Figure 2 *Detail "A".*

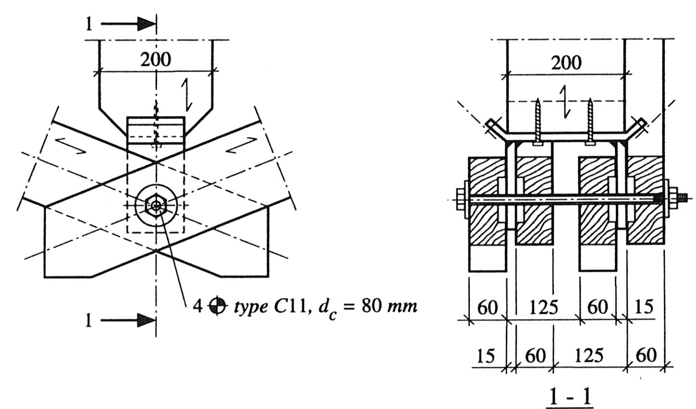

Figure 3 *Detail "B".*

Material
Members: solid timber C24

Characteristic values:

$f_{m,k}$	$= 24\ N/mm^2$	$f_{c,0,k}$	$= 21\ N/mm^2$	$f_{t,0,k}$	$= 14\ N/mm^2$
$f_{c,90,k}$	$= 5{,}3\ N/mm^2$	$E_{0,05}$	$= 7400\ N/mm^2$	$E_{90,05}$	$= 2 \cdot 370/3\ N/mm^2$
ρ_k	$= 350\ kg/m^3$	$E_{0,mean}$	$= 11000\ N/mm^2$	$E_{90,mean}$	$= 370\ N/mm^2$

EN 10025 — Steel element in Detail B : Fe360
prEN 912 — Fasteners: connector types C10 and C11, 80 *mm* diameter

Design value of action
Permanent point load $F_d = 25{,}0\ kN$
$k_{mod} = 0{,}6$ solid timber
$k_{def} = 0{,}6$ solid timber, service class 1

Calculation of internal forces
The internal forces can be calculated by using a computer program for frames or as follows by solving the equation for the geometrical condition for the statically indeterminate force X in the member 2.

$$u_{1,F} - u_{1,X} = \delta_{2,X} + \delta_{3,D} / \sin\alpha + \delta_{4,D} / \sin\alpha + \delta_{5,D} / \sin\alpha + \delta_L \qquad (1)$$

$u_{1,F}$ is the deflection of beam 1 (span $l = 6{,}0\ m$) due to the point load F_d
$u_{1,X}$ is the deflection of beam 1 (span $l = 6{,}0\ m$) due to the point load X
$\delta_{2,X}$ is the elastic deformation of member 2 parallel to grain direction and the deformation of beam 1 perpendicular to grain direction due to the force X
$\delta_{3,D}$ is the elastic deformation of member 3 due to the force $D = X / (2 \sin\alpha)$
$\delta_{4(5),D}$ is the slip of the connector joint 4(5)
δ_L is the vertical slip caused by tolerance of the hole diameter in Detail B

The instantaneous deformations are:

$$u_{1,F} = \frac{25000 \cdot 6000^3 \cdot 12}{48 \cdot 7400 \cdot 200 \cdot 260^3} = 51{,}9\ mm$$

$$u_{1,X} = 51{,}9 \frac{X}{25000}\ mm$$

$$\delta_{2,X} = \frac{X\ 1200}{7400 \cdot 200^2} + \frac{1}{2} \frac{X\ 260}{\frac{2}{3} \cdot 370 \cdot 200^2} = 1{,}72 \cdot 10^{-5}\ X$$

$$\delta_{3,D} = \frac{X\ 3231}{2 \sin\alpha \cdot 7400 \cdot 2 \cdot 60 \cdot 140} = 3{,}50 \cdot 10^{-5}\ X$$

$$\delta_{4(5),D} = \frac{X}{2 \sin\alpha\ 2\ K_u} = 8{,}01 \cdot 10^{-5}\ X$$

$\delta_L = 2\ mm$ (assumed)

STEP lecture C10: Eq.(6) — with $K_u = 2\ K_{ser} / 3 = 2 \cdot 0{,}45 \cdot 80 \cdot 350 / 3 = 8400\ N/mm$, as 5-percentile values for K_u are not available.

Substitution in equation (1) gives
$X = 22600\ N$
$N_{2,d} = 22{,}6\ kN$
$M_{1,d} = 3{,}6\ kNm$

$D_{3,d}$ = 22,6 / (2 sin α) = 30,4 kN
$N_{1,d}$ = 22,6 / (2 tan α) = 28,3 kN

When K_{ser}, $E_{0,mean}$ and $E_{90,mean}$ are used instead of K_{u}, $E_{0,05}$ and $E_{90,05}$ the results are:
X = 18700 N
$N_{2,d}$ = 18,7 kN
$M_{1,d}$ = 9,45 kNm
$D_{3,d}$ = 25,2 kN
$N_{1,d}$ = 23,4 kN
The comparison of the results shows the governing influence of the bending stiffness of the beam.

Verifications
Diagonal strut D_3 (member 3)

$$A_n = 2 \cdot 60 \cdot 140 - 120 \cdot 21 - 2 \cdot 550 = 13200 \; mm^2$$

$$\sigma_{t,d} = \frac{30400}{13200} = 2,3 \; N/mm^2$$

$$f_{t,d} = \frac{0,6 \cdot 14,0}{1,3} = 6,5 \; N/mm^2$$

$$2,3 \; / \; 6,5 = 0,35 < 1$$

STEP lecture B6

Beam (member 1)

$$\lambda_z = \frac{6000}{0,289 \cdot 200} = 104 \quad thus \; k_c = 0,289$$

$$\sigma_{m,d} = \frac{9,45 \cdot 10^6}{2,25 \cdot 10^6} = 4,2 \; N/mm^2$$

$$\sigma_{c,0,d} = \frac{28,3 \cdot 10^3}{200 \cdot 260} = 0,544 \; N/mm^2$$

$$\frac{0,544}{0,289 \cdot \frac{0,6 \cdot 21}{1,3}} + \frac{4,2}{\frac{0,6 \cdot 24}{1,3}} = 0,194 + 0,379 = 0,57 < 1$$

The instantaneous deflection of the beam midpoint at serviceability limit state due to the point load $F_k = F_d \; / \; 1,35 = 18,5 \; kN$ is:

$u_{1,inst} = u_{1,F} - u_{1,X} = 7 \; mm = l \; /857$

and the final deflection is:
$u_{net,fin} = 7 \; (1 + 0,6) = 11 \; mm = l \; / \; 545 < l \; / \; 200$

Joints: see STEP lecture C10.

Example of a truss made from glulam

Trapezoidal truss in the roof of a hall, service class 1
Members: glulam GL32h
Joints: steel plate with t = 8 mm in slots & dowels of 16 mm diameter
Wind load will be neglected.
The top chord is laterally restrained at points 3,8 m apart.

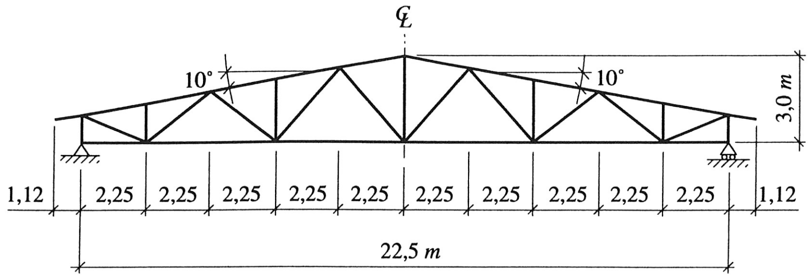

Figure 4 Truss system.

Characteristic values of actions

Permanent actions:

Roof covering + purlins + bracing		2,0 *kN/m*
Truss dead load (0,15 + (22,5 - 15) / 200) 5,0	≈	1,0 *kN/m*

Load split: top chord $2,0 + 0,5 = G_{top,k} = 2,5$ *kN/m*

bottom chord $= G_{bott,k} = 0,5$ *kN/m*

Snow load $Q_{top,k} = 5,0$ *kN/m*

Load cases

1) g $g_{top,d} = 1,35 \cdot 2,5 = 3,38$ *kN/m*

$g_{bott,d} = 1,35 \cdot 0,5 = 0,68$ *kN/m*

2) g + s $q_{top,d} = 1,35 \cdot 2,5 + 1,5 \cdot 5,0 = 10,90$ *kN/m*

$q_{bott,d} = 0,68$ *kN/m*

3) g + s/2 $q_{top,d} = 1,35 \cdot 2,5 + 1,5 \cdot 5,0 / 2 = 7,12$ *kN/m*

$q_{bott,d} = 0,68$ *kN/m*

	Characteristic values of actions		Design values of action for verification of the				
			Serviceability limit states		Ultimate limit states for load case		
	G_k	Q_k	1,0 G_k	1,0 Q_k	1)	2)	3)
top chord	2,5	5,0	2,5	5,0	3,38	10,90	left :7,12 right:3,38
bottom chord	0,5	-	0,5	-	0,68	0,68	0,68

Table 1 Characteristic and design values of actions in kN/m.

Material

prEN 1194: 1995

prEN 1194: all members in GL32h

$f_{m,g,k}$ = 32,0 *N/mm²*	$f_{t,0,g,k}$ = 22,0 *N/mm²*	$f_{t,90,g,k}$ = 0,45 *N/mm²*
$f_{c,0,g,k}$ = 30,5 *N/mm²*	$f_{c,90,g,k}$ = 6,0 *N/mm²*	$f_{v,g,k}$ = 2,9 *N/mm²*
$E_{0,g,mean}$ = 13300 *N/mm²*	$E_{90,g,mean}$ = 440 *N/mm²*	$G_{g,mean}$ = 830 *N/mm²*
$E_{0,g,05}$ = 10600 *N/mm²*	($E_{90,g,05}$ = 350 *N/mm²*)	($G_{g,05}$ = 660 *N/mm²*)
$\rho_{g,k}$ = 430 *kg/m³*		

Steel plates t = 8 *mm* Fe 360 according EN 10 025

Characteristic yield strength f_y = 235 *N/mm²*

Characteristic tensile strength f_u = 360 *N/mm²*

Modulus of elasticity $E = 210\,000\ N/mm^2$

Dowel Ø 16 *mm* Fe 360 according EN 10 025; flush with timber surface

Simplified analysis

Conditions

- there are no re-entrant angles in the external profile;
- some part of the bearing width lies vertically below the support node;
- the truss height $H = 3{,}0\ m > 10\ h_{chord}$ thus $h_{chord} < 300\ mm$;
- $H = 3{,}0\ m = 0{,}133\ l \approx 15\%$ of l.

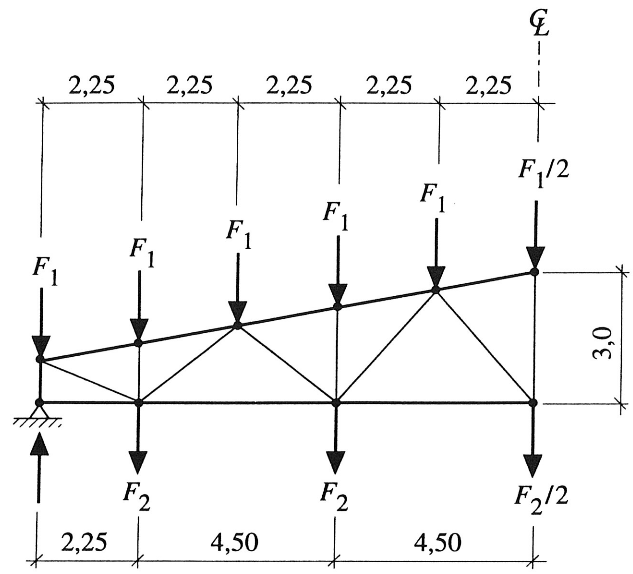

Figure 5 Structural system for the simplified analysis.

		Serviceability limit states design		Ultimate limit states design for load cases		
		G	Q	1)	2)	3)
at top chord	$F_{1,d} =$	5,6	11,3	7,6	24,5	left: 16,0 right: 7,6
at bottom chord	$F_{2,d} =$	2,3	-	3,1	3,1	3,1

Table 2 Design values of point loads in the nodes.

Calculation of the internal forces by using a computer program for frames.

Verification for top chord:

Load case 2 (g + s) governs: $k_{mod} = 0{,}9$

$N_d = 284\ kN$ (compression)

$$M_d \leq \frac{10{,}90 \cdot 2{,}25^2}{8} = 6{,}9\ kNm$$

chosen □ 200 x 200 *mm* GL32h

$A = 40 \cdot 10^3\ mm^2 \quad W_y = 1{,}33 \cdot 10^6\ mm^3$

$$\lambda_y = \frac{2285}{0{,}289 \cdot 200} = 40; \qquad \lambda_z = \frac{3810}{0{,}289 \cdot 200} = 66 \qquad \textit{thus}: k_{c,z} = 0{,}718$$

$$f_{c,0,d} = \frac{0{,}9 \cdot 30{,}5}{1{,}3} = 21{,}1 \ N/mm^2 \qquad f_{m,y,d} = \frac{0{,}9 \cdot 32{,}0}{1{,}3} = 22{,}1 \ N/mm^2$$

$$\sigma_{c,0,d} = \frac{284 \cdot 10^3}{40 \cdot 10^3} = 7{,}1 \ N/mm^2 \qquad \sigma_{m,y,d} = \frac{6{,}9 \cdot 10^6}{1{,}33 \cdot 10^6} = 5{,}2 \ N/mm^2$$

$$\frac{7{,}1}{0{,}718 \cdot 21{,}1} + \frac{5{,}2}{22{,}1} = 0{,}469 + 0{,}235 = 0{,}70 < 1$$

Verification for bottom chord:
Load case 2 (g + s) is governing: $k_{mod} = 0{,}9$

$N_d = 270\ kN$ (tension)
using □ 200 x 160 *mm* GL32h
$A = 32 \cdot 10^3\ mm^2$
$A_n = 32 \cdot 10^3 - 10 \cdot 160 - 2 \cdot 16\ (200-10) = 24{,}3 \cdot 10^3\ mm^2$

$$f_{t,0,d} = \frac{0{,}9 \cdot 22{,}0}{1{,}3} = 15{,}2 \ N/mm^2$$

$$\sigma_{t,0,d} = \frac{270 \cdot 10^3}{24{,}3 \cdot 10^3} = 11{,}1 \ N/mm^2$$

$11{,}1 \ / \ 15{,}2 = 0{,}73 < 1$

Design load-carrying capacity of a dowel:

$R_d = 32{,}5\ kN$ for $\alpha = 0°$

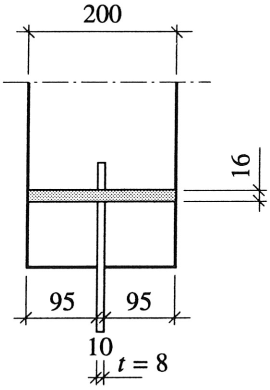

Figure 6 Dowelled joint.

Calculation of the required number of dowels per joint:

$n_{req} = N_d \ / \ R_d$ for the joint of the internal member to the steel plate.
For joints between the steel plate and the external member (chord) the resultant of the point load (in the node) and the change of force in the chord should be taken into consideration. Furthermore, the angle between the resultant force and grain direction of the chord will not be zero.

Calculation of the deflection at the serviceability limit:
The influence of the slip occurring in the truss joints can be assessed by using an effective cross-section

$$A_i^* = A_i \,/\, (1 + \frac{E_{mean}\, A_i}{l_i} (\frac{1}{n_{a,i}\, K_{ser}} + \frac{1}{n_{e,i}\, K_{ser}})) \qquad (2)$$

with

E_{mean} = 13300 N/mm^2 $\qquad K_{ser}$ = 14300 N/mm per dowel

A_i is the cross-section of member i

l_i is the length of member i

$n_{a,i}$, $n_{e,i}$ are the numbers of dowels at the member ends

$u_{2,inst}$ = 24,6 mm = l / 926 < l /300

$u_{1,inst}$ = 14,8 mm

u_0 = 40 mm (chosen)

$u_{2,fin}$ = 24,6 (1 + 0) = 24,6 mm

$u_{1,fin}$ = 14,8 (1 + 0,6) = 23,7 mm

$u_{net,fin}$ = 23,7 + 24,6 - 40 = 8,3 mm = l / 2711 < l / 200

General analysis

First order linear analysis of the truss as a framed structure can be applied by using a computer program for plane frames.

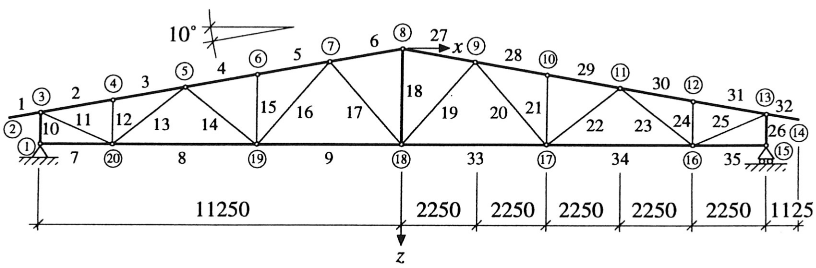

Figure 7 System.

Initial analysis of internal forces and moments for the ultimate limit states design with:

- bottom chord continuous along the total length;
- top chord continuous up to the ridge;
- ultimate limit states design for load case g + s;
- modulus of elasticity of the member is $E_{0,g,05}$ = 10600 N/mm^2.

Final analysis of internal forces and moments for the ultimate limit states design with:

- conditions according to analysis above;
- the effective cross-section A^* based on $K_u = 2\, K_{ser} / 3$;
- K_{ser} = 14300 N/mm;
- $A_i^* = A_i \,/\, (1 + \frac{E_{0,g,05}\, A_i}{l_i} (\frac{1}{n_{a,i}\, K_u} + \frac{1}{n_{e,i}\, K_u}))$;
- displacements in node 5, 7, 19, 20 due to change of force in the chord are disregarded.

The results of the analyses are shown in Table 3. The normal forces are independent of joint stiffnesses unlike bending moments of the chords.

Member No	Internal force/ moment	Simplified analysis	General analysis disregarding the influence of slip	General analysis including the influence of slip
4	N_d	284 kN	283 kN	282 kN
	M_d	$\frac{q_d\, l_4^2}{8} = 6{,}9\ kNm$	3,6 kNm	5,7 kNm
9	N_d	270 kN	268 kN	268 kN
	M_d	$\frac{g_{d,bott}\, l_9^2}{8} = 1{,}7\ kNm$	1,22 kNm	1,50 kNm
11	N_d	206 kN	201 kN	202 kN
18	N_d	61,9 kN	64,8 kN	63,8 kN

Table 3 Comparison of internal forces and moments in the load case g + s.

Initial analysis of serviceability limit states design with:
- bottom chord continuous along the total length;
- top chord continuous up to the ridge;
- internal members pinned;
- load cases g and s;
- $E_{0,g,mean} = 13300\ N/mm^2$.

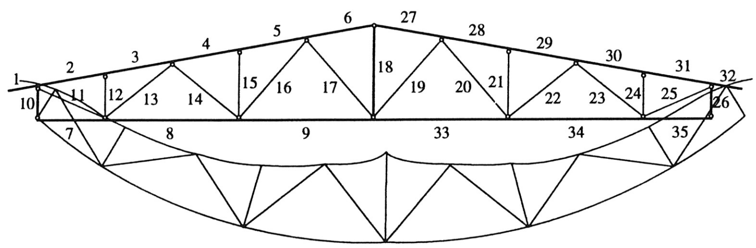

Figure 8 Deformation of the system in the load case s (initial analysis).

Final analysis of serviceability limit states design with:
- conditions according analysis above;
- the effective cross-section A^* based on $K_{ser} = 14300\ N/mm$;
- $A_i^* = A_i \,/\, (1 + \frac{E_{0,g,mean}\, A_i}{l_i} (\frac{1}{n_{a,i}\, K_{ser}} + \frac{1}{n_{e,i}\, K_{ser}}))$;
- displacements in node 5, 7, 19, 20 due to change of force in the chord are disregarded.

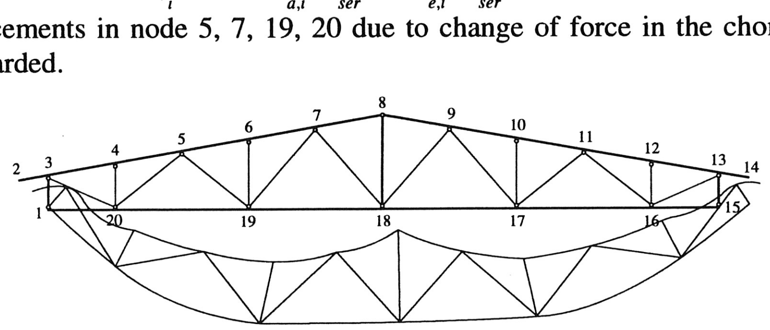

Figure 9 Deformation of the system in the load case s (final analysis).

Results of the initial analysis (disregarding the influence of slip occurring in the joints):

$u_{2,inst}$ = 14,6 mm
$u_{1,inst}$ = 8,8 mm

Results of the final analysis (showing the influence of slip):
$u_{2,inst}$ = 24,1 mm < l /300
$u_{1,inst}$ = 14,5 mm
$u_{2,fin}$ = 24,1 (1 + 0) = 24,1 mm
$u_{1,fin}$ = 14,5 (1 + 0,6) = 23,2 mm
u_0 = 40 mm (chosen)
$u_{net,fin}$ = 23,2 + 24,1 - 40 = 7,3 mm = l / 3082 < l / 200

An example of the truss joints is given in Figure 10.

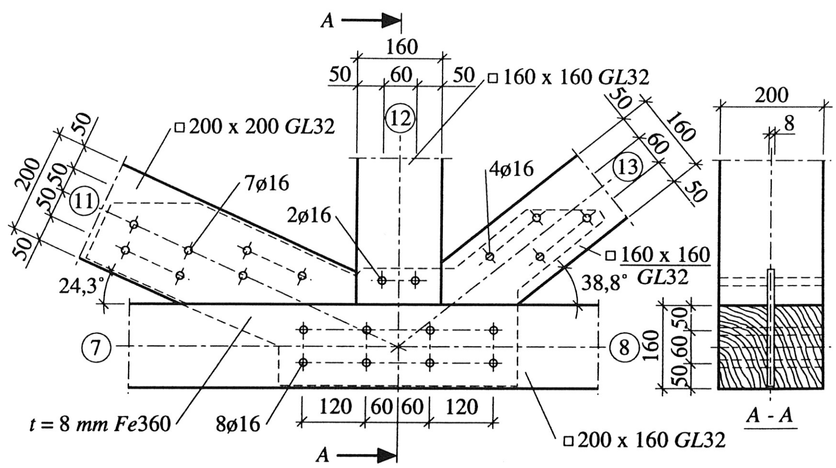

Figure 10 *Node 20.*

Simplified analysis including slip			General analysis disregarding slip		General analysis including slip		
$u_{1,inst}$	$u_{2,inst}$	$u_{net,fin}$	$u_{1,inst}$	$u_{2,inst}$	$u_{1,inst}$	$u_{2,inst}$	$u_{net,fin}$
14,8	24,6	8,3	8,8	14,6	14,5	24,1	7,3

Table 4 *Comparison of the deflections of the bottom chord midpoint. Deflection values in mm; the chosen precamber value u_0 is 40 mm.*

Concluding summary concerning the glulam truss example

- The computation of the internal truss forces based on the simplified analysis leads to reliable results (see Table 3).

- The internal moments in the loaded top chord depend significantly on the displacements of the nodes.

- For the calculation of the deflection slip should be taken into account (see Table 4). Otherwise it is expedient to halve the deflection limits recommended in EC5.