Wood-based panels - Plywood

STEP lecture A10
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Objective

To explain the critical properties, particularly the structural behaviour, of plywood as an example of layered boards.

Prerequisites

A4 Wood as a building material
A12 Adhesives

Summary

The production of plywood is described and the technical terminology is explained. The essential physical properties of plywood are summarised. In more detail the structural properties and their dependencies on the lay-up are shown. Some examples of characteristic values of mechanical properties for established products are given.

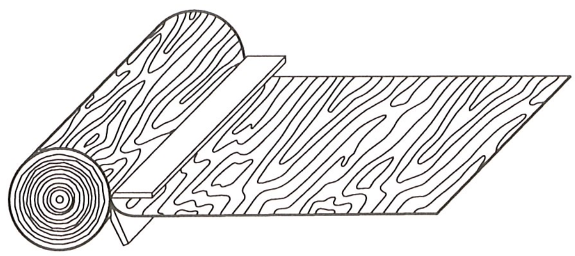


Figure 1 Production of an "endless" ply ribbon by rotary peeling.

Introduction

Wood in thin layers, known as plies or veneers, has been used since ancient times for example by the Egyptians and Romans to finish wooden surfaces. Since the beginning of the 20th century, plywood has been industrially produced. Plywood as a building material consists of an odd number of layers (at least three) which are bonded using various types of adhesives (STEP lecture A12). The suitability of plywood for the aircraft industry initiated intensive research into veneer bonding and the structural properties of plywood. Initially only natural adhesives were available but today plywood as a constructional material is produced using synthetic adhesives. Plies can be manufactured by rotary peeling, slicing or sawing. Plies for the structural plywoods used in building components are produced by the rotary peeling of steamed logs (see Figure 1). This procedure resembles the unwinding of the log to obtain a wooden ribbon of about 2 *mm* to 4 *mm* thickness. The next step is to cut the ribbon into sheets. After kiln drying and gluing, the veneers are laid up with an angle of 90° between the grain direction of adjacent layers and bonded under pressure. Figure 2 shows the layered composition of a plywood cross section. Adjacent veneers provide stability in the panel by reducing the possibility of perpendicular to the grain movements due to swelling and shrinkage. The edge of the panel is protected in all directions since at least one veneer will have the grain running parallel to the panel edge. Plywood is structurally suited for use as a panel material in various components, for example as the web or flange of beams, in diaphragms, as wall panels or as gussets in spaced columns and trusses.

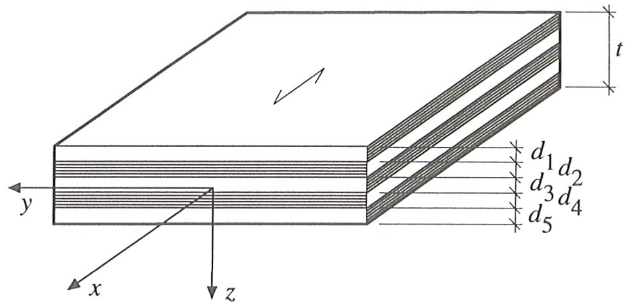


Figure 2 *Composition of balanced, 5 layers plywood cross section.* $d_4 = d_2$; $d_5 = d_1$.
⟵ : grain direction of face veneer

Physical properties

Density

One of the most important physical properties of wood based materials is the density. Depending on the percentage of adhesive and the compression of the bonding, the density of plywood is generally higher than the density of the wood from which it was made. As with solid timber, the elastic properties and strength of plywood are correlated with density. Density values are given in Table 2.

Moisture content

Like solid wood, the veneers are hygroscopic, and therefore the moisture content of plywood depends on the climatic conditions of the surrounding air (see Table 1). The moisture content of plywood is less than of solid timber due to the glue lines.

Surrounding air with temperature of 20°C and relative humidity of	30%	65%	85%
Equilibrium moisture content of plywood	~5%	~10%	~15%
Equilibrium moisture content of softwood	~6%	~12%	~17%

Table 1 *Equilibrium moisture content.*

Swelling/shrinkage

Changes in plywood moisture content below fibre saturation point cause changes in the geometrical properties of plywood panels. Because of the grain directions of adjacent layers, the deformations in the plane of the panel are small (about 0,02% per 1% change in moisture content). Perpendicular to the panel plane, in the case of rotary peeled veneers, a radial swelling/shrinkage similar to that of the solid wood species can be expected.

Creep

The increase in deformation of plywood with time, due to the combined effect of creep and moisture, is taken into account by the factor k_{def}. Plywood panels are slightly more prone to creep than solid timber due to the glue lines.

EC5: Part 1-1: Table 4.1

Durability

The natural durability of wood based panels depends less on the species of wood than solid timber. Additional factors which may affect the durability of plywood are

- thickness of veneers
- composition (use of different materials within the board)
- properties and quantity of adhesives.

Improved durability can be obtained by using selected wood species for the veneers, special lay-ups or by chemical protection. For the choice of specific wood species of suitable durability see EN 350-2 "Durability of wood and wood products. Natural durability of wood - Part 2: Guide to the natural durability and treatability of selected wood species of importance in Europe". The application of hazard classes of biological attack to wood based panels is given in EN 335-3 "Durability of wood and wood-based products. Definition of hazard classes of biological attack - Part 3: Application to wood-based panels".

EN 350 - 2

EN 335 - 3

Structural properties

The structural properties of plywood are affected by the following parameters

- geometrical factors (number and thickness of veneers; composition)
- material factors (wood species; moisture content)
- load factors (type of stresses; direction of stress related to grain direction of face veneer; duration of load).

In the case of bending, it is important to differentiate between

- bending perpendicular to the plane of the panel (see Figure 3)
- in-plane bending (see Figure 4).

It is also important to note the difference in properties related to the orientation of the board. The stress distribution in all cases is based on a linear stress-strain relation for the lay ups of the veneers and will be explained using an example for a 5-layered plywood panel.

Bending perpendicular to the plane

Bending perpendicular to the plane causes deflection of the panel perpendicular to the plane. The theoretical bending stiffness of a plywood panel with five veneers of thickness d is given by

$$EI = \Sigma E_i I_i \tag{1}$$

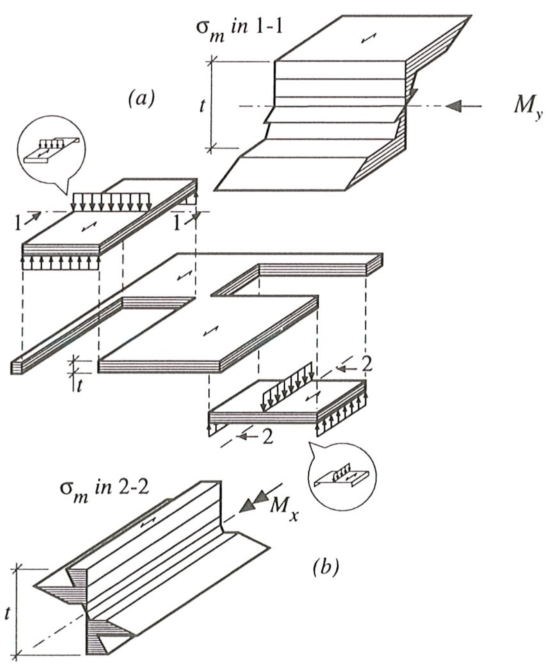


Figure 3 Bending perpendicular to the plane. (a) parallel to the grain of face veneer, (b) perpendicular to the grain of face veneer.

In an approximate calculation for the bending stiffness EI may be assumed as $E_{90,mean} = 0$ for the layers, i. e. ignoring the contribution of veneers stressed perpendicular to their grain.

With $E_{0,mean} = E_0$ and $b = 1$ gives for σ_m parallel to grain of face veneer (Figure 3a)

$$E_{\parallel} I = E_0 \left(3 \frac{d^3}{12} + 2\, d\, (2d)^2\right) = \frac{33\, E_0\, d^3}{4} \tag{2}$$

and for σ_m perpendicular to grain of face veneer (Figure 3b)

$$E_{\perp} I = E_0 \left(2 \frac{d^3}{12} + 2\, d\, d^2\right) = \frac{13\, E_0\, d^3}{6} \tag{3}$$

The resulting equations for the moduli of elasticity of the panel are as follows:

$$E_{\parallel} = \frac{33\, E_0\, d^3\; 12}{(5d)^3\; 4} = 0{,}79\; E_0 \tag{4}$$

$$E_{\perp} = \frac{13\, E_0\, d^3\; 12}{6 \cdot 125\; d^3} = 0{,}21\; E_0 \tag{5}$$

If, however $E_{90,mean}$ is taken as 1/30 $E_{0,mean}$, as would be typical for softwood veneers, the improvements in moduli are:

$E_{\parallel} = 0{,}80\, E_0$ for σ_m $\parallel$ grain of face veneer (6)
$E_{\perp} = 0{,}24\, E_0$ for σ_m $\perp$ grain of face veneer. (7)

For calculation of deflections the bending stiffness EI of plywood panels is needed where E means the modulus of elasticity, defined as above and I the second moment of total cross section. The weighting for different stiffness of the veneers is then attained.

When bending perpendicular to the plane is carried out, then planar shear ("rolling shear") occurs in the plane of the plies of a plywood panel (see Figure 5b).

In-plane bending
As a common case of in-plane bending the load carrying behaviour of I- and box-beam webs is well known. Usually the plywood panel of the web has the grain of face veneer running parallel to the beam axis.

For the plywood panel in the above example, in-plane bending results in the following. Firstly, ignoring the contribution of veneers stressed perpendicular to their grain, gives

$$E_{\parallel} I = 3 \frac{dh^3}{12} E_0 \quad \text{for } \sigma_m \parallel \text{ grain of face veneer} \tag{8}$$

$$E_{\perp} I = 2 \frac{dh^3}{12} E_0 \quad \text{for } \sigma_m \perp \text{ grain of face veneer} \tag{9}$$

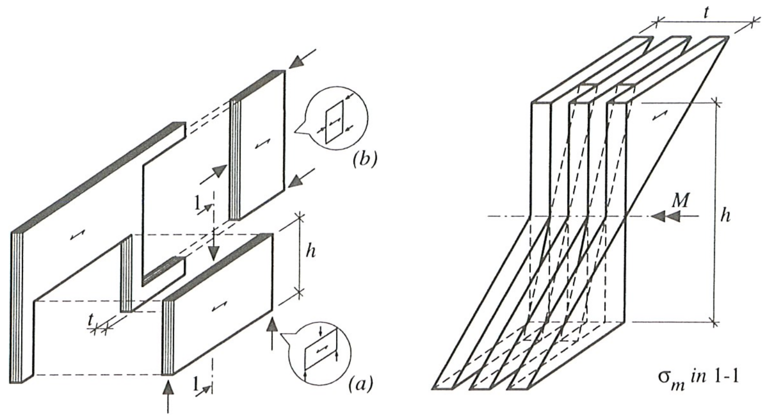


Figure 4 *In-plane bending (a) parallel and (b) perpendicular to the grain of face veneer.*

The resulting equations for the moduli of elasticity of the panel are as follows:

$$E_{\parallel} = \frac{d\ h^3\ E_0\ 12}{4 \cdot 5\ d\ h^3} = 0{,}60\ E_0 \tag{10}$$

$$E_{\perp} = \frac{2\ d\ h^3\ E_0\ 12}{12 \cdot 5\ d\ h^3} = 0{,}40\ E_0 \tag{11}$$

If $E_{90,mean} = E_{0,mean}/30$ is introduced, then it leads to

$$E_{\parallel} = 0{,}61\ E_0 \tag{12}$$
$$E_{\perp} = 0{,}41\ E_0. \tag{13}$$

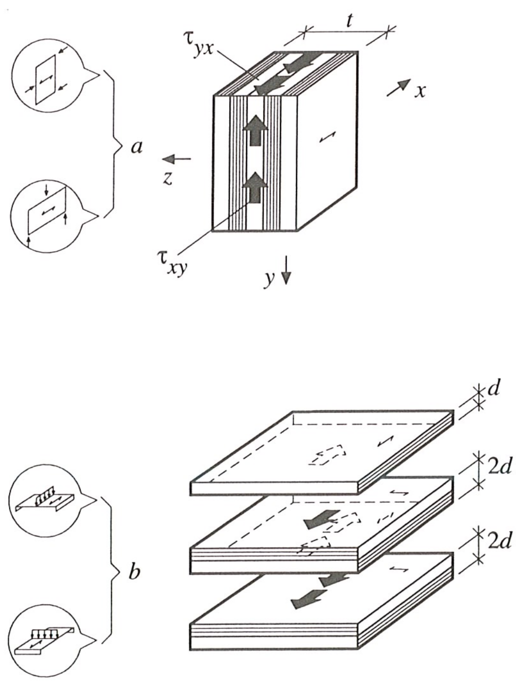


Figure 5 *(a) panel shear stress (b) planar shear stress (normal stresses are not shown).*

In the case of in-plane bending, panel shear occurs perpendicular to the plane of the panel (see Figure 5a). The panel shear strength is much higher than planar shear strength.

Tension and compression

For tension and compression in plane of plywood panels (see Figure 6) the elastic deformation may be calculated by using the summation of the longitudinal stiffnesses

$$EA = \sum E_i A_i \tag{14}$$

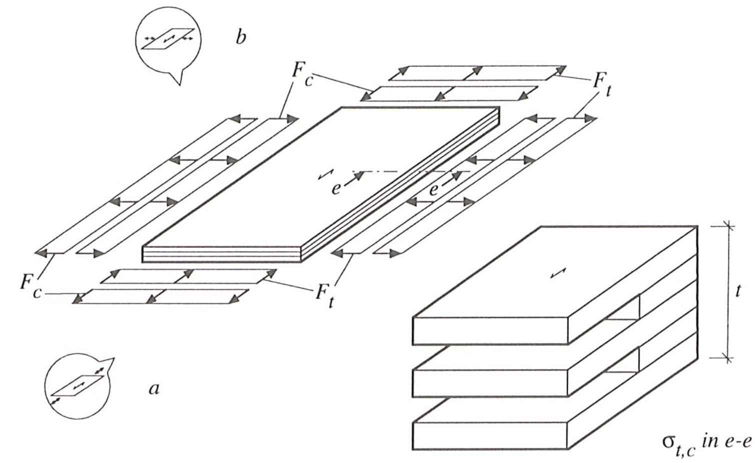


Figure 6 *In-plane tension and compression (a) parallel (b) perpendicular to the grain of face veneer.*

The application in the above example gives

$$E_{\parallel} = \frac{1}{5\,d}(3\,d\,E_0 + 2\,d \cdot 0) = 0{,}60\,E_0 \quad \text{for } \sigma_{t,c} \parallel \text{grain of face veneer} \tag{15}$$

$$E_{\perp} = \frac{1}{5\,d}(2\,d\,E_0 + 3\,d \cdot 0) = 0{,}40\,E_0 \quad \text{for } \sigma_{t,c} \perp \text{grain of face veneer} \tag{16}$$

Tension stresses perpendicular to the plane of plywood panels are to be avoided. Compression stresses perpendicular to the plane of plywood panels induce smaller deformation than in timber of the same species of wood, from which the veneers are made, because the transverse deformation is reduced by the lay up of the veneers.

Characteristic values

EN TC 112.406

For plywood panels which have a long history of structural use in the EC and EFTA countries, the characteristic values of mechanical properties and density values are given in EN TC 112.406 "Wood-based panels - Characteristic values for established products". For types of plywood not listed in EN TC 112.406, characteristic values shall be determined using the sampling techniques set out in EN 1058 - "Wood-based materials - Determination of characteristic values of mechanical properties and density" and testing procedures given in EN 789 "Timber structures - Testing of wood-based panels for the determination of mechanical properties for structural purposes".

EN 1058
EN 789

Characteristic density

The characteristic densities in EN TC 112.406 range from 350 kg/m^3 for softwood species up to 550 kg/m^3 for beech plywood. Some characteristic density values are given in Table 2.

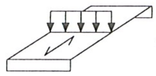
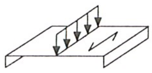
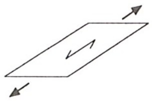
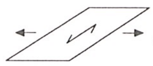
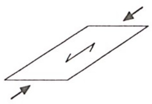
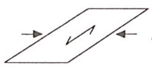
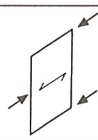
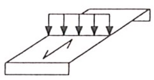
Fig.	type of characteristic strength	S-plywood[1] t mm	S-plywood[1] f_k N/mm²	FIN-plywood[2] t mm	FIN-plywood[2] f_k N/mm²	US-plywood[3] t^6 mm	US-plywood[3] f_k N/mm²	CAN-plywood[4] t mm	CAN-plywood[4] f_k N/mm²	D-plywood[5] f_k N/mm²
3(a)	 $f_{m,0,k}$	12,0	23,0	12,0	37,2	12,5	23,5	12,5	19,0	$77k_1$
		24,0	21,6	24,0	34,8	21,0	14,8	25,5	15,8	
3(b)	 $f_{m,90,k}$	12,0	11,4	12,0	27,6	12,5	12,2	12,5	7,3	$77(1-k_1)/k_3$
		24,0	12,4	24,0	29,0	21,0	10,1	25,5	8,7	
6(a)	 $f_{t,0,k}$	12,0	15,0	12,0	38,9	12,5	13,6	12,5	9,9	$77k_2$
		24,0	15,4	24,0	37,2	21,0	10,5	25,5	10,6	
6(b)	 $f_{t,90,k}$	12,0	12,0	12,0	32,9	12,5	7,2	12,5	6,3	$77(1-k_2)$
		24,0	11,4	24,0	34,1	21,0	6,9	25,5	6,6	
6(a)	 $f_{c,0,k}$	12,0	15,0	12,0	19,9	12,5	13,9	12,5	12,6	$58k_2$
		24,0	15,4	24,0	19,3	21,0	10,6	25,5	14,1	
6(b)	 $f_{c,90,k}$	12,0	12,0	12,0	17,5	12,5	8,1	12,5	9,0	$58(1-k_2)$
		24,0	11,4	24,0	18,1	21,0	7,7	25,5	9,7	
5(a)	 $f_{v,k}$	12,0 / 24,0	2,9	12,0 / 24,0	9,8	12,5 / 21,0	3,2	12,5 / 25,5	3,2	8,0
5(b)	 $f_{r,k}$	12,0 / 24,0	0,9	12,0 / 24,0	2,5	12,5 / 21,0	0,9	12,5 / 25,5	0,9	3,0
characteristic density ρ_k			410		550		410		410	550

Table 2 *Characteristic strength values in N/mm² and characteristic density values in kg/m³ according to EN TC 112.406 for established products.*

1. *Swedish plywood P30, spruce, unsanded*
2. *Finnish birch plywood, 1,4 mm veneer, sanded*
3. *US plywood C-D, exposure 1, group 1, unsanded*
4. *Canadian plywood, Douglas fir, regular or regular select sheathing, unsanded*
5. *German beech plywood (for k_1, k_2, k_3 see Equations (17), (18) and (19))*
6. *≥ 5-layers*

Characteristic mechanical properties

EN 635 - 2 and 3

Tables 2 and 3 give a selection of the established products from EN TC 112.406. Characteristic values for French and German plywood panels consisting of uniform wood species can be derived using the composition factors of equations (17) - (19), see Figure 7. The required equations listed in Tables 2 and 3 are valid for E, I and II veneer grades in accordance with EN 635 "Plywood. Classification by surface appearance", part 2 for hardwood and part 3 for softwood.

$$k_1 = \frac{d_m^3 - d_{m-2}^3 + d_{m-4}^3 - .... \pm d_1^3}{d_m^3} \qquad (17)$$

$$k_2 = \frac{d_m - d_{m-2} + d_{m-4} - .... \pm d_1}{d_m} \qquad (18)$$

$$k_3 = \frac{d_{m-2}}{d_m} \qquad (19)$$

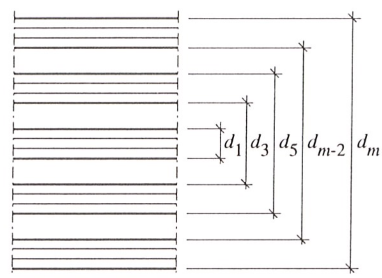


Figure 7 Multilayer (m layers).

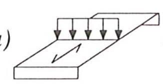
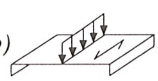
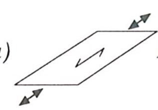
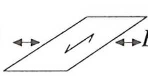
Fig.		S-plywood[1] t mm	S-plywood[1] E_{mean} N/mm²	FIN-plywood[2] t mm	FIN-plywood[2] E_{mean} N/mm²	US-plywood[3] t^6 mm	US-plywood[3] E_{mean} N/mm²	CAN-plywood[4] t mm	CAN-plywood[4] E_{mean} N/mm²	D-plywood[5] E_{mean} N/mm²
3(a)	 $E_{m,0,mean}$	12,0	9200	12,0	9800	12,5	10300	12,5	9200	$11000k_1$
		24,0	8700	24,0	8900	21,0	7800	25,5	6700	
3(b)	 $E_{m,90,mean}$	12,0	4600	12,0	6200	12,5	2500	12,5	2000	$11000(1-k_1)$
		24,0	5000	24,0	7100	21,0	2500	25,5	3300	
6(a)	 $E_{t(c),0,mean}$	12,0	7200	12,0	8500	12,5	6800	12,5	6000	$11000k_2$
		24,0	7400	24,0	8300	21,0	5200	25,5	6300	
6(b)	 $E_{t(c),90,mean}$	12,0	4800	12,0	7500	12,5	4600	12,5	4400	$11000(1-k_2)$
		24,0	4600	24,0	7700	21,0	3900	25,5	4300	

Table 3 Mean[7] values of modulus of elasticity in N/mm² according to EN TC 112.406 for established products.

Footnotes 1 to 6 see Table 2.
7. Characteristic value $E_{i,k} = 0,8\ E_{i,mean}$

For plywood of mixed wood species, EN TC 112.406 gives extended composition factors in order to take into consideration layers consisting of different wood species in one plywood cross section.

The factors k_1 and k_2 can be used for the calculation of characteristics of in-plane bending strength $f^*_{m,k}$ on the basis of bending strength perpendicular to plane $f_{m,k}$:

$$f^*_{m,0,k} = f_{m,0,k} \frac{k_2}{k_1} \tag{20}$$

$$f^*_{m,90,k} = f_{m,90,k} \frac{(1-k_2)}{(1-k_1)} \tag{21}$$

The mean value of the panel shear modulus $G_{v,mean}$ for the products in Table 2 ranges from 500 N/mm^2 for softwood species up to ~700 N/mm^2 for German beech plywood.

Concluding summary

- Plywood, a classic wood-based panel is produced on the basis of a well-established technology and used for many structural components.

- For the application of characteristic values it is important to differentiate between
  - bending perpendicular to the plane of the panel
  - in-plane bending.

- Characteristic values of mechanical properties for established plywood products can be taken from EN TC 112.406.

	type of characteristic strength	S-plywood[1]		FIN-plywood[2]		US-plywood[3]		CAN-plywood[4]		D-plywood[5]
Figure		*t* *mm*	f_k *N/mm*^{2}	*t* *mm*	f_k *N/mm*^{2}	*t*[6] *mm*	f_k *N/mm*^{2}	*t* *mm*	f_k *N/mm*^{2}	f_k *N/mm*^{2}
3(a)	$f_{m,0,k}$	12,0 24,0	23,0 21,6	12,0 24,0	37,2 34,8	12,5 21,0	23,5 14,8	12,5 25,5	19,0 15,8	$77k_1$
3(b)	$f_{m,90,k}$	12,0 24,0	11,4 12,4	12,0 24,0	27,6 29,0	12,5 21,0	12,2 10,1	12,5 25,5	7,3 8,7	$77(1\text{-}k_1)/k_3$
6(a)	$f_{t,0,k}$	12,0 24,0	15,0 15,4	12,0 24,0	38,9 37,2	12,5 21,0	13,6 10,5	12,5 25,5	9,9 10,6	$77k_2$
6(b)	$f_{t,90,k}$	12,0 24,0	12,0 11,4	12,0 24,0	32,9 34,1	12,5 21,0	7,2 6,9	12,5 25,5	6,3 6,6	$77(1\text{-}k_2)$
6(a)	$f_{c,0,k}$	12,0 24,0	15,0 15,4	12,0 24,0	19,9 19,3	12,5 21,0	13,9 10,6	12,5 25,5	12,6 14,1	$58k_2$
6(b)	$f_{c,90,k}$	12,0 24,0	12,0 11,4	12,0 24,0	17,5 18,1	12,5 21,0	8,1 7,7	12,5 25,5	9,0 9,7	$58(1\text{-}k_2)$
5(a)	$f_{v,k}$	12,0 24,0	2,9	12,0 24,0	9,8	12,5 21,0	3,2	12,5 25,5	3,2	8,0
5(b)	$f_{r,k}$	12,0 24,0	0,9	12,0 24,0	2,5	12,5 21,0	0,9	12,5 25,5	0,9	3,0
characteristic density	ρ_k	410		550		410		410		550

Table 2 *Characteristic strength values in N/mm^2 and characteristic density values in kg/m^3 according to prEN TC 112.406 for established products.*

1. Swedish plywood P30, spruce, unsanded
2. Finnish birch plywood, 1,4 mm veneer, sanded
3. US plywood C-D, exposure 1, group 1, unsanded
4. Canadian plywood, Douglas fir, regular or regular select sheathing, unsanded
5. German beech plywood (for k_1, k_2, k_3 see standing above)
6. 5-layers

		S-plywood[1]		FIN-plywood[2]		US-plywood[3]		CAN-plywood[4]		D-plywood[5]
Figure		*t* *mm*	E_{mean} *N/mm²*	*t* *mm*	E_{mean} *N/mm²*	t^6 *mm*	E_{mean} *N/mm²*	*t* *mm*	E_{mean} *N/mm²*	E_{mean} *N/mm²*
3(a)	$E_{m,0,mean}$	12,0 24,0	9200 8700	12,0 24,0	9800 8900	12,5 21,0	10300 7800	12,5 25,5	9200 6700	$11000k_1$
3(b)	$E_{m,90,mean}$	12,0 24,0	4600 5000	12,0 24,0	6200 7100	12,5 21,0	2500 2500	12,5 25,5	2000 3300	$11000(1-k_1)$
6(a)	$E_{t(c),0,mean}$	12,0 24,0	7200 7400	12,0 24,0	8500 8300	12,5 21,0	6800 5200	12,5 25,5	6000 6300	$11000k_2$
6(b)	$E_{t(c),90,mean}$	12,0 24,0	4800 4600	12,0 24,0	7500 7700	12,5 21,0	4600 3900	12,5 25,5	4400 4300	$11000(1-k_2)$

Table 3 *Mean[7] values of modulus of elasticity in N/mm² according to prEN TC 112.406 for established products.*
footnotes 1 to 6 see Table 2
7. characteristic value $E_{i,k} = 0,8\ E_{i,mean}$